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Drilling Temperature and Hole Quality in Drilling of CFRP/Aluminum Stacks Using Diamond Coated Drill

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Composite/metal stack materials, most often consisting of carbon fiber reinforced polymer (CFRP) composites and aluminum or titanium alloy (Al or Ti), have been widely used in the aviation industry. It is still a challenge to make holes on the composite/metal stack materials with high quality. This paper aims to investigate the influence of drilling parameters on the drilling of stack materials consisting of T800/X850 CFRP and 7075-T651 Al with regard to drilling force, drilling temperature, hole diameter and hole surface quality. Diamond coated drill bits with double point angles were employed in the drilling tests. The drilling temperature was measured utilizing a rotational motion temperature measuring system. It is indicated that maximum drilling temperature increases with the increase of spindle speed, while, it decreases with increasing feed rate. The thrust force and drilling temperature increase abnormally during drilling of the Al layer, which can be attributed to the evacuation difficulty of the long and flexible Al chips. It is found that sudden drops in the surface profile of CFRP are caused by the cavities owning to the resin degradation effects. The influences of different stack sequences on the drilling temperature and hole surface quality have also been discussed.

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NOMENCLATURE

n = Spindle speed
f = Feed rate
Fz = Thrust force
T = Drilling temperature
d = Drilling depth
D = Hole diameter
t = Time

1. Introduction

From the F35 Lightning II to the Airbus A380 and the Boeing 787 Dreamliner, composite/metal stack materials, most often consisting of multiple layers of carbon fiber reinforced polymer (CFRP) composites and aluminum or titanium alloy (Al or Ti), have been widely used in aviation industry. For example, the Boeing 787 Dreamliner is made up of 50% composite, 20% Al, 15% Ti, 10% steel and 5% other materials.[1] During the assembly of composite/metal components, tens of thousands of holes need to be drilled to meet the mechanical bolting or riveting demand. The assembly accuracy of them is of vital importance to the flight performance of the aircrafts. The assembly accuracy depends critically on the quality of machined holes. In order to obtain high quality holes, "single shot" drilling has been proposed as a potential solution instead of drilling each material separately.[2] However, It is an extremely challenging task to drill of composite/metal stacks due to the different machinability characteristics between them. Various hole defects often occur which have seriously affected the assembly accuracy.

During drilling of composite/metal stack materials, potential hole quality issues may include: poor diameter tolerance, poor hole surface quality, matrix resin degradation, fiber burrs and delamination. Different researchers[3-6] have indicated that most of the hole quality problems mentioned above are mainly associated with an incorrect application of the tool geometry and inappropriate machining conditions.

Diameter tolerance is one of the important indicators evaluating the hole quality. The difference of elastic modulus between composite and metal will cause different machining deformations. Therefore, the diameters of different layers in the same hole are inconsistent and the diameter deviation is usually large.[7] Garrick, et al.[8] studied the machined hole diameter in drilling of CFRP/Ti stacks. The results showed that the diameter tolerance could be up to 25 mm using a standard twist drill over the course of 34 holes, while a PCD drill with the same diameter achieved a diameter tolerance of 10mm over the course of 200 holes. Park et al.[9] investigated the influence of Ti layer on the size of the machined CFRP holes in their comparative study on drilling of CFRP and CFRP/Ti stacks. It is indicated that the drilling of Ti layer has significantly influences on the diameter of the CFRP holes due to the increased tool instability.

In addition to hole diameter, the machined hole surface between CFRP and metal layer is also quite different as drilling of CFRP /metal stacks. During drilling of the CFRP layer, the chips often generated in the form of powders instead of ribbon chips as metal cutting proceeded, so it is difficult to form an excellent surface finish on the hole surface of CFRP. The surface roughness of CFRP (Ra 2~9 mm) is always much higher than that of metal (Ra 0.3~2 mm) due to various machining defects of CFRP.[2,10] Cavities, micro cracks and matrix resin degradation on the hole surface of CFRP were observed by Xu et el.[5] during drilling of T800S/250F CFRP laminates and Montoya et al.[11] during drilling of CFRP/Al stacks which was closely related to the too high drilling temperature.

Drilling temperature is one of the most important factors affecting the machined hole surface quality, especially for the CFRP. When drilling of CFRP, large amounts of cutting heat and friction heat will be generated due to the abrasive nature of carbon fibers and tool wear, which usually makes the drilling temperature elevated rapidly. However, the degradation temperature of matrix resin is usually low (150~250°C), which is far below the drilling temperature of metals. An excessive high drilling temperature may lead to a risk of thermal degradation of matrix resin. Overall, this risk causes carbonization of thermosetting matrices and fusion of thermoplastics matrices. Sometimes, it can also damage the carbon fibers (burning of the carbon fibers). In addition, an excessive high cutting speed can also significantly increase the drilling temperature.

However, there are only few experimental studies have been done on drilling temperature in drilling of CFRP or CFRP/metal stacks. M. Ramulu et al.[12] studied the drilling heat induced damage on CFRP while drilling of graphite/bismaleimide (Gr/Bi) and Ti stacks. Discoloration rings around the hole exit of the composite layer due to heat effect during drilling process were observed. Drilling temperature was measured by Davies, M.[13] and Brinksmeier, E.[14] to study the influence of the drilling process on the surface layer of the Al/CFRP/Ti stacks. The investigations reveal that local temperature peaks, due to high cutting speeds or evacuated Ti chips, will damage the hole surface of the CFRP materials. The drilling temperature measured on the tool rake face was about 90°C for Al layer, 191.6°C for CFRP layer and about 350°C for Ti layer under the cutting parameters of 40m/min for cutting speed and 5 mm/min for feed rate. Le Coz et al.[15] demonstrated a measurement system for rotating tools with a measurement accuracy of 1°C. The thermocouple embedded in the tool was connected to a data acquisition unit in tool holder and temperature signals were sent to an amplifier by using a transmitter integrated in the tool holder and a Radio Frequency Antenna placed nearby the tool holder. Repeated drilling tests revealed the repeatability of the measurement. However, the measurement system was complex and costly.

The wear mechanism of the tool in drilling of CFRP was primarily abrasive wear due to the abrasive nature of the carbon fibers.[16,17] While, the wear mechanism of the tool in drilling of CFRP/metal stacks was usually abrasive wear and adhesion wear due to metal build up edge.[18-20] Diamond has ideal properties for machining of CFRP or CFRP/ Alumnium stacks. The nature of hardness makes it more resistant to abrasive wear than any other cutting materials.[21,22] According to Montoya et al.,[11] the use of a diamond coating can decrease the trust force (by limiting wear) by 65% for CFRP and by 35% for Al. Zitoune et al.,[23] Karpat et al.[24-26] have studied the effect of geometry structure of the drill bits during drilling of CFRP/metal stacks. The results indicated that the double point angle drill bit outperformed the standard twist drill bit in terms of thrust force as well as tool wear and hole surface quality. Besides, when drilling of CFRP/metal stacks, push-out burrs and delamination of the CFRP laminates can be significantly reduced due to the supporting from the metal layer(s).[2,27]

In the present study, diamond coated drills with double point angles were employed in drilling of CFRP/Al stack materials. The aim of the experiments is to investigate the influence of drilling parameters on the drilling force, drilling temperature, hole diameter and hole surface quality. The influences of different stack sequences on the drilling temperature and hole surface quality have also been discussed.

2. Experimental Procedure

2.1 Workpiece materials

The stack materials utilized in the present study are composed of T800/X850 CFRP and 7075-T651 Al. The size of the stack plate is 300 mm × 200 mm × 14.74 mm. The thickness of CFRP and Al is 8.74 mm and 6 mm, respectively. They are closely assembled through ten bolts. The side view of the stack plate is shown in Fig. 1.

The T800/X850 CFRP composite laminate is made of 46 unidirectional-plies which are laid-up at different fiber directions (i.e., cross-ply). The laying-up sequence of the composite laminate is [±45/0/-45/0/+45/0/+45/90/-45/0/-45/0/+45/0/+45/90/-45/90/-45/0/+45/0]s. The aluminum alloy layer, Al 7075-T651, is a typical high strength aluminium alloy with good-corrosion cracking resistance, which is extensively used in aircraft and aerospace industry. Table 1 and 2 present the detailed composition of T800/X850 CFRP and the comparative mechanical properties between T800/X850 CFRP and 7075-T651 Al.

2.2 Cutting tool

Diamond coated cemented carbide drill bits were utilized in this work. The geometry of the drill bit is similar to the twist drill, but it has double point angles at the drill tip and two inner-cooling holes were designed at the flank surfaces. The drill bits were obtained from the manufacturer KOMET GROUP. Table 3 gives the detail geometric parameters of the used drill bits and the tool morphologies are shown in Fig. 2.

2.3 Experimental setup

Fig. 3 shows the experimental setup used in the drilling tests. The drilling trails were conducted on a DMU70V CNC machining center.

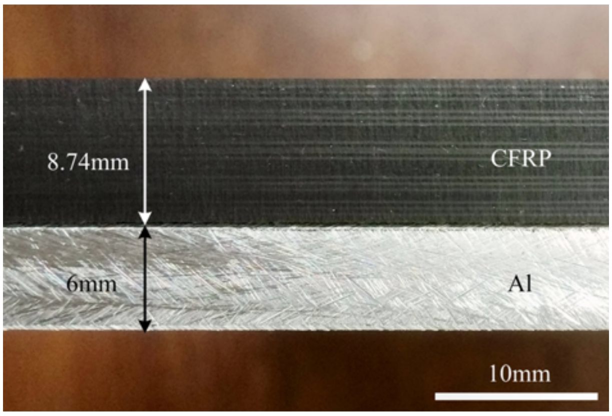

Fig. 1 Stack materials used in the present study consisting of T800/X850 CFRP and 7075-T651 Al

Table 1 Composition of T800/X850 CFRP composite laminates

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

Table 2 Mechanical properties of the stack materials

Properties	T800/X850 CFRP	7075-T651 Al
Tensile strength (MPa)	5490	570
Strain (%)	1.9	11
Thermal conductivity (W/(m•k))	-	130
Single-beam intensity (g/1000m)	445 (12K)	-

The travel range of the machined tool is defined as: X-710 mm, Y-520 mm, Z-520 mm, five axes (X, Y, Z, B and C); spindle speed range: 20~12000 rpm. A full factorial experiment with 12 cutting conditions was designed which is detailed illustrated in Table 4. In the tests, the holes were drilled into from the CFRP layer and drilled out from the Al layer except for Section 3.5. Constant feed rate is employed to drilling of the CFRP and Al. Besides, all the tests were performed under dry cutting conditions.

In terms of measurement devices, a four-component force dynamometer Kistler 9272 was used to gather cutting force signals. The measured signals were transmitted to a multichannel charge amplifier Kistler 5070A, then to an A/D board and recorded on a personal computer using data acquisition software Labview 7.1.

A rotational motion temperature measuring system was utilized in the experiments to obtain the drilling temperature. In the measuring system, two K-type standard thermocouples were mounted in the inner-cooling holes at the flank surfaces of the drill bit. The location and size of the inner-cooling holes are shown in Fig. 2. Each of the thermocouples was connected with a data storage device though the inner-cooling hole and the tool holder, as shown in Fig. 3. The sample frequency of the temperature measuring system was 1 Hz. The temperature measurement range of the K-type standard thermocouple is -260~1370°C and its accuracy is ±0.5°C. After the tests, the temperature data storage device can be connected to the computer and the temperature data can be exported.

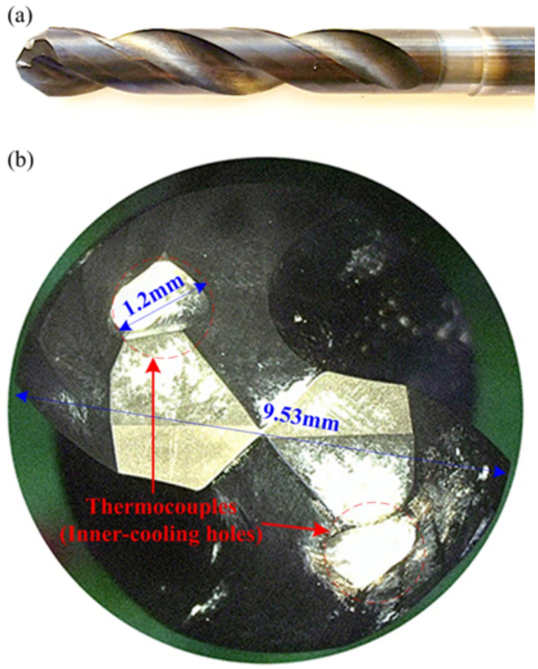

Fig. 2 Tool morphologies of the used drill bits (a) side view, (b) drill tip view

Table 3 Geometric parameters of the used drill bit

Diameter	9.53 mm
Cutting edge length	58 mm
First drill point angle	130°
Second drill point angle	60°
Helix angle	30°
Coating	Diamond (4 μm)

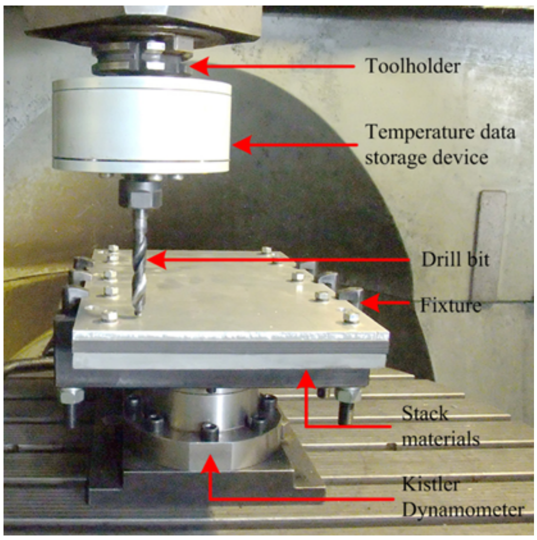

Fig. 3 Experimental setup for the drilling tests

A three point internal micrometer was used to measure the diameter of the holes after the drilling tests. The measurement range of the micrometer is 8~10 mm with a measurement accuracy of 0.004 mm

Table 4 Drilling parameters and their levels

Drilling parameters	Levels			
	Level 1	Level 2	Level 3	Level 4
Spindle speed, n (rpm)	1000	2000	3000	-
Feed rate, f (mm/rev)	0.02	0.04	0.06	0.08

and a display accuracy of 0.001 mm. The surface roughness (Ra) of the holes was measured by surface roughness measurement instrument Mitutoyo SJ-210 with a sampling length (cut-off length) of 0.8 mm. The number of the samples was set to five and the measurement distance was 4.0 mm. The travelling speed of the probe was 0.5 mm/s when measuring Ra of the workpiece. A digital microscope system Keyence VHX-500FE combined with a scanning electron microscope (SEM) JEOL JSM-6390LV was used to study the hole surface quality.

3. Experimental Results and Discussion

3.1 Thrust force

Fig. 4(a) shows the evolution of the thrust force (Fz) recorded during the drilling of CFRP/Al stacks as a function of the feed rate. It can be noted that each point of the Fig. 4 represents an average value of the thrust force curves for CFRP or Al. It can be indicated that the thrust force is almost proportional to the feed rate for both CFRP and Al. Furthermore, the thrust force recorded during drilling of Al was found to be about two times higher than these recorded during drilling of CFRP. For example, while drilling with a spindle speed of 2000 rpm and a feed rate of 0.06 mm/rev, the thrust force increased from 143 N in CFRP to 286 N in Al.

Fig. 4(b) shows the evolution of the thrust force (Fz) recorded during the drilling of CFRP/Al stacks as a function of the spindle speed. It can be seen that the thrust force is slightly elevated with the increase of the spindle speed. While drilling with a constant feed rate (0.06 mm/rev) and the spindle speed changed from 1000 rpm to 3000 rpm, the thrust force increased by 22% for CFRP and 16% for Al. Therefore, feed rate is the most important factor influencing the thrust force no matter for CFRP or Al.

3.2 Drilling temperature

Matrix resin in the CFRP is an amorphous polymer material. According to the temperature of the matrix resin, it can generally be divided into three different mechanical states: glassy, high elastic state and viscous flow state. The transition between the glassy state and high elastic state is called glass-transition. The corresponding transition temperature is called glass-transition temperature. At room temperature, the resin is in the glassy state. When its temperature reaches the glass-transition temperature (typically 200°C for epoxy resin), the mechanical properties will changed significantly which will cause the resin degradation and debonding with carbon fibers. Therefore, in drilling of the CFRP, appropriate drilling parameters should be employed to avoid the drilling temperature reaching or exceeding its glass-transition temperature.

The thrust force and drilling temperature obtained during drilling of the CFRP/Al stacks reveal important information about the drilling process, which can be used to monitor the drilling state and optimize

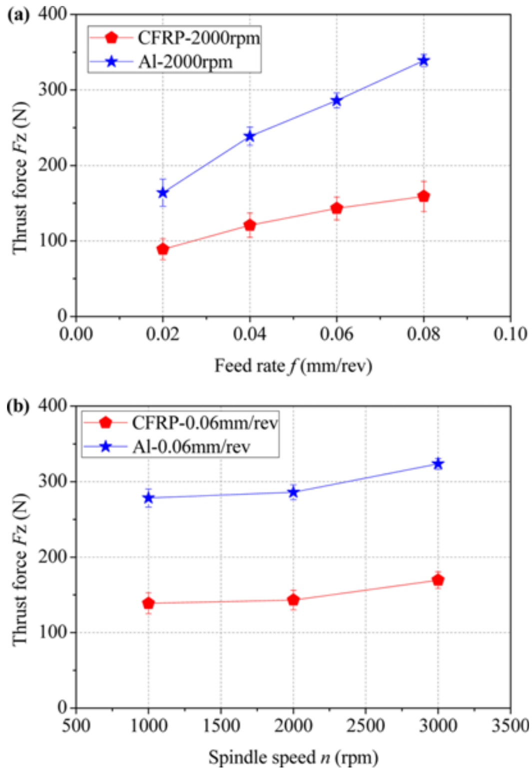

Fig. 4 Evolution of the thrust force as a function of the (a) feed rate and (b) spindle speed

machining parameters. Fig. 5(a) illustrates the thrust force and drilling temperature curves as a function of drilling depth measured during drilling of the stacks under the drilling parameters of n = 2000 rpm and f = 0.02 mm/rev. The starting point (A) on the thrust force and drilling temperature curves corresponds to the location where the chisel edge of the drill bit enters the material. It is indicated that when drilling of the CFRP layer, the temperature rises rapidly and reaches the peek value (232°C) at the end of the region AB. However, as drilling of the Al layer, the drilling temperature drops quickly from the peek value. The drilling temperature drops from 232°C to 115°C and the decline amplitude reaches 117°C. It is revealed that the difficult-to-cut machinability of the CFRP material. It can be attributed to the abrasive nature of the carbon fibers and the poor thermal conductivity of CFRP. During drilling of CFRP, large amounts of heat was generated and accumulated. However, the material of Al possesses the excellent thermal conductivity property and the accumulated heat in drilling of the CFRP layer can be diffused rapidly. Therefore, the drilling temperature did not rise but decreased.

The thrust force for CFRP slightly decreases after all the drill tip immerged into the CFRP. As soon as the chisel edge enters the Al layer, the thrust force increases rapidly. It must be noted that the thrust force is elevated suddenly as the drill tip approaching the hole exit in the region BC. It can be attributed to the problem of chip removal during drilling of the Al. In the lower right of Fig. 4(a), the picture of Al chips is present under the machining parameters of n = 2000 rpm and f = 0.02 mm/rev. The long and flexible Al chips can accumulate in the spiral groove of the drill bit, which is difficult to discharge. The Al chips rotate with the drill bit in a high speed and squeeze with the hole

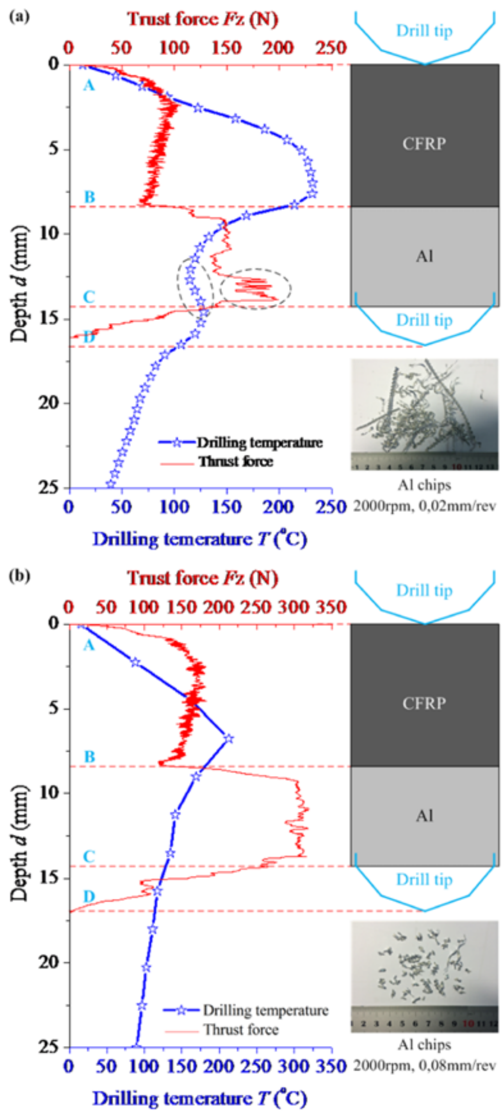

Fig. 5 Drilling temperature and thrust force curves with the evolution of drilling depth during drilling of the CFRP/Al stacks. (a) 2000 rpm, 0.02 mm/rev, (b) 2000 rpm, 0.08 mm/rev

surface of Al and CFRP. On the one hand, the friction between the Al chips and the hole surface will elevate the thrust force. On the other hand, the friction heat will also increase the temperature of the stack materials and the drill bit. Therefore, the phenomenon of "second rise" of the drilling temperature as the drill tip approaching the hole exit in the region BC. After the drill tip drilling out of the Al (location C), the drilling process is still continued due to the length of the drill tip. After location D, the drilling temperature decreases gradually under the cooling air.

Fig. 5(b) gives the thrust force and drilling temperature curves as a function of drilling depth measured during drilling of the stacks under the drilling parameters of $n = 2000$ rpm and $f = 0.08$ mm/rev. As we can see, the evolution of the thrust force and drilling temperature curves is similar to that of Fig. 5(a). It must be noted that short C-type Al chips are generated under the drilling parameters of $n = 2000$ rpm and $f = 0.08$ mm/rev. This greatly reduced the difficulty of the chip removal issue. Therefore, both the phenomena of sudden rise of the thrust force

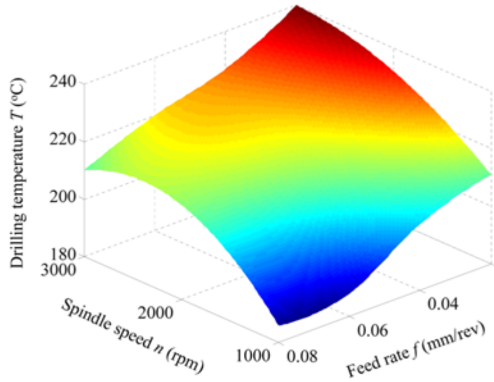

Fig. 6 Drilling temerature with the evolution of spindle speed and feed rate during drilling of CFRP/Al stacks

and "second rise" of the drilling temperature are disappeared.

However, the drilling temperature decreases with the increase of the feed rate, which is quite different from that in metal cutting.[28] This phenomenon can be attributed to the abrasive effect and the friction between the tool and CFRP. During the machining of CFRP, the carbon fibers act as the abrasive grains, which accelerate the friction effect and the tool wear. When a smaller feed rate is employed, the abrasive wear will be aggravated and the drilling period is also be prolonged, therefore, more cutting heat will be generated in the drilling process and the drilling temperature will be higher. As a whole, lower spindle speed and larger feed rate can achieve a lower drilling temperature.

3.3 Hole diameter

Tight dimensional and geometric tolerances are vital important in the assembly of the stack materials, especially in aviation industry. Usually, 30 mm and lower diameter tolerances are required for mechanical bolting of stack materials.[7] When drilling of the stack materials, the difference of hole diameters among different layers is usually large due to the great differences in physical and mechanical properties among them. In order to investigate the effect of the machining parameters on the diameter difference, the drilled hole diameter was measured by employing a three point internal micrometer. The diameter was measured at two locations in CFRP (hole entry and hole exit) and mid-thickness in Al. The measurement was performed four times at four different angle locations of the holes and the average of the four diameters is taken as the final result. The schematic illustration of the diameter measurement is shown in Fig. 7. The measurement results of Al entry, CFRP entry and CFRP exit under different drilling parameters are given in Fig. 8.

It can be seen that diameters of Al, CFRP exit and CFRP entry show an increasing trend with the increase of feed rate under three spindle speed levels. It can be attributed to the cutting vibration and the instability of the cutting condition as the feed rate increased. It can be indicated that the diameter of CFRP is always bigger than that of Al. The phenomenon was also observed by Montoya et al..[11] It can be attributed to the increased tool instability when drilling the bottom Al layer. With a spindle speed of 1000 rpm, (see Fig. 8 (a)), the maximum diameter difference between CFRP and Al is 50 mm as a feed rate of 0.08 mm/rev is employed. While, the diameter difference with the

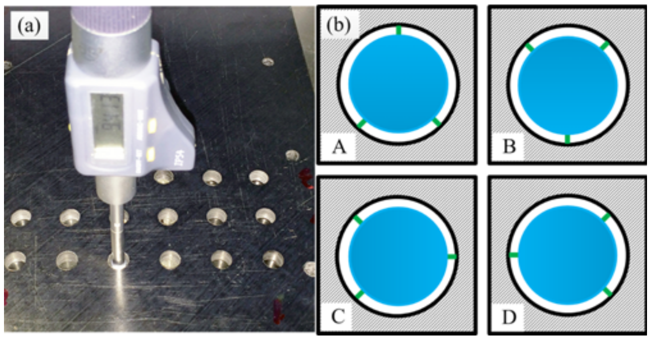

Fig. 7 Schematic illustration of the diameter measurement (a) three point internal micrometer used in the tests, (b) four angle locations of the three point internal micrometer measuring a hole

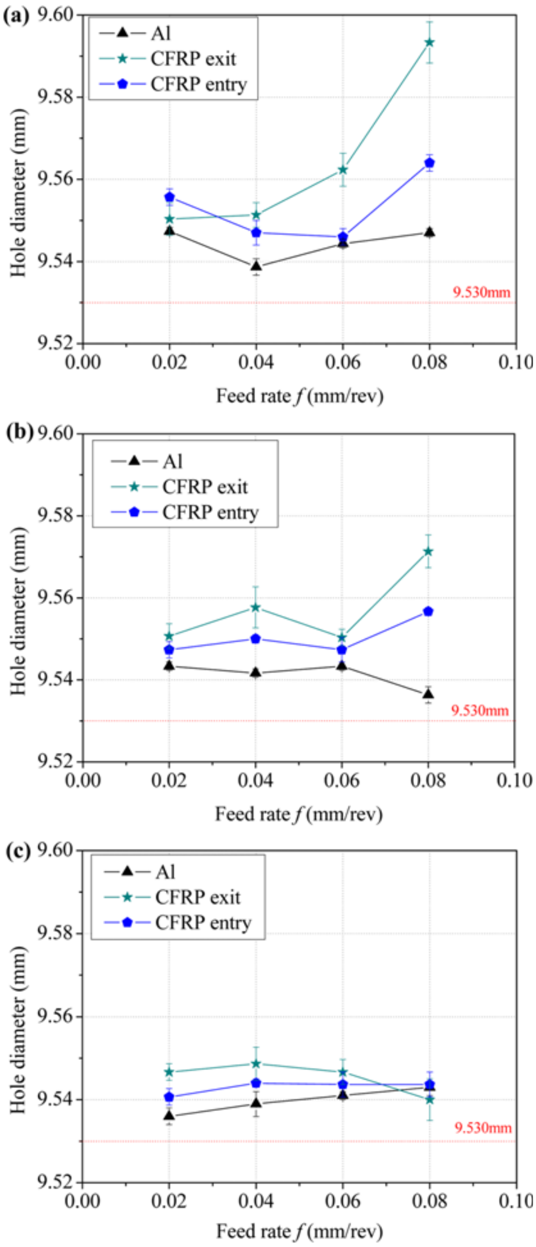

Fig. 8 Hole diameter with the evolution of the feed rate under different spindle speed (a) 1000 rpm, (b) 2000 rpm, (c) 3000 rpm

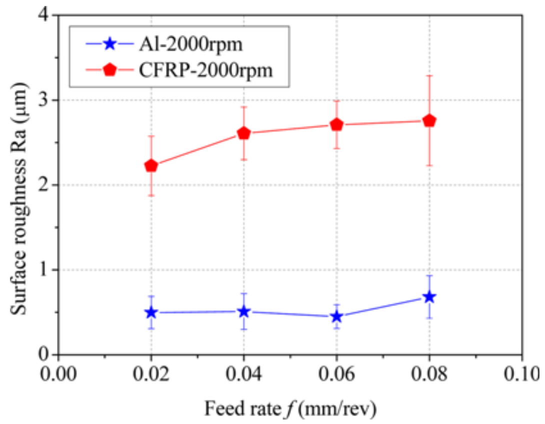

Fig. 9 Surface roughness Ra as a function of feed rate for the hole surface of CFRP and Al

spindle speed of 2000 rpm (Fig. 5(b)) and 3000 rpm (Fig. 5(c)) are 35 mm and 11 mm respectively. It is indicated that a higher spindle speed can achieve a smaller diameter tolerance between CFRP and Al, which is beneficial to the final assemblies. In addition, the diameter of the CFRP exit is always bigger than that of CFRP entry. On the one hand, it can be attributed to the increased tool run out when drilling the bottom Al layer. On the other hand, the produced Al chips will erode the resin of CFRP exit, which will be discussed in detail in Section 3.4.

3.4 Hole surface quality

The quality of the hole surface is also an important aspect influencing the assembly accuracy. The surface roughness of the hole was measured on the longitudinal direction of the hole by the surface roughness measurement instrument Mitutoyo SJ-210. The value of surface roughness is the average of six measurements at different locations of the corresponding machined surface. The surface roughness (Ra), which is mostly employed in industries, was taken for the present study. Currently, the maximum acceptable surface roughness (Ra) in aviation industry is 1.6 mm for Al and 3.2 mm for CFRP.[11]

Fig. 9 shows the evolution of Ra as a function of feed rate with a constant spindle speed of 2000 rpm for Al and CFRP. It can be seen that the increase of feed rate leads to a slightly increase in the value of the roughness for both of the Al and CFRP layers. The drilling experiments performed by Zitoune[10] shown that, the feed rate had a significant influence on the surface roughness Ra. However, the values of the surface roughness Ra measured in the CFRP layers are significantly higher than those measured in the Al layers. This can be attributed the generation of the machined defects in CFRP. Due to the anisotropic and non-homogeneous material structure, machinability characteristics of CFRP are significantly different for different fiber directions. Various machined defects lead to the uneven surface of CFRP. Fig. 10 presents the surface profiles and surface morphologies of the hole surfaces of the CFRP and Al under the drilling parameters of 2000 rpm and 0.06 mm/rev. It can be seen that several sudden drops appear in the surface profile of CFRP corresponding to an uneven machined surface. Conversely, the hole surface of Al is very smooth and the evaluation profile is flat and no sudden drops. In terms of the value of Ra, the value for CFRP (Ra = 2.664) is far greater than that

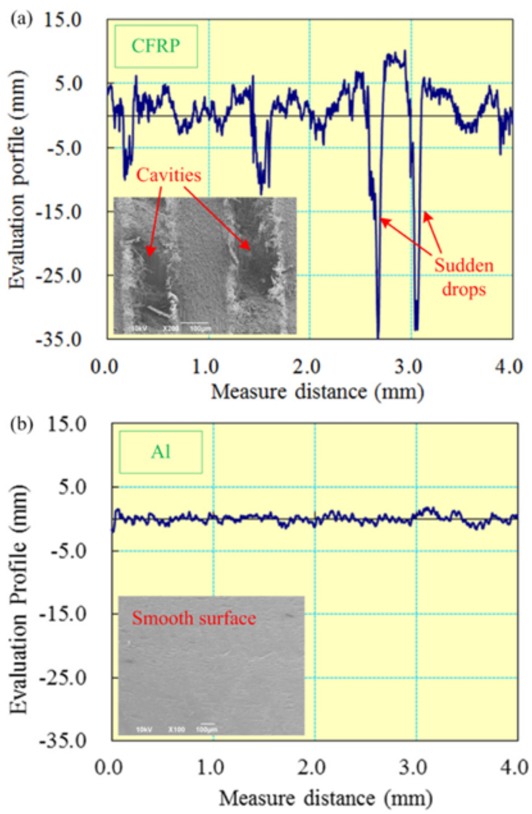

Fig. 10 Evaluation profile and SEM photographs of the hole surface under the drilling parameters of 2000 rpm and 0.06 mm/rev. (a) Ra = 2.664 for CFRP, (b) Ra = 0.488 for Al

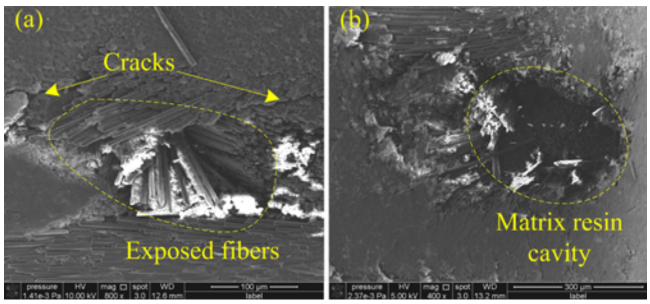

Fig. 11 Hole surface defects on the CFRP layer

for Al (Ra = 0.488). Taking no account of sudden drops, the evaluation profile seems to be flat and steady. Therefore, it is precisely because of these sudden drops that the surface roughness Ra of CFRP is elevated. Obviously, these sudden drops are caused by the cavities on the surface of some plies of the CFRP. These cavities are composed of the matrix resin depressions and carbon fiber fill-out. There are mainly two reasons that cause these machining defects. On the one hand, the mechanism of material removal is different for different carbon fiber cutting directions. On the other hand, the excessive drilling temperature will lead to resin degradation directly and cause interfacial deboning of resin and carbon fiber which may result in the surface cracks, matrix resin depressions and carbon fiber pull-out defects, and in turn matrix resin cavities occurred, as shown in Fig. 11.

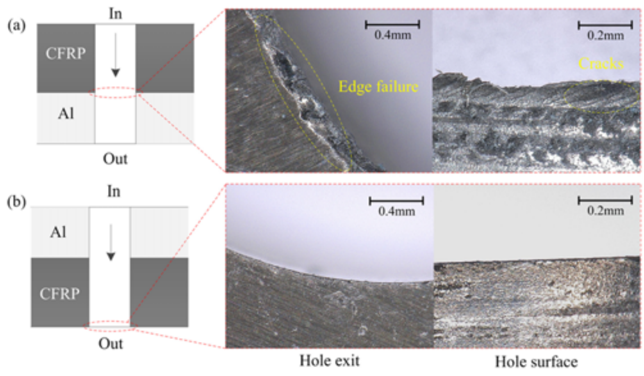

Fig. 12 Hole surface of CFRP under the drilling parameters of n = 1000 rpm, f = 0.08 mm/rev. (a) Hole surface of CFRP drilling from CFRP to Al, (b) Hole surface of CFRP drilling from Al to CFRP

3.5 Influence of different drilling sequence on drilling temperature and hole quality

In industrial production, the drilling sequence of CFRP/metal (CFRP is placed on the top of metal, i.e., the holes are drilled from CFRP and drill out from metal.) is usually employed in most cases in order to avoid the hole exit burrs and delamination defects of CFRP. However, in some cases, the drilling sequence of metal/CFRP has to be employed.

The influences of those two drilling sequence on the drilling process are different. Fig. 12 present the hole surface photographs of CFRP at critical locations under different drilling sequences. As shown in Fig. 12, at the hole exit of CFRP (i.e., interface between Al and CFRP), severe edge failure and surface cracks and were observed. However, when drilling from the Al layer, a neatly and sharp hole edge was obtained and the surface cracks almost disappeared, in other to say, the hole quality of CFRP is significantly improved without the support of the Al layer. On the one hand, it has been confirmed that the double point angle drill bit can achieve a smaller thrust force, reduce the delamination defects and obtain an excellent hole exit even without support.[25,26] On the other hand, this can probably be attributed to the more efficient evacuation of Al chips from the hole. Similar experimental results were reported by Wertheim.[29] It was shown that during drilling of the CFRP/Al stacks, the flow of Al-chips may cause a “washing out” effect of the shim material between the CFRP layer and the Al layer. When drilling from the CFRP layer, the chip removal issue will be occurred. The long and flexible Al chips generated during drilling of the bottom Al layer may accumulated in the spiral grooves and rotate with the drill bit. They will erode the matrix resin of the hole exit in the CFRP layer, which leads to edge failure and surface cracks defects and enlarges the hole diameter of the CFRP layer. The Al chips will also scrape the machined surface of CFRP and cause the degradation of matrix resin. However, when drilling from the Al layer, the Al chips usually can be removed from the hole quickly and almost have no influence on the following drilling process. Therefore, the hole exit edge of the CFRP is neatly. The comparative drilling temperature curves may give us some help to understand this detail.

Fig. 13 shows the drilling temperature curves measured under those two drilling sequences. As we can see that the maximum drilling temperature of Al/CFRP sequence is lower than that of CFRP/Al sequence. When the Al is on the bottom of the stacks, the produced Al

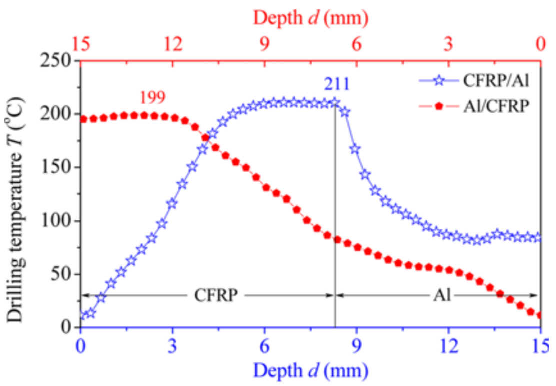

Fig. 13 Comparative analysis of drilling temerature with different drilling sequences under the drilling parameters of 1000 rpm and 0.02 mm/rev

chips cannot be evaluated timely; as a consequence, the clogging chips will deteriorate the temperature diffusion and damage the CFRP surface which locates on the top of the Al layer.

It must be noted that when the CFRP is place on the bottom of the Al layer, the fiber plies at the hole exit of CFRP will lose support and protection. When the cutting edge wear out and rounded or an excessive thrust force is generated, the risk of delamination will increase significantly.

4. Conclusions

The experimental investigation on drilling of CFRP/Al stacks using a diamond coated drill bit with double tip point angles was conducted. The influence of drilling parameters on the drilling process were studied in terms of thrust force, drilling temperature, hole diameter and hole surface quality, respectively. The main conclusions can be drawn as follows:

(1) The thrust force is almost proportional to the feed rate for both CFRP and Al while it is slightly elevated with the increase of the spindle speed.

(2) The drilling temperature was measured utilizing a rotational motion temperature measuring system. The results show that the drilling temperature increases with the increase of spindle speed, while, it decreases with increasing the feed rate. When drilling of the CFRP/Al stacks, the thrust force and the drilling temperature increase abnormally during drilling of the Al layer, which can be attributed to the evacuation difficulty of the long and flexible Al chips.

(3) The hole diameter measured in the CFRP layer is always larger than that measured in the Al layer, which can be explained by the increase of tool instability as drilling of the Al layer. It is indicated that a higher spindle speed can achieve a smaller diameter difference between the CFRP and Al.

(4) It is found that sudden drops in the surface profile of CFRP are caused by the matrix resin cavities which may be the result of resin degradation. The surface roughness is also closely related to the matrix resin cavities.

(5) Severe edge failure and surface cracks are found at the exit of the CFRP holes when drilling of the CFRP/Al stacks.

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