Methods for Reducing Interface Aperture Inconsistency During NC Orbital Milling of Aircraft Laminates with Coarse Pitch

SHAN Yicai[1,3*], *HE Ning*[2], *LI Liang*[2], *WU Kai*[3]

1. College of Mechanical and Electrical Engineering, Nanjing College of Information Technology, Nanjing 210046, P.R. China; 2. College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, P.R. China; 3. School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, P.R. China

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Abstract: The methods for reducing interface aperture inconsistency are studied in NC orbital milling (NCOM) of CFRP/Ti6Al4V laminates with coarse pitch. Comparative experiments show burr, aperture inconsistency and error are typical interface defects. Meanwhile, aperture inconsistency and error are more serious than burr in NCOM with coarse pitch. As one of the major causes of interface defects, axial force and radial force are intensively studied. Based upon the machining principle of orbital milling (OM) and the actual hole-making condition in laminated structures, NCOM experiments with coarse pitch are conducted on CFRP/Ti6Al4V laminates under different cutting conditions. Then, the effects of interlayer clamping, minimal quantity lubrication (MQL), twice milling instead of reaming, and interlayer speed change on interface aperture are analyzed. Research shows that interlayer clamping, interlayer speed change and MQL can effectively reduce out-of-tolerance of interface aperture. When making holes of different diameters with one cutter, axial feed has a greater effect on interface aperture precision than tangential feed. When making holes of the same diameter with different cutters, small diameter cutter will reduce interface aperture precision in a single processing. But the method of "twice milling instead of reaming" can improve the aperture precision effectively.

Key words: CFRP/Ti6Al4V laminates; NC orbital milling; coarse pitch feed; interface aperture

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0 Introduction

As a high-end equipment of modern aviation industry, the quality and efficiency of lamination assembly in large aircraft has a great influence on flight security and manufacturing cost[1-2]. Studies find that the machining quality of connecting holes has significant influence on laminated components, such as roundness, perpendicularity, position accuracy, hole surface quality, burr and chip between layers, fatigue life, etc[3-4]. Due to the coupling effect of various factors in machining process, it is difficult to effectively control the interlayer defects. Now, interlayer defect control has become a technical bottleneck when making holes efficiently and nondestructively in laminates, especially in typical CFRP/alloy laminates[5-7].

Many scholars have carried out a lot of research on interlayer defect control when push drilling (PD) of CFRP/alloy laminates. Ramulu et al. found that the cutting heat generated in PD of titanium alloy with high-speed would burn the composite material at the interface, and the cutting parameter sets for more difficult-to-cut material of the two laminated components were more suitable for processing the interface connection area[8]. Since the upper layer CFRP was supported by the lower layer Ti, the delamination and tearing defects at CFRP exit were inhibited[9]. During PD test of clamped aluminum al-

*Corresponding author, E-mail address: shanyc@njcit.cn.

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loy laminations, Melkote et al. found that high cutting speed, low feed speed and twist drill with a small top angle could reduce interlayer gap and interlayer burr. In addition, clamping position had a significant effect on both[10]. Bi et al. confirmed that applying pressing force or changing lamination sequence was a feasible method to reduce the height of interlayer burr[11-12]. Luo studied the defects of holes in CFRP/Ti laminates, and pointed out that the higher the cutter feed speed, the lower the workpiece stiffness, and the more serious the damage between layers[13]. Gao revealed the generation mechanism of non-coaxiality in PD of CFRP/Ti laminates, and proposed process measures to effectively control interlayer gap and non-coaxiality[14].

The above researches have played an important role in reducing interlayer defects when PD of CFRP/alloy laminates. However, with the trend of thin wall, large size and lightweight in modern aviation components, the weak rigidity of laminated structures has a more prominent effect on interlayer defects[14]. Refs.[15-16] found that the excessive axial force in PD of CFRP/alloy laminates is more likely to cause interlayer gap. Therefore, it is necessary to study hole-making technology with small axial force.

Recent research shows orbital milling (OM) has more advantages than PD in cutting difficult-to-cut materials, since it has small axial force, low cutter wear and high hole-making precision[17], which becomes a new research spot when making holes in CFRP/alloy laminates[18]. Denkena studied the effect of tangential and axial feed on OM of CFRP/Ti6Al4V laminates, and indicated that high tangential feed speed and low axial feed speed were conducive to reduce aperture deviation[19]. Gui found interlayer clamping and sharp cutter were both helpful in inhibiting interface orifice burr and CFRP internal delamination during OM of CFRP/Ti6Al4V laminates[20]. Wang found that big laminated thickness and large number of holes might increase cutter wear when OM of aviation laminates, and further reduce the precision and quality of holes[21]. Pan proposed an online laminated interface identification method for making holes in CFRP/Ti laminates[22]. Gao et al. proposed an ultrasonic vibration assisted helical milling method, which significantly reduces the manufacturing defects, such as tearing and burr[23]. Hu installed OM unit on robot to carry out hole-making tests in CFRP/Ti6Al4V laminates, and found that the poor machining stability of robot system brought large aperture size of CFRP exit[24].

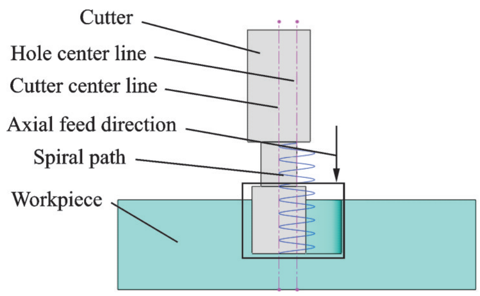
Although a lot of research has been done on interfacial burns, hole surface quality and interlayer burrs of CFRP/alloy laminates, the research on interface aperture inconsistency is still lacking. The interface aperture inconsistency can affect the quality of lamination assembly, and even lead to the failure of lamination assembly. Presently, the combined process of "drilling and reaming" is often used to improve the interface aperture consistency. But its processing efficiency is very low. Although non-coaxiality in PD of CFRP/Ti laminates has been studied in Ref.[14], few reports can be found on interface aperture inconsistency of OM. Affected by resultant cutting force and cutter revolution radius, interface aperture error occurs frequently in OM[25]. Limited by processing equipment and hole-making precision, present OM mostly uses small pitch. With the wide use of CFRP/Ti6Al4V laminates in modern aircraft structures, the influence of spiral feed on hole-making efficiency becomes a significant problem.

To improve the hole-making quality and efficiency in CFRP/alloy laminates, He et al. proposed a new machining method as OM with coarse pitch[26-27]. He discovered the processing efficiency of coarse pitch was about 3—18 times that of small pitch when OM of Ti6Al4V. During OM of CFRP, the efficiency is 2—10 times[28]. However, the increase of axial feed pitch brings larger cutting force and accelerates cutter wear. This paper attempts to explore methods to reduce interface aperture inconsistency when NC orbital milling (NCOM) of CFRP/Ti6Al4V laminates with coarse pitch. The research is helpful to improve hole-making efficiency and precision when NCOM of laminated structures.

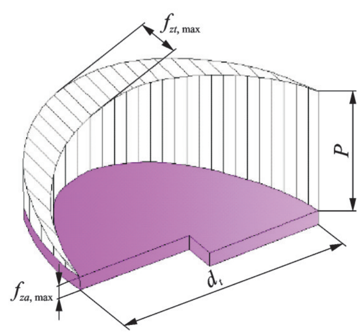
1 Machining Principle of NCOM with Coarse Pitch

1.1 Machining principle

As shown in Fig. 1(a), cutter rotation is the main cutting movement, and cutter spiral feed movement is composed of feed along z direction and linear interpolation motion along x and y directions. In OM the bottom edge performs continuous milling and the side edge participates in intermittent milling. According to the relative motion between the cutter and the workpiece, the undeformed chip model is established in Fig.1(b).



(a) Machining principle



(b) Undeformed chip model

Fig.1 NCOM

The cutting thickness per tooth of the bottom edge and the side edge can be calculated by Eqs. (1)—(2).

$$f_{zt,\max} = \frac{2\pi e n_\omega}{n_s \times Z} \tag{1}$$

$$f_{za,\max} = \frac{P \times n_\omega}{n_s \times Z} \tag{2}$$

where n_s is the cutter rotation speed; n_ω the cutter revolution speed; e the cutter revolution radius; Z the number of cutter teeth; P the axial feed pitch; $f_{zt,\max}$ the cutting thickness per tooth of side edge; $f_{za,\max}$ the cutting thickness per tooth of bottom edge.

If the cutter and other cutting parameters remain unchanged, NCOM efficiency increases when P increasing. Meanwhile, $f_{za,\max}$ and the axial cutting depth of side edge are also increased. Finally the increase of cutting forces of two cutting edges accelerates cutter wear.

However, studies show that optimizing cutting parameters (such as increasing n_s, decreasing n_ω and increasing e) can realize the optimization of cutting force[29]. Furthermore, under the same processing efficiency, coarse pitch feed can reduce cutter revolution speed, increase axial cutting depth of side edge, and decrease tangential cutting thickness of side edge. The increase of the contact length of side edge and the decrease of cutter revolution speed can enhance the machining stability of NCOM.

1.2 Experimental design

The comparative experiment is design for making holes in CFRP/Ti6Al4V laminates. The size of the laminates is 150 mm×100 mm×13.8 mm. The thickness of CFRP is 3.8 mm and the thickness of Ti6Al4V is 10 mm, as shown in Fig. 2(a). Since laminated structures are not suitable to be cut in from the side of titanium alloy, CFRP is set on the upper side. Two four-tooth carbide end mills and one two-tooth carbide drill are used in experiment. The diameters of the two carbide end mills are Φ6 mm and Φ8 mm. The diameter of the carbide drill is Φ10.2 mm. All these cutters are coated by TiAlN. The shape of carbide end mill and carbide drill is shown in Fig.2(b).

The hole-making experiment of NCOM with coarse pitch is carried on UPC710 machine center, as shown in Fig.2(c). Cutting parameters are set as follows. n_s=3 000 r·min^{-1}, f_{zt}=0.06 mm, e=1.1 mm, P=1 mm. In PD experiment, drilling speed is 800 r·min^{-1} and axial feed speed is 80 mm·min^{-1}. CFRP chip is removed by vacuum. Minimal quantity lubrication (MQL) is used when cutting Ti6Al4V.

The cutting force acquisition system is mainly composed of three-dimensional dynamometer Kistler 9275B and the corresponding charge amplifier Kistler 5019. Under the workpiece coordinate sys-

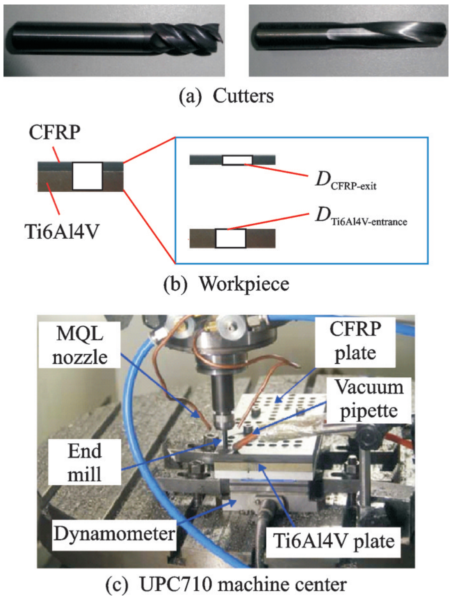


Fig.2 Experimental system

tem, Kistler 9275B measures the cutting forces in three directions as F_x, F_y and F_z. However, to study the influence of cutting forces on aperture precision in NCOM, it is more recommended to analyze tangential force F_t, radial force F_r and axial force F_a in the cutter coordinate system. According to the kinematic relationship between the two coordinate systems, as shown in Fig.3, F_x, F_y and F_z can be converted to F_r, F_t and F_a by Eq.(3).

$$\begin{bmatrix} F_t \\ F_r \\ F_a \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1} \cdot \begin{bmatrix} \cos\beta & 0 & 0 \\ 0 & \cos\beta & 0 \\ -\sin\beta & -\sin\beta & 1 \end{bmatrix}^{-1} \cdot \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \tag{3}$$

where θ is the cutter rotation angle; ϕ the cutter revolution angle; β the cutter spiral angle.

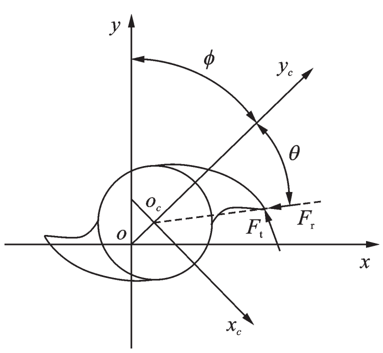


Fig.3 Schematic diagram of cutter movement in NCOM

Coordinate measuring instrument Micro Hite DCC is adopted to measure the interface apertures of CFRP exit and Ti6Al4V entrance. Each aperture is measured in different circumferential positions for 3 times, and the average value is taken as the final interface aperture.

2 Experimental Analysis

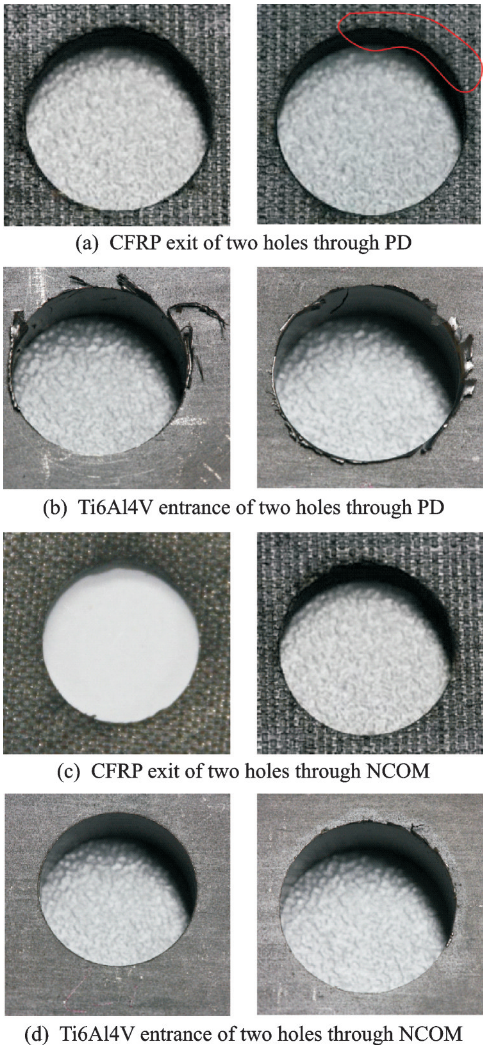
2.1 Analysis of interface defects

The morphology of CFRP exit and Ti6Al4V entrance is photographed. The ideal diameter of the holes is Φ10.2 mm. Some of the holes are processed by NCOM with a Φ8 mm carbide end mill, the others are processed by PD with a Φ10.2 mm carbide drill.

Experimental results show the interlayer material at CFRP exit by two processing methods has no delamination, but still has some tear and burr, as can be seen from Fig.4(a) and Fig.4(c). In PD, the high cutting temperature generated when drilling of Ti6Al4V brings some resin ablative trace at CFRP exit. While in NCOM with coarse pitch, burr and trace ablative are not obvious.

Seen from Fig.4(b), a large number of burrs accumulate at Ti6Al4V entrance in PD because drilling produces excessive axial force. The burrs at Ti6Al4V entrance in NCOM with coarse pitch are not particularly obvious, as shown in Fig.4(d). With the increase of cutter wear in NCOM with coarse pitch, a small number of burrs gradually appear at Ti6Al4V entrance.

Fig.5 shows the apertures of entrances and exits when CFRP/Ti6Al4V laminates are processed by PD and NCOM with coarse pitch. The measurements show that the aperture precision of CFRP entrance and Ti6Al4V exit reaches IT9 under two machining methods, but the apertures at the interface have large dimension error. In Fig.5, the interface aperture precision of NCOM with coarse pitch is lower than that of PD. However, the interface aperture consistency of NCOM with coarse pitch is significantly better than that of PD. With the increase of hole number, the interface apertures might exceed IT9.



(a) CFRP exit of two holes through PD

(b) Ti6Al4V entrance of two holes through PD

(c) CFRP exit of two holes through NCOM

(d) Ti6Al4V entrance of two holes through NCOM

Fig.4 Morphology of CFRP exit and Ti6Al4V entrance

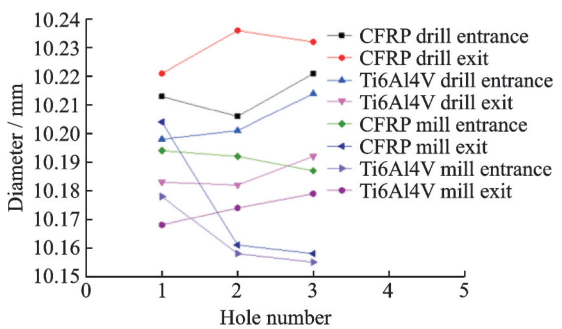


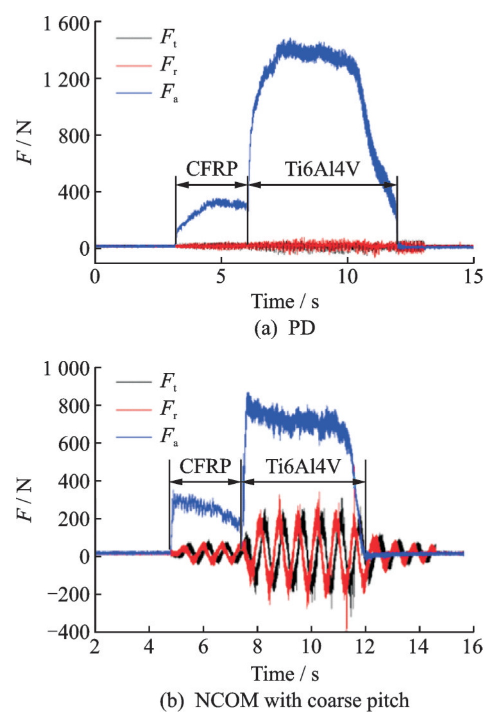
Fig.5 Exit and entrance apertures of CFRP and Ti6Al4V

In a word, NCOM with coarse pitch could obtain better orifice burr and higher aperture consistency at the interface than PD, and but low interface aperture precision. When the increase of axial feed pitch P would sharply worsen interface defects, interface aperture inconsistency and error happen more serious than burr. In experiments of NCOM with coarse pitch, it is also discovered that interface aperture consistency and precision are not only affected by cutting force, but also by coupling effect of many other factors, such as cutter diameter and cutting stability, etc.

2.2 Analysis of cutting force

Cutting force is an important factor that directly affects interface aperture precision of CFRP/Ti6Al4V laminates. Fig.6 shows two kinds of cutting forces produced by Φ10.2 mm carbide drill and Φ8 mm carbide end mill. In PD, F_a in the upper CFRP is about 350 N, and F_a in the lower Ti6Al4V is about 1 470 N. While in NCOM with coarse pitch, the values of F_a in CFRP and Ti6Al4V are about 320 N and 820 N. When machining the upper CFRP, F_a of NCOM with coarse pitch is slightly less than that of PD. In the lower Ti6Al4V, F_a of NCOM with coarse pitch is about 50% of that of PD. At the moment when the cutter cuts into Ti6Al4V from CFRP, the effect of F_a on interface aperture precision in NCOM is less than that in PD. This maybe one of the important reasons that the interface aperture consistency of NCOM is better than that of PD.

Fig.6 also shows F_r of NCOM is obviously bigger than that of PD when processing CFRP/



(a) PD

(b) NCOM with coarse pitch

Fig.6 Cutting forces of two hole-making methods

Ti6Al4V laminates. The excessive F_r might cause cutter relieving along radial direction, thus enlarging aperture error. So the aperture precision of NCOM is lower than that of PD. As the processing depth of CFRP/Ti6Al4V laminates increases in NCOM, the increase of the F_r difference between Ti6Al4V and CFRP reduces the interface aperture consistency.

Seen from Fig. 6 (a), F_a in CFRP increases slowly at first, then reaches steady state. Next, a sudden change appears in F_a, which indicates that the cutter cuts into the lower Ti6Al4V. When making holes in CFRP/Ti6Al4V laminates and CFRP respectively by PD, the change of F_a in the upper CFRP of laminates is obviously different from that in CFRP materials[30]. The reason is that the material properties of CFRP in the laminated structures are affected by the drilling temperature. The constraint of the lower Ti6Al4V can avoid cutter relieving, so the axial force at CFRP exit is relatively stable. However, in PD experiments on CFRP/Ti6Al4V laminates and Ti6Al4V materials, the variations of F_a in two materials are very similar.

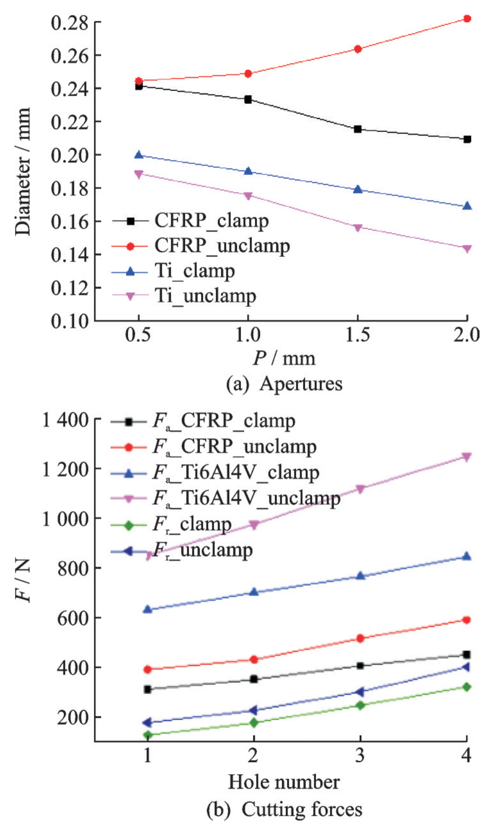
Experiments of NCOM with coarse pitch are carried out on CFRP/Ti6Al4V laminates, CFRP materials and Ti6Al4V materials respectively. F_a amplitudes in the upper CFRP of laminates and CFRP materials are very close. While F_a in the lower Ti6Al4V of laminates is significantly larger than that in Ti6Al4V materials. There are two possible reasons for this: the first is cutter wear during the machining of CFRP, the second is the CFRP chip which has not been sucked away in time. When Ti6Al4V is processed, the chip sticks to the rack and flank faces of the cutter and increases the friction.

3 Control Methods for Reducing Interface Aperture Inconsistency

Based upon current research on hole-making technology in large aircraft, NCOM with coarse pitch is studied in this paper to reduce interface defects of CFRP/Ti6Al4V laminates by analyzing interlayer clamping, cutting parameters, lubrication, cooling, twice milling instead of reaming, and interlayer variable speed, etc.

3.1 Interlayer clamping

Influenced by the shape and size of the workpiece and the axial force in hole-making process, interlayer gap occurs when making holes in aircraft laminates. After NCOM with coarse pitch, a small amount of chip accumulates in the interlayer gap, which produces burrs at the interface orifice. When the cutter cutting into Ti6Al4V from CFRP, the interlayer gap intensifies the cutter impact, and affects the interface aperture precision. To study the effect of interlayer clamping on interface aperture precision in CFRP/Ti6Al4V laminates, two methods of clamping and non-clamping are adopted in experiments of NCOM with coarse pitch to make holes of Φ10.2 mm. The thickness of CFRP is 3.8 mm and the thickness of Ti6Al4V is 10 mm. A Φ8 mm carbide end mill with four teeth is selected. n_s is 3 000 r·min^{-1}, f_{zt} is 0.03 mm, e is 1.1 mm, P is set as 0.5, 1, 1.5 and 2 mm. The test results are shown in Fig.7.



(a) Apertures

(b) Cutting forces

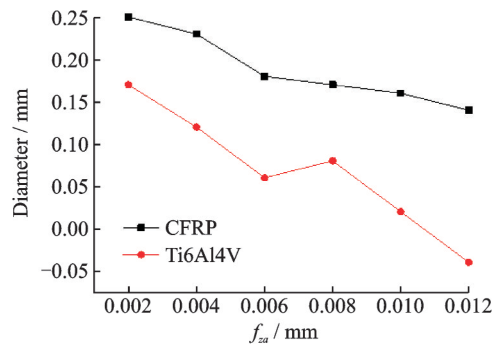
Fig.7 Influence of interlayer clamping on hole-making in laminated structures

From Fig.7(a), it is found that interlayer clamping is helpful for improving aperture precision and consistency of CFRP exit and Ti6Al4V entrance. When the interlayer clamping is adopted, both apertures at CFRP exit and Ti6Al4V entrance gradually decrease with the increase of P. And the aperture of CFRP exit is more and more close to the designed aperture, while the aperture of Ti6Al4V entrance is more and more deviated from the designed aperture. But the interface aperture consistency of CFRP exit ant Ti6Al4V entrance barely changes. Without interlayer clamping, the aperture of CFRP exit becomes larger when P increases, and the aperture of Ti6Al4V exit decreases continuously with the increase of P. Both of the two apertures deviate from the designed aperture. Under a certain P value, the aperture change of interlayer clamping is smaller than that without clamping. Fig.7(b) shows F_a and F_r of each hole. Therefore, the interlayer clamping can effectively improve the rigidity of cutting area and restrain the abrupt change of interlayer cutting force, alleviate cutter impact and vibration, and help to reduce the interface aperture defect.

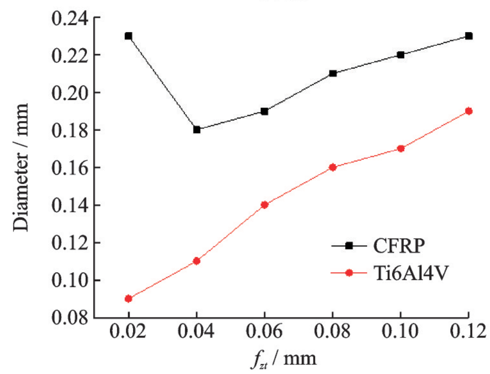
3.2 Cutting parameters

Reasonably controlling cutting force by adjusting cutting parameters is one of the most convenient ways to improve interface aperture precision of aircraft laminates in NCOM with coarse pitch. Relevant studies show that axial feed and tangential feed have significant influence on cutting force. In this paper, single factor experiment of NCOM with coarse pitch is conducted to discuss the influence of axial feed and tangential feed on the interface aperture of laminates. A Φ8 mm carbide end mill with four teeth is used. Cutting parameters are set as follows. n_s=1 600 r·min^{-1}, e=1.1 mm, f_{zt}=[0.02, 0.04, 0.06, 0.08, 0.10, 0.12] mm, f_{za}=[0.002, 0.004, 0.006, 0.008, 0.010, 0.012] mm.

Fig.8 shows the variation of interface aperture with f_{za} and f_{zt}. Under the same f_{za} or f_{zt}, the interface aperture precision of CFRP exit is always higher than that of Ti6Al4V entrance. With the increase of f_{za}, the apertures decrease continuously in Fig.8(a). As shown in Fig.8(b), with the increase of f_{zt}, the aperture of CFRP exit decreases first and then increases. The apertures of the Ti6Al4V entrance keep getting bigger.



(a) f_{za}



(b) f_{zt}

Fig.8 Influence of feed on NCOM of laminates

To further analyze the influence of f_{za} and f_{zt} on interface aperture in NCOM with coarse pitch, the relationship of cutting forces and cutting thickness per tooth is analyzed under the cutting parameters as n_s=1 600 r·min^{-1}, e=1.1 mm, f_{zt}=0.06 mm, the relation of f_{za} and cutting forces are described in Fig.9. F_r and F_t show an increasing trend with the increase of f_{za}. F_a of Ti6Al4V shows a steady trend, and F_a of CFRP shows fluctuation. The reason is the cutting thickness of bottom edge and the cutting depth of side edge both increase with the increase of f_{za}, so F_r and F_t also increase accordingly. The uncertain change in F_a of CFRP indicates that f_{za} is not the only factor affecting cutting force. Due to the characteristics of CFRP, such as anisotropy and low interlaminar bonding strength, F_a of CFRP is oscillating. As F_r increases in Fig.8(a), the aperture dimensions of CFRP exit and Ti6Al4V entrance have a general trend of decreasing. Because of little change in F_a, the interface aperture consistency of CFRP exit and Ti6Al4V entrance is not changing much.

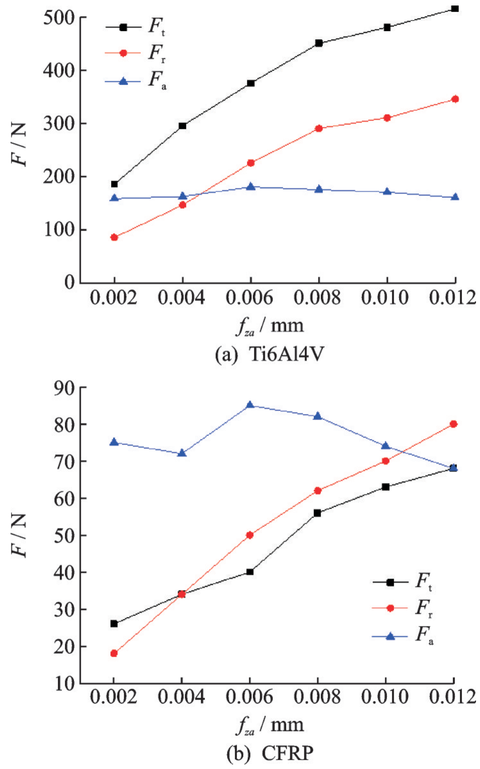


Fig.9 Influence of f_{za} on cutting forces

Fig.10 shows the variation of cutting forces with f_{zt} when f_{za} is 0. 006 mm. The other two parameters as n_s and e are the same as Fig.9. According to Eqs.(1)—(2), n_ω increases with the increase of f_{zt}, thus the cutting thickness of the side edge increases. However, the axial cutting depth of side edge decreases with f_{zt} increasing. Since the circumferential cutting of the side edge plays a big role, F_r and F_t show a downward trend. F_a is mainly from the continuous milling of the bottom edge. With the increase of f_{zt}, F_a varies within a certain range. In Fig.8(b), the decrease of F_r brings an increase tendency of apertures at CFRP exit and Ti6Al4V entrance. The little change in F_a leads to the little change in interface aperture consistency of CFRP exit and Ti6Al4V entrance.

3.3 Cutter diameter

In NCOM, carbide end mill with small diameter is used to reduce cutting forces. But the low rigid cutter might affect aperture machining accuracy. To

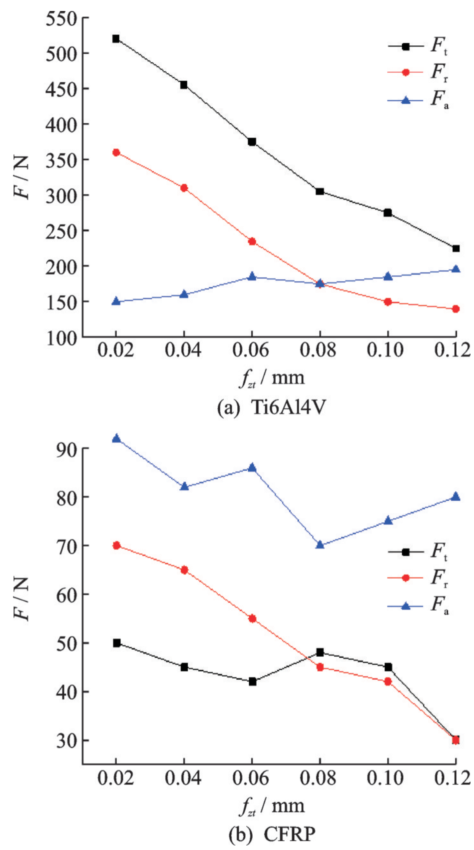


Fig.10 Influence of f_{zt} on cutting forces

study the influence of cutter diameter on interface aperture in CFRP/Ti6Al4V laminates, two four-tooth carbide end mills coated by TiA1N are used in hole-making experiments. The diameters of the two cutters are Φ8 mm and Φ6 mm. The test results are shown in Table 1. The apertures of CFRP exit and Ti6Al4V entrance produced by Φ6 mm end mill are less than that produced by Φ8 mm end mill, which can be explained by Fig. 11. But Φ6 mm end mill can get better interface aperture consistency than Φ8 mm end mill.

Under the same cutting parameters, a Φ6 mm end mill and a Φ8 mm end mill are separately used

Table 1 Apertures at CFRP exit and Ti6Al4V entrance under different cutter diameters

No.	Cutter diameter/mm	CFRP exit aperture/mm	Ti6Al4V entrance aperture/mm
1		10.167	10.154
2	Φ6	10.159	10.143
3		10.158	10.138
4		10.204	10.178
5	Φ8	10.161	10.158
6		10.162	10.155

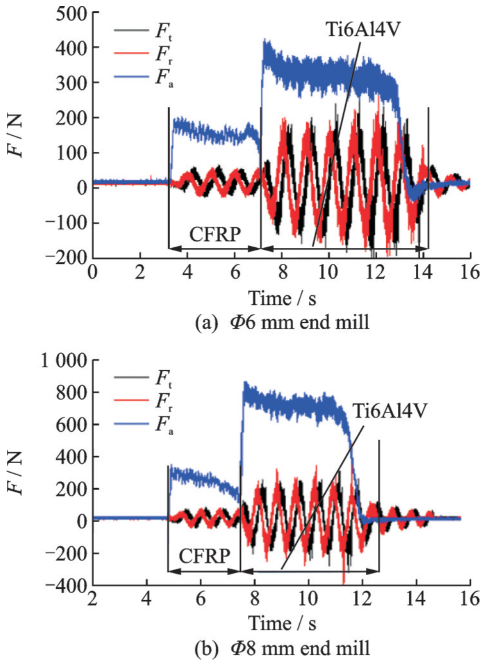


Fig.11 Influence of cutter diameter on cutting forces

in NCOM Φ10.2 mm holes. The cutting forces are described in Fig.11. When a Φ6 mm end mill is used in machining, F_a in CFRP is about 200 N and F_a in Ti6Al4V is about 450 N. Compared with Fig.11(b), F_a in CFRP and Ti6Al4V is reduced by 37.5% and 45.12% respectively. With the decrease of cutter diameter, the material cut by the bottom edge is decreasing in continuous milling, and the material cut by the side edge is increasing in intermittent milling. Meanwhile, the increasing chip removal space is good for cutting heat dissipation and chip removal, thus cutter wear is reduced. Based upon the above factors, F_a produced by Φ6 mm end mill is significantly smaller than that produced by Φ8 mm end mill. In NCOM with Φ6 mm end mill, the mutation of F_a at interface is relatively small. This might be the reason that the interface aperture consistency produced by Φ6 mm end mill is better than that produced by Φ8 mm end mill. Meanwhile, the data of F_r in Fig.11(a) is larger than that in Fig.11(b). Since the stiffness of Φ6 mm end mill is weaker than that of Φ8 mm end mill, Φ6 mm end mill is more likely to be affected by impact and F_r. Therefore, interface aperture precision exists in holes produced by Φ6 mm end mill is lower than that produced by Φ8 mm end mill as shown in Table 1. When cutting laminates with small diameter cutter, finish machining is needed to improve interface aperture precision.

3.4 MQL

To improve cutting performance of NCOM with coarse pitch, MQL is a good choice. A comparative experiment with MQL and dry milling was conducted in CFRP/Ti6Al4V laminates to study the effect of MQL on interface aperture. The thickness of upper CFRP is 3.8 mm, and the thickness of lower Ti6Al4V is 2 mm. The hole diameter to be made is Φ5 mm. The cutter is a Φ4 mm carbide end mill with four teeth. Cutting parameters are set as follows. n_s=5 000 r·min^{-1}, f_{zt}=0.06 mm, e= 0.5 mm, P=1 mm. The test results are shown in Table 2.

Seen from Table 2, MQL has little influence on interface aperture in NCOM with coarse pitch. Fig.12 describes the forces in MQL and dry milling. F_a of CFRP and Ti6Al4V in dry milling is about

Table 2 Actual aperture and aperture error

Material	Test item	MQL	Dry
CFRP exit aperture	Actual aperture/mm	4.99	4.97
	Aperture error	−0.01	−0.03
Ti6Al4V entrance aperture	Actual aperture/mm	4.98	4.99
	Aperture error	−0.02	−0.01

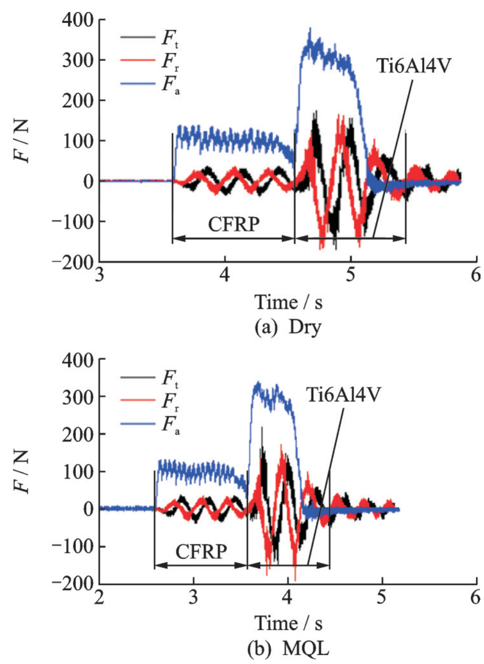


Fig.12 Influence of MQL and dry milling on cutting forces

120 N and 340 N respectively. When MQL is adopted, F_a of CFRP and Ti6Al4V is about 110 N and 320 N respectively. Since the amplitude reduction of F_a caused by MQL is small, MQL has little effect on aperture precision.

3.5 Replacing reaming with twice milling

To obtain high machining accuracy, twice NCOM are needed in hole-making process. The first NCOM is regarded as rough machining and the second NCOM is finish machining. The second NCOM can improve the aperture precision, thus realizing the function of replacing reaming with second milling. To study the effect of the second NCOM on interface aperture, a Φ6 mm carbide end mill and a Φ8 mm carbide end mill are used in NCOM experiments respectively to process Φ10.2 mm holes with coarse pitch. The first set of experiments includes twice NCOM by a Φ6 mm end mill. In the first NCOM, e is set as 1.9 mm. Then the second NCOM with e=2.1 mm finishes the hole-making process. The second set of experiments uses a Φ8 mm end mill in NCOM for one time with e=1.1 mm. The other cutting parameters of the two sets of experiments are the same.

The experimental results are shown in Table 3. The interface aperture precision and consistency of twice NCOM with a Φ6 mm carbide end mill is much better than that of once NCOM with a Φ8 mm carbide end mill. The reason is that the CFRP/Ti6Al4V laminates are mainly cut by the side edge in the second NCOM. Fig.11(a) shows the cutting force of the first NCOM by Φ6 mm carbide end mill. Fig.13 gives the cutting force of the second NCOM by Φ6 mm carbide end mill. Compared with Fig.11(a), it is found that F_a in the finishing stage of twice NCOM is very small. F_r and F_t in Fig.13 are also greatly reduced. In the second NCOM, F_a changes very little when the cutter cutting into Ti6Al4V from CFRP. Though Φ6 mm end mill obtains less aperture precision than Φ8 mm end mill in a single NCOM, the second NCOM with Φ6 mm end mill can improve the aperture precision, and further improve the interface aperture consistency.

Table 3 Apertures at CFRP exit and Ti6Al4V entrance under different types of milling

No.	Twice NCOM by Φ6 mm end mill		Once NCOM by Φ8 mm end mill	
	CFRP exit aperture/mm	Ti6Al4V entrance aperture/mm	CFRP exit aperture/mm	Ti6Al4V entrance aperture/mm
1	10.197	10.185	10.204	10.178
2	10.182	10.179	10.161	10.156
3	10.178	10.174	10.162	10.155
4	10.183	10.178	10.163	10.157
5	10.180	10.171	10.168	10.156
6	10.179	10.174	10.157	10.149

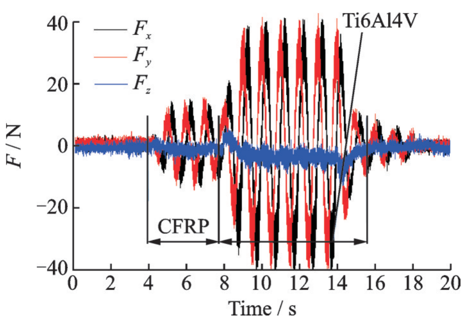


Fig.13 Cutting forces of finish machining in twice NCOM coarse pitch by Φ6 mm carbide end mill

3.6 Interlayer speed change

Due to the difference in cutting performance of different materials, there are two main methods for PD of CFRP/Ti6Al4V laminates[31]. The first method adopts diamond cutter to drill the upper CFRP firstly, then uses carbide drill to process the lower Ti6Al4V, and finally uses carbide reamer to carry out reaming on CFRP/Ti6Al4V laminates. The second method adopts appropriate cutting parameters for drilling of Ti6Al4V, and machines CFRP/Ti6Al4V laminates by once drilling. Although the former method is easy to be realized by online interlayer speed change of CNC machine tools, the frequent cutter change may reduce processing efficiency. The cutting parameters used in the second method might aggravate cutter wear and reduce processing quality. NCOM with coarse pitch can realize the interlayer speed change by using the z-axis quasi-stop function of 5-axis CNC machine center. Based upon reasonable cutting parameter, twice NCOM with coarse pitch can effectively obtain high aperture precision, which avoids the defects of the above two PD methods. Table 4 shows the cutting parameters of a Φ8 mm carbide end mill in conditions of changing speed and unchanging speed during NCOM.

Table 4 Cutting parameters under two control methods

Control method	Cutting parameter	Material	
		Ti6Al4V	CFRP
Changing speed	n_s /(r•min^{-1})	3 000	7 000
	f_{zt}/mm	0.05	0.03
	P/mm	1	0.5
Unchanging speed	n_s /(r•min^{-1})	3 000	3 000
	f_{zt}/mm	0.05	0.05
	P/mm	1	1

Fig.14 shows the curves of the diameter and F_a when NCOM of CFRP/Ti6Al4V laminates with coarse pitch under changing and unchanging speed. From Fig.14(a), it can be seen that interlayer aperture precision and consistency under changing speed are better than that of unchanging speed. With the increase of hole numbers, the advantage of interlayer speed change is more obvious in improving aperture precision. The reason is that the amplitude of F_a is smaller under changing speed, as shown in Fig. 14(b), which leads to better machining precision.

To further analyze the influence of interlayer speed change on the interface aperture precision of NCOM with coarse pitch, the effect of interlayer speed change on cutter wear is observed. Fig.15(a) gives the morphology of the bottom edge and the side edge before machining. Fig. 15(b) shows the cutter morphology after the sixth hole has been processed with constant speed. Under the high temperature and high pressure, the chips stick tightly on the cutter spiral groove and attach to the rake face of the

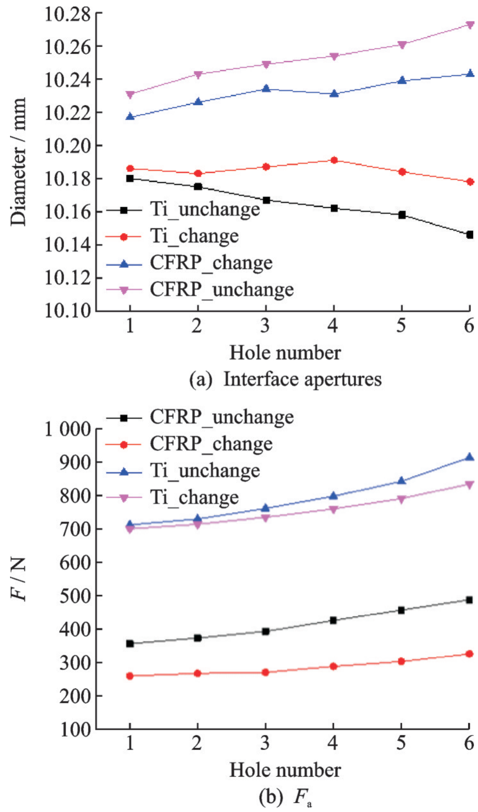


Fig.14 Influence of interlayer speed change on interface apertures and F_a

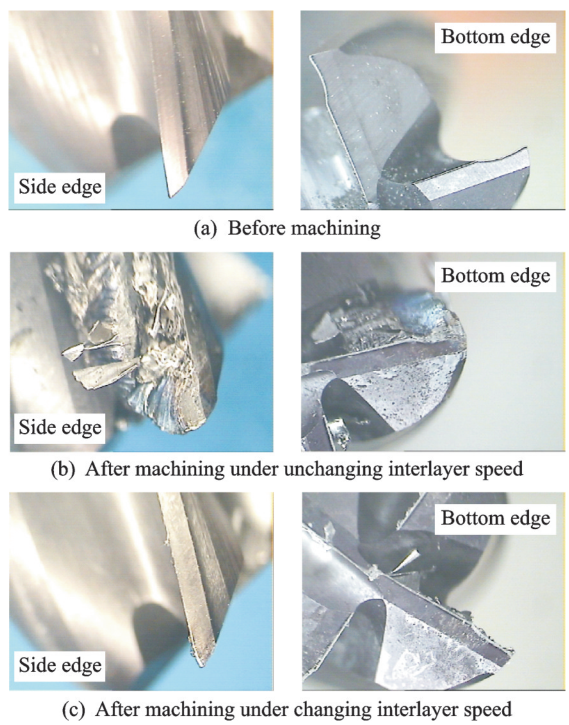


Fig.15 Influence of interlayer speed change on cutter wear

side edge and the bottom edge. And severe wear occurs on the flank face of the bottom edge. Fig.15(c) gives the cutter morphology after the sixth hole has been processed with variable speed. Except for a small amount of chips, the side edge has no significant wear. The wear on the flank face of the bottom edge is lighter than that with constant speed. Therefore, the interlayer speed change can effectively reduce the cutter wear when NCOM of laminated structures with coarse pitch, which is beneficial to improve the interface aperture precision.

4 Conclusions

The comparative experiment when NCOM with coarse pitch and PD of CFRP/Ti6Al4V show the following conclusions: (1) the interface aperture consistency and orifice burr of NCOM are much better than those of PD, further the interface aperture inconsistency and error are more serious than burr in NCOM. (2) NCOM with coarse pitch could reduce axial force of CFRP by about 9% and axial force of Ti6Al4V by about 42%, which is more suitable for machining the low rigid CFRP/alloy laminates, but big radial force also enlarges interface aperture error.

To suppress the unfavorable effect of interlayer cutting impact, interlayer clamping can effectively improve the processing stability and aperture quality of the laminated interface. When NCOM of CFRP/Ti6Al4V with coarse pitch, interlayer speed change can effectively reduce cutter wear and cutting force, and inhibit interface aperture inconsistency. Besides, MQL can also help to improve interface aperture quality.

In NCOM, axial feed has more influence on cutting force and aperture precision than tangential feed when cutter diameter is determined and rotation speed is constant. Therefore, it is recommended to choose large tangential feed and moderate axial feed. When NCOM with small diameter cutter, low rigid cutter will reduce the aperture precision at laminated interface. Especially for large holes and deep thickness of CFRP/Ti6Al4V laminates, it is more appropriate to adopt "twice NCOM with coarse pitch".

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Author Prof. **SHAN Yicai**, born in 1976, is currently a senior visiting scholar to school of Mechanical Engineering, Nanjing University of Science and Technology, China. He is a professor in Nanjing College of Information Technology, China. His research interests include robotic hole-making technology and advanced cutting process.

Author contributions Prof. **SHAN Yicai** is responsible for hole-making test, data processing and paper writing. Profs. **HE Ning** and **LI Liang** provide some suggestions for experimental design in this paper. Mr. **WU Kai** offers some suggestions for revising the text.

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大螺距数控螺旋铣削飞机叠层结构界面孔径非一致性缺陷抑制方法

单以才[1,3]，何　宁[2]，李　亮[2]，武　凯[3]

(1.南京信息职业技术学院机电学院，南京 210046，中国；2.南京航空航天大学机电学院，南京 210016，中国；3.南京理工大学机械工程学院，南京 210094，中国)

摘要：研究了大螺距数控螺旋铣削(NC orbital milling, NCOM)飞机叠层结构界面孔径非一致性缺陷的抑制方法。对比试验表明，毛刺、孔检非一致性和误差是典型的界面缺陷，其中大螺距螺旋铣削制孔时孔径非一致性和误差比毛刺更为严重。作为影响界面缺陷的主要因素，对轴向力和径向力进行了深入研究。从螺旋铣孔(Orbital milling, OM)的加工机理和叠层制孔的实际工况出发，对CFRP/Ti6Al4V叠层结构进行了不同切削条件下大螺距NCOM制孔试验，分析了叠层夹紧、切削参数、微量润滑(Minimal quantity lubrication, MQL)、以铣代铰、层间变速等方法对界面孔径的影响。研究结果表明，层间夹紧、层间变速及MQL均可有效抑制界面孔径对接超差缺陷。当采用一把刀具加工不同尺寸孔径时，轴向进给对界面孔径精度的影响比切向进给显著；当采用多把不同加工同一尺寸孔径时，小直径刀具会降低一次加工时界面孔径精度，但可以采取“二次以铣代铰”方法改善孔径加工精度。

关键词：CFRP/Ti6Al4V 叠层；数控螺旋铣削；大螺距进给；界面孔径