Study on helical hole-making process of CFRP/Al alloy laminated materials

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Received: 13 March 2022 / Accepted: 8 July 2022 / Published online: 20 July 2022
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Abstract
To ensure assembly accuracy and efficiency, the holes are made directly on the laminated material composed of CFRP and Al alloys. However, due to the sudden change of axial force in the transition area with different laminated sequence, a method of micro-lifting tool was proposed. First, the motion of helical milling was analyzed. The level values of influence the quality of the hole-making are determined, such as spindle speed, pitch, and preload. The response surface method (RSM) was used to design experiments, and the burr height between Al alloy interlayer and the tear value of CFRP was used as the standard to analyze the experimental results. The optimal parameter combination for different laminated sequences were predicted and used for cutting force analysis. The results show that sudden increase in cutting force is prone to occur in the transition area. Secondly, the hole-making processes with variable parameters study were carried out, and the method of micro-lifting tool is proposed for the experimental study of the sudden change of axial force in the transition between interlayer with constant parameters. The results show that the aperture of the hole-making with variable parameters of the laminated materials using the optimal process parameters all meets the H9. The interlayer burr of the Al alloy and the tear value of the CFRP at the entrance and exit conform to the technical requirements. The hole-making axial forces of CFRP and Al alloy are less than 50 N and 60 N, which are 70% and 83% of constant parameters milling.

Keywords Helical milling · Response surface method (RSM) · Variable parameters · Micro-lifting tool

1 Introduction

CFRP has been widely used as structural or functional parts in aerospace and other fields due to their low density, high specific modulus, high specific strength, strong corrosion resistance, high temperature resistance, and other excellent properties [1–5]. Al alloy is one of the commonly used metal materials in aircraft structures due to their low density, corrosion resistance, high fatigue resistance, and high specific strength [6, 7]. Advanced composite materials, Al alloys and Ti alloys, are the most widely used laminated materials in the aerospace field [8]. However, the laminated structure of CFRP and Al alloy occupies a very large proportion in aircraft structural parts [9]. But integrated hole-making of two or more aerospace materials has always been a challenge in aerospace manufacturing, especially for laminations between different materials [10].

In recent years, scholars at home and abroad have carried out a lot of study on the hole-making of laminated materials [11]. Zhang et al. [12] carried out a low-frequency vibration hole-making parameter optimization test to improve the hole-making quality and tool life. Wang et al. [13] revealed the effect of low frequency vibration on material removal and processing quality at Al entrance, CFRP exit, and hole wall of the laminated structure. Zhang et al. [14] established the drilling experiment platform of high- and low-frequency compound vibration to compare and analyze four drilling methods, axial force, titanium alloy chip breaking, drilling temperature, CFRP hole entrance and exit quality, and CFRP morphology at hole wall. Sun et al. [15] carried out drilling experiments of CFRP/Ti alloy laminated materials to study the influence of drilling parameters on the hole-making defects of laminated materials. Wang et al. [16] designed an experiment for drilling CFRP/titanium alloy laminations based on chip breaking process method. The results show
that it can effectively improve the hole wall surface quality of CFRP and titanium alloys. Wang et al. [17] proposed a method based on geometric function setting feed rate to reduce the fiber tear and burr of CFRP/Al alloy-laminated holes. Peng [18] used the carbon nanotube buckypaper to enhance the interlaminar strength; thus, the defects (delamination, burrs) had been reduced, and further, the hole quality has been further effectively improved.

Xie et al. [19] arranged a series of experiments by using the control variable method to study the influence of different machining methods and different machining parameters on tool wear. On the basis of the same processing efficiency, Wang et al. [20] measured in the helical milling and drilling of machining holes process cutting line speed, the cutting force, and the length of tool flank wear. Li et al. [21] used automatic hole-making equipment to test, obtained experimental data, and analyzed the chip effect, tool life, and other aspects. Under the same cutting parameters, Wang et al. [22] measured the cutting force, tool flank wear length, CFRP entrance quality, and Ti exit quality of the 2-blade and 4-blade of milling tool. Ma [23] based to the wear of cutting tool in helical milling and traditional drilling. The experiment carried out on CFRP/Ti-laminated materials with helical milling and traditional drilling test.

Luo et al. [24] proposed an optimization method for the preparation process of assembly components of laminated materials and technical scheme for hole-making by step combination. This study had greatly improved the quality of the hole-making in laminated materials. Xu et al. [25] proposed the application of variable parameter drilling technology to achieve efficient and precise machining of laminated structures. Wei [26] studied the CFRP/Al alloy laminations, analyzed the process problems in the hole-making process with constant parameters, and proposed a process method of hole-making with variable parameters. Huang et al. [27] carried out an experimental study on helical milling of CFRP/titanium alloy laminations by using parameters decreasing and reciprocating variation process. The experiments were carried out to analyze the surface roughness of the hole wall and the hole error.

The aperture accuracy of the laminated structure is one of the important factors to affect the fatigue performance of the connector [28]. Zitoune et al. [29] conducted drilling experiments on CFRP/Al alloy laminations. The results show that the phenomenon of shrinkage holes occurs when the CFRP aperture is smaller than the drill bit diameter. However, Li et al. [30] found that there is still room for improvement in the current drilling process, and the problem of shrinkage holes in laminated materials is effectively avoided. Wang et al. [31] conducted an experimental study on the drilling of CFRP/Al laminations. The influence of different laminated sequences on the axial force was studied. The results show that the hole-making quality is significantly improved when drilling from the side of the two materials. Sun et al. [32] used two methods of drilling and helical milling to study the damage generation mechanism of titanium/CFRP/aluminum laminations. Based on the orthogonal experimental method, the main reasons for the damage in the process of machining were studied.

Xu et al. [33] studied drilling-associated damages of CFRP through a critical review focusing on their formation mechanism, evaluation, and suppression. Danish et al. [34] explored the milling performance of CFRP in sustainable lubri-cooling mediums, namely dryness, minimal quantity lubrication (MQL), cryogenic-liquid nitrogen (N2liquid), and carbon dioxide (CO2ice). Xu et al. [35] characterized the temperature variation and evolution during the CFRP drilling using diamond-coated candlestick and step tools. Progression of the composite drilling temperatures was recorded using an infrared thermography camera.

To sum up, drilling and helical milling technology has received extensive attention. The current researches include low-frequency vibration hole-making process, chip-breaking process, the method of setting the feed rate by geometric function, and the influence of tool wear and shape on the machining quality of laminated materials. There are also many scholars who have compared variable parameter research between helical milling and traditional drilling. However, in-depth studies on the transition area of laminated materials are relatively rare. Aiming at the sudden change of axial force in the transition area in this paper, a method of micro-lifting the tool is proposed. Through this method, the burr height at the entrance and exit of the aluminum alloy material, the tear value of the CFRP material, and the magnitude of the axial force are reduced, and thereby effectively improve the hole quality of the CFRP/Ti laminated material.

\section{Motion analysis of helical milling}

Helical milling hole usually uses a tool to complete a variety of holes greater than or equal to the tool diameters. The principle of hole-making is shown in Fig. 1. The movement process can be decomposed into two kinds of movement.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{hole-making_schematic_diagram.png}
\caption{Hole-making schematic diagram}
\end{figure}
that one is the feed motion of the tool in the circumferential direction and the other is the feed motion of the tool in the axial direction. \(D_t\) is tool diameter. The eccentric amount of axis during revolution motion and rotation motion in the process of helical milling is ignored. The angle relationship can be shown in Fig. 2.

As shown in Fig. 2, the coordinate of any point \(P\) on the tool at time \(t\) is:

\[
\begin{align*}
  x(t) &= r_0 \cdot \cos \beta + r_s \cdot \cos \alpha \\
  y(t) &= r_0 \cdot \sin \beta + r_s \cdot \sin \alpha \\
  z &= -ft = h_0 
\end{align*}
\]

In the equation, \(r_0\) theoretical revolution radius; \(r_s\) theoretical tool radius; \(h_0\) axial initial coordinate value; \(f\) and axial feed rate \(f\).

When \(t=0\), the revolution angle \(\beta=0\), and the rotation angle \(\alpha\) is equal to the initial angle \(\alpha_0\). When the revolution speed is \(n\), the revolution speed is \(n_p\), then:

\[
\begin{align*}
  \alpha &= \alpha_0 + \frac{2\pi n_p}{60}t \\
  \beta &= \frac{2\pi n_p}{60}t
\end{align*}
\]

According to equation (1) and equation (2):

\[
\begin{align*}
  x(t) &= r_0 \cdot \cos \frac{2\pi n_p}{60}t + r_s \cdot \cos \left(\alpha_0 + \frac{2\pi n_p}{60}t\right) \\
  y(t) &= r_0 \cdot \sin \frac{2\pi n_p}{60}t + r_s \cdot \sin \left(\alpha_0 + \frac{2\pi n_p}{60}t\right) \\
  z &= -ft = h_0
\end{align*}
\]

If the column matrix is \(S = [t, r_0, r_s, \alpha_0, h_0, n, n_p, f]^T\), it can be seen that the matrix \(S\) determines the \(P\) point.

The Python software is used to import the motion equation and input the corresponding parameters of matrix \(S\), which can generate the trajectory of the tool nose, end edge, and side edge.

When using \(\phi 5\) mm tool to mill \(\phi 6\) mm hole, the corresponding parameters are as follows: \(r_0=0.5\) mm, \(R_t=2.5\) mm, \(n=3000\) r/min, \(n_p=120\) r/min, \(\alpha_0=0\), \(f=0.15\) mm/s. \(R_t\) is tool radius. The trajectory equation and simulation results are:

1. **tool nose**

   Since the tool nose satisfies \(r_s=D_t/2=R_t\), \(h_0=0\), they are brought into equation (3) and simplified to obtain equation (4).

\[
\begin{align*}
  x(t) &= r_0 \cdot \cos \frac{\pi n_p}{30}t + R_t \cdot \cos \left(\alpha_0 + \frac{\pi n_p}{30}t\right) \\
  y(t) &= r_0 \cdot \sin \frac{\pi n_p}{30}t + R_t \cdot \sin \left(\alpha_0 + \frac{\pi n_p}{30}t\right) \\
  z &= -ft
\end{align*}
\]

2. **end edge**

   The end edge can be regarded as a collection of a series of points, and it satisfies \(0 \leq r_s \leq R_t\), \(h_0=0\). Its equation satisfies:

\[
\begin{align*}
  x(t) &= r_0 \cdot \cos \frac{\pi n_p}{30}t + r_s \cdot \cos \left(\alpha_0 + \frac{\pi n_p}{30}t\right) \\
  y(t) &= r_0 \cdot \sin \frac{\pi n_p}{30}t + r_s \cdot \sin \left(\alpha_0 + \frac{\pi n_p}{30}t\right) \\
  z &= -ft \\
  0 &\leq r_s \leq R_t
\end{align*}
\]

In a four-blade tool, the trajectory curve of one tool nose from \(t=0\) to \(t=1\)s is shown in Fig. 3.

As seen from figure, when the tool nose revolves around the axis of the hole, it also rotates around the axis of the milling tool.

Fig. 3 3D trajectory of tool nose

Fig. 4 3D trajectory of tool nose

Fig. 5 3D trajectory of tool nose
3. side edge

The side edge can also be regarded as a collection of a series of points, and it satisfies \(-ft \leq h_0 \leq 0, r_s = r_t\), and its equation satisfies:

\[
\begin{align*}
    x(t) &= r_0 \cdot \cos \left( \frac{\pi}{30} t \right) + R_t \cdot \cos \left( \alpha_0 + \frac{\pi}{30} n_p t \right) \\
    y(t) &= r_0 \cdot \sin \left( \frac{\pi}{30} t \right) + R_t \cdot \sin \left( \alpha_0 + \frac{\pi}{30} n_p t \right) \\
    z &= -ft + h_0 \\
    -ft \leq h_0 \leq 0
\end{align*}
\]

In the four-blade tool, the trajectory curve of one side edge from \(t=0\) to \(t=1\)s is shown in Fig. 5. It can be seen that different from the cutting of end edge, the side edge trajectory is not circular. And one week per revolution, the side edge is not in contact with the hole wall for some time. Therefore, the cutting of each side edge is discontinuous.

3. The experiment of helical milling

3.1 Experimental conditions

The materials used in this experiment are 2024 Al alloy and CFRP, and the fiber type of CFRP is T700. Al alloy with a size of 150 \(\times\)100 \(\times\)2 mm and CFRP with a size of 150 \(\times\)95 \(\times\)5 mm are selected as shown in Fig. 6. The material of the four-blade milling tool is cemented carbide (tungsten steel) and the diameter is 5 mm. The diameter of the hole is 6 mm. The basic parameters of the milling tool are shown in Table 1.

3.2 Experimental design

RSM is an extension of univariate analysis and is a statistical method for solving multivariate problems. RSM can solve multi-objective optimization problems, making it more and more widely used. Danish et al. [36] examined the effect of both cryogenic and dry machining of AZ31 magnesium alloy on temperature and surface roughness. An arithmetic model using the response surface method was also developed to predict the maximum temperature at the surface during cryogenic and dry machining. Danish et al. [37] utilized response surface methodology (RSM) with three-level factorial design and desirability approach was to optimize thermal conductivity and viscosity of TiO2-water nanofluid simultaneously. Maqsood et al. [38] utilized the response surface methodology (RSM) and artificial neural network (ANN) was modeled to predict thermal conductivity and viscosity of NF. Yousuf et al. [39] employed response surface method to optimize cutting parameters for micro-milled surfaces to obtain high surface smoothness. It can be seen that the response surface method is the most commonly used in optimization design one of the methods.

According to literature [40, 41], it can be seen that the most important factors influencing the quality of hole-making are spindle speed and pitch. Meanwhile, some studies have found that hole-making of applying preload has significant inhibitory effect on the burr height and damage of the interlayer gap. The main reason is that the

| Table 1 Tool parameters |
|--------------------------|
| Overall length (mm) | Blade length (mm) | HRC | Helical angle (°) |
| 50 | 15 | 58 | 35 |
formation of burrs between laminations is inhibited by inhibiting the extra gap under the action of flow force when hole-making of applying preload [42]. Therefore, this paper chooses the preload as the third influence factors for the helical milling of laminated materials. The spindle speed is between 2000 and 3000 r/min, and the pitch is between 0.15 and 0.22 mm, which has greater impact on the quality of the hole. Therefore, the selected factor levels are shown in Table 2.

### 3.3 Analysis of Al alloy/CFRP

The spindle speed, pitch and preload are used as design variables, and the burr of Al alloy and the damage values of CFRP are used as response values. The 17 groups of response surface experiments were obtained by experiments as shown in Table 3. Because BBD experiment is suitable for a small number of factors (generally less than 5 factors and 3 levels), it is selected in this paper. According to the literature [43], the response surface method is used to analyze and determine the optimal parameters. First, a large amount of test data is needed to establish a suitable mathematical model, and then the mathematical model is used to make graphs and analyze.

The maximum burr for the Al alloy at the entrance and exit are listed in Table 3, respectively (group-1). Through the nonlinear fitting method, the variables and the burr size of the Al alloy are subjected to multiple regression fitting and the following mathematical model of the multiple regression equation is obtained, where A is spindle speed, B pitch, and C preload.

$$H = 273 - 0.09995A - 293.35B - 0.4185C - 0.018AB$$
$$+ 7.708 \times 10^{-6}AC - 0.0958BC + 1.6677 \times 10^{-5}A^2$$
$$+ 1045.25B^2 + 5.401 \times 10^{-4}C^2$$

(7)

After the mathematical model of the regression equation is obtained, it is necessary to further test the fit and reliability of the model itself. The analysis of variance regression equation is shown in Table 4.

The F is used to judge the significant degree of each item. Large F value and small Prob>F value represent higher significance of the relevant items [44]. As seen from Table 4, the Prob>F value is 0.0001 and is less than 0.05. This indicates that the model is significant and regression equation is efficient. The Prob>F value of the model lack of fit term is 0.0597 greater than 0.05. This indicates that it is not significant. The Prob>F values of B and C are far less than 0.05, which indicates that their influence on hole-making is relatively large.

As seen from Fig. 7(a), the residual arrangement is approximately a straight line. As seen from Fig. 7(b), each experimental point is relatively dispersed. Both of them

| No. | Spindle speed-A (rpm) | Pitch-B (mm) | Preload-C (N) | Results (mm) |
|-----|-----------------------|-------------|---------------|-------------|
|     |                       |             |               | Group-1     |
| 1   | 3000                  | 0.3         | 240           | 44.2        |
| 2   | 3000                  | 0.2         | 360           | 16.2        |
| 3   | 3000                  | 0.1         | 480           | 27.2        |
| 4   | 2000                  | 0.2         | 240           | 44.8        |
| 5   | 3000                  | 0.1         | 240           | 32.5        |
| 6   | 3000                  | 0.2         | 360           | 16.2        |
| 7   | 4000                  | 0.2         | 480           | 38.6        |
| 8   | 3000                  | 0.2         | 360           | 17.8        |
| 9   | 2000                  | 0.2         | 480           | 38.2        |
| 10  | 2000                  | 0.3         | 360           | 48.5        |
| 11  | 3000                  | 0.2         | 360           | 15.6        |
| 12  | 3000                  | 0.3         | 480           | 34.3        |
| 13  | 2000                  | 0.1         | 360           | 39.8        |
| 14  | 4000                  | 0.3         | 360           | 43.5        |
| 15  | 3000                  | 0.2         | 360           | 15.8        |
| 16  | 4000                  | 0.2         | 240           | 41.5        |
| 17  | 4000                  | 0.1         | 360           | 42.0        |
indicate that the model has high concordance between the prediction and the experimental value.

The RSM is used to analyze the results, and while one experimental factor remains unchanged, the influence of the interaction between other experimental factors on the burr height of the Al alloy at the entrance and exit are explored.

As seen from Fig. 8(a), when the preload remains constant, with the increase of the spindle speed, the Al alloy burr height first decreases and then increases. When the spindle speed is about 3000 r/min, the burr height increases. The value tends to be stable and the burr height decreases to the lowest value when the pitch is about 0.18 mm.

As seen from Fig. 8(b), when the pitch remains constant, the burr height first decreases and then increases with the increase of the spindle speed and the overall change trend is obvious. When the spindle speed is around 3000 r/min, the burr height first decreases and then tends to be stable. The burr height first decreases and then tends to be stable with the increase of preload, but the overall change trend is not obvious. When the spindle speed is around 3000 r/min and the preload is around 380 N, the burr height is reduced to the lowest level.

As seen from Fig. 8(c), when the spindle speed remains constant, the burr height first decreases with the increase of the pitch, tends to be stable, and then increases greatly. This shows the burr height trend to be stable when the pitch is in the range of 0.1–0.2 mm. However, the hole-making efficiency is considered. Therefore, the pitch size is chosen to be 0.2 mm. The burr height first decreases and then tends to be stable with the increase of the preload. When the preload reaches about 380 N, the burr reaches the lowest level and tends to be stable.

The RSM is used to predict the experimental results of Al alloy. Taking the minimum burr height at the exit and entrance as the goal, the optimal parameter combination is obtained as shown in Fig. 9.

For CFRP, the maximum tear value at the entrance and exit is used as the criterion for analysis. The tear values of CFRP are listed in Table 3 (group-2).

The multiple regression fitting is performed on the variables and the CFRP value by the nonlinear fitting method, and the following multiple regression equation is obtained. Table 5 is the regression equation of variance analysis table.

\[
H = 1.81875 - 1.2708 \times 10^{-3}A - 2.34B + 3.5552 \times 10^{-3}C - 5.5 \times 10^{-4}AB - 1.7708 \times 10^{-7}AC + 2.632 \times 10^{-17}BC + 1.85875 \times 10^{-7}A^2 + 3.2125B^2 - 4.80035 \times 10^{-6}C^2
\]  

(8)

The F value is 128.56 and the Prob>F value is less than 0.0001. This indicates that the model is significant and regression equation is efficient. The influence degree of each parameter on the response value from large to small is as follows: A, B, C, and the interaction of B and A have very significant influence on the tear.
As seen from Fig. 10(a), the residual arrangement is approximately a straight line. As seen from Fig. 10(b), each experimental point is relative dispersed. In general, this model is reliable for predicting the tear value of CFRP holes.

As seen from Fig. 11(a), when the preload remains constant, with the increase of the spindle speed, the tear value of the CFRP at the entrance first decreases and then remains stable. When the spindle speed is about 3000 r/min, the tear value of CFRP tends to be stable. When the spindle speed is about 3500 r/min and the pitch is about 0.11 mm, the burr height is reduced to the lowest.

As seen from Fig. 11(b), when the pitch remains constant, the tear value of the CFRP decreases first and then tends to be stable with the increase of the spindle speed, and the overall change trend is not obvious. When the spindle speed is about 3600 r/min, the tear value along the hole tends to be stable. The tear value decreases first and then tends to be stable with the increase of the preload, but the overall change trend is obvious. When the preload reaches about 450 N, the tear value along the hole reaches the minimum and tends to be stable.

Taking the minimum tear value at the entrance and exit as the goal, the optimal process parameter combination is obtained as shown in Fig. 12.

### 3.4 Analysis of CFRP/Al alloy

The tear value of the CFRP material at the entrance and exit are used as the response value. The tear values are listed in Table 3 (Group-3), and the following mathematical model of multiple regression equation is obtained. Table 6 is the variance analysis table of regression equation.

\[
H = 0.61687 - 3.72 \times 10^{-4}A - 2.56375B - 2.1979 \times 10^{-4}C
- 1.1 \times 10^{-3}AB - 1.45833 \times 10^{-7}AC - 2.39583 \times 10^{-3}BC
+ 8.0123 \times 10^{-8}A^2 + 8.8875B^2 + 1.31076 \times 10^{-6}C^2
\]  

(9)

| Source of variance | Sum of square | F | Prob>F |
|--------------------|--------------|---|--------|
| Model              | 1.38         | 128.56 | <0.0001 |
| A                  | 0.87         | 726.60 | <0.0001 |
| B                  | 0.31         | 261.25 | <0.0001 |
| C                  | 0.022        | 18.02  | 0.0038 |
| AB                 | 0.012        | 10.13  | 0.0154 |
| AC                 | 1.806E-003   | 1.51  | 0.2585 |
| BC                 | 0.000        | 0.000  | <0.0001 |
| A^2                | 0.15         | 121.79 | <0.0001 |
| B^2                | 4.345E-003   | 3.64  | 0.0981 |
| C^2                | 0.020        | 16.84  | 0.0045 |
| Residual           | 8.361E-003   |       |        |
| Lack of fit        | 8.131E-001   | 27.14  | 0.054  |
As seen from Table 6, the model term is significant. The influence degree of each parameter on the response value from large to small is as follows: B, A, C, and the interaction of B and A have very significant influence on the tear. As seen from Fig. 13, this model is reliable for the predicting the tear value of CFRP holes. Taking the minimum tear value at the entrance and exit as the goal, the optimal process parameter combination is obtained as shown in Fig. 14.

Table 6 Variance analysis

| Source of variance | Sum of square | F      | Prob>F |
|-------------------|--------------|--------|--------|
| Model             | 0.64         | 36.05  | <0.0001|
| A                 | 0.21         | 107.92 | <0.0001|
| B                 | 0.31         | 154.03 | <0.0001|
| C                 | 4.28E-003    | 2.15   | 0.1858 |
| AB                | 0.048        | 24.35  | 0.0017 |
| AC                | 1.225E-003   | 0.62   | 0.4582 |
| BC                | 3.306E-003   | 1.66   | 0.2381 |
| A²                | 0.027        | 13.60  | 0.0078 |
| B²                | 0.033        | 16.73  | 0.0046 |
| C²                | 1.500E-003   | 0.75   | 0.4138 |
| Residual          | 0.014        |        |        |
| Lack of fit       | 0.18         | 7.08   | 0.0445 |
As seen from Table 7, the model is significant. The B and the interaction between the B and the A also have very significant influence on the burr height. As seen from Fig. 15, this model is reliable for the predicting the burr height. Taking the minimum burr height at the entrance and exit as the goal, the optimal parameter combination is obtained as shown in Fig. 16.

Taking the minimum burr height at the entrance and exit as the goal, the optimal parameter combination is obtained as shown in Fig. 16.

Taking into account the hole-making efficiency and quality, the optimal parameter combination for the Al alloy are obtained: the spindle speed is 3000 r/min, the pitch is 0.17 mm, and the preload is 380 N. The optimal parameter combination of CFRP are obtained: the spindle speed is 3700 r/min, the pitch is 0.11 mm, and the preload is 430 N.

3.5 Analysis of cutting force

In the machining process, important physical quantities such as the cutting state of the material, cutting quality, and tool life can be reflected by cutting force and axial force.

Therefore, it is of great significance to study the cutting force and axial force in the cutting process.

The radial force in the hole-making process is composed of the combined force of the FC3D 120 three-dimensional force sensor in the X and Y directions. The axial force is composed of the force in the Z direction of the sensor. The USB3200 signal collector is mainly used to process the collected signal information and convert it into a signal that can be recognized by the computer. The function of the computer monitor is to display the collected signal visually. The data collection for the force is shown in Fig. 17.

Figure 18(a) and (b) is the comparative analysis diagrams of the X and Y direction force and the axial force of the helical milling hole. The axial force during the hole-making process of the laminated materials can be roughly divided into five stages. The first stage is the entrance stage of milling CFRP. The second stage is the stable milling CFRP. The third stage is the transition stage of milling CFRP/Al alloy laminations. The fourth stage is stable milling Al alloy. The fifth stage is the milling Al alloy exit stage.

| Source of variance | Sum of square | F    | Prob>F   |
|--------------------|--------------|------|----------|
| Model              | 2223.11      | 376.46 | <0.0001  |
| A                  | 9.25         | 14.09 | 0.0071   |
| B                  | 271.45       | 413.70 | <0.0001  |
| C                  | 18.00        | 27.43 | 0.0021   |
| AB                 | 14.82        | 22.59 | 0.0021   |
| AC                 | 1.10         | 1.68  | 0.2360   |
| BC                 | 1.56         | 2.38  | 0.1667   |
| A²                 | 772.78       | 1177.76 | <0.0001 |
| B²                 | 542.17       | 826.30 | <0.0001 |
| C²                 | 395.96       | 603.47 | <0.0001 |
| Residual           | 4.59         |       |          |
| Lack of fit        | 3.97         | 7.08  | 0.0545   |

Fig. 13 Analysis of tear value of CFRP. a Residual normal diagram. b Correspondence between residual and equation prediction value

Fig. 14 The optimal process parameters

\[ H = 250.125 - 0.076935A - 356.65B - 0.49467C \\
- 0.01925AB - 4.375 \times 10^{-6}AC + 0.052083BC \\
+ 1.35475 \times 10^{-3}A^2 + 1134.75B^2 + 6.73437 \times 10^{-4}C^2 \]
The cutting forces in Figure 18(a) and (b) were machined with the optimal parameters combination of CFRP and Al alloy, respectively. Compared with Fig. 18(a), the axial force of CFRP in Fig. 18(b) is about 12 N larger (The axial force is about 39 N and about 51 N, respectively), the fluctuation is greater, and the quality of the obtained hole wall is poor. Therefore, the process parameters are not suitable for milling hole of CFRP. On the other hand, although the axial force of Al alloy is 11N larger in Fig. 18(b) and greater than Fig. 18(a) (The axial force are about 41 N and about 52 N respectively), the fluctuation is smaller and the efficiency is higher. Therefore, these parameters are suitable for milling holes of Al alloy. The axial force using the process parameters of Fig. 18(a) is relatively small; it is suitable for CFRP and Al alloy. However, the low efficiency of this parameters and the axial force will increase sharply when the milling tool transitions from CFRP to Al alloy. Therefore, hole-making with variable parameters is considered to observe whether this sudden change in force can be eliminated.

Fig. 15 Analysis of tear value of Al alloy. a Residual normal diagram. b Correspondence between residual and equation prediction value

Fig. 16 The optimal process parameters

Fig. 17 Data acquisition schematic diagram

Fig. 18 Milling force comparison of CFRP/Al alloy laminated materials. a The optimal parameters combination of CFRP. b The optimal parameters combination of Al alloy
4 Experimental of hole-making with variable parameters

Two groups of optimal process parameters were obtained using RSM. They carried out hole-making with variable parameters on four different types of laminated materials of CFRP/Al alloy, Al alloy/CFRP, CFRP/Al alloy/CFRP, and Al alloy/CFRP/Al alloy. The process parameters used are as follows: the spindle speed is 3000 r/min and the pitch is 0.17 mm for the Al alloy hole; the spindle speed is 3700 r/min and the pitch is 0.11 mm for the CFRP hole; and the preload of the whole hole-making process is 430 N. The feasibility of hole-making with variable parameters is discussed. Finally, it is analyzed whether the process parameters are suitable for the hole-making with variable parameters of three or more laminated materials.

When testing with CFRP/Al alloy-laminated materials, the Al alloy is machined first and the depth is 2 mm. Then, the CFRP is machined with different parameters and the depth is 5 mm. In the same way, the same method is used for the other three laminated materials.

4.1 Analysis of entrance and exit morphology

In order to meet the precision requirements of hole-making, the morphology of the CFRP hole and the entrance and exit burrs of the Al alloy hole are tested. The influence of variable parameter machining at the entrance and exit morphology of CFRP and burrs of Al alloy at the entrance and exit were analyzed.

The machining requires at the entrance and exit: smaller burrs of Al alloy hole, and fewer burrs and tears of the CFRP hole. This is the evaluation standard to judge the quality of the machining hole.

Using the camera to take a picture of the overall morphology of the hole, the maximum tear value in CAD is marked and the maximum tear value finds w, as shown in Fig. 19.

As seen from Table 8, the aperture is all within the required range (0~+43 μm), and the aperture deviation meets the requirements of H9. The aperture will gradually decrease with the cutting depth of the tool. The main reason is the gradually weakening of the rigidity of the tool.

4.2 Analysis of aperture and hole wall

The aperture of Al alloy and CFRP holes were measured using the claw inner diameter micrometer. Each hole was measured three times, and the average value was finally taken, as shown in Table 8.

As seen from Table 8, the aperture is all within the required range (0~+43 μm), and the aperture deviation meets the requirements of H9. The aperture will gradually decrease with the cutting depth of the tool. The main reason is the gradually weakening of the rigidity of the tool.

The hole wall morphologies of Al alloy and CFRP holes were examined using ultra-depth three-dimensional microscopy. As seen from Fig. 21, the inner wall of the CFRP hole in the four groups of experiments has clear milling texture and smooth inner wall curve. This shows that the hole-making with variable parameters has a significant influence on CFRP. As seen from Fig. 22, the inner wall morphology of the Al alloy holes in the four groups of tests is clear and has no obvious defects. The black materials in the figure are caused by the cutting chips powder after the CFRP hole-making.

4.3 Analysis of cutting force

When constant parameters are used for hole-making, the axial force in the transition phase will suddenly increase. In the hole-making with variable parameters, the method of
micro-lifting the tool is used to eliminate the influence of the material elastic deformation on the axial force of hole-making. The sudden increase of the axial force is avoided.

In the hole-making with variable parameters experiment, the cutting force and axial force of the hole-making are roughly divided into two categories. The first category is the two laminated methods of CFRP/Al alloy and Al alloy/CFRP. They are roughly divided into five stages. The details are shown in Figs. 23 and 24.

![Fig. 20](image)

**Fig. 20** The burr 3D morphology of entrance and exit of the hole. a CFRP/Al alloy. b Al alloy/CFRP. c CFRP/Al alloy/CFRP. d Al alloy/CFRP/Al alloy. e Al alloy/CFRP/Al alloy

| Layers Name | 1   | 2   | 3   |
|-------------|-----|-----|-----|
| CFRP/Al alloy | 6.025 | 6.031 |
| Al alloy/CFRP | 6.038 | 6.009 |
| CFRP/Al alloy/CFRP | 6.025 | 6.019 | 6.002 |
| Al alloy/CFRP/Al alloy | 6.036 | 6.021 | 6.015 |
As seen from Fig. 23(a), in the first stage, when the tool just contacts the CFRP, the axial force increased sharply from 0 to about 48 N in a short time, and there are large fluctuations. The main reason is the instability caused by the tool spiraling in contact with the material. The duration of this fluctuation is about the time of one revolution of the tool. After entering the second stage, the tool is completely milled into the CFRP. At this time, the axial force curve fluctuates slightly, and the fluctuation value is between 30 and 35 N. The reason for the fluctuation is that due to the nonlinearity of the CFRP material, the contact between the tool and the workpiece is discontinuous during the milling process. But the fluctuations at this stage are stable within a certain range, and there are obvious stable characteristics. The Al alloy has better continuity, so the axial force fluctuation is better than the CFRP. The third stage is that the milling tool enters the Al alloy from the CFRP, which is the parameters change stage. The change process is accompanied by the action of micro-lifting the tool to eliminate the sudden increase of the axial force. When the tool first contacts the Al alloy, the axial force increases sharply from 0 to about 50 N in a short time and then tends to a stable. The stability of milling Al alloys axial force is better than the CFRP. The fourth stage is similar to the second stage, it belongs to the stable milling stage, and the axial force of this stage is about 50 N. The fifth stage is that the milling tool is about to complete the Al alloy machining. In this stage, the milling axial force is gradually reduced from 50 to 0 N. The bottom edge of the tool is milled out of the material until it completely penetrates the material, and the side edge of the tool continues to complete the hole-making process. The duration of this stage is longer than the ideal state. The main reason is that the uncut parts
Fig. 22  Morphology of hole wall of Al alloy. a CFRP/ Al alloy. b Al alloy /CFRP. c CFRP/ Al alloy /CFRP. d CFRP/ Al alloy/ CFRP. e Al alloy/ CFRP/ Al alloy
of Al alloy and CFRP will produce elastic deformation. And the elastic deformation will increase with the reduction of uncut parts of Al alloy until the hole-making machining is completed. The milling of the Al alloy/CFRP laminations in Fig. 23(b) also goes through the above five stages.

The second category is the two laminated methods of CFRP/Al alloy/CFRP and Al alloy/CFRP/Al alloy. Because these two laminated materials are composed of three layers materials, there are two transition stages, so it can be roughly divided into seven stages. Take CFRP/Al alloy/CFRP-laminated materials as an example.

As seen from Fig. 24(a), in the first stage, when the tool just contacts the CFRP, the axial force increased sharply from 0 to about 25 N in a short time, and there is a big fluctuation. But it will soon enter the second stage. The tool is completely milled into the CFRP. At this time, the axial force fluctuates slightly between 20 and 25 N. But the fluctuations in this stage are stable within a certain range. The Al alloy has better continuity, so the axial force fluctuation is better than the CFRP. The third stage is that the milling tool enters the Al alloy from the CFRP, and this stage is also the parameter change stage. The change process is accompanied by the action of micro-lifting tool to eliminate the sudden increase in the axial force. When the tool first contacts the Al alloy, the axial force increases sharply from 0 to about 50 N in a short time, and then tends to be a stable. The fourth stage is similar to the second stage, it belongs to the stable milling stage, and the axial force of this stage is about 50 N. The fifth stage is the transition stage from Al alloy to CFRP material, and this stage is also the parameters change.
As the milling tool enters the CFRP, the axial force continues to rise from 0 to a maximum of 50 N, and then tends to be stable. The sixth stage is similar to the second and fourth stages and belongs to the stable milling stage. The axial force in this stage is about 28 N. The seventh stage is the stage when the milling tool is about to complete the Al alloy machining. In this stage, the milling axial force is gradually reduced to 0 N. The milling of Al alloy/CFRP/Al alloy laminations in Fig. 24(b) also goes through the above seven stages. The cutting force of Al alloy and CFRP obtained by hole-making with variable parameters does not change much, but the axial force of CFRP is reduced from the original 40–45 to 25–30 N.

In summary, it is helpful to improve the quality of the holes by hole-making with variable parameters in laminated materials. This method can not only improve the burr in the gap between the Al alloy and the CFRP laminations, but also improve the tear value of the CFRP. At the same time, it can improve the hole wall morphology of Al alloy and CFRP and reduce the axial force of CFRP.

5 Conclusion

Taking the interlayer burr height of Al alloy and the tear value of CFRP as the judgment standard, the optimal process parameters for Al alloy and CFRP hole-making are predicted and obtained as follows: the spindle speed are 3000 r/min and 3700 r/min, the pitch are 0.17 mm and 0.11 mm, and the preload are 380 N and 430N, respectively.

Figure 23(a) has relatively small axial force for milling hole, which is suitable for both CFRP and Al alloys.
However, the efficiency of these parameters is low, and there is a sudden increase in the axial force when the milling tool transitions from CFRP to Al alloy.

Using hole-making processes with variable parameters, the feasibility of four different laminated materials is respectively verified. It can be found that the burr in the gap between the Al alloy and the CFRP are significantly reduced. The shear value of CFRP is much smaller than the 2.54 mm required by the process parameters. The axial force of CFRP and Al alloy reduced by 70% and 83%. The micro-lifting method effectively reduces the sudden change of the axial force between interlayers.

Funding This paper was funded by the Natural Science Foundation of Liaoning Province Grant (no.2019-ZD-0029) and the University of Science and Technology Liaoning Talent Project Grants (no.601011507-32).

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

1. Wang HJ (2016) Investigation on generation mechanism and control strategy of defect in drilling of resin-based composite materials. Shandong University

2. Wang L, Zhang L, Tian W et al (2017) Control strategy of delamination in drilling carbon fiber reinforced composites. Aeronaut Sci Technol 28(2):69–73. https://doi.org/10.19452/j.issn1007-5453.2017.02.069

3. Li WP (2020) Investigation on hole making process and connection performance of CFRP/aluminum alloy laminated components. Dalian University of Technology

4. Dong ZG, Zhang B, Kang RK et al (2020) A method for restraining axial force in process of helical Milling of CFRP. Aeronaut Manuf Technol 63(17):14–20. https://doi.org/10.16080/j.issn1671-833x.2020.17.014

5. Fang CP, Zhao JZ, Ye ZM et al (2020) Progress in helical milling holes for carbon fiber reinforced polymer. Compos Sci Eng 11:123–128

6. Jiang XY (2021) Study on fatigue performance of aluminum alloy components with helical Milling hole. Dalian University of Technology

7. Editorial committee of china aviation materials manual (2013) China aviation materials manual volume 3 aluminum alloy magnesium alloy. Beijing: Tsinghua University Press

8. Guo F, Wang WH, Li ZY et al (2019) Research on precision hole-making control technology for aerospace laminated materials. Chin Plant Eng 22:112–113

9. Yu HF, Xue HF (2017) Prediction of dynamic thrust force in drilling of CFRP/aluminum-alloy stacks. Mech Sci Technol Aeron 36(1):68–73. https://doi.org/10.13433/j.cnki.1003-8728.2017.0110

10. Wang H, Hu J, Sun X (2015) Experimental research on drilling process of carbon fiber reinforced plastic and aluminum alloy stacks. Tool Eng 49(11):63–67. https://doi.org/10.16567/j.cnki.1000-7008.2015.11.035

11. Yu XJ, Cao ZQ, Jing HY et al (2011) Investigation of drilling process for carbon fiber reinforced plastic (CFRP) and titanium sandwich structure. 3:95–97

12. Zhang H, Li MP, Li HW et al (2021) Experimental study on low-frequency vibration drilling of titanium alloy/CFRP laminate structure. Aeronaut Manuf Technol 64(11):88–95. https://doi.org/10.16080/j.issn1671-833x.2021.11.088

13. Wang SF, Wang FJ, Su SK et al (2020) Low frequency vibration aided drilling technology for Al/CFRP laminated structure. Mech Electr Eng 37(12):1447–1452

14. Zhang SJ, Jiao F, Li YX et al (2020) Experimental study on high and low frequency compound vibration drilling of carbon fiber reinforced plastic /titanium alloy laminated structure. Mach Des Res 36(6):120–124, 129. https://doi.org/10.13952/j.cnki.jofmndr.2020.0248

15. Sun PC, Ge YF, Zhou K et al (2020) The influence of machining parameters on the surface defects of CFRP/titanium alloy laminates. Nanjing Institute of Technology (Natural Science Edition) 18(2):7–12. https://doi.org/10.13960/j.issn.1672-2558.2020.02.002

16. Wang ZG, Yu SR (2017) The experiment research on drilling of CFRP/titanium alloy stack with varying parameters. Mach Des Res 33(1):114–117, 126. https://doi.org/10.13952/j.cnki.jofmndr.2017.0025

17. Wang SP, Liang J, Cui ST et al (2022) Analysis of Burr morphology of CFRP/Al laminated material in variable feed drilling. Modular Machine Tool & Automatic Manufacturing Technique 2:95–98. https://doi.org/10.13462/j.cnki.mmtamt.2022.02.022

18. Peng T (2019) Research on drilling technology of CFRP/Ti laminate by embedding carbon nanotubes buckypaper. Shenyang Aerospace University

19. Xie DZ, Sun ZH, Liu B (2021) Effects of different parameters on tool wear in low frequency vibration aided drilling of CFRP/Ti laminates, Tool Eng 9:88–91

20. Wang B, Ma ZB, Wang MH et al (2018) Comparison and analysis on tool wear of helical milling and conventional drilling in machining CFRP/Ti laminated material. Tool Eng (52):6:12–15

21. Li HW, Zhang JX, Yue Q (2020) Research on hole-making based on low frequency vibration of titanium alloy laminated material. 902–909. https://doi.org/10.26914/cnkihyb.2020.012088

22. Wang B, Ma ZB, Liu N et al (2018) Study of helical milling in machining CFRP/Ti laminated materials with different number of edging mills. Modular Machine Tool & Automatic Manufacturing Technique 6:135–138. https://doi.org/10.13462/j.cnki.mmtamt.2018.06.034

23. Ma ZB (2018) Damage mechanism and countermeasures of helical milling CFRP/ titanium alloy laminated components. Shenyang Aerospace University

24. Luo YG, Yuan XM, Zhang Y et al (2019) Research on precision hole making process for laminated materials of aircraft. Manuf Technol Mach Tool 9:122–126. https://doi.org/10.19287/j.cnki.1005-2402.2019.09.026

25. Xu JY, Li C, Ji M (2020) Review on recent advances in drilling of CFRP/Ti stacks. Tool Eng 12:3–9

26. Wei XW (2019) Research on drilling aircraft laminated materials with variable parameters. Nanjing University of Aeronautics and Astronautics

27. Huang BT, Luo HQ, Pu JW et al (2020) Experimental research on variable parameters of helical milling hole for CFRP/titanium
28. Wei XW, Tian W, Qiu YP et al (2020) Influence of variable parameters on aperture accuracy of drilling CFRP and aluminum alloy stacks. Mach Build Auto 49(1):40–43. https://doi.org/10.19452/j.issn1007-5453.2020.01.012

29. Zitoune R, Krishnaraj V, Collombet F (2010) Study of drilling of composite material and aluminium stack. Compos Struct 92(5):1246–1255. https://doi.org/10.1016/j.composites.2009.10.010

30. Li C (2019) Research on the technology of lamination of carbon fiber composites and titanium alloys. Telecom World 8:370–371

31. Wang GD, Zhou L, Zhong Q et al (2017) Technical investigation on drilling of CFRP/aluminum stack. Sci Technol Eng 17(6):152–157

32. Sun L, Gao H, Wang B et al (2020) Mechanism of reduction of damage during helical milling of titanium/CFRP/aluminium Stacks. Int J Adv Manuf Technol. 107:4741–4753. https://doi.org/10.1007/s00170-020-05177-1

33. Xu JY, Yin YK, Li LF et al (2022) A critical review addressing the drilling-induced damage of CFRP composites. Compos Struct. https://doi.org/10.1016/j.composites.2022.115594

34. Danish M, Gupta MK, Rubaiee S et al (2021) Machinability investigations on CFRP composites: a comparison between sustainable cooling conditions. Int J Adv Manuf Technol 114:3201–3216. https://doi.org/10.1007/s00170-021-07073-8

35. Xu JY, Lin TY, Davim JP (2022) On the machining temperature and hole quality of CFRP laminates when using diamond-coated special drills. J Compos Sci 6(2):45. https://doi.org/10.3390/jcs6020045

36. Danish M, Ginta TL, Habib K et al (2017) Thermal analysis during turning of AZ31 magnesium alloy under dry and cryogenic conditions. Int J Adv Manuf Technol 91:2855–2868. https://doi.org/10.1007/s00170-016-9893-5

37. Danish M, Yahya SM, Saha BB (2020) Modelling and optimization of thermophysical properties of aqueous titania nanofluid using response surface methodology. J Therm Anal Calorim 139:3051–3063. https://doi.org/10.1007/s10973-019-08673-z

38. Maqsood K, Ali A, Ilyas SU et al (2022) Multi-objective optimization of thermophysical properties of multiwalled carbon nanotubes based nanofluids. Chemosphere 286(2). https://doi.org/10.1016/j.chemosphere.2021.131690

39. Yousuff CM, Danish M, Wei Ho ET et al (2017) Study on the optimum cutting parameters of an aluminum mold for effective bonding strength of a PDMS microfluidic device. Micromachines 8(8):258. https://doi.org/10.3390/mi8080258

40. Fang XE (2019) Research on the hole-making quality of CFRP/Ti alloy laminated materials during a new method of gyro milling process. Nanchang Hangkong University

41. Li Y, Hu YX, Yao ZQ (2014) Experimental investigation of the effect of clamping force on the inter-layer drilling burr of stacked aluminum alloy sheets. Modular Machine Tool & Automatic Manufacturing Technique 2:110–113. https://doi.org/10.13462/j.cnki.mmtamt.2014.02.029

42. Wang H, Sun X, Hu J (2016) Experimental research on interlayer burrs based on lamination materials under different pressing conditions. Machinery 54(1):51–53

43. Danish M, Rubaiee S, Ijaz H (2021) Predictive modelling and multi-objective optimization of surface integrity parameters in sustainable machining processes of magnesium alloy. Materials 14(13). https://doi.org/10.3390/ma14133547

44. Zhang W, Wei G, Xiao XK (2013) Constitutive relation and fracture criterion of 2A12 aluminum alloy. Acta Armamentarii 34(3):276–282

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