Recent Advances in Hole Making of FRP/Metal Stacks: A Review

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Abstract: Weight reduction is a key driving force for materials development in aerospace industry, which leads to extensive usage of lightweight structural materials such as fiber reinforced polymer (FRP), titanium alloy, aluminum alloy, etc. Hole making is indispensable to assembling these lightweight components by riveted or bolted joints. However, hole making of FRP / metal stacks is always the most challenging task due to differences of material properties between FRP and metals. A comprehensive literature review on hole making of FRP/metal stacks in the last decade is given with a focus on four main aspects including drilling operation, drilling damages and machining parameter optimization, tool performance and wear, and developments in hole making technology. Finally, in order to ensure the precise and efficient hole making of FRP / metal stacks, an idea of low frequency vibration assisted drilling (LFVAD) FRP/metal stacks based on material removal characteristics is put forward by fully exploiting the unique advantages of LFVAD technology.

Key words: fiber reinforced polymer (FRP)/metal stacks; drilling; machining quality; tool wear; helical milling; vibration assisted drilling; abrasive water jet machining

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0 Introduction

Reducing structural weight is one of the major ways to improve aircraft performance and reduce oil consumption[1]. Therefore, the demand of lightweight structural materials with excellent mechanical properties, including fiber reinforced polymer (FRP), titanium and aluminum alloys, has been rapidly rising in the modern aerospace industry. These materials have been extensively used in both civil and military aircraft. For example, in Boeing 787 Dreamliner, FRP accounts for 50% by weight, while aluminum and titanium alloys account for 20% and 15%, respectively[2]. Meantime, the use of FRP is about 35% of the total structural weight, and titanium and aluminum alloys account for about 18% and 20% in three variants of F-35 Joint Strike Fighter which are conventional takeoff and landing (CTOL), shore take off/vertical landing (STOVL) and carrier variant (CV), as shown in Fig.1[3].

FRP is usually combined with titanium alloy, aluminum alloy or other metal materials to form FRP/metal stacks, which can obtain excellent mechanical properties with relatively low weight, and take the advantages of different materials and compensate their disadvantages by the combination of the respective positive material properties, e.g. ductile failure behavior of titanium and aluminum alloys with high specific stiffness and strength of FRP[4-7]. It is beneficial to reduce the emission and to develop new designs and part dimensions[6,8]. Carbon fiber reinforced polymer (CFRP) and titanium alloy are the primary candidates that are used as FRP/metal stacks due to comparable coefficient of thermal expansion and less potential for galvanic corrosion[9]. Specifically, titanium alloy is the only lightweight

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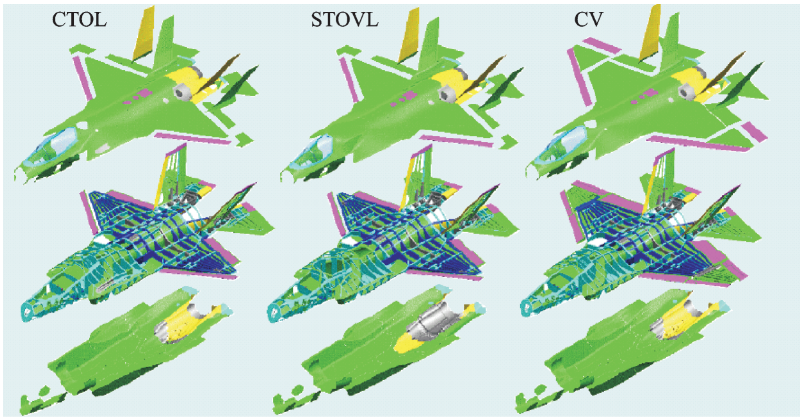


Material	CTOL/%	STOVL/%	CV/%
Aluminum-Lithium	5.2	4.9	3.8
Aluminum	17.9	16.3	13.9
Graphite/Epoxy	32.2	32.1	32.8
Graphite/BMI	2.4	2.6	2.4
Titanium	17.0	18.7	17.5
Steel	11.6	11.3	16.9
Other	13.6	14.0	12.7

Fig.1 Schematic diagram of F-35 materials[3]

metal material that can be directly combined to CFRP components without developing corrosion defects[10]. To assemble these lightweight components made of aluminum alloy, titanium alloy and FRP by riveted or bolted joints, hole making is an essential operation. Currently in aerospace industry, holes in FRP/metal stacks are produced by drilling each material layer separately followed by temporary assembly of the components for subsequent deburring and finishing to meet critical tolerance requirements[6,11-12]. For example, a three-step method was used in the Boeing Company: (1) Drilling CFRP with a diamond coated twist drill; (2) drilling titanium alloy with a carbide drill; (3) reaming the hole with a carbide reamer[13]. Single-shot drilling of stacks (without prior drilling, deburring and reaming) has become the main subject in recent years due to an urgent demand to improve productivity and efficiency[11]. For aircraft assembly, numerous holes are to be produced through the entire stacks, which requires a stable drilling process of stacks in a single procedure[14-15]. However, drilling FRP/metal stacks is still a challenge because FRP and metal materials have vastly different mechanical and thermal properties which make the tool and machining parameters of drilling FRP material different from those of drilling metal materials[16-17]. FRP drilling requires sharp cutting edges and special tool geometries, and these sharp cutting edges lead to high tool stresses and advance tool wear in metal drilling[15]. Meanwhile, the optimized processing parameters for drilling FRP, normally with high speed and low feed rate are different from those for drilling aluminum alloy or titanium alloy with low speed and medium feed rate[18-19]. Particularly for drilling CFRP/Ti stacks, titanium alloy belongs to difficult-to-machine due to its low thermal conductivity, high chemical affinity, and continuous chips[20], so drilling CFRP/Ti stacks usually results in rapid tool wear and severe hole damage including delamination, matrix degradation, and exit burr defect[17]. In addition, the heat generated during drilling metals may cause thermal damage to FRP and expedite tool wear, meanwhile the metal chips may scrape the surface of the machined surface of FRP hole wall. Therefore, the extensive application of FRP/metal stacks, the considerable quality and tool wear issues in drilling process provide motivation for academic and industrial research in the last decade.

In this paper, the drilling characteristics of FRP/metal stacks are first presented. Then the machining quality problems and tool wear are reviewed. Finally, the promising methods for improving quality and tool life in hole making of FRP/metal stacks are also summarized. This comprehensive review will help researchers to understand the necessary knowledge for hole making of FRP/metal.

1 Drilling Operation

Drilling is an essential operation for assembling FRP and metal materials. Although drill passes sequentially through FRP and metal materials, drilling FRP / metal stacks is somewhat different from drilling individual layer (FRP or metal materials) because the process of drilling the lower layer material will affect the quality of the machined surface of the upper layer. Furthermore, drilling forces and temperature significantly affect machining quality in drilling FRP / metal stacks. In this section, a brief description of characterization, forces and temperature of drilling FRP/metal stacks will be given.

1.1 Drilling process characterization

There are four stacked sequences in drilling FRP/metal stacks, i.e. FRP/metal, metal/FRP, metal/FRP/metal and FRP/metal/FRP stacks. No matter what sequence, drill must cut two or more different materials. Furthermore, drill simultaneously entangles two materials in the bi-material interface, as shown in Fig. 2[21]. Thus, drill subjects to variable mechanical and thermal loads in a short time due to differences of material properties between FRP and metal materials, which could easily lead to premature tool failure.

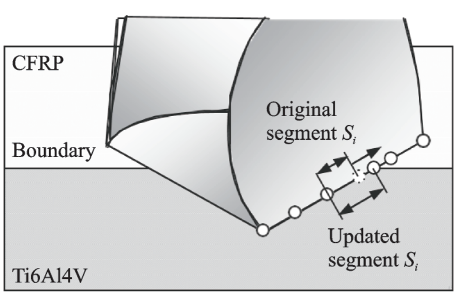


Fig.2 Schematic of drilling bi-material interface[21]

In addition, chip of lower layer materials has to flow through the upper layer when it transports through the chip grooves. FRP layer is located in the upper, the sharp, hot and hard metal chip could scrape and damage the hole surface of FRP[8,22]. Moreover, the adhesion of metal chips on the cutting edges and clogging of drill flutes by continuous metal chips could consequently deteriorated the machined surface as shown in Fig.3[22]. In general, premature tool failure and chip removal problem are two key challenges in drilling FRP/metal stacks.

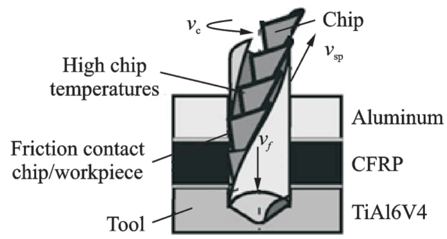


Fig.3 Chip removal problems in drilling FRP / metal stacks[22]

1.2 Drilling forces

Drilling forces include thrust force and torque. Typical thrust force and torque vary with depths in drilling FRP / metal stacks, as shown in Fig. 4[23]. There are seven regions in the thrust force and torque profiles according to the drill locations. It was found that tool geometry, feed rate and spindle speed have significant effects on thrust force[17,24]. The feed rate has more significant effects on the thrust force than spindle speed does[23].

Since the thrust force has a linear relationship with the push-out delamination[24] and surface roughness[25], some researchers have predicted the critical

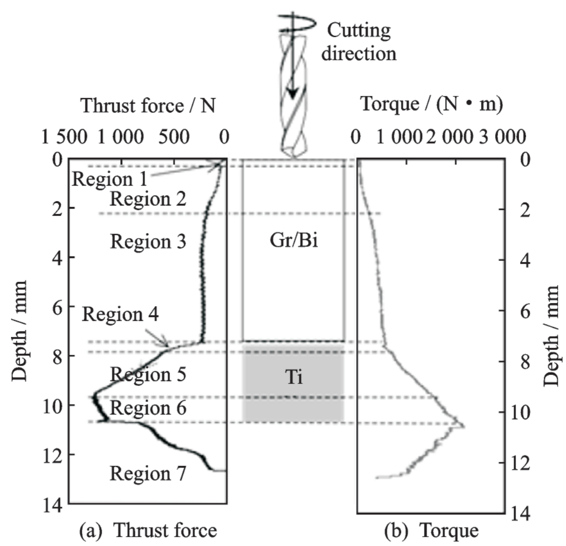


Fig.4 Typical cutting forces versus depths[23]

thrust force by establishing mathematical model or finite element model to avoid delamination in drilling of FRP/metal stacks. Matsumura et al.[21] presented a cutting force model in which cutting edges were divided into small segments in drilling of multi-layer materials. Qi et al.[26] established a mechanical model for predicting the critical thrust force on the basis of linear elastic fracture mechanics, classical bending plate theory and the mechanics of composites. In order to predict the thrust force variation with worn drill, Luo et al.[27] developed a mechanistic model which was characterized by the cutting edge radius in drilling FRP/metal stacks.

1.3 Drilling temperature

High temperature, which is produced by metal cutting or caused by metal chips accumulated inside the drill flutes, could result in FRP matrix degradation when drilling FRP/metal stacks and increased the radial distance of damage at the interface of FRP/metal[23]. Moreover, high temperature in the drilling region increased tool wear leading to poor surface finish. Especially for drilling CFRP / Ti stacks, low thermal conductivity and strong affinity to tool materials of titanium further increase temperature[20,23,25]. It was observed that high temperature induced CFRP damage near and around the hole region at the CFRP / Ti interface, as shown in Fig.5[23].

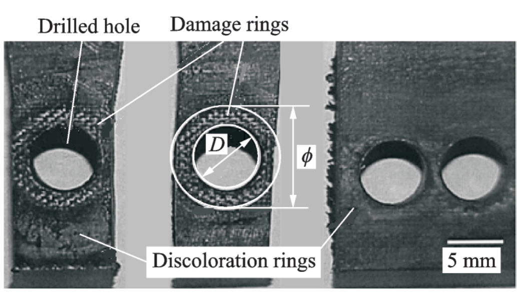


Fig.5 CFRP damage region at the CFRP/Ti interface[23]

Brinksmeier et al.[28] observed that the average temperature increased significantly from drilling the aluminum, over CFRP, to the titanium layer during drilling Al/CFRP/Ti stacks and indicated that heat generated during Ti drilling damaged CFRP. Wang et al.[29] investigated the drilling temperature in drilling CFRP / Al stacks and found that it increased with the increase of spindle speed and with the decrease of feed rate. At the same time, the cavities were formed in the surface of CFRP due to the resin degradation by high drilling temperature.

2 Drilling Damages and Machining Parameter Optimization

Hole machining defects in drilling FRP/metal stacks include delamination, fiber pullout, and hole wall damage by metal chip in the FRP component, exit burrs in the metal component, and hole size error, roundness error, position error, etc. in both components. Fig. 6[8,30] shows the schematic diagram of the hole machining defects distribution in FRP/metal stacks. These defects usually result in performance deterioration in the components as well as failure to meet the high-precision requirements of the aircraft industry[20]. Thus, in this section, the drilling parameter optimization will be introduced after drilling damages are summarized in drilling FRP/metal stacks.

2.1 Delamination in FRP laminates

Drilling-induced delamination is a phenomenon which the layers of the FRP laminates separate when the thrust force exceeds the inter-laminar strength of the FRP[24]. Unfortunately, it leads to a considerable reduction in the fatigue strength, which degrades the long-term performance of the FRP[24]. Moreover, due to delamination damages, the rejection of FRP components once was as high as 60% in aircraft industry[26,31]. Thus, delamination has always been the focus of academic and industrial attention. For drilling single FRP laminate, there are two kinds of delamination, i.e. peel-up delamination at the entry and push-out delamination at the exit, as shown in Fig.7[32]. The delamination at the exit is generally severe and often extends many layers into the laminate. Thus, numerous literatures focus on exit delamination[24,26,33-37].

For drilling FRP/metal stacks, the mechanism of delamination formation is similar to that for drilling single FRP laminate, but delamination severity mainly depends on the stacked sequence of the FRP / metal stacks. Normally, delamination when

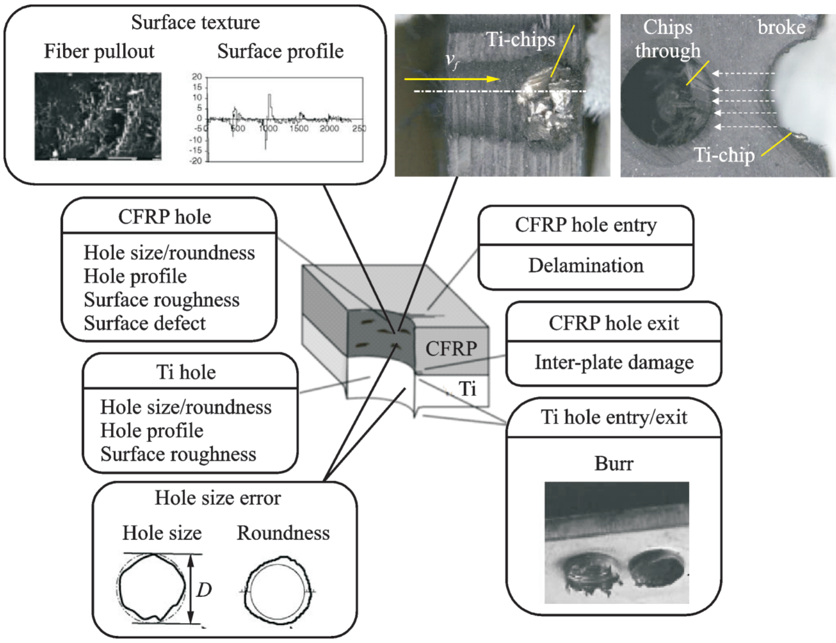


Fig.6 Hole quality features of FRP/metal stacks[8,30]

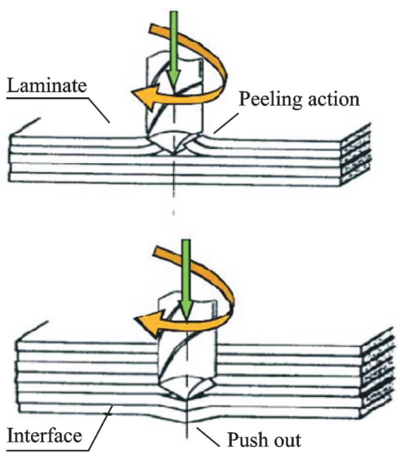


Fig.7 Delamination at the entry and exit[32]

drilling starts from FRP to metal is less serious than that of drilling from metal to FRP, because the metal can act as a backup plate to reduce delamination[23-25,38-40]. However, difference from drilling single FRP laminate is that delamination at the entry and in the shim-layer between FRP and metal is affected by the metallic chip transport during drilling FRP/metal stacks[22,41]. Based on the experimental results in drilling CFRP/Ti stacks, Park et al.[42] concluded that entry delamination of CFRP laminate became pronounced due to Ti chips and Ti adhesion on the tool drill margin. Montoya et al.[41] has proved it by observing the images before and after metal part drilling and chip evacuation, as shown in Fig. 8. There was not FRP delamination observed before creating metallic chip (Fig.8(a)), but after completed drilling process, the FRP delamination reached more than 2 mm (Fig.8(b)).

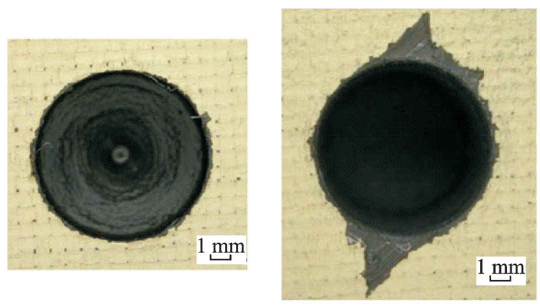


Fig.8 CFRP damages at the hole entry[41]

Xu et al.[43] has studied the chip formation process under the Ti→CFRP cutting sequence as shown in Fig.9. In this condition, delamination dam-

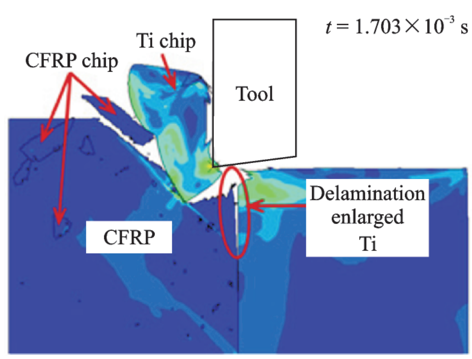


Fig.9 Chip formation process under the Ti→CFRP cutting sequence[43]

age took place on the Ti/CFRP contact boundary because the Ti chip could easily bend into the interface region and CFRP phase, then could push down the uncut CFRP layer.

2. 2 Damage on hole wall of FRP

The damage on the FRP hole wall during drilling FRP/metal stacks is more serious than that during drilling single FRP laminate because the metallic chip continuously scratches the internal surface of the FRP hole wall. Brinksmeier et al.[22] carried out the drilling experiment of Al/CFRP/Ti stacks and observed catastrophic erosion of the CFRP. The similar results were also confirmed by other studies[5,44-45].

Shyha et al.[6] studied the hole quality of drilling CFRP/metal stacks and compared the effects of aluminum chip and titanium chip on the machined surface of CFRP by observation of topographic maps for the CFRP hole, as shown in Fig.10. Results indicated that the spiral sharp Ti chip caused more serious damage to the CFRP hole wall than Al chip did.

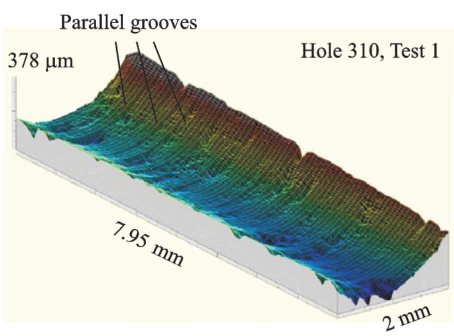


Fig.10 Topographic maps for the CFRP hole[6]

In addition, Yagishita[46] observed that the space between CFRP and Ti layers was clogged with continuous Ti chips and the exit of CFRP was scraped by the chips. Accordingly, the exit of CFRP was chamfered as shown in Fig.11(a). Fig.11(b) indicated the schematized section of CFRP/Ti stacks after the chamfering occurred.

2. 3 Exit burrs of metal material

Most drilling processes cause burrs on both entry and exit of aluminum and titanium alloys. The exit burr is usually concerned because it is much

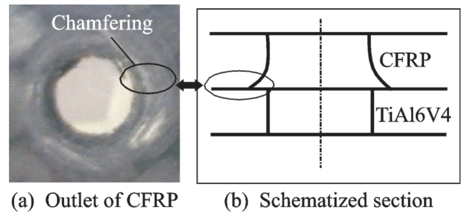


Fig.11 Microscope photograph of outlet of CFRP and schematized section of stacks after chamfering[46]

larger in size. In FRP/metal stacks, especially in FRP/Ti stacks, the burr between FRP and metal is a major problem, which needs disassembly of the stacks, deburring and reassembly[38]. Therefore, prevention or minimization of the burrs formation is significant.

The main reasons of the burr formation reported in Refs.[4,6,47] are attributed to the high localized temperature and mechanical influences. In addition, the burr formation primarily depends on the cutting conditions, the tool material and geometry[47].

Ramulu et al.[23] studied the effects of drill materials and process parameters on Ti burrs during drilling CFRP/Ti stacks and found that carbide drill led to the smallest burrs compared with high-speed steel (HSS) and high-speed steel cobalt (HSS-Co) drills. At the same time, low spindle speed and high feed rate was prone to diminishing the burr height. Kim et al.[30,48] pointed out that polycrystalline diamond (PCD) drill could reduce the burr height when drilling CFRP/Ti stacks.

2. 4 Hole size and geometrical accuracy

The dimensional mismatch is another consideration where FRP holes are always larger than the metal holes[6,9,11,23], while the non-coaxiality and perpendicularity in drilling FRP/metal stacks are also common problems[49-50]. According to Refs.[6, 22, 45], the different elastic modulus and thermal expansion coefficients between FRP and metals resulted in different elastic deformation during drilling process and varying dimensional tolerances along the drilled hole. Park et al.[45] studied the effect of cutting parameters on the dimensional tolerance and the hole roundness, and found that the amount of oversize was high at high cutting speed and low feed because of vibrations induced at higher cutting speed and feed. The results obtained by Shyha et al.[6] showed undersized holes were produced using flood coolant while oversized holes were produced using the spray mist environment for both Ti and CFRP segments. The main reason was thermal expansion of the materials from increased cutting temperature caused by the lack of coolant access and poor chip evacuation. Brinksmeier et al.[22] presented that reduction of mechanical loads by using the step drill caused minor elastic behavior and lower tolerances. Meanwhile, dimensional tolerances were reduced by using minimum quantity lubrication (MQL).

In addition to the experimental study of machining defects, the subsurface damage of the interface by numerical approach has also been presented[51].

2.5 Machining parameter optimization

The machining condition in drilling plays an important role on hole quality and tool life. Due to the different machining properties of two or more distinct materials, there are different optimal cutting parameters, tool geometries and materials for each material[52], which leads to a compromise in tool geometries and cutting parameters. The cutting parameter selection in drilling FRP / metal stacks should match that of the more difficult to drill material rather than that of the easier to drill material[39]. For example, the machining parameter selection in drilling FRP / Ti should match titanium alloy because the drilling of titanium alloy causes the biggest problem.

In order to improve machining quality, optimization of machining parameters including cutting speed and feed rate has been investigated. Ramulu et al.[23] recommended that the best condition for drilling CFRP/Ti stacks was at 0.08 mm/r and 660 r/min with carbide drills. Zitoune et al.[18] investigated the machining parameters during drilling of CFRP / Al stacks and concluded that preferable spindle speed and feed rate was 2 020 r/min, 0.1 mm/r and above to break the chip of aluminum and feed rate 0.05 mm/r was suitable for demanding of CFRP surface. Kim et al.[48] utilized PCD drill to drill the CFRP / Ti stacks. It was found that hole size errors highly depended on feed rate and exit burr heights increased with the increase of the speed and feed. Park et al.[42] presented that better hole surface finish could be obtained on the condition of low speed in drilling CFRP/Ti stacks. Kuo et al.[11] evaluated the influence of cutting speed and feed rate on workpiece surface integrity with diamond coated drill in drilling Ti/CFRP/Al stacks. The results showed that hole quality in CFRP deteriorated with increasing feed rate, which was confirmed by another literature[38]. Zhang et al.[53] concluded that the best machining parameters were at the spindle speed of 4 000 r/min, and the feed rate of 0.04 mm/r in drilling CFRP/Al stacks. Caggiano et al.[54] asserted that the best results were obtained at moderate spindle speed (3 000 and 4 500 r/min) and medium feed 0.10 and 0.15 mm/r in drilling Al/CFRP stacks.

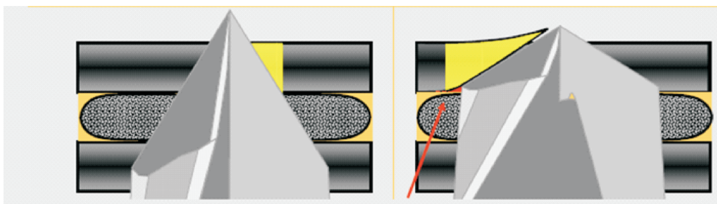
Furthermore, Neugebauer et al.[55] and Wertheim et al.[56] changed the machining parameters during drilling CFRP/Al stacks to overcome the compromise, i.e., using the most suitable parameters for each material. The results showed that the drill position could be monitored by the acoustic emission system. However, the machining quality was not analyzed in detail.

3 Tool Performance and Wear

Besides frequently occurring damages of the hole surface, tool wear or catastrophic failure is another major problem in drilling FRP / metal stacks[17]. Even though the cutting parameters may be adopted in accordance with the actual material layer, compromises have to be made in selecting tool geometry and materials that always results in the short tool life, poor machining quality and high machining cost[14,17]. Especially for drilling CFRP/Ti stacks, the high chemical reactivity, low thermal conductivity and deformation coefficient of titanium alloy always result in severe tool wear, while the high hardness of carbon fibers in CFRP also decreases the tool durability[22-23,42,57-58]. Thus, some studies focused on the tool performance, tool wear as well as its impacts on drilling machinability of FRP/metal stacks[59]. In this section, the drill performance of various geometries and materials, as well as drill wear mechanism will be reviewed in drilling FRP/metal stacks.

3.1 Tool performance

As above mentioned, the significantly divergent machining conditions of FRP and metal materials need compromises in tool geometries as well as materials[14]. For example, PCD and diamond coating drills have preferred in drilling FRP while carbide drills have been the preferred tool for drilling metals, since a lot of heat generated in drilling metals would degrade the diamond coating and carbide drills would be worn out very fast in drilling FRP[13,39]. The point angle of drill for FRP avoiding delamination in the exit is usually smaller than that for metals as shown in Fig.12[16]. Since the geometries of FRP drills cannot meet the demands of FRP / metal stacks drilling, twist drill geometries are more appropriate and must be improved[15,23].



(a) Small point angle (b) Large point angle

Fig.12 Effect of point angle on delamination[16]

In terms of drill geometry, Brinksmeier et al.[22] pointed out that use of adapted step drills improved machining quality and tool wear, while using tool coatings of TiB_2 or diamond were only achievable for tool wear during drilling CFRP/Ti/Al stacks. Zitoune et al.[60-61] showed that double cone drill outperformed standard drill in thrust force and damages in drilling of copper mesh/CFRP stacks and CFRP/Al stacks. However, Soo et al.[62] pointed out that double cone geometry drill was inappropriate for drilling CFRP / Al stacks. Senthilkumar et al.[52] pointed out that the overall performance of 130° point angle drill was better than that of 118° point angle drill. Alonsoa et al.[63] assessed the influence of flute number and a stepped design in drilling CFRP / Ti stacks and found that the stepped drill with three flutes yielded better performance.

In terms of the drill materials, most recent studies focused on carbide, coating and PCD. Park et al.[39,64] comparatively investigated characteristics of boron - aluminum - magnesium (BAM) coated drill, PCD drill and carbide drill. It is found that BAM coating is beneficial for drilling CFRP/titanium stacks at high cutting speed and the PCD drill was superior to carbide drill. In addition, nano-coated (nc-CrAlN/a-Si3N4) drill improved the machining quality by compared with uncoated drill in drilling CFRP/Al stacks[5].

However, some studies showed that coated tools may not always produce promising results. Shyha et al.[6] pointed out that there were only marginal effects of drill surface condition (diamond coated, uncoated, C7 coated) on hole quality. Li et al.[58] investigated the cutting performance of milling tools with and without coatings (diamond coating, TiAlN+AlCrN coating and TiAlN coating) in helical milling of Ti/CFRP stacks. It was found that uncoated tools exhibited the best cutting performance while diamond-coated tools showed the greatest degradation. Kuo et al.[65] also suggested that the diamond coated tool was not suitable for drilling FRP/metal stacks.

3.2 Tool wear analysis

FRP drilling involves excessive abrasive wear (edge rounding wear) and tool edge chipping[39,66]. On the contrary, tool wear mechanisms in metal drilling are different from those in FRP drilling. For example, Ti drilling mainly involves the severe edge chipping and flank wear. Furthermore, the mechanisms in FRP/metal stacks drilling are usually a mixture of them, and more complicated, coupled and interrelated[17].

Park et al.[39,42] studied the wear mechanisms of carbide and PCD drills in drilling CFRP/Ti stacks. It is found that abrasion and adhesion of titanium were the dominant tool wear mechanisms. Ti adhesion for the carbide drills was more serious than that for the PCD drills, but the PCD drills had a significant amount of cutting edge chipping. In addition, Ti drilling accelerated flank wear while CFRP drilling deteriorated cutting edge.

Wang et al.[66] presented that the tool life in drilling CFRP/Ti stacks was improved due to the elimination of severe edge chipping which prevails in Ti drilling. In drilling CFRP/Ti stacks, because the carbon fibers in CFRP layer brushed off the Ti adhesion and smoothed the cutting edge, the severe edge chipping was eliminated. However, Poutord et al.[57] concluded that the major tool wear came from CFRP while the wear generated by Ti was mostly restricted to cutting edge chipping on the drill corner. The build-up layer of Ti adhesion was not so strong that could protect the tool edge during the CFRP drilling. In addition, Isbilir et al.[25] concluded that tool wear was accelerated in drilling CFRP/Ti stacks because of the combination of the wear mechanisms. Fernandez-Vidal et al.[67] studied wear mechanisms produced in drilling CFRP/Al stacks. It was found that the main wear form was adhesion. Wang et al.[68] found that tool wear was affected by the interaction of carbon fiber and Ti-adhesion in drilling Ti/CFRP stacks using carbide step drill. In addition, metal chips frequently clogged in drill flute which caused premature tool failure[22]. Meanwhile, excessive cutting edge rounding due to the brittle and abrasive fibers led to the increase of cutting forces and temperature in the metals, which usually resulted in a catastrophic failure of the tools[14].

4 Developments in Hole Making Technology

Due to the limited improvement in machining quality and tool life by the selection of tool and optimization of cutting parameters in single-shot drilling FRP/metal stacks, the interest to overcome the challenges of drilling is still rising. So far the alternative methods include helical milling, ultrasonic assisted drilling, low frequency vibration assisted drilling (LFVAD), abrasive water jet (AWJ) machining, etc. In this section, developments of these hole making technologies will be introduced.

4.1 Helical milling

Helical milling or orbital drilling generates holes by use of a milling tool on a helical path into the workpiece (Fig.13)[69]. Thus, the hole diameter is determined by the tool diameter and the diameter of the helical path. Compared with the conditional drilling, lower force and temperature are generated while better hole quality can be achieved in helical milling process due to the small contact area between tool and workpiece and sufficient chip removal space[7].

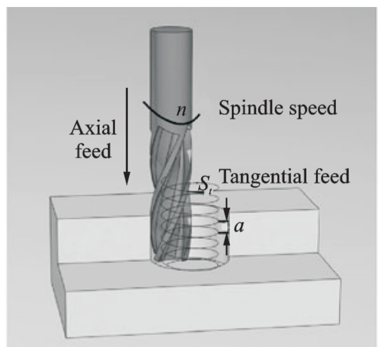


Fig.13 Schematic of helical milling process[69]

Brinksmeier et al.[28] investigated the thermal and mechanical influence of helical milling and conventional drilling processes during drilling Al / CFRP / Ti stacks. It was found that significantly lower thermal and mechanical loads and better surface integrity were obtained at the same cutting speed and material removal rate in helical milling. He et al.[69] employed varying machining parameters during helical milling CFRP / Ti stacks and pointed out that tool life, cutting forces and hole quality were improved compared with those without varying machining parameters. Wang et al.[7] investigated the strategies in helical milling CFRP / Ti stacks and found the best milling sequence and the advantage of pilot holes in hole quality. Then, they presented a two-step technique to reduce delamination of large diameter holes in helical milling CFRP/Al stacks[19].

4.2 Ultrasonic assisted drilling

Ultrasonic assisted drilling combines conventional drilling with high-frequency vibration at low amplitude superimposed at the tooltip, as illustrated in Fig.14[70], which enhances the cutting process and improves hole quality in difficult-to-machine materials[13,71-72].

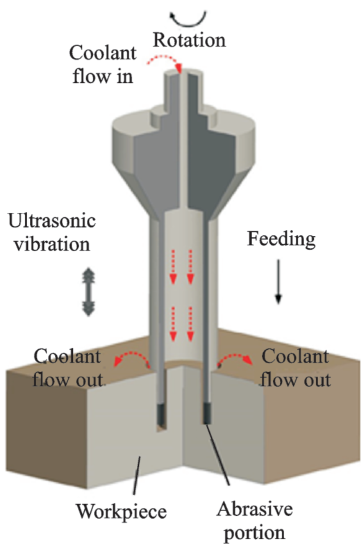


Fig.14 Illustration of ultrasonic assisted drilling[70]

Cong et al.[13,72] investigated the cutting force, machining quality and tool life in ultrasonic assisted drilling CFRP/Ti stacks. The results demonstrated reductions in cutting force, torque, CFRP surface roughness as well as delamination and improvement in tool life. They also compared variable feed rate (high feed rate for CFRP and low feed rate for Ti) with fixed feed rate in ultrasonic assisted drilling of CFRP/Ti stacks. Onawumi et al.[71] investigated the effect of feed rate on hole quality of ultrasonic assisted drilling CFRP/Ti stacks by comparison with conventional drilling and found improvement in hole quality using ultrasonic assisted drilling. Dong et al.[73] studied burr formation during ultrasonic assisted drilling of CFRP/Al stacks and developed a theoretical burr height model. James et al.[74] explored the possibility of micro ultrasonic assisted drilling CFRP/Ti stacks and studied the effects of process parameters on the surface quality and material removal rate.

4.3 Low frequency vibration assisted drilling

In Low frequency vibration assisted drilling (LFVAD) process, the feed rate is superimposed by axial sinusoidal oscillations to control the tool engaging and retracting mechanism, which owns much lower frequencies and higher amplitudes in comparison to ultrasonic assisted drilling[8,14,20].

Pecat et al.[8,14] investigated hole quality, cutting temperature and tool wear of carbide drills with varied coatings in LFVAD CFRP/Ti stacks. The results showed that damage of the CFRP hole surface and the cutting temperature were significantly reduced, and flank wear and the adhesions at the cutting edges were notably lower, as well as the tool life were increased in comparison with conventional drilling due to lower process temperature and more stable process. At the same time, the chip extraction was more efficient due to small chip segments. Bleicher et al.[15] also pointed out that chip congestion could be avoided due to the small chip segments, and the surface damage was significantly reduced, and a burr formation could be avoided by the experiment of LFVAD CFRP/Steel stacks. Additionally, LFVAD resulted in a reduction of the cutting force and tool wear. Hussein et al.[20] investigated the effect of machining parameters with MQL on LFVAD CFRP/Ti stacks. The results showed that cutting temperature was significantly reduced due to fluent chip evacuation and cooling mechanisms, as well as chip morphology changed. Li et al.[75] investigated the performance of LFVAD CFRP/Ti stacks through forced air-cooling equipment. The results indicated that the small titanium chip segments were removed efficiently with the help of the forced air-cooling, and flank wear rates and cutting temperature were reduced compared with the conventional drilling.

4.4 AWJ machining

AWJ machining has the advantages in cutting speed, environmental dust and thermal damage residual stresses[9]. In recent years, AWJ machining has been explored to overcome the limitation of conventional machining processes. Ramulu et al.[9,76-77]

investigated the feasibility and machinability of AWJ contouring CFRP / Ti stacks and developed mathematical models to predict the influence of process parameters on machining quality. Escobar-Palafox et al.[78] studied the characteristics of AWJ drilling Ti/CFRP and CFRP/Ti stacks and developed mathematical models to predict taper ratio in relation to process variables. Alberdi et al.[79] and Ruiz-Garcia et al.[80] evaluated the viability of AWJ industrial application for machining CFRP / metal stacks and optimized the process parameters. The results showed that the positive taper in titanium and negative in CFRP led to an X-type or barrel-type kerf profile according to the stacks configuration, as shown in Fig.15[79].

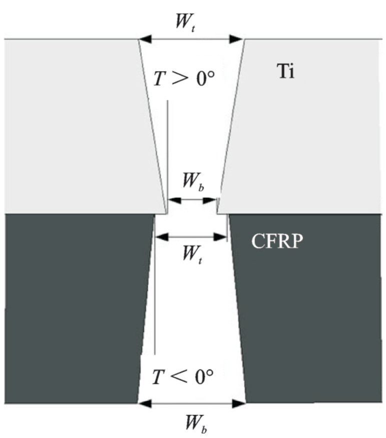


Fig.15 Example of kerf profile[79]

5 Conclusions

This paper has presented a comprehensive review on the achievements of hole making of FRP/ metal stacks in the last decade in terms of drilling operation, drilling damages and machining parameters optimization, tool performance and wear, and developments in hole making technology. On the basis of comprehensive analyses, several conclusions and prospects on future work are summarized as follows.

(1) The remarkable challenges in drilling FRP/ metal stacks are premature tool failure and chip removal problem. So far cutting theories focus on modeling and predicting the cutting forces, but cutting temperature that leads to deterioration of FRP material properties and reduction of tool life is still under studied. Future work should be expected to address the issue.

(2) For conventional drilling, the cutting parameter optimization and tool geometrical design only partly solve the problems of machining quality and tool wear caused in drilling FRP / metal stacks because of inefficient evacuation of metal chip and high temperature.

(3) The alternative methods mainly include helical milling, ultrasonic assisted drilling, LFVAD and AWJ machining to overcome the challenges in the hole making of FRP / metal stacks. However, rapid tool wear still occurs in helical milling. Furthermore, helical milling has lower machining efficiency and high requirements for equipment, which makes it difficult to use at the assembly line. On the other hand, the kerf variation and metal burr formation are unavoidable phenomena when AWJ machining FRP/metal stacks. Therefore, AWJ machining hardly meet the quality requirements.

Ultrasonic assisted drilling and LFVAD both belong to vibration assisted drilling methods. Ultrasonic assisted drilling with high frequency vibration and low amplitude is beneficial for thinning metal chip, but it still generates continuous chip. Thus, there is still the problem of chip removal and meanwhile ultrasonic equipment is not feasible to apply in practical assembly. On the contrary, LFVAD with low frequency vibration and high amplitude results in an interrupted cut, which considerably facilitates extraction of the metal chips and reduces the cutting temperature. Currently, the research on this technology is just beginning, and single sinusoidal vibration mode, the same amplitude and frequency for different materials are usually adopted. This may lead to delamination of FRP and tool fracture due to high dynamic loads. Therefore, in the future work, the studies of vibration mode, the matching between vibration parameters and material removal characteristics are urgently to address the problems in hole making of the FRP/metal stacks.

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