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ORIGINAL ARTICLE

A comparative study on helical milling of CFRP/Ti stacks and its individual layers

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Abstract Carbon fiber-reinforced plastics (CFRPs) and titanium alloys have different mechanical properties and show the unique processing characteristics in the cutting process. In order to complete hole-making of CFRP/Ti stacks with larger thickness, a comparative study was conducted on the stacks of CFRP/Ti versus CFRP and titanium alloy single plate in the helical milling process. Experimental results show that cutting performance including cutting force and tool wear pattern and hole quality in helical milling of stacks are all different to single plate. The impact of tool wear on the cutting force is relatively significant while machining of CFRP compared to titanium alloy. While machining of CFRP/Ti stacks, axial forces of titanium alloy suddenly change very larger than single titanium plate due to tool wear, and tool wear state shows combination of several wear pattern. Undersized CFRP holes and oversized Ti plate holes are produced when milling single plate; however, oversized CFRP and undersized Ti plate holes are observed when machining of stacks. The results also indicate that tool wear in helical milling of CFRP will influence the cutting performance of stacks.

Keywords Helical milling · CFRP · Titanium alloy · CFRP/Ti stack · Cutting performance

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1 Introduction

The widespread use of carbon fiber-reinforced plastic (CFRP) and titanium components will inevitably lead to the appearance of the joining between these two kinds of material. It needs to simultaneously process a large number holes of the stack, then join during aircraft manufacturing and assembly process, so hole-making technique is a key step to achieve reliable joining before being riveted or bolted. In order to improve the efficiency and quality of machining and assembling of aircraft, the hole-making problem in CFRP/Ti integrated joining part has become the focus and challenging work on the aviation area.

Currently, hole-making in the stack with CFRP/metal is still dominated by conventional drilling. Kim and Ramulu [1–3] carried out experiment for drilling composite/titanium laminate (Gr/Bi-Ti) using three kinds of tools, and found that the high temperature in the drilling process caused obvious damage defects at the exit hole of composite in the joining surface between two materials. Park et al. [4] studied on the tool wear problem using carbide and diamond drill bits in drilling of CFRP/Ti. The results showed that the diamond drill had good processing characteristics, but it could easily produce chipping because of brittleness when cutting of titanium, and increased tool wear would influence the cutting zone temperature. Flank wear was accelerated when drilling of Ti while cutting edge was deteriorated when drilling of CFRP, and hole quality was worse while drilling of stacks than only CFRP [5]. Zitoune et al. [6, 7] analyzed the cutting parameters, cutting force, torque, and surface integrity with different drill bits in the drilling of CFRP/Al stacks. It showed that tool wear was more serious when drilling of CFRP, the axial force increased about 90 %, while cutting force in drilling aluminum only increased about 6 %. Zhang [8] studied on drilling of CFRP/Ti

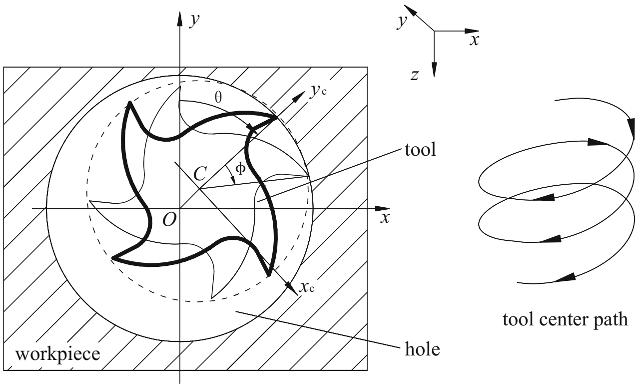


Fig. 1 Helical milling process

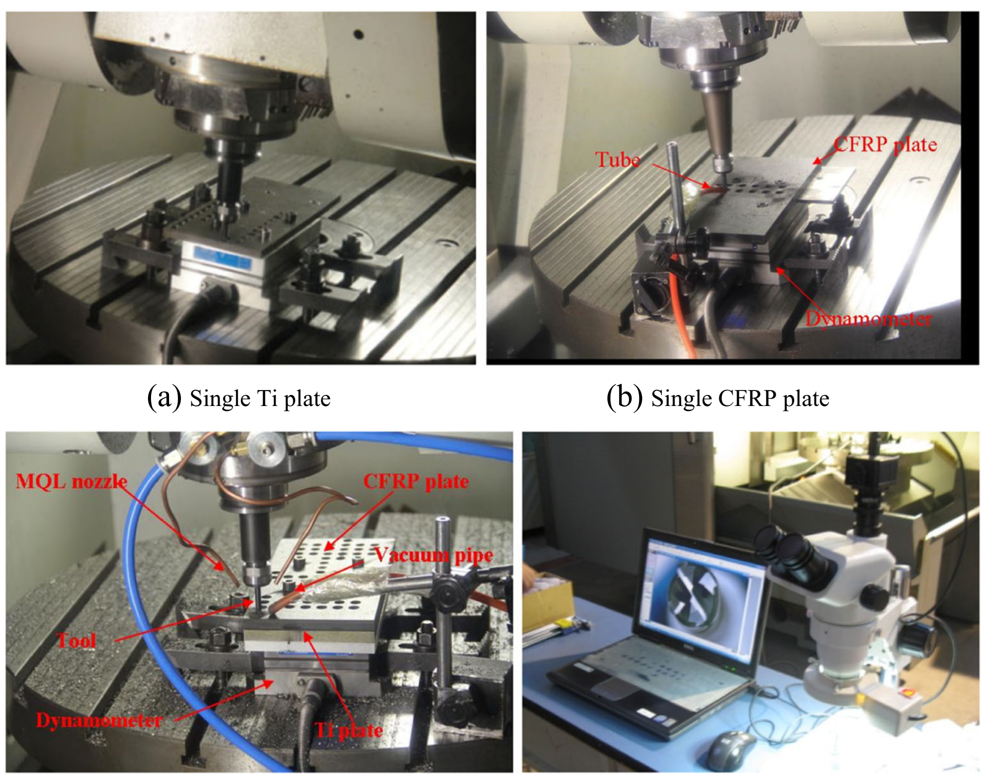
using PCD tool with varying cutting parameters. The results showed when the drill tip initially contacted surface on the titanium after machining of CFRP with changing cutting parameters, it could significantly improve the quality and tool life. Montoya et al. [9] found abrasion was the dominant tool wear pattern and measured wear progression of the cutting edges when drilling of CFRP/Al stacks using tungsten carbide drills.

Due to the different mechanical properties, it is relatively difficult to complete hole-making for laminated material composed with CFRP and metal. Processing efficiency and quality are the main difficulties in the hole-making process. Therefore, improving hole quality, longer tool life, and improving the efficiency have become the hot and difficult points in the aviation industry.

As a new hole-making technique, helical milling is developed to generate holes in the aircraft industry for typical difficult-to-cut material. In the machining process, a special tool less than the hole diameter rotates around its own axis and around the axis of the hole with offset and maintains axial feed [10–12]. It is an intermittent cutting process like all general milling, but the notable difference lies in the tool center path is no longer a straight line but a spiral line; there is either the tangential feed or the axial feed, as shown in Fig. 1. The cutting process contains a discontinuous cutting on the side cutting edge and a continuous cutting of the front edges.

In recent years, relative research efforts have been focused on helical milling techniques. Iyer et al. [10] carried out experiment of machining AISI D2 tool steel using helical milling and drilling techniques, found that helical milling was capable of machining H7 quality holes and with a good surface roughness than drilling process. Sasahara et al. [11] analyzed helical milling hole-making process of aluminum alloy with minimum quantity lubrication (MQL), and the analysis was compared with drilling process. Brinksmeier et al. [12] analytically

Fig. 2 Cutting experiments setup for CFRP/Ti stacks and individual layers



(a) Single Ti plate (b) Single CFRP plate

(c) Stack of CFRP/Ti (d) Investigation on tool wear

Table 1 Cutting parameters in helical milling process

Materials	Spindle rotation speeds (rpm)	Feed rates per tooth (mm/t)	Feed rates in axial direction (mm/rev)
Titanium alloy	4000	0.04	0.1
CFRP	6000	0.04	0.1
CFRP/Ti	6000/4000	0.04	0.1

described the helical milling kinematics with the consideration of the geometrical relation between periphery cutting zone and front cutting zone; the result conformed that the cutting process of helical milling was from drilling to milling. The influence of the axial and tangential feed on the cutting forces and borehole quality of CFRP/Ti was investigated [13]. In addition, Qin et al. [14–17] established analytical modeling of cutting force and cutting temperature about titanium alloy and CFRP in helical milling process, and feasibility study on the minimum quantity lubrication in high speed helical milling titanium alloy was specially analyzed. Liu et al. [18] studied cutting force modeling in the helical milling process using a combination of simulation and experimental methods. Li et al. [19] studied on the hole quality by surface topography and roughness in the helical milling process.

In short, the studies on helical milling technique in recent years have been gradually carried out, but few studies aimed at hole-making technical problem for stacks material, especially for larger thickness. So the particular objective of present work is to observe the related fundamental problems including cutting force and tool wear and hole quality between the CFRP/Ti stacks and single plate by conducting the experiments.

2 Experimental procedure

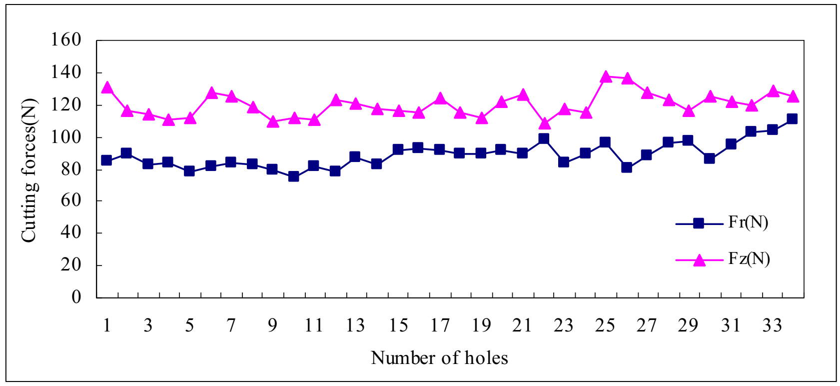
When processing laminated material, stacking sequence, selection of cutting parameters and tool will have great influence on hole quality and tool wear. The experimental setup was illustrated in Fig. 2.

To analyze the cutting performance of CFRP/Ti stack in the helical milling process, single titanium and CFRP plate and their stack were carried out, respectively, as shown in Fig. 2. The cross-sectional area of single plate was 250 × 120 mm with having a thickness of 10 mm. CFRP was an unidirectional plate with a total fiber volume of 65 %, fiber material was carbon fiber (T700); matrix material was bismaleimide (BMI) with fiber orientation of 0° along to the length direction. CFRP plate rested on top of the Ti alloy; thus, the CFRP/Ti stack plates had a total thickness of 20 mm.

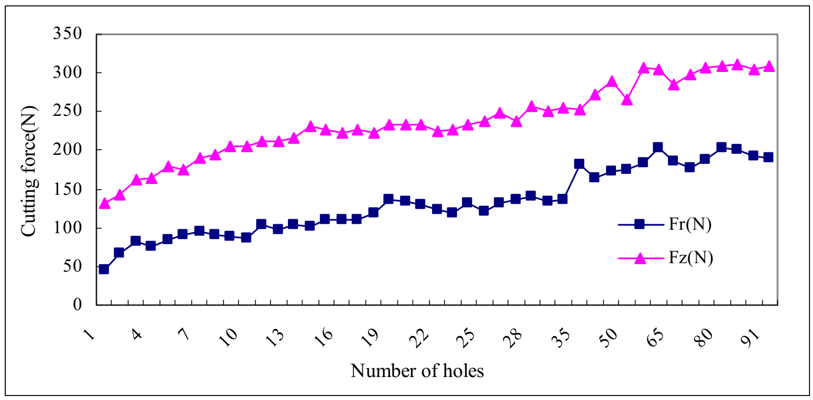
All the experiments were carried out on DMC75V linear five-axis high-speed machining center; hole diameters were all 10 mm. The cutting experiments were carried out under near dry condition, namely the coolant fluid was sprayed to the machining area before the start of the cutting, which will reduce the temperature of cutting zone in a certain extent, and cannot make composite powder chip into a ball. Three-dimension cutting forces were measured by using a Kistler 9257B three-component dynamometer, which was connected to a Kistler charge amplifier. The output of the amplifier (5261) was transformed into the signal through a computer storing the force signals versus cutting time using the dynoware software. There are several cutting parameters in the helical milling process. Once the tool and hole-making diameter are determined, only given three cutting parameters, the movement will be basically assured. Here spindle rotation speed, feed rate per tooth in tangential direction, and feed rate every orbit in axial direction are used as cutting parameters to

Fig. 3 Special tool for helical milling process

Fig. 4 Cutting forces versus the hole number



(a) Titanium alloy



(b) CFRP

analyze. Cutting parameters in the experiment are illustrated in Table 1.

Four-blade carbide tools with diameter 7 mm and TiAlN coating were used in the cutting process, as shown in Fig. 3. A scanning electron microscope (SEM) was used to observe the progression of tool wear. Wear patterns after milling titanium and CFRP only and CFRP/Ti stack were analyzed and compared. Tool wear state was observed using microscope, as shown in Fig. 2d. Further investigation on elemental distribution was performed using energy dispersive spectrometer (EDS).

The delamination state of holes was investigated using the super depth of field microscope KEYENCE VHX-600E microscope after all the experiments, diameter error was measured using coordinate measuring machine (CMM), taking three points in the middle of all the holes, and the average value was taken as the experimental result.

3 Results and discussion

3.1 Cutting force

Cutting forces are easily disturbed by various factors, so to avoid the noise impact of partial interference frequency, a 50-Hz low-pass filter is used, and the filtered signals are used to analyze. The radial force (Fr) is calculated as follows:

$$F_r = \sqrt{F_x^2 + F_y^2} \quad (1)$$

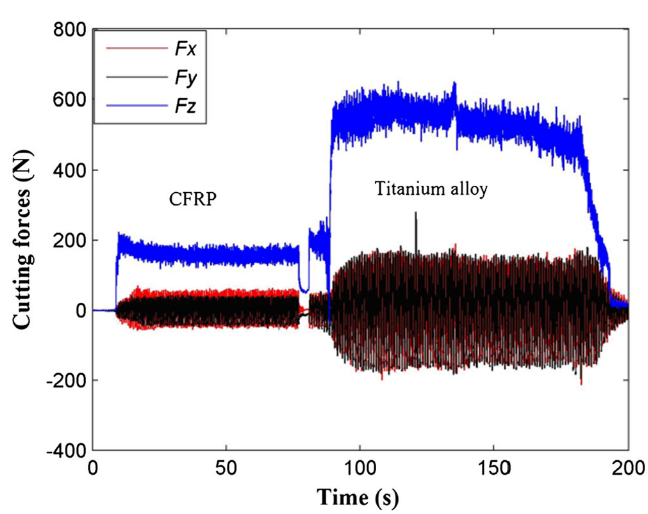
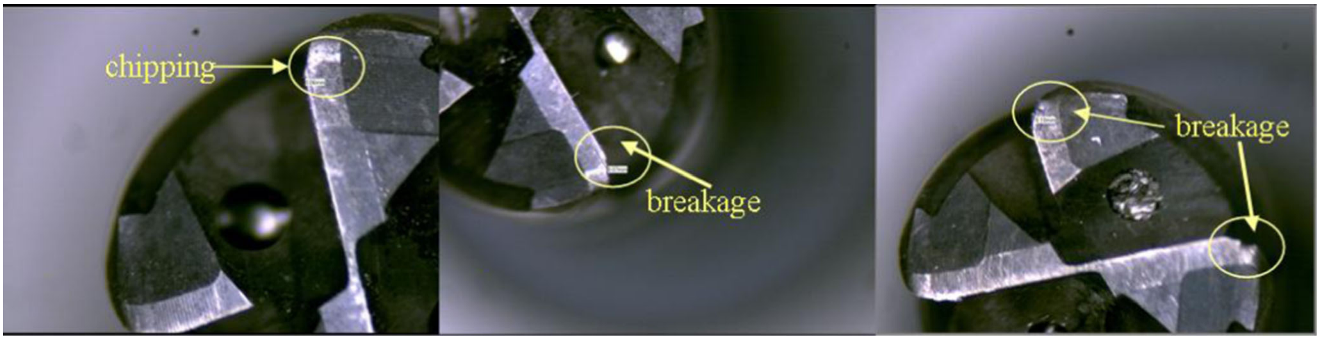


Fig. 5 Cutting forces about CFRP/Ti stack



a) After the 5th hole b) After the 15th hole c) After the 30th hole

Fig. 6 Tool wear detected result in machining of titanium alloy

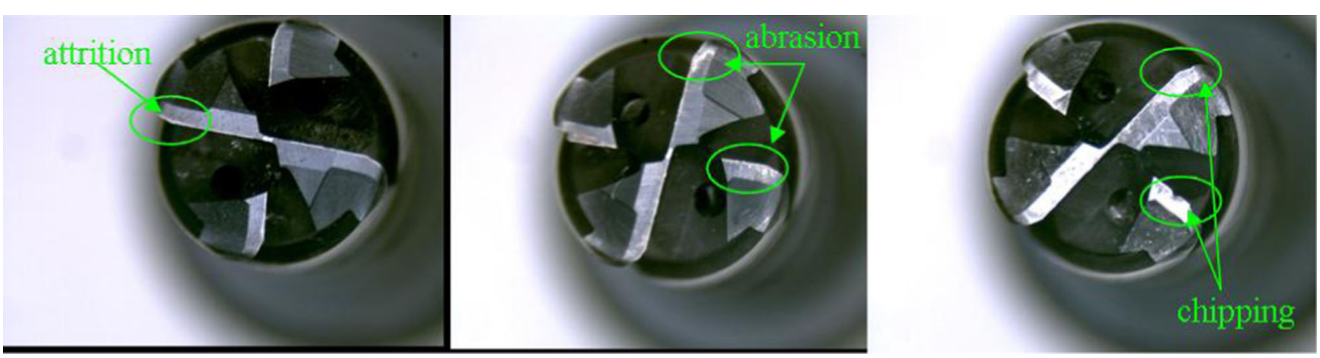
where F_x and F_y are respectively cutting forces in X and Y directions in XOY plane.

During whole cutting process, as illustrated in Fig. 4, axial forces (Fz) are always larger than radial forces (Fr). There are little changes of axial forces and radial forces in machining of titanium, as shown in Fig. 4a, but the initial value of the axial force in machining of CFRP is about 150 N, and it increases with the number of holes, the axial force reaches approximately 340 N while machining the 80th hole, and the radial forces increase from initial 60 to 240 N, as shown in Fig. 4b.

The relationships between the average cutting forces and the hole number in helical milling of titanium alloy and CFRP are also showed in Fig. 4. It can be seen that cutting forces increase with the number of holes, and the numbers of hole-making represent the degree of tool wear, namely cutting forces will increase with the increase of tool wear. But to the different material, the increasing trend is different. Obviously, the impact of tool wear on the cutting force is relatively significant while machining of CFRP compared to titanium alloy. For the titanium alloy, as illustrated in Fig. 4a, the holistic trend of the axial and radial average cutting forces increase a little with the increase of holes number before reaching the initial wear limit. The effect of tool wear on the cutting forces is positive, but the effect is not too large. Tool wear is serious while helical milling of CFRP, the relationship between cutting force and tool wear is nonlinear, and the effect of tool wear on cutting force in helical milling of CFRP is very large, as illustrated in Fig. 4b.

The filtered cutting force of CFRP/Ti stack is shown in Fig. 5.

The whole cutting process is relatively stable, average cutting forces in milling two materials are significantly different, cutting forces in X and Y directions in milling of composite are about 60 N, and cutting force in Z direction is about 180 N. However, cutting force in X and Y directions when machining of titanium are approximately 140 N, the axial forces reach approximately 480~550 N, and three-direction forces are all much greater than the cutting force only under the same conditions of machining of titanium. The main reason maybe lies in that upper CFRP material causes severe wear of side edge and front edge of the tool, resulting cutting force of Ti in



a) after the 5th hole b) after the 52th hole c) after the 134th hole

Fig. 7 Wear state of tool in helical milling of CFRP

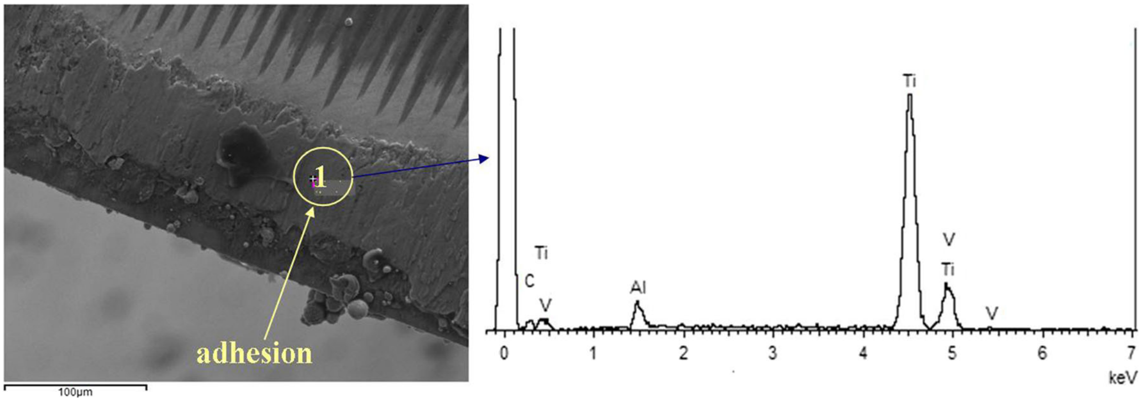


Fig. 8 EDS analysis after wear in the front edge of the cutter

laminate material is far greater than the separate processing of titanium alloy materials. So the wear pattern and state in helical milling of CFRP need to be analyzed in detail.

3.2 Tool wear analysis (considering front edge)

Tool wear is the result of load, friction, and high temperature between tool and workpiece [20]. Helical milling process is an interrupted operation, where cutting edge enters and exits the workpiece several times per second with constant axial feed, so tool wear will be different to general milling and drilling process. In the cutting process, the tool is removed every 3–5 holes processed for detecting. The microscope is used to observe the progression of tool wear and wear patterns. The average 0.2-mm non-uniform flank wear and maximum 0.3-mm flank wear and excessive chipping/flaking are considered as the wear limits.

1. Titanium alloy

The helical milling results of titanium alloy show that only 35 holes are machined before reaching the wear limit. The wear degree and state of the front edge of the cutter with the holes number are shown in Fig. 6.

When the hole-making number is 15 as shown in Fig. 6b, small breakage appears, while in the Fig. 6a, there is only little chipping while machining of 5 holes; when the number accumulates to 30, the front edge is close to the wear limit, and the relative large breakage appears in one front edge. On the whole, tool wear in helical milling of titanium alloy appears micro chipping and groove wear, breakage, and tool tip wear. There are several wear patterns with crater, adhesion, and chipping about the front cutting edge in the helical milling process; energy dispersive spectroscopy (EDS) micro-analysis has found traces of work material (Ti and Al); and it is usually due to the high chemical activity of titanium alloy. It should be noted that the more chemical composition of W and Co and the less chemical composition of Ti, Al can be found, suggesting that the titanium coating has been partially desquamated with cemented carbide substrate [21].

Table 2 Worn elements and atomic weight

Element	C	Al	Ti	W	V	Total weight
Weight (%)	20.16	4.41	70.99	/	4.44	100
Atomic (%)	30.59	5.85	60.40	/	3.16	100

2. CFRP

As shown in Fig. 7, the tool does not appear significant fragmentation tendency while helical milling of CFRP, larger chipping and breakage phenomenon is invisible, but tool wear is still more serious with edge rounding wear. CFRP contains highly abrasive carbon fibers, which will produce severe abrasive tool wear and edge chipping. When the 5th hole is made, little attrition appears, and with the increase of hole-making number, front cutting edge appears more and more obvious edge rounding and abrasion after machining the 52th hole, while machining of the 134th hole, a large of chippings emerge, and tool wear is very serious.

EDS is used to analyze the wear state of front edge, the results are shown in Fig. 8, and the percentage of worn elements and atomic weight are listed in Table 2. Since the tool is TiAlN coating, element N should exist in the worn tool element, but the test results show element N is not there, replaced by V element.

In Fig. 8, the coating does not fall off; a small amount of element V appears in the surface of the tool; the most likely reason is that affinity action takes place in a short process for the through-hole, because in the cutting process, the titanium plate is placed below the CFRP plate; and V content is about 3.5–4.5 % for the Ti6Al4V.

3. Stack

Tool wear pattern is different between CFRP and titanium alloy in helical milling process. Breakage or adhesive wear

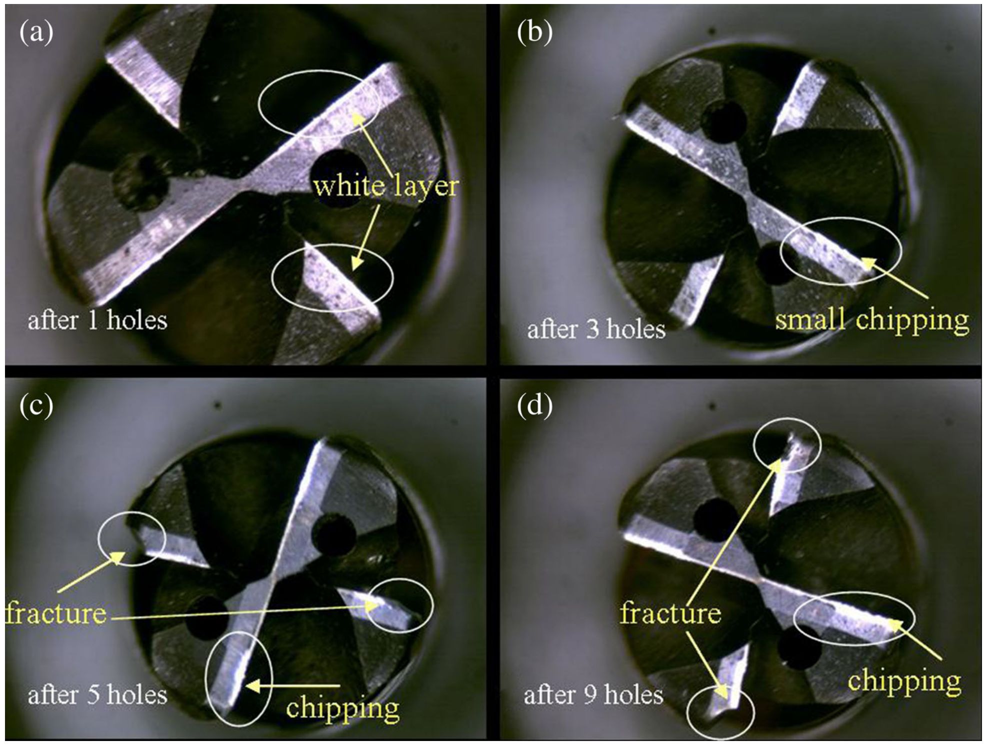


Fig. 9 Tool wear state in machining of stack

often occurs when machining of titanium alloys, while abrasive wear generally emerges in the processing of composite materials. When machining of stack composed of two materials, wear state of the tool should be superimposed theoretically. Due to the different cutting performance of two kind of materials, stack processing is very difficult, only 9 holes were made in the experimental stage, the tool was unable to continue with serious wear, when the 10th hole was made, the ablation suddenly appeared in the cutting zone, and the blade was completely melt. The experiment was repeated three times; the numbers of hole-making were respectively 4, 8, and 9; and the main reason lies in the thickness of the stack and the select of cutting parameters by preliminary analysis.

The photomicrographs of the front edge wear condition when machining CFRP/titanium laminate for first, three, five, nine holes are shown in Fig. 9. The main tool wear occurs at the end of the blade flank. As can be seen in Fig. 9a, a slight edge wear appears in the cutting process with white layer after one hole; it shows the wear further increases after three holes with small chipping, as shown in Fig. 9b. It can be seen from Fig. 9c that a clear chipping and fracture appear in the two corner regions of the tool. With the continue of cutting, another tool edge appears slightly damage with fracture, and worn

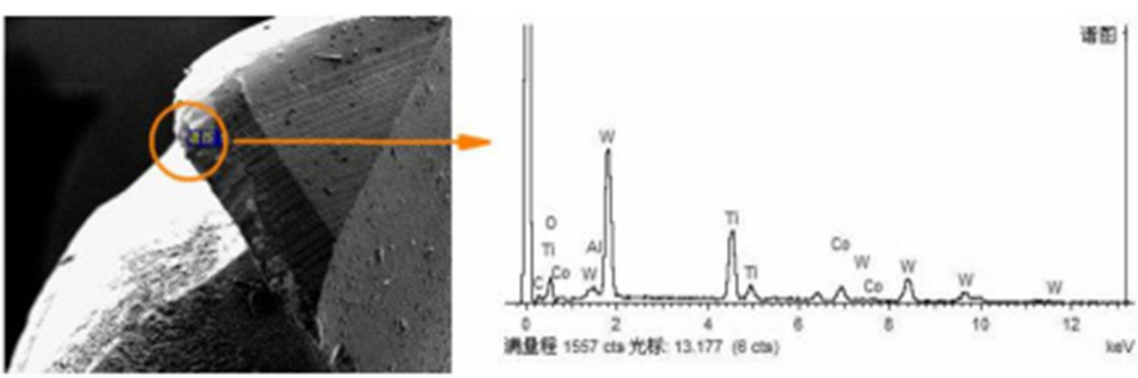


Fig. 10 EDS analysis after wear in the front edge of the cutter

Table 3 Worn elements and atomic weight of front cutting edge

Element	C	O	Al	Ti	W	Co	Total weight
Weight (%)	6.65	18.04	0.96	19.55	47.77	7.03	100
Atomic (%)	22.10	45.04	1.42	16.31	10.38	4.75	100

band width further increases after nine holes, as shown in Fig. 9d.

In the processing of stack materials, tool wear is always a thorny issue. In order to further analyze chemical abrasion of the tool, EDS is also used to analyze the wear state of the front edge, the results are shown in Fig. 10 and Table 3. It can be seen that elements W, C, and Co in the tool substrate appear on the surface of a cutting edge, which further verifies the coating fall off, and element of Ti and Al emerge, which illustrates the diffusion wear appears. Because no severe cooling condition is used, the cutting temperature is higher; when machining of laminated material, cutting temperature will steadily accumulate with the increase of depth; under the high-temperature conditions, elements W and C in the tungsten carbide diffuse to the chip; and Ti and C atoms in the chip diffuse to the tool, which decreases inter-atomic bonding strength and abrasion resistance of the tool, thus diffusion wear forms. In addition, element O also appears in the tool, which shows that oxidation reaction occurs.

3.3 Hole quality analysis

1. Single layer

Entry and exit part of the hole-making about titanium are microscopically observed, as shown in Fig. 11. It can be seen when the cutting force is small, the entry and exit parts substantially are free of visible titanium glitches.

Microscopic picture of hole entry part after helical milling of CFRP is shown in Fig. 12a. It can be seen that entry quality of holes is better with little glitches. While there is a piece of plate in the export of holes, the microscopic picture of hole exit edge is shown in Fig. 12b; exit quality is significantly better with little delamination including small tear and glitches compared to Fig. 12c. While machining without backing in the export of holes, obvious glitches and tears appear as shown in Fig. 12c; the exit quality is very poor. Therefore, the action of backing plate is very important, the obvious delamination appears without backing, while under the plate, there is no visible larger defect, which further explains the reason that CFRP material is often set on the titanium alloy while machining of stack material.

2. Stack

Poor hole quality is another major problem in machining of stack. When machining with a new tool, the entry quality is very good without obvious defects, as shown in Fig. 13a, but typical delamination appears in the entrance of the hole with a worn tool, as shown in Fig. 13b. Entry delamination is consistent with single-layer material; the less serious of tool wear is, the better of the entry hole quality gets. But due to the impact of tool wear, delamination in exit site shows relative greater, as shown in Fig. 13c. d, where titanium plate plays a role of backing plate.

Apart from the two materials, there is a small amount of ablation traces at the joints.

Burr case in entry and exit of titanium laminate is also related to the tool wear, when the tool wear is gradually serious, the number and length of glitches also show gradually increasing trend, as shown in Fig. 14. When the axial force in machining of titanium alloy of the stacks exceeds 500 N, inlet and outlet burrs appear. The performance of the inlet burrs show uniform rolled state, as seen in Fig. 14a, c, which are difficult to remove and the exit burrs are also large without

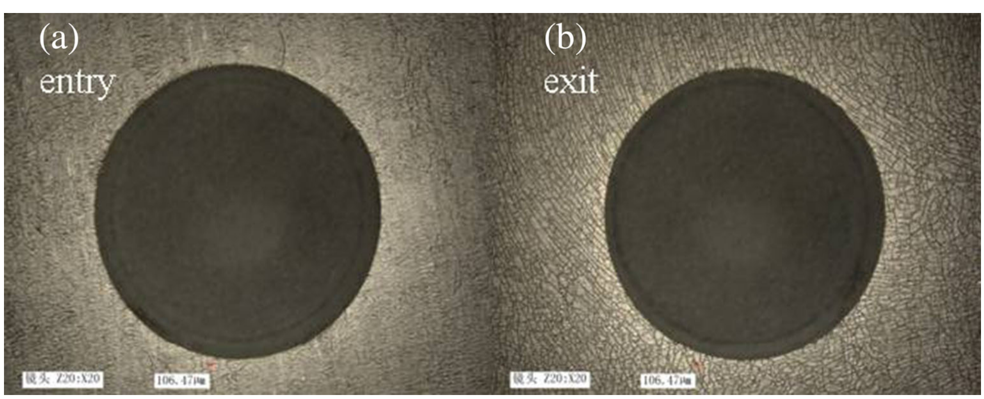


Fig. 11 Hole quality of titanium alloy in entry and exit part

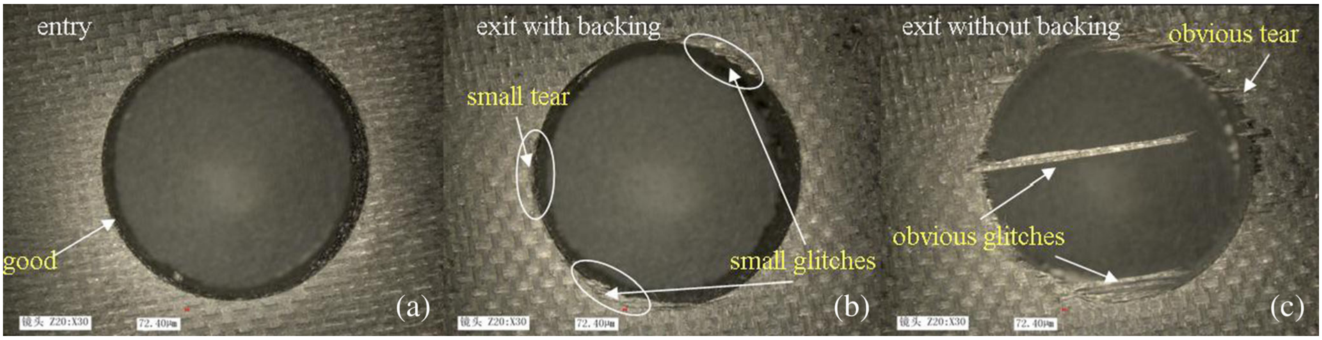


Fig. 12 Hole quality of CFRP in entry and exit part

uniform distribution in the edge of holes, as shown in Fig. 14b, d. It is worth mentioning that the burrs around the hole will not cause scrap material and just need to increase the deburring process.

3.4 Hole size

1. Single layer

In order to analyze the change of hole diameter, 20 holes are selected as a detection standard; the detected results are shown in Fig. 15. Diameters of hole-making basically lie in 10.005–10.025 mm to the titanium alloy, while for the CFRP, diameters basically are in 9.99–10.009 mm. Namely, the diameter errors meet the basic requirements of IT7-IT9 for hole diameter of 10 mm with 15~36 μm, while the shrinkage phenomenon occurs in helical milling of CFRP.

2. Stack

Because only nine holes were made for the stack material, so these holes are selected as the detection basis. The inlet and outlet diameter of each hole are measured using the CMM; the results are shown in Fig. 16. Entry diameter of CFRP and outlet diameter of titanium are relatively stable, but for the joining portion of the two materials, there has a large fluctuation of the diameter in the inlet titanium and outlet CFRP material, and the value of the entire hole diameter of titanium alloy is smaller than the exit diameter of CFRP, and the deviation of entry hole for the CFRP changes from −20 to +10 μm, while the deviation of the exit of the holes changes between the −30 ~ + 10 μm. For the titanium, maximum entry hole deviation is −50 μm, the minimum is −20 μm, and deviation at the exit hole is approximately between −35 and −15 μm.

In general, nearly undersized holes are produced when helical milling CFRP only, and oversized holes are produced when processing Ti only. However, oversized CFRP holes with undersized Ti holes are observed when machining of stack. The change of hole-making diameter shows very different characteristics; it may be due to the increased tool wear of blunt chisel edge and cutting lip when processing the bottom Ti plate.

In addition, it can be seen that size fluctuations are relatively large in exit of CFRP and entrance of titanium alloy, resulting in significantly increase of the diameter error. For laminated materials, hole diameter will change when machining from one into another material, it is one of the major

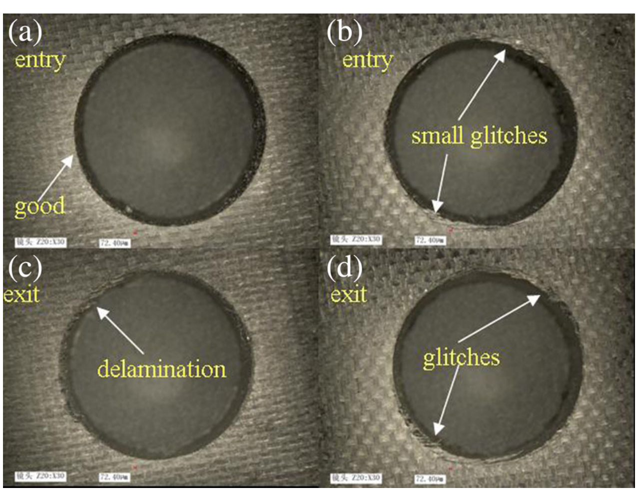


Fig. 13 Microscopic pictures of CFRP

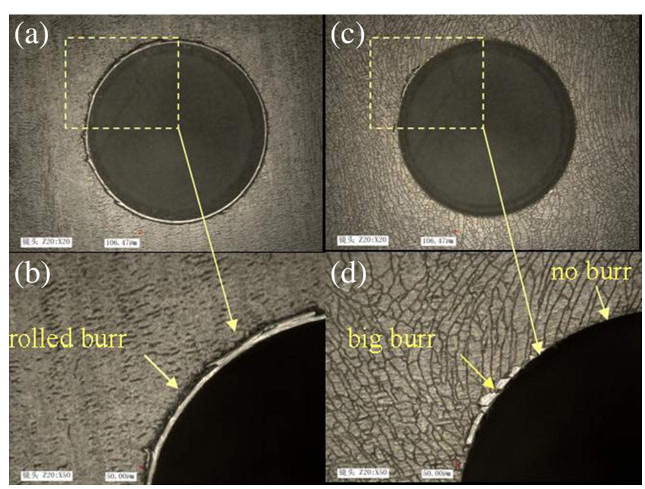


Fig. 14 Microscopic pictures of titanium

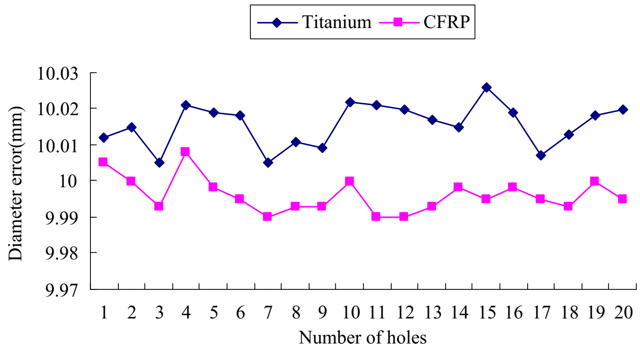


Fig. 15 Hole diameter in helical milling of single plate

quality problems. The size does not meet IT7~IT9 tolerance requirements of laminated materials, it needs to be reamed subsequently. The reason for this phenomenon is that the following aspects: first, processing characteristics of two materials are different, the jointing face will impact the tool cutting state; second, the material thickness will influence the temperature of cutting zone, thus cause the serious tool wear; and third is the geometry dimensions and material or coating material of the tool used is not suitable for machining CFRP materials or laminated materials.

4 Conclusions

Hole-making in stacks composed of CFRP and titanium alloy is very difficult all over the world, especially for larger thickness. The experimental studies on the performance evaluation in helical milling of CFRP-Ti stacks (10 + 10 mm) and their single plate were conducted. The results are illustrated as follows:

1. Cutting forces increase with the increasing hole number via tool wear. In the machining of titanium alloy, the relation is nearly linear, while in machining of CFRP, the relation is nonlinear because of the abrasion of carbon fiber. In the stack with CFRP/Ti, change of cutting force in machining of titanium alloy suddenly increases; the value is far larger than the CFRP in the stack and single titanium alloy layer. The main reason lies in the abrasive wear of CFRP resulted in the increase of cutting force, especially axial force in machining of titanium.
2. Tool wear is mainly abrasive wear in processing of CFRP, while tool is always broken while machining of titanium. So in the machining of CFRP/Ti stacks, tool wear state shows combination of two wear patterns.
3. The hole edge quality is good while machining of titanium alloy, and entry delamination will appear in milling of CFRP; exit quality of the holes depends on if there is a supporting plate in the export parts. While in the helical milling of stack, due to the impact of tool wear, the number and length of glitches also show gradually increasing trend for the CFRP either in the entry or the exit parts than single plate. Burrs in the entry part show uniform rolled state about titanium alloy, which will increase the deburring process, while the exit burrs are also large without uniform distribution state.
4. In general, undersized CFRP holes are produced and oversized for titanium alloy single plate. However, oversized CFRP holes and undersized for titanium alloy are observed when helical milling of stacks.

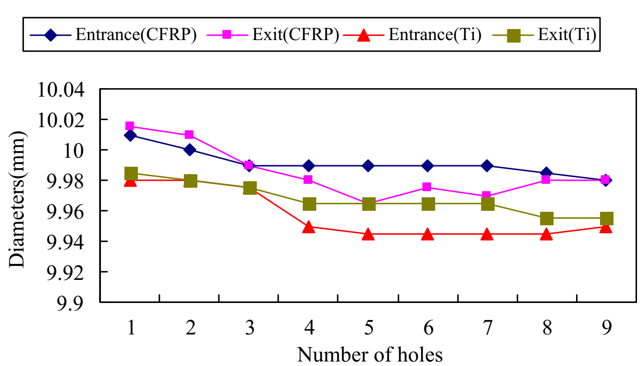


Fig. 16 Entrance and exit of holes diameter in helical milling of stack

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