Influence of drill helical direction on exit damage development in drilling carbon fiber reinforced plastic

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Abstract. Drilling is inevitable for CFRP components’ assembling process in the aviation industry. The exit damage frequently occurs and affects the load carrying capacity of components. Consequently, it is of great urgency to enhance drilling exit quality on CFRP components. The article aims to guide the reasonable choice of drill helical direction and effectively reduce exit damage. Exit observation experiments are carried out with left-hand helical, right-hand helical and straight one-shot drill drilling T800S CFRP laminates separately. The development rules of exit damage and delamination factor curves are obtained. Combined with loading conditions and fracture modes of push-out burrs, and thrust force curves, the influence of drill helical direction on exit damage development is derived. It is found that the main fracture modes for left-hand helical, right-hand helical, and straight one-shot drill are mode I, extrusive fracture, mode III respectively. Among them, mode III has the least effect on exit damage development. Meanwhile, the changing rate of thrust force is relative slow for right-hand helical and straight one-shot drill in the thrust force increasing phase of stage II, which is disadvantaged for exit damage development. Therefore, straight one-shot drill’s exit quality is the best.

1. Introduction

Carbon fiber reinforced plastic (CFRP) composites have been widely adopted for manufacturing aircraft and spacecraft structural parts because of their superior properties such as excellent damage tolerance, high strength-to-weight and stiffness-to-weight ratios [1]. Although CFRP composites are produced to near-net shape, machining is still inevitable in the assembly process. Among machining processes, drilling is one of the most frequently used to make holes for screws, rivets and bolts, and often a final operation during aerostructures assembly [1-2].

CFRP composites have strong anisotropy, lamination property and low layer-to-layer bond strength at the macro level. Meanwhile, the thrust force produced in drilling is quite large, so it is easy to generate delamination. In addition, other damage, such as cracks and burrs, often occurs because of fiber bending when it is difficult to cut off fiber. Damage reduces the service life of CFRP components substantially [3-4]. For example, as much as sixty percent of composite components failure is caused by delamination [5-6]. Damage can be classified as exit damage, entry damage and hole wall damage according to the damage position. Among them, exit damage is the most serious which can decrease the strength, stiffness and bearing capacity of laminates to a large extent [7]. It is known that drill geometry affects the contact state between tool and workpiece directly and is one of the most important factors affecting exit damage [8].
Drill geometry can be categorized to drill bit geometry and drill flute geometry. Many researchers have made great efforts to study the effect of drill bit geometry on exit damage. Hocheng et al. [4, 9-13] investigated the exit damage in drilling CFRP using twist drill or the drill with special drill bit geometry, such as saw drill, candle stick drill and step drill, and built the corresponding critical thrust force model of push-out delamination. The results indicated that push-out burrs and push-out delamination caused by one-shot drill are weaker than those caused by twist drill. Jain and Yang in Reference [14], and Tsao and Hocheng in Reference [15] found that the lower point angle of twist drill, the lower push-out delamination. Chisel edge had an important effect on push-out delamination, and derived the optimal range of chisel edge with respect to drill diameter. Durão et al. [16] pointed out that decreasing twist drill’s helix angle would contribute to increasing the thrust force, torque and push-out delamination. Above all for the final exit damage, in order to make further optimization on drill bit geometry and decrease drilling damage, some researchers experimentally studied the formation and development of exit damage as well. Dipaolo et al. [17] photographed the integrated development process of exit damage, and significant damage types of each drilling-out stage were observed. Correlations between the average drill forces and damage development, relations between instantaneous forces and damage development in different fiber cutting angle were shown respectively. However, there is still a lack of study that explains the influence of drill flute geometry on exit damage development at present. Drill helical direction is one of the most important components of drill flute geometry, and most of drills adopt right-hand helical flutes while few of them have the left-hand helical or straight flutes [18-19]. Drill helical direction affects drill cutting angle and chip flowing directly, and further changes drilling forces and temperature, which has a great effect on exit quality. Therefore it is important to study the influence of drill helical direction on exit damage development.

This article conducts drilling experiment using right-hand helical, left-hand helical, and straight one-shot drill to drill T800S CFRP laminates separately. Based on the experimental results, the development rules of exit damage are shown drilling with three kinds of one-shot drills. Combined with the loading conditions and fracture modes of push-out burrs, and thrust force analysis, the influence of drill helical direction on exit damage development is derived, which guides the reasonable choice of drill helical direction.

2. Exit observation experiments using one-shot drills with different helical directions

2.1. Experimental drills

The paper conducts exit observation experiments with three kinds of one-shot drills whose helical directions are right-hand helix, left-hand helix and straight respectively. Drills are made of K44UF tungsten carbide without coating which have two primary cutting edges, four secondary cutting edges, and four minor cutting edges as illustrated in Table 1. The helix angles of right-hand helical one-shot drill and left-hand helical one-shot drill are both 6°, while the helix angle of straight one-shot drill is 0°. Other dimensions of three one-shot drills are identical whose specific values are shown in Table 2.

| Table 1. One-shot drills with different helical directions. |
|------------------------------------------------------------|
| Left-hand helical one-shot drill | Right-hand helical one-shot drill | Straight one-shot drill |
|----------------------------------|----------------------------------|------------------------|
|                                  |                                  |                        |
### Table 2. Specific dimensions of one-shot drills.

| Diameter (mm) | Primary point angle (°) | Secondary point angle (°) | Rake angle of primary cutting edges (°) | Helical rake angle (°) | Chisel edge length (mm) | Axial length of primary cutting edges (mm) | Axial length of secondary cutting edges (mm) |
|--------------|------------------------|--------------------------|----------------------------------------|-----------------------|------------------------|-------------------------------------------|------------------------------------------|
| 7.94         | 120                    | 18                       | 5                                      | 10                    | 0.41                   | 0.57                                       | 18.8                                     |

### 2.2. Experimental materials and equipment

In order to guide drilling of aviation parts preferably, the workpiece used in the experiments is multidirectional CFRP composites and laminated by 20 layers of P2352 prepreg in the fiber orientation of [(-45/0/45/90)_2s/0/0]. The reinforced fiber is Toray-T800S and the fiber volume content is 60%. The mechanical properties of the composites are listed in Table 3. After curing under high temperature and pressure conditions, the workpiece has the dimensions of 150×20×4 mm.

### Table 3. Mechanical properties of composites.

| Longitudinal tensile strength (MPa) | Transverse compressive (MPa) | Longitudinal Young’s modulus (GPa) | Transverse Young’s modulus (GPa) | Poisson’s ration |
|------------------------------------|------------------------------|-----------------------------------|---------------------------------|-----------------|
| 2842                               | 165.6                        | 160                               | 8.97                            | 0.28            |

A series of drilling operations were carried out on the GONA 5-axis machining center. In order to observe conveniently, the spindle adopted angle head to change vertical drilling into horizontal drilling. High-speed camera was used to photograph the drilling-out process of one-shot drills whose frame rate was set as 1000fps. A Kistler force sensor, 9257B dynamometer, was fixed on the platform of the machining center to support the clamping system and measure the thrust force during drilling. The kistler amplifier and data acquisition were employed to read and save data from the force sensor in a sampling frequency of 3 KHz, and experimental equipment is shown in Figure 1. CFRP laminates were observed on Keyence digital microscope to measure the final exit quality, and the observation rate was 20. Drilling parameters of 3000rpm in spindle speed, 150mm/min in feed rate, 25mm in clamping length and 30mm in drilling-in length were adopted in the experiments, and drilling operations were performed under dry condition.
Figure 1. Experimental equipment.

3. Results and discussion

3.1. Analysis of the loading conditions and fracture modes of push-out burrs

The paper divides one-shot drills' drilling-out process into three stages as shown in Figure 2. The chisel edge and primary cutting edges drill out of workpiece in stage I. During this stage, the chisel edge, primary cutting edges and secondary cutting edges, or primary cutting edges and secondary cutting edges participate in drilling. Stage II is the process of secondary cutting edges drilling-out gradually. Secondary cutting edges drill alone at the beginning, and then minor cutting edges drill into the workpiece. The process of minor cutting edges drilling-out is defined as stage III which only has minor cutting edges drilling. Because of the difference of three one-shot drills’ helical direction near secondary cutting edges and minor cutting edges, the influence of drill helical direction on exit damage still exits. Among them, the position containing helical direction acts on exit directly in stage II and stage III, which has a significant effect on exit damage.

Feed rate is far less than cutting speed, so the instantaneous relative motion between one-shot drill and exit of CFRP laminates can be approximated to rotary motion. It can be seen that feed motion has little effect on exit loading conditions. Considering the comprehensive effect of relative motion and drill helical direction, the resultant force for a point A on laminates’ exit can be decomposed into the thrust force $F_z$ aligned with the drill axis, the lateral force $F_x$ along the radial direction, and the
tangential force $F_y$ that is perpendicular to both in stage II, as in Figure 3. At the same time, Figure 4 shows that the resultant force for a point B on laminates’ exit can be decomposed into the thrust force $F_z$ aligned with the drill axis and the tangential force $F_y$ corresponding to the tangential direction in stage III. The thrust force $F_z$ produced by right-hand helical drill still points from exit, while it has opposite direction for left-hand helical drill and straight drill. In addition, the thrust force $F_z$ generated by left-hand helical drill is higher than that generated by straight drill.

(a) Left-hand helical one-shot drill  (b) Right-hand helical one-shot drill  (c) Straight one-shot drill

**Figure 3.** Exit loading conditions in stage II.

(a) Left-hand helical one-shot drill  (b) Right-hand helical one-shot drill  (c) Straight one-shot drill

**Figure 4.** Exit loading conditions in stage III.

For left-hand helical one-shot drill and straight one-shot drill, the thrust force $F_z$ stretch burr to exit at the point, which causes the fracture of mode I, and the tangential force $F_y$ shears exit burr, which contributes to the fracture of mode III. However, mode I of left-hand helical one-shot drill is more significant compared to that of straight one-shot drill because left-hand helical drill has higher thrust force $F_z$. The current research showed mode I had more serious effect on exit damage than mode III [20]. Consequently, straight one-shot drill is more superior in exit quality than left-hand helical one-shot drill. Moreover, exit burrs is extruded into laminates and sheared along the tangential direction drilling with right-hand helical one-shot drill. The fracture modes are mode III and extrusive fracture.

Figure 5 and Figure 6 show that left-hand helical drill tears burrs outside laminates, straight drill mainly shears burrs along the tangential direction whose tearing effect is weak, and right-hand helical drill extrudes burrs into laminates and shears them along the tangential direction. The experimental results correspond to the above analysis of loading conditions and fracture modes of push-out burrs.
3.2. Thrust force

The data obtained from drilling is filtered in the software with a low pass filter set to 10Hz, because the axial motion is a continuous low frequency process. The obtained typical thrust force curves are shown in Figure 7. It can be seen that thrust force curves of three one-shot drills are almost same. The main cutting edges enter the workpiece gradually in drilling in stage I, which leads to the thrust force increasing rapidly. The maximum value of thrust force occurs when the chisel edge is close to the bottom of laminates. The thrust force decreases quickly in stage I, and is found to: first decrease, then increase and decrease again in stage II. During stage III, it is very low and maintains a constant value basically. However, the thrust force changing rate of left-hand helical drill is much higher than that of right-hand helical drill and straight drill in the increasing phase of stage II. Besides that, in stage III, the thrust forces of left-hand helical drill, right-hand helical drill and straight drill are positive value, negative value and nearly zero separately.
3.3. Exit damage

The experimental results indicate that the development rules of exit damage are fundamentally uniform for three drills. A longitudinal bulge along fiber orientation is observed at laminates exit when the chisel edge is close to the bottom of laminates, whose main damage type is delamination. In the stage of chisel edge drilling-out, a longitudinal crack along fiber orientation produces at laminates exit, which has the damage of delamination and cracks in Figure 8. Primary cutting edges drill exit fiber and generate massive burrs because of their weak removal capacity in the stage of primary cutting edges drilling-out. During this stage, burrs can’t be removed timely, which makes further efforts to aggravate cracks and delamination, and cracks mainly grow along fiber orientation in Figure 9. In stage II, plenty of push-out burrs are removed rapidly, meanwhile cracks and delamination aggravate at first. Subsequently, secondary cutting edges drill few remaining burrs corresponding to fiber orientation, damage decreases constantly, and cracks develop along fiber orientation as well in Figure 5. Minor cutting edges drill push-out burrs, and burrs, delamination and cracks develop slowly in stage III, as shown in Figure 6. It is clear that the recovery capacity of stage II is higher and stage II has a significant influence on the final exit quality.

![Figure 8. CFRP laminates exit in stage of chisel edge drilling-out.](image)

![Figure 9. CFRP laminates exit in stage of primary cutting edges drilling-out.](image)

The main damage types are delamination, burrs and cracks for three drills drilling CFRP laminates from above analysis. Among them, delamination effects bearing capability of parts greatly, so the paper adopts it as the basis of evaluating quality. There are many ways to measure and evaluate push-out delamination at present, and this article chooses the widely applicable and convenient delamination factor as evaluation basis. The delamination factor was defined as the ratio of the maximum diameter, $D_{max}$, of the delamination area to the hole normal diameter, $D_{norm}$, described as the following equation, and illustrated in Figure 10.

$$ F_d = \frac{D_{max}}{D_{norm}} $$ (1)
Delamination factor curves of three drills are all found to: first increase, then decrease quickly and increase slowly again in stage II, while they increase slowly as the increasing of drilling-out length in stage III as shown in Figure 11. It agrees with above analysis of exit damage development. Maximum values of delamination factor are 2.071, 2.262, 2.217 for left-hand helical drill, right-hand helical drill and straight drill respectively in stage II. When secondary cutting edges drill out completely, values of delamination factor are about 1.282, 1.365, 1.181 for left-hand helical drill, right-hand helical drill and straight drill separately. It can be calculated that reduction values of delamination factor are 0.789, 0.897, 1.036 for left-hand helical drill, right-hand helical drill and straight drill respectively, so secondary cutting edges’ recovery ability is the best for the straight drill compared with other two drills. The delamination factor changes a little and has less effect on exit damage in stage III. The final holes’ delamination factor are 1.379, 1.432, 1.185 for left-hand helical drill, right-hand helical drill and straight drill respectively in Figure 12. In conclusion, the drilling quality of straight drill is better than that of left-hand helical drill and right-hand helical drill.
(a) Left-hand helical one-shot drill  (b) Right-hand helical one-shot drill  (c) Straight one-shot drill

**Figure 12.** The final exit quality of three one-shot drills.

Figure 13 shows that the decreasing phase of delamination factor curve corresponds to the increasing phase of thrust force curve in stage II. The increasing rate of thrust force for left-hand helical one-shot drill is high, and the drill’s damage recovery capacity is the worst. For right-hand helical one-shot drill and straight one-shot drill, their increasing rate of thrust force is very low and basically a constant, but their damage recovery capacity is high. Therefore it can be concluded that the damage recovery capacity is irrelevant to thrust force’s value but is relevant to thrust force’s changing rate. Meanwhile the thrust force’s changing rate for right-hand helical one-shot drill and straight one-shot drill is almost same, but the damage recovery capacity of straight one-shot drill is higher than that of right-hand helical one-shot drill. The reason may be that extrusive fracture is beneficial to damage development compared with mode III.

![Graphs showing thrust force and delamination factor contrastive curves of three one-shot drills.](image)

(a) Left-hand helical one-shot drill  (b) Right-hand helical one-shot drill  (c) Straight one-shot drill

**Figure 13.** Thrust force and delamination factor contrastive curves of three one-shot drills.

4. Conclusions

(1) In stage II and stage III, left-hand helical one-shot drill tears burrs outside laminates, which mainly causes mode I. Straight one-shot drill mainly shears burrs along the tangential direction whose tearing effect is weak, and mode III is the major fracture mode. Right-hand helical one-shot drill extrudes burrs into laminates and shears them along the tangential direction, which mainly generates extrusive fracture. Among them, mode III has the least influence on exit damage development.

(2) The thrust force changing rate of left-hand helical one-shot drill is much higher than that of right-hand helical one-shot drill and straight one-shot drill in the increasing phase of stage II. The damage recovery capacity is irrelevant to thrust force’s value, but it is relevant to thrust force’s changing rate.

(3) Development rules of exit damage are fundamentally uniform for three drills. Delamination factor curves of three drills are all found to: first increase, then decrease quickly and increase slowly again in stage II. Secondary cutting edges’ recovery ability and the drilling quality are the best for the straight one-shot drill compared with other two drills.

**Acknowledgments**

This work is supported by National Natural Science Foundation of China-Joint Funds of Liaoning Province, No. U1508207; National Natural Science Foundation of China, No.51575082; National Key Basic Research Program of China (973 Program), No. 2014CB046503; National Innovative Research Group, No.51621064; Education Ministry’s New Century Excellent Talents Supporting Plan Program, No.NCET-13-0081.
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