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The Critical Axial Force Model in Drilling of Carbon Fiber Reinforced Composites under Different Stacking Modes

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Abstract. Delamination is a failure mode in which the initial crack propagates along the interlayer due to the axial force pushing the uncut material beyond the interlaminar shear strength during drilling. Therefore, it is necessary to study the effect of axial force on the delamination of carbon fiber reinforced composites (CFRP) during drilling. The critical axial force model of different stacking modes is established based on linear elastic fracture mechanics, thin plate bending theory, composite mechanics and superposition principle. The experimental results show that the theoretical values are in good agreement with the experimental values and can be used to predict the critical axial force to suppress the formation of delamination defects.

1. Introduction

In order to meet the lightweight and durability goals of modern aircraft structural design, laminated components are widely used in aircraft wing and tail, which are composed of carbon fiber composite materials (CFRP) and metal materials (aluminum alloy and titanium alloy) [1,2]. The quality of connection holes is directly related to connection strength, stiffness and safety [3,4]. The integrated laminated drilling reduces the complicated process of "Split specimen-Deburring-Reassembly", which has ensured the accuracy and accuracy of hole size, and has attracted wide attention.

There are many reasons for the drilling defect in the drilling process of CFRP, delamination is one of the most important processing defects. From a macro perspective, it is mainly caused by the drilling force, especially the axial force and the temperature produced in the process of machining, the former has a greater influence than the latter. The internal stress of the interlayer increases with the increase of drilling axial force, fiber layering due to the fracture of the resin when reaching or exceeding the strength of the resin [5]. At present, many scholars have done a lot of research on axial force during drilling. Qi et.al [6] established critical thrust force predicting modeling for delamination-free drilling of metal-CFRP stacks, the location and expansion rate of the composite material are determined. A theoretical critical axial force model for tool/material contact considering the variation of energy release rate of I type crack propagation with the relative fiber angle between laminates is established by Lachaud et.al [7], experiments show that the theoretical model under uniformly distributed load is the closest to the test results. Pierre et al [8] established mathematical models under different load states considering the influence of tools geometry on stress state of materials, the results of the experiment show that the test data are in good agreement with the data under the composite loading state. Rahme et.al [9] further studied the relationship between drilling axial force and process...
parameters on the basis of studying critical axial force, and put forward the concept of critical feed rate, the experiment shows that the CFRP does not delaminate when the feed rate is lower than critical feed rate, which provides a good way to control drilling delamination by changing process parameters. Ohzeki et al [10] monitor and feedback the axial force signal in real-time during drilling CFRP, and change the feed parameter according to the change of the axial force signal to control the axial force of drilling, so as to avoid export layering defects.

This study will establish a mechanical model of critical axial force by considering the different stacking sequence of CFRP-Al material, that is, different drilling directions. The delamination mechanism at the exit of CFRP was investigated and provides a basis for predicting delamination defects of laminated components.

2. Critical axial force model

2.1. Stacking sequence: Metal → CFRP

When drilling the laminates from the metal layer, which means that the metal plate is above the CFRP plate, the mechanism of composite material delamination is the same as that of single drilling CFRP, because there is no support for the lower layer of CFRP. Not only should we consider the contact conditions of the connection parts, but also we should reasonably simplify the axial force. So the study assumes that the drilling area is a circular thin plate subjected to axisymmetric load, the circular plate is referred to in Figure 1. According to the theory of thin plates in elasticity, its equilibrium differential equation is:

$$\frac{\partial^2 M_\text{xx}}{\partial x^2} + \frac{\partial^2 M_\text{yy}}{\partial y^2} + \frac{\partial^2 M_\text{xy}}{\partial x \partial y} = -q$$

(1)

Because the contact area between the drill and the workpiece is axisymmetric, the stress / strain relationship model can be expressed as:

$$\begin{bmatrix} M_{\text{xx}} \\ -M_{\text{yy}} \\ -M_{\text{xy}} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{21} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \frac{\partial^2 \omega}{\partial x^2} \\ \frac{\partial^2 \omega}{\partial y^2} \\ -2 \frac{\partial^2 \omega}{\partial x \partial y} \end{bmatrix}$$

(2)

where, $M_{\text{xx}}$, $M_{\text{yy}}$, $M_{\text{xy}}$ is bending moments in different directions. $q$ is uniformly distributed load on uncut sheet. $D_{ij}$ is bending stiffness.

According to the theory of composite laminates, the stiffness matrix of a single plate can be drawn from the following equation:

$$|D_{ij}| = \sum_{k=1}^{n} \left( \overline{Q}_{ij} \right) \left( \frac{Z_k^i - Z_{k-1}^i}{3} \right)$$

(3)

The CFRP used in this paper are orthotropic, then $D_{16} = D_{26} = 0$, and the stiffness matrix is:

$$[Q] = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{11} \end{bmatrix}$$

(4)

The equation (2) and (3) are substituted by differential equations (1).

$$D_{11} \frac{\partial^4 \omega}{\partial x^4} + 2(D_{12} + 2D_{66}) \frac{\partial^4 \omega}{\partial x^2 \partial y^2} + D_{22} \frac{\partial^4 \omega}{\partial y^4} = -q$$

(5)
\[ \omega(r) = \frac{q(a^2 - r^2)}{64D} \]  

where, \( q = \frac{F_c}{\pi a^2} \) and \( D = \frac{1}{8}(3D_{11} + 2D_{12} + 4D_{66} + 3D_{22}) \)

According to the principle of virtual displacement and linear elastic fracture mechanics, the total energy done by uniformly distributed load equals to the sum of the elastic strain energy and the crack growth energy of the material \([11,12]\). The equation is:

\[ \delta W = \delta U + \delta Ud \]  

In the equation, \( \delta W \) is the total virtual energy produced by uniform load per unit area, \( \delta U \) is the change of elastic strain energy of the material, and \( \delta d \) is the crack propagation energy per unit area, reflecting the ability of the material to resist fracture damage.

The total virtual energy produced by uniform distributed load:

\[ W = \int_0^{2\pi} \int_0^a q \cdot w(r) r \cdot drd\theta = \frac{F_c^2 a^2}{192\pi D} \]  

\[ \delta W = \frac{\partial W}{\partial a} \delta a = \frac{F_c^2 a^2}{96\pi D} \]  

Variation of elastic strain energy:

\[ \delta U = \frac{\partial U}{\partial a} \delta a = \left( \frac{F_c}{16D} \right)^2 \frac{a}{\pi} \left[ \frac{D_{11} + D_{22}}{2} + \left( \frac{D_{12} + D_{66}}{3} \right) \right] \delta a \]  

The crack propagation energy per unit area:

\[ \delta Ud = \frac{\partial Ud}{\partial q} \delta a = 2G_{ic}\pi a \delta a \]  

Among them, \( G_{ic} \) is the I-type crack propagation energy per unit area.

The equation (9) (10) (11) was substituted (7), the critical axial force can be introduced:

\[ F_c = 8\pi \left( \frac{G_{ic}D}{(1/3) - (D/8D)} \right)^{1/2} \]  

Where, \( D = \frac{D_{11} + D_{12}}{2} + \frac{D_{12} + D_{66}}{3} \)

2.2. Stacking sequence: CFRP → Metal

The stress characteristics of composite plates are quite different from those of individual drilling when the stacking sequence is CFRP to Metal. The overall stress condition of the composite plate will be affected due to the additional supporting force. In addition, the displacement and deformation of laminated plates also affect the critical axial force of lamination, so the shape of the plate, boundary conditions, fixture conditions and other factors should be considered when establishing the model of critical axial force. The stress state is shown in Figure 2. At this point, the borehole area can still be regarded as a circular thin plate with fixed edges.

The concentrated force generated by a chisel edge:

\[ F_c = \xi F \]
Among them, $F_c$ is the total axial force. $\xi$ is the ratio of the axial force produced by the transverse edge part to the total axial force, also called the proportion coefficient.

The offset of each point on the circular plate is:

$$\omega_c(r) = \omega_{c'}(r) - \omega_{c''}(r) = \frac{F_c - P_{re}}{16\pi D} \left[ 2r^2 \ln \frac{r}{a} + \left( a^2 - r^2 \right) \right]$$ (14)

In the equation, $r$ is the extreme radius of circular plate and $D$ is the flexural rigidity of the uncut layer. From the conclusion in document [8,13], $P_{re}$ can be obtained from the following equation:

$$P_{re} = F_c - 2\sqrt{3}\pi\sqrt{G_{m}}D = \xi F - 2\sqrt{3}\pi\sqrt{G_{m}}D$$ (15)

Because the composite plate is subjected to axial force and supporting force, the displacement of every point on the plate is determined:

$$\omega_c(r) = \frac{F_c - P_{re}}{16\pi D} \left[ 2r^2 \ln \frac{r}{b} + \left( b^2 - r^2 \right) \right]$$ (16)

Among them, $D_c$ is equivalent flexural rigidity of composite plates can be obtained by equation (3). $b$ is the diameter of plates.

When the metal plate is thin plate (the ratio of plate thickness to plate diameter: $\delta/2b\leq1/8$), the displacement of metal plates at various points is:

$$\omega_m(r) = \frac{3(1-v^2)}{4\pi Eh^2} \frac{P_{re}}{D_c} \left[ 2r^2 \ln \frac{r}{b} - \left( b^2 - r^2 \right) \right]$$ (17)

As shown in Figure 2, the displacement of the uncut region is the same as that of the metal plate based on the hole edge of the composite plate, that is:

$$\omega_c(r = 0) + \omega_c(r = a) = \omega_m(r = 0)$$ (18)

The critical axial force is obtained by substituting equation (14) (15) (16) (17) into (18):

$$F_c = \frac{2\sqrt{3}}{\xi - K} \sqrt{G_{m}}D$$ (19)

Where, $K = \frac{\xi a^2}{D} + \frac{2a^2 \ln \frac{a}{b} + \left( b^2 - a^2 \right)}{D_c}$

$$D_c = \frac{9(1-v^2)b^4}{2Eh^3} + \frac{a^2}{D} + \frac{2a^2 \ln \frac{a}{b} + \left( b^2 - a^2 \right)}{D_c}$$

Figure 2. The schematic diagram of forces on each part of the drill pin from CFRP to metal

3. Experimental research

3.1. Experimental devices and materials
The experimental equipment is LGmazak430Al CNC machining center, the thrust force and torque during machining were measured using piezoelectric dynamometer (Interface1216), two ME SGA/A charge amplifiers and PC are used for data acquisition and analysis, as shown in Figure 3. Carbon fiber-reinforced composite materials (CCF300) of 200×200×3.07mm and aluminum alloy (Al7075-T7) of 200×200×3.1mm were used for experiments, its mechanical and physical properties are shown in table 1. The CFRP is orthogonal woven structure, laid up according to an orientation of [0°/90°], which is composed of 24 plies, each layer thickness \( h = 0.125 \text{ mm} \), Properties of each layer of material as shown in Table 2. The tool is diamond coated carbide twist drill with a diameter of 5mm.

Table 1. Mechanical and physical properties of CCF300 and Al7075

| Material  | Mechanical and physical properties |
|-----------|-----------------------------------|
|           | Tensile strength (MPa) | Elasticity modulus (GPa) | Density (g/cm\(^3\)) | Elongation (%) |
| CCF300    | 3950                          | 232                       | 1.76                     | 1.7             |
| Al7075    | 572                           | 71.7                      | 2.81                     | 12              |

Table 2. Mechanical properties each layer of CCF300

| Mechanical properties | CCF300 |
|-----------------------|--------|
| Shear strength /MPa   | 89     |
| Longitudinal elastic modulus /GPa | 137     |
| Transverse elastic modulus /GPa | 8.7     |
| Longitudinal and transverse shear modulus /GPa | 4.2     |

3.2. Experimental design

In order to verify the relationship between delamination and axial force the relationship model between axial force and machining parameters should be established, and the fitting equation of axial force should be obtained. Firstly, using the orthogonal experimental design method, each experiment condition was repeated five times to get consistent values and avoid accidental error. The parameter level of spindle speed and feed rate is shown in Table 3. Then, the spindle is not rotated during the experiment, only a vertical downward fixed load was applied and a constant feed rate of 10mm/min was used, the axial force gradually increases until delamination defects occurs in order to verify the accuracy of the critical axial force model.

Table 3. Level table of cutting parameters

| Name          | Units       | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---------------|-------------|---------|---------|---------|---------|---------|
| Spindle speed | \( n/(\text{r}\cdot\text{min}^{-1}) \) | 2700    | 3500    | 4300    | 5100    | 5900    |
| Feed rate     | \( f/(\text{mm}\cdot\text{r}^{-1}) \) | 0.03    | 0.04    | 0.05    | 0.06    | 0.07    |

4. Results and discussion

4.1. Effect of cutting variables on thrust force and torque

The thrust force and torque time-history curve when drilling CFRP/Al stacks as shown in Figure 4. The axial force and torque increase gradually from the drill point to the composite material, and then
stabilize when it enters the composite material completely. When the drill tip reaches the transition zone of the laminated member, the cutting force increases suddenly and reaches the maximum value after drilling into the aluminum alloy completely. The axial force and torque gradually decrease to zero when the drill bit is drilled from the bottom of the aluminum alloy. The axial force of the aluminum alloy at stable stage is about 1.5 times of the axial force of the CFRP.

The effect of the process parameters on the thrust force of CFRP and Al7075-T7 when drilling CFRP/Al stacks as shown in Figure 5 and Figure 6, respectively. It's obvious that the spindle speed and feed rate have a certain effect on cutting force, but the influence of feed rate is greater than that of spindle speed. The variance analysis of cutting force is made in order to judge the degree of influence, as shown in Table 4. The main effect has a significant effect on the cutting force, and the interaction between them has a certain influence on the cutting force, but the main effect is not obvious.

4.2. Effect of cutting variables on thrust force and torque
According to the law of axial force changing with cutting parameters, there is a nonlinear relationship between axial force and spindle speed, feed rate and their interaction. Therefore, quadratic regression model can be used to fit the empirical equation, the fitting equation as follows:

\[ F_{CFRP} = 53.36 - 0.0055n + 2.4598 \times 10^{-7} n^2 + 885.87 f - 5692.9 f^2 - 0.0585 nf \]  (20)

\[ F_{Al} = 88.3323 - 0.0125n + 1.1038 \times 10^{-6} n^2 + 344.38 f + 5792.9 f^2 - 0.0074nf \]  (21)

Among them, \( F \) is axial force, \( n \) is spindle speed, \( f \) is feed rate, \( C_0 \ldots C_5 \) is an undetermined constant.

The determination coefficients of the fitting equation are all greater than 0.9, indicating that the fitting results are ideal. It can be concluded that the regression equation can be used as an empirical
equation to predict the axial force within the selected process parameters. In practical application, higher spindle speed and lower feed rate should be selected to reduce the lamination defect of CFRP. At the same time, reducing the cutting force can weaken the impact on the tool in the drilling process and thus prolong the service life of the tool.

4.3. **Critical axial force in different stacking modes**

4.3.1. *Critical axial force when drilling Al to CFRP stacks.* A comparison between the critical axial force model value and the experimental result as shown in Figure 7 when the stacking sequence is Al to CFRP. The critical axial force also increases linearly as the number of uncut layers increases. The experimental value is always smaller than the model value, this is because the axial force is uniformly distributed on the main cutting edge and the chisel edge under the assumption of uniform load, which weakens the pushing effect of the concentrating force on the cross edge on the material and makes the critical axial force in the model is higher. The experimental values are consistent with the model values when the number of uncut layers of CFRP is small ($n < 6$), it is considered that the model is more precise. When the uncut layers exceeds 6 ($H=0.75\text{mm}$), the model will produce a great error with the experimental value. The main reason is the establishment of the critical axial force model is mainly for thin plates, the pushing force of the cutting force on the material is strengthened when the uncut part exceeds 0.75mm, the occurrence of delamination is not only due to the propagation of cracks, but also to the stress concentration.

![Figure 7](image-url) **Figure 7.** The comparison diagram between the critical axial force model value and the experimental result when the stacking sequence is Al to CFRP.

4.3.2. *Critical axial force when drilling CFRP to Al stacks.* Figure 8 is the relationship between the critical axial force and the fixed boundary radius. The critical axial force decreases with the increase of fixed boundary radius, which means that delamination is more likely to occur at the exit of CFRP with the increase of fixed boundary radius. It can be seen from equation (19) that the critical axial force is directly proportional to the thickness of $h$, the undrilled thickness of CFRP decreases gradually with the increase of drilling depth, and the critical axial force for delamination decreases. To avoid stratification of the production, cutting edges of the tools should be sharp enough to cut quickly.

![Figure 8](image-url) **Figure 8.** The relationship between the critical axial force and the fixed boundary under different thickness.

![Figure 9](image-url) **Figure 9.** The comparison diagram between the critical axial force model value and the experimental result when the stacking sequence is CFRP to Al.
From Figure 9, axial force decreases as the number of uncut layers decreases when the number of uncut layers is less than 4, and the difference between theoretical value and experimental value is very small. No matter how thick the thickness of the uncut layer is, the experimental data are always slightly higher than the theoretical value. This is mainly due to the fact that the ratio of the concentrated load generated by chisel edge to the total cutting force in the model is less than the ratio in actual cutting. \( \xi \) is related to the structural form of the drill bit and the geometric angle of the cutting edge. In general, \( \xi \) is 0.4–0.6, the value of this model is 0.5.

5. Conclusions
In this study, the effect of different stacking sequences of Metal/CFRP on the delamination of CFRP was analyzed, and the mechanism of delamination defects in two different stacking sequences was studied. The study on controlling the delamination of composite materials enables the following conclusions. The spindle speed and feed rate have a certain effect on cutting force, but the influence of feed rate is greater than that of spindle speed. The experimental values are consistent with the model values when the number of uncut layers of CFRP is small \( (n < 6) \), when the stacking sequence is Al to CFRP. Contrary, when the stacking sequence is CFRP to Al, the critical axial force is related not only to the thickness but also to the radius of the fixed boundary. The axial force is the main factor for the delamination of composite materials. The deformation of the metal plate will inhibit the delamination of the composite material, and its critical axial force will be greatly improved when the metal plate is supported below the composite material.

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