Theoretical analysis and experimental research on the pressing force of robot drilling CFRP sheet

Pengqiang Fu1,2 · Yan Wang1,2 · Yuhang Miao1,2 · Yiwen Wang1,2 · Lijie Zhou1,2 · Sisi Yang3

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Abstract
In the process of drilling CFRP sheets by industrial robots, the contact stiffness between the terminal actuator and the sheet is poor, which causes the hole position to vibrate during processing. The design of a presser foot device in front of the terminal actuator can effectively solve this problem. The Navier method is used to solve the allowable range of the pressing force of the presser foot. A numerical simulation model for drilling CFRP sheets is established, the influence of different pressing forces within the allowable range on the drilling quality is studied, and the recommended value of the pressing force of the presser foot is obtained. Drilling experiments are carried out under different pressing forces. The experimental results show that the optimized pressing force of the presser foot can effectively reduce the vibration of the CFRP sheet during the drilling process, and the surface roughness of the drilling hole wall can reach 1.8 μm. At the same time, the surface morphology at the exit of the machined hole is improved.

Keywords Robot drilling · End effector · Press foot device · Pressure force · Numerical simulation

1 Introduction
CFRP (carbon fiber-reinforced composite) is increasingly used as the primary structural material for aircraft skins due to its high strength, corrosion resistance, and light-weight. The physical characteristics of the CFRP itself have an anisotropy result in a metal material that is different from the same sex, the cooling environment when processing CFRP is also different from that of ordinary metals; it is better to process CFRP in the lubrication environment such as N2 liquid and CO2, to realize green processing better [1, 2]. Therefore, in drilling CFRP, stabilizing high-quality drilling has become a critical issue that needs to be solved. The aviation manufacturing quality requirements of the connecting holes are stringent; this requirement increases the difficulty of drilling CFRP [3]. According to statistics, 70% of the aircraft body fatigue fails is caused by its structural members; and the fatigue crack of the structural member is produced at the connection hole, so the drilling quality has a crucial impact on the life of the aircraft [4–6].

With the arrival of Industrial 4.0 and the Intelligent era, robot-automated drilling technology is applied to the field of aircraft manufacturing and assembly; how to effectively improve the quality of drilling has become one of the focuses of domestic and foreign scholars. The skin, as the central structural part of the aircraft wall panel, is usually composed of thin-walled parts. In the process of robotic drilling of thin-walled parts, the thin-walled parts are subjected to large axial cutting loads that produce elastic deformation and vibration, ultimately leading to poor drilling quality [7, 8]. For such problems, scholars Olsson [9], von [10] for...
improving contact stiffness between terminal actuators and workpieces to design a rigid presser foot before the terminal actuator to suppress the vibration of the hole position during drilling, and EI [11] The MFEE developed by the company uses pneumatic manner to press the presser foot to reduce the vibration of the workpiece during the drilling process. Although some scholars have verified in drilling experiments that compression force can suppress workpiece vibration when drilling thin-walled parts, thus improving the quality of surface roughness and cylindricity of the hole, however, the compression force used for CFRP thin plate is still less researched [12]. The size of the pressing force is a problem [13], the pressing force is too small to eliminate the vibration of the workpiece, and the pressing force is too large to cause the workpiece to produce severe deformation or even cracks. Therefore, there is an urgent need to eliminate vibrations in the workpiece during machining without the compression force causing severe deformation and cracking in the sheet.

To solve the above problems, take the robot and the particular terminal actuator for drilling CFRP sheet as the platform. This paper calculates the allowable range of compression force through Navier analytical method. Based on the permissible compression force range, the finite element model of drilling CFRP sheet is established through finite element software ABAQUS to analyze further the impact of different compression forces on drilling quality within the allowable range. The influence law of different pressing forces on drilling quality is revealed, and the optimized pressing force parameter value is obtained; finally, through the drilling experiment, the drilling quality under different pressing forces is compared to verify that the drilling process under the optimized pressing force of the presser foot can improve the surface roughness of the hole wall and improve the surface morphology at the outlet of the processed hole.

2 Action principle of presser foot pressing force of robot drilling terminal actuator

2.1 Drilling end effector

The drilling end effector is connected to the robot via a quick-change flange and is mounted on the end of the robot. The structure of the drilling terminal actuator XNZF01 designed in this paper is shown in Fig. 1; it consists of five main components: spindle unit, feed unit, clamping unit, vision unit, and a standard detection unit. The spindle is infinitely variable, with a maximum speed of 9,000 r/min. The feed movement is driven by servo motors driving high-precision ball screws mounted on the actuator frame. The servo motor is connected to a high-precision ball screw via a flexible coupling to precisely position the tool relative to the workpiece and perform the machining feed.

2.2 Pressing device

The main structure of the pressing device is integrated into the front end of the terminal actuator, as shown in Fig. 2. Four sheet metal members are used to fix the cylinders on the left and right sides. During operation, the cylinder pushes the structural components connected above the slider to provide linear displacement. Its moving direction is parallel to the feed direction. The moving distance is limited by the mechanical limit installed on the actuator frame. The annular presser foot is in direct contact with the workpiece and provides pressing force. The ring presser foot has an inner diameter of 8 mm and an outer diameter of 12 mm, as shown in Fig. 3. It is secured to the structural components attached above the slider by hexagonal bolts.

2.3 Action principle of presser foot pressing force

In the process of drilling thin-walled parts, the thin-walled parts will be subjected to a large axial load; this leads to thin-walled parts that will lead to different degrees of vibration along the tool axis. The greater the tool feed speed, the greater the amplitude. As a one-way pressing device used in robot automatic drilling, the presser foot is used primarily to reduce the vibration of the workpiece in the processing process, as shown in Fig. 4. Although the presser foot can reduce the vibration of the workpiece along the hole when machining thin-walled parts, it is a complex problem to apply the magnitude of the pressing force. The pressing force is too small, the effect of restraining workpiece vibration during processing is poor, and the hole inlet and outlet continuously shrink and expand, resulting in the rise of hole wall surface roughness. If the pressing force is too large, the sample will produce large deformation before machining, resulting in the increase of instantaneous rebound amplitude.
after drilling, which will bring more vibration and noise [14]. For carbon fiber composites, matrix cracks can easily occur when the bending deformation exceeds 0.3 mm. Matrix crack propagation will lead to weak interlayer bonding and even brittle fracture of composites, which will seriously affect the drilling quality [15]. It is, therefore, crucial to solve for the permissible range of compression forces.

3 Solving for the permissible range of presser foot pressing force

3.1 Drilling end effector

Taking the vertical wall panel of the aircraft tail as an example, its local curvature to be machined is slight, so

![Fig. 3 Annular presser foot](image)

the surface of the vertical sample to be machined can be regarded as a flat plate. Its four sides are fixed with special clamps, which limits x, y, z, and four degrees of freedom rotating around the z-axis in three-dimensional space so that it can be regarded as a simple support. Assuming that the length of the sample is a, the width is b, the thickness is h, and the axial force during drilling is Fa, the pressing force of the presser foot is evenly distributed on the sample. The pressure is Pb, and the inner and outer radii of the presser foot acting on the sample are r and R, respectively; force conditions of the sample during processing are shown in Fig. 5.

Since the pressing force action area of the presser foot and the drilling axial force action area are tiny relative to the sample area, the radius around the center of the presser foot is \( R_1 = (R + r)/2 \); the uniformly distributed linear load with pressure P represents the pressing force [16]. The drilling axial force acts on the presser foot center, and the simplified force diagram is shown in Fig. 6.

3.2 Navier method to calculate the allowable range of compression force

The critical bending boundary value of the CFRP thin plate is solved by the Navier method. According to the Navier double trigonometric series method, the general solution of the deflection function of a simply supported plate on four sides can be expressed as [17]:

\[
\omega = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} 4 \int_0^a \int_0^b q(x,y) \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} dx dy / \pi^4 abD \left( \frac{m^2}{a^2} + \frac{n^2}{b^2} \right)^2
\]

(1)

![Fig. 4 Schematic diagram of vibration amplitude during workpiece processing (a) Drilling without the presser foot. (b) Drilling with the presser foot](image)

![Fig. 5 Schematic diagram of forces during sample processing](image)

![Fig. 6 The simplified force diagram](image)
where \( D \) is the bending stiffness and its expression is:

\[
D = \frac{E_c^3}{12(1 - \nu^2)} \tag{2}
\]

Let the coordinates of the drilling axial force acting on the CFRP template be \((x_0, y_0)\); the simplified relationship between the pressing force radius of the presser foot and the axial force coordinate in 2.1 is used as the parameter equation \((x_0 + R_0 \cos \theta, y_0 + R_0 \sin \theta), 0 \leq \theta \leq 2\pi\) indicates. When the template is jointly acted by the drilling axial force and pressing force, the deflection formula of any point \((x, y)\) in the template is:

\[
\omega = \frac{4Fa}{\pi^4 abD} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \left( \frac{m^2}{a^2} + \frac{n^2}{b^2} \right)^2 + \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} \frac{4p}{\pi^4 abD} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \int_0^{2\pi} R_0 \sin \left( \frac{m\pi(x_0 + R_0 \cos \theta)}{a} \right) \sin \left( \frac{n\pi(y_0 + R_0 \sin \theta)}{b} \right) d\theta \tag{3}
\]

The internal moment of force is:

\[
M = \sqrt{(M_x)^2 + (M_y)^2} \tag{4}
\]

where \(M_x\) and \(M_y\) are the inner moment of force in the \(x\) direction and \(y\) direction, respectively, and their expressions are:

\[
\begin{align*}
M_x &= \int_{-c/2}^{c/2} \delta_x u du = -D \left( \frac{\partial^2 \omega}{\partial x^2} + \nu \frac{\partial^2 \omega}{\partial y^2} \right) \\
M_y &= \int_{-c/2}^{c/2} \delta_y u du = -D \left( \frac{\partial^2 \omega}{\partial y^2} + \nu \frac{\partial^2 \omega}{\partial x^2} \right) \tag{5}
\end{align*}
\]

In this paper, T800 CFRP sample is selected as the experimental workpiece, with length \(a = 200\, \text{mm}\), width \(b = 28\, \text{mm}\), thickness \(h = 3.6\, \text{mm}\), average elastic modulus E of 294 GPA, and Poisson’s ratio \(\nu = 0.3\), allowable bending strength \([\sigma]\). The approximate value is 780 MPa. The internal and external radii \(r\) and \(R\) of the presser foot are 8 mm and 12 mm, respectively; then \(R_0 = (R + r) / 2 = 10\, \text{mm}\). The axial force of composite drilling is usually much less than that of metal, and \(F_x\) can be taken as 200 N [18]. The allowable internal force moment can be obtained according to the following formula:

\[
[M] = \int_{-c/2}^{c/2} \int_{-c/2}^{c/2} \left[ \frac{\sigma}{c} \right] s^2 ds \tag{6}
\]

Find \([M] \approx 867\, \text{N.mm}\). Taking the center point of the template as an example, substitute it into Formula (3) to obtain the specific expression of the deflection at this point:

\[
\omega = \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} \frac{4Fa}{\pi^4 abD} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \left( \frac{m^2}{a^2} + \frac{n^2}{b^2} \right)^2 + \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} \frac{4p}{\pi^4 abD} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \int_0^{2\pi} R_0 \sin \left( \frac{m\pi(x_0 + R_0 \cos \theta)}{a} \right) \sin \left( \frac{n\pi(y_0 + R_0 \sin \theta)}{b} \right) d\theta \tag{7}
\]

Then substitute it into Formula (5) to obtain the internal moment of the center point in the \(x\) direction and \(y\) direction, which are respectively:

\[
\begin{align*}
M_x &= 0.0131p + 105.5 \\
M_y &= 0.0162p + 116.7 \tag{8}
\end{align*}
\]

Obtained internal closing moment is:

\[
M = \sqrt{4.3405 \times 10^{-4} p^2 + 6.54518p + 24749.14} \tag{9}
\]

Theoretically \([M] \leq M\), so the allowable pressing force \(F\) of the presser foot can be solved \(F \leq [F]\) = \(2\pi R_0 p \approx 850\, \text{N}\). That is, when the pressing force of the presser foot does not exceed 850 N, the CFRP sample will not produce matrix cracks due to excessive bending deformation [19]. Due to the slow convergence speed of the Navier trigonometric series solution process, it is impossible to select infinite items in the calculation. The obtained linear load \(p\) is the approximate solution. In practical application, 850 N can be regarded as the allowable value range of compression force.

When the sample size and material change, the allowable value range of the corresponding pressing force can be obtained by referring to the above method.

### 4 Numerical simulation

Based on the allowable range of compression force, the finite element model of drilling CFRP thin plate is established through the finite element software ABAQUS, and the
influence of different compression forces on drilling quality within the allowable range is further analyzed.

4.1 Finite element modeling

The finite element model of drilling CFRP sample in this paper is shown in Fig. 7. The displacement of the sample in the x and y directions is limited by the fixture. The tool diameter is 6 mm, the front angle is 130°, and the rear angle is 12°; it is set as rigid. The length, width, thickness, and pressing force action area of the model are consistent with the sample. The total number of elements included in the tool and CFRP sample after meshing is 23469 and 209532. The model refines the mesh around the drilling area to ensure simulation accuracy and efficiency. Four reference points are set in the whole model. Reference point 1 acts on the tool to output the drilling axial force results, and reference points 2, 3, and 4 around the drilling area to work the sample amplitude results. The single-layer thickness of CFRP unidirectional laminate is about 0.33 mm, a total of 10 layers, and the fiber direction angle is 0°. Before its failure, it is simulated as an anisotropic elastic material, and the material constitutive model is established by the VUMAT subroutine. Adding adhesive layer cohesive element between CFRP solid element layers, cohesive interface element adopts 8-node three-dimensional cohesive element (coh3d8), and CFRP solid element adopts 8-node linear hexahedron element and reduced integral, which can effectively improve modeling accuracy.

4.2 Parameter setting

To ensure the accuracy of the finite element simulation calculation, the mechanical parameters of T800 grade CFRP unidirectional laminates used in the numerical simulation are consistent with those used in the experiment. See Table 1 for some mechanical properties of CFRP unidirectional laminates used in the experiment. The unidirectional CFRP layer is simulated as an equivalent homogeneous material with anisotropic characteristics, and the damage initiation criterion is based on Hashin theory. The cohesive layer is located between two continuous layers. When the normal stress exceeds the stress limit, the interface element fails. In this study, the quadratic nominal stress criterion (quads damage) is used as the damage initiation criterion of the cohesive element, as shown in Formula (10), the element properties of the cohesive element are shown in Table 2, and the process parameters used for drilling simulation are shown in Table 3.

\[
\left(\frac{1}{n_i} \right)^2 + \left(\frac{1}{s_i} \right)^2 + \left(\frac{1}{t_i} \right)^2 = 1
\]

4.3 Result analysis

4.3.1 Drilling process

The numerical simulation of the entire drilling state process is divided into three steps, namely just drilling, drilling in progress, and after drilling. The simulation results are shown in Fig. 8.

It can be seen from Fig. 8a that when just drilling, the drill tip is in direct contact with the CFRP sheet, and the
sheet has elastic severe deformation due to the extrusion of the drill tip. With the cutting of the drill bit, the extrusion energy generated by the drill tip and the sheet is released to the CFRP matrix, and the elastic deformation gradually decreases; at this time, the fibers with weak fiber-matrix bonding strength peel off from the matrix and begin to form cuttings. During the drilling process, as shown in Fig. 8b, the cuttings gradually increase, while the macro chip size of CFRP is usually at the micron level. The formation of simulated chips is related to the grid size and failure displacement. The single grid of this model is about 105 ~ 230 μm. Therefore, the macro model of drilling CFRP samples established does not form long strip and C-type cuttings with a size of more than 1 mm. After drilling, as shown in Fig. 8c, more fine ribbon fiber debris residues are on the sample’s surface. After processing, the outlet and inlet surfaces are relatively neat.

In the dynamic simulation process with a feed speed of 90 mm/min and compression force of 850 N, the stress nephogram of the CFRP template at different times is shown in Fig. 9. It can be seen that in the whole numerical simulation process, the CFRP samples outside the drilling area do not produce large stress. Therefore, the samples outside the drilling area will not have fiber separation and fracture during the drilling process.

4.3.2 Drilling area amplitude

In the drilling process, the CFRP template is limited by four sides, and there is no other force in x and y directions. Therefore, it is only necessary to analyze the displacement change in the z direction in the drilling area [20]. The three reference points set in the drilling area reflect the vibration and deformation of the drilling area. In the simulation results, there is no significant difference in the z-direction displacement of the three reference points, so one of them is taken for analysis. When the feed speed is 90 mm/min, and the sampling frequency is 1 kHz, four different compression forces act on the sample. The z-direction vibration simulation results of the reference point are shown in Fig. 10.

From the simulation results in Fig. 10, it can be seen in drilling that the vibration degree of the drilling area in the z direction is related to the value of the pressing force of the presser foot. When the pressing force is 0 N, during the drilling process from 0.2 to 2.6 s, the sample is only subjected to the drilling axial force in the z direction. Therefore, the deformation $D_f$ in the z direction of the drilling area at the beginning of drilling is small, with a value of 0.08 mm, but the amplitude in the drilling area is large, and the maximum amplitude $S_{max}$ is 0.37 mm. As the pressing force increases to 850 N, the deformation in the drilling area increases continuously at the beginning of drilling, and the maximum deformation $D_f$ reaches 0.27 mm, which is due to the joint action of the pressing force and the drilling axial force.

### Table 2 Parameters of a coherent unit

| Parameter | $\rho$ (kg/cm$^3$) | $E_{na}$ | $E_{ns} = E_{nt}$ | $\tau_{t0}$ | $\rho_{t0} = \rho_{t}$ | $G_{ic}$ |
|-----------|------------------|---------|-------------------|----------|---------------------|-------|
| Value     | $4.0 \times 10^{-9}$ | 40GPa   | 10GPa             | 60 MPa   | 90 MPa              | 280 J/m$^2$ |

### Table 3 Simulation process parameters

| d/mm | Rotating speed (r/min) | Feed rate (mm/min) | Fs/N |
|------|-----------------------|-------------------|------|
| 6    | 3000                  | 90 + 150 + 210    | 0 + 250 + 550 + 850 |

Fig. 8 Simulation process of drilling CFRP sheet. (a) Just drilling. (b) Drilling in progress. (c) After drilling.
force at the beginning of drilling. However, as the pressing force increases, the amplitude generated in the drilling area decreases continuously during drilling.

At 850 N, the maximum amplitude $S_{\text{max}}$ is only 0.08 mm. If the pressing force is continually increased, the bending deformation of the sample will exceed 0.33 mm before drilling, which will produce matrix cracks. During drilling, the matrix cracks will continue to expand, resulting in brittle fracture.

Taking into account the different degrees of variation in amplitude during the drilling time, the maximum displacement of the sample part during this time period, i.e. the maximum amplitude $S_{\text{max}}$, is taken to represent the amplitude of the drilling area in the direction of the spindle feed, where the maximum amplitude increases with the compression force for different feed speeds as shown in Fig. 11. It can be seen from Fig. 11 that the maximum amplitude of the CFRP sample has a great correlation with the compression force, and the overall trend is to decrease with the increase of compression force. When the pressing force is 850 N, the maximum amplitude under different feed rates reaches the lowest, the sample amplitude in the drilling process is the lowest, and the hole wall quality is the highest.

### 4.3.3 Drilling axial force

In the dynamic simulation of spindle speed 3000 R/min, feed speed 210 mm/min, and pressing force 0 N, it is obtained that the average drilling axial force $F_{\text{m}}$ is 159.7 N and the maximum drilling axial force $F_{\text{max}}$ is 198.0 N. When other parameters remain unchanged, and the pressing force is increased to 850 N, the average drilling axial force $F_{\text{m}}$ is 122.4 N, and the maximum drilling axial force $F_{\text{max}}$ is 172.0 N. In the whole simulation process, when the feed speed is 90 mm/min, and the pressing force is 850 N, the average drilling axial force reaches the lowest value of 77.3 N. Figure 12 shows the relationship between the average drilling axial force $F_{\text{m}}$ and the pressing force $F_{\text{s}}$ at different feed speeds.

As shown from Fig. 12, the drilling axial force decreases gradually with the increase of the pressing force. For the CFRP workpiece, the main reason for its surface tear flaw is the drilling axial force. Reducing the drilling axial force can effectively inhibit its surface tear flaw [21]. Therefore, through simulation analysis, when the pressing force of the presser foot is 850 N, the drilling axial force is the smallest, and the drilling surface quality is the highest.

### 5 Drilling experiment

#### 5.1 Experimental condition

To verify the influence of the pressing force of the presser foot on the drilling quality and the correctness of the simulation results, a robot drilling system, as shown in Fig. 13, is built; the working principle of the system is...
shown in Fig. 14. The robot drilling system shown in Fig. 13 includes robot (FANUC robot R-2000ic/165F), drilling terminal actuator, dynamometer (Kistler 9257b), CFRP sample, upper computer, etc. In the experiments, the quality of the drilled holes varied using cutting tools of different materials [22]; as there is no in-depth study of cutting tool materials in this paper, the more common 6-mm carbide-coated twist drill bit with a sharp angle of 130° and a back angle of 12° was used for the experimental tool, its high hardness, good thermal hardness, and good wear resistance. T800 unidirectional laminated template is selected for CFRP sheet, with a size of 200 mm × 28 mm × 3.6 mm. During the drilling process, the angle between the tangential velocity direction of the cutting edge and the fiber direction along the clockwise rotation is called the fiber direction angle θ; the fiber direction angle θ varies from 0 to 180° for each week of tool rotation. Diagram of fiber orientation angle during drilling are shown in Fig. 15. The drilling terminal actuator is integrated into the end flange of the robot. During the experiment, the robot drives the drilling actuator to the target pose, and the feed unit feeds and carries out the drilling experiment.

5.2 Experimental result

5.2.1 Axial force results

It is using the parameters in Table 4, the drilling axial force measurement experiment with Kistler 9257b. The hole-making results are shown in Fig. 16. The average axial force measured at a spindle speed of 3000 r/min feed rate of 210 mm/min clamping force of 0 N was 151.3 N, and the maximum drilling axial force was 191.4 N. The experimentally measured drilling axial force variation curve with time is shown in Fig. 17. The average drilling axial force Fm was measured to be 125.6 N, and the maximum drilling axial force Fmax was 162.0 N when the pressing force was increased to 850 N, keeping other parameters constant. The maximum drilling axial force calculated in the simulation and the actual measured maximum drilling axial force do not exceed 200 N. This justifies the previous calculation of the permissible range of compression force by taking 200 N for the drilling axial force.

The comparison of experimental and simulated drilling axial force data is shown in Fig. 18. It can be seen from Fig. 18 that there is a certain error between the maximum
drilling axial force $F_{\text{max}}$ and the average drilling axial force $F_{\text{m}}$. The main reasons for this error are as follows: (1) the Hashin model of progressive failure of composites is not perfect, (2) insufficient mesh refinement, (3) mesh distortion may occur when the fiber is separated from the matrix, and (4) there are inevitable differences between the simulated
boundary conditions and the actual boundary conditions. The above reasons lead to the error of experiment and simulation. The experimental and simulated drilling axial force data are shown in Table 5. It can be seen from Table 5 that the error between the maximum drilling axial force and the average drilling axial force is no more than 10%, which proves that the simulation is still reliable.

5.2.2 Hole wall roughness comparison

The surface roughness of the wall of the machined hole was observed using a white light interferometer (Taylor Hobson CCI MP). Taking hole 1 as an example, Fig. 19 shows the three-dimensional morphology of the hole wall surface of hole 1 when the pressing force is 0 N. It can be seen from the figure that due to the large amplitude of the processing process when the pressing force is 0 N, the hole wall surface is uneven, forming some white and red areas with high protrusions, and the area of the whole protrusion area is large. When the pressure tightening force is increased, the amplitude of the processing process decreases, and the area of uneven surface area and the convex area gradually decreases. Figure 20 shows the three-dimensional surface morphology of the hole wall of hole 1 when the pressing force is different. The x-axis and y-axis represent the area of the observation area, and the z-axis represents the maximum height roughness of the hole wall surface.
It can be seen from the figure that when the pressing force is 250 N, the area of the raised red area is significantly reduced compared with that when the pressing force is 0 N, and the surface quality of the hole wall is improved. When the pressing force is increased to 550 N, the raised white area has disappeared, and the surface roughness value of the hole wall is reduced. When the pressing force continues to increase to 850 N, the area of the raised area is the smallest, and the surface roughness value of the hole wall is the lowest, directly reflected in the relatively smooth hole wall.

After three repeated experiments, the average value of hole wall roughness $R_a$ of machined holes under different pressing forces is shown in Fig. 21. The standard deviation is shown in Fig. 22. It can be seen from Fig. 21 that when the pressing force is 0 N, there are many vibration marks on the hole wall of the machined hole. The average surface roughness of the hole wall of holes 1–3 is 4.6–6.3 $\mu$m when the pressing force is increased to 250 N, the hole wall quality of the machined hole is improved to a certain extent, the vibration pattern is gradually reduced, and the average surface roughness of the hole wall of holes 1–3 is 3.3–4.6 $\mu$m.

When the pressing force is further increased to 550 N, the hole wall quality of the machined hole is greatly improved, the vibration lines on the hole wall are significantly reduced, and the appearance is smooth. The average roughness of the hole wall of holes 1–3 is about 1.8–3.3 $\mu$m. When the pressing force increases to 850 N, the hole wall finish is greatly improved, and the average surface roughness of holes 1–3 is 1.8 $\mu$m within, the minimum value of multiple experiments is 1.58 $\mu$m. It can be seen from the results in Fig. 22 that the standard deviation of holes 1–3 is less than 0.35 $\mu$m. It shows that the surface roughness of holes 1–3 obtained from many experiments is close to the average value, and the single experimental data is reliable. Therefore, increasing the high-pressure tightening force within the allowable range of tightening force can significantly improve the hole wall roughness after drilling and improve the drilling quality.

### 5.2.3 Comparison of borehole surface flaws

By observing the surface morphology of the machined holes with a super depth of field microscope (KEYENCE VHX-500FE), it can be found that there are no apparent flaws at the entrance of the holes. By observing the outlet morphology, it can be seen that when the pressing force is 0 N, the outlets of holes 1–3 have different degrees of tearing flaws, among which the tearing flaw of hole 3 is the most serious, because under the same pressing force, the larger the feed rate, the greater the drilling axial force, and the main reason affecting the tearing flaw is the excessive drilling axial force; therefore, the tearing flaw causing hole 3 is the most serious. When the pressing force is 250 N, the tearing flaws...
of holes 1–3 have been improved, but the flaws are still apparent. With the pressing force increasing to 550 N, there are no obvious tearing flaws at the outlet of machined hole 1, and the tearing flaws of holes 2 and 3 still exist. However, compared with the pressing force of 0 N, the surface quality of holes 2 and 3 have been dramatically improved. When the
pressing force is further increased to 850 N, the machined holes 1~3 have no tear flaws. Taking hole 1 as an example, Fig. 23 compares the outlet surface morphology of hole 1 under different pressing forces.

5.3 Result analysis

According to the analysis of the above experimental results, when the presser foot pressing force is 850 N, the average drilling axial force and the maximum drilling axial force are lower than 0 N, 250 N, and 550 N; when the presser foot pressing force is 850 N, the average drilling axial force of holes 1~3 is about 33.2 N lower than that when the presser foot pressing force is 0 N. Maximum drilling axial force is reduced by 25.4 N, and the fundamental reason is that the large pressing force suppresses the vibration of CFRP thin plate during drilling, which improves the processing conditions and reduces the drilling axial force.

Compare the quality of the hole after the drilling process, when the pressing force of the presser foot is 850 N; it is

| Pore sequence | Experiment $F_m$(N) | Simulation $F_m$(N) | Error | Experiment $F_{max}$(N) | Simulation $F_{max}$(N) | Error |
|---------------|---------------------|---------------------|-------|-------------------------|-------------------------|-------|
| 1–1           | 99.7                | 105.8               | −6.12%| 147.4                   | 138.1                   | 6.31% |
| 1–2           | 91.8                | 98.2                | −6.97%| 135.5                   | 126.3                   | 6.79% |
| 1–3           | 88.1                | 81.4                | 7.60% | 126.1                   | 118.4                   | 6.11% |
| 1–4           | 73.4                | 77.3                | −5.31%| 111.7                   | 117.6                   | −5.28%|
| 2–1           | 135.3               | 127.7               | 5.62% | 165.8                   | 155.1                   | 6.45% |
| 2–2           | 120.4               | 110.4               | 8.31% | 158.3                   | 148.7                   | 6.06% |
| 2–3           | 111.9               | 101.2               | 9.56% | 144.2                   | 131.5                   | 8.81% |
| 2–4           | 103.5               | 93.9                | 9.28% | 132.1                   | 125.2                   | 5.22% |
| 3–1           | 151.3               | 159.7               | −5.55%| 191.4                   | 198.0                   | −3.45%|
| 3–2           | 139.5               | 151.3               | −8.46%| 174.6                   | 181.6                   | −4.02%|
| 3–3           | 131.1               | 138.6               | −5.72%| 168.3                   | 160.2                   | 4.81% |
| 3–4           | 125.6               | 122.4               | 2.55% | 162.0                   | 172.0                   | −6.17%|

Fig. 19 Three-dimensional morphology of hole wall surface of hole 1 under compression force of 0 N
**Fig. 20** Three-dimensional morphology of hole wall surface of hole 1

**Fig. 21** Mean value of hole wall roughness in three experiments

**Fig. 22** Standard deviation of hole wall roughness
greatly improved compared with 0 N, 250 N, and 550 N, which is mainly reflected in the better outlet surface morphology and higher hole wall finish. Therefore, under the same processing conditions, the pressing force of the presser foot is close to the upper limit of the allowable range, which can effectively improve the quality of the processed hole.

6 Conclusions

1. By designing the pneumatic presser foot device in front of the end actuator of the industrial robot, the vibration generated by the hole position during drilling CFRP thin plate can be effectively suppressed, and the hole-making quality can be effectively improved.

2. The allowable range of presser foot pressing force is 0 ~ 850 N by the Navier method.

3. Through the finite element method, the process of drilling CFRP thin plate under the compression force of 0 N, 250 N, 550 N, and 850 N is numerically simulated, and the influence of different compression forces on the drilling quality within the allowable range of presser foot compression force is further analyzed. It is concluded that 850 N compression force is the optimal value within the permissible range of presser foot compression force.

4. Through the drilling experiment, the drilling quality under the compression force of 0 N, 250 N, 550 N, and 850 N is compared. It is verified that the surface roughness of the hole wall can reach 1.8 when drilling under the compression force of 850 N presser foot μm. At the same time, it can improve the surface morphology at the outlet of the machined hole, which is the best drilling quality within the allowable range of the pressing force of the presser foot.

Author contribution All the authors have been involved equally in the realized work. Mr. Pengqiang Fu, Yan Wang, Yuhang Miao, Yiwen Wang, Mrs. Lijie Zhou, and Sisi Yang: paper writing, problem

Fig. 23 Comparison of outlet morphology of hole 1 under different pressing forces
formulation, approaches proposal, and experimental performing and analysis.

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Data availability The used data and materials are available when requested.

Declarations

Ethics approval The submitted work is original and has never been published elsewhere in any form or language.

Consent to participate Not applicable.

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Conflict of interest The authors declare no competing interests.

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