



New Compound Drill Bit for Damage Reduction in Drilling CFRP

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Abstract

This paper focuses on finding a suitable drill bit for drilling Carbon Fiber Reinforced Plastic (CFRP). The drilling characteristics of the dagger drill, the double point angle drill, and the candle stick drill are studied. The results show that the side edge has poor ability to remove burrs, and the tip structure of the outer corner of the candle stick drill can greatly reduce the entry damage. However, the outer corner small tip structure of the candle stick drill cannot effectively remove the uncut fiber around $\theta = 0^\circ$ of hole exit. The long secondary cutting edge of the dagger drill makes a small thrust force at the drilling exit stage and reduces the dropping speed of the thrust force, leading a lower impact on the laminate bottom. Then, a new tool is developed for drilling CFRP based on the advantages of the three kinds of drill bits. The drill has a long secondary cutting edge, a small tip diameter and a small tip structure of the outer corner. And its drilling characteristics are analyzed. The result shows that the new compound drill bit can effectively remove fibers and reduce thrust force at the drilling exit stage, form burr-free and small delamination hole. The drill reduces the waste of CFRP in manufacturing process since the exit damage is reduced substantially, which is in line with the concept of green manufacturing.

Keywords Drilling · CFRP · Compound drill bit · Damage reduction · Drill structure

List of Symbols

- θ The angle between the cutting speed and the fiber direction
 β Helix angel
Fd Delamination factor

1 Introduction

Carbon Fiber Reinforced Plastic (CFRP) is an advanced composite material, and it is widely used in aerospace industry because of the excellent comprehensive performances such as high strength-to-weight ratio, high-stiffness-to-weight ratio [1, 2]. In order to connect with other parts, a

connection hole inevitably needs to be processed for CFRP. At present, the hole processing method of CFRP is mainly drilling. Therefore, the quality of the drilling will directly affect the quality and efficiency of the assembly.

CFRP part is mainly a laminated structure. It has special characteristics like anisotropy, low interlayer strength, fiber hardness and low thermal conductivity. Therefore, the drilling process is significantly different from the traditional metal drilling process. It's easy to produce many unique features like cracks, burrs, uncut fibers, fiber pull-out and delamination [3–5]. The damages can reduce the load carrying capacity of the parts, the service reliability and service life of the components [6]. Therefore, minimizing drilling damage is the key to increase efficiency and safety.

With the urgent needs of the aviation industry and the challenges of CFRP drilling, many researchers have done extensive study. From the previous study, the main factors affecting the quality of the drilling holes are machining parameters, tool structure and tool material [7]. A lot of researchers intended to reduce the maximum thrust force and increasing the critical thrust force of delamination. The literatures [8–10] show that a low feed rate can reduce the thrust force, while the effect of spindle speed is not significant. El-Sonbaty et al. [11]. found out that the thrust force and torque increases by increasing the drill diameter.

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In addition, the thrust force increases with the increase of the point angle, and the helix angle has little impact on the thrust force [12]. Fernandes et al. [13]. found that the thrust force increases with number of holes drilled with a one shot drill bit. Shyha et al. [14]. used a conventional drill and a stepped drill drilling CFRP, the result showed that the stepped drill structure at a higher feed rate and 140° point angle achieves a lower thrust force. Jia et al. developed an upward cutting model, and proposed a novel intermittent-sawtooth drill structure to reduce damages in drilling CFRP [15]. It is well known that the tool geometry determines the cutting conditions of the tool-workpiece. The current studies on the geometrical effects of CFRP drills is focused on how to decrease the maximum thrust force by using multi-stage drills such as one-shot drill bit and stepped drill bit. But, the impact of these studies on reducing exit damage is limited. The initial delamination begins to spread after the main cutting edge contacts the uncut material at the hole exit, which will produce burrs and fiber pull-out [16–18]. The presence of these damages is mainly due to the absence of restrictions at the exit. Many researchers have proposed a method of exit back-up to reduce the delamination [19–21], and the method was proved to be an effective way to reduce most of the damage, and its effects on delamination was also analyzed [19]. However, it is impractical to add back-up for each hole in the actual production process, it also increases the production cost [22].

The purpose of this paper is to find a drill bit suitable for drilling CFRP on the basis of conventional drill bit structure. Firstly, the advantages and disadvantages of the dagger drill, the double point angle drill and the candle stick drill are investigated. Then, a new tool is designed for drilling

CFRP based on the benefits of these three kinds of drill bits, followed by the analysis of its drilling characteristics. Finally, the effects of reducing hole damage are analyzed and compared to these four types of drill bits in drilling CFRP.

2 Drilling Process Analysis

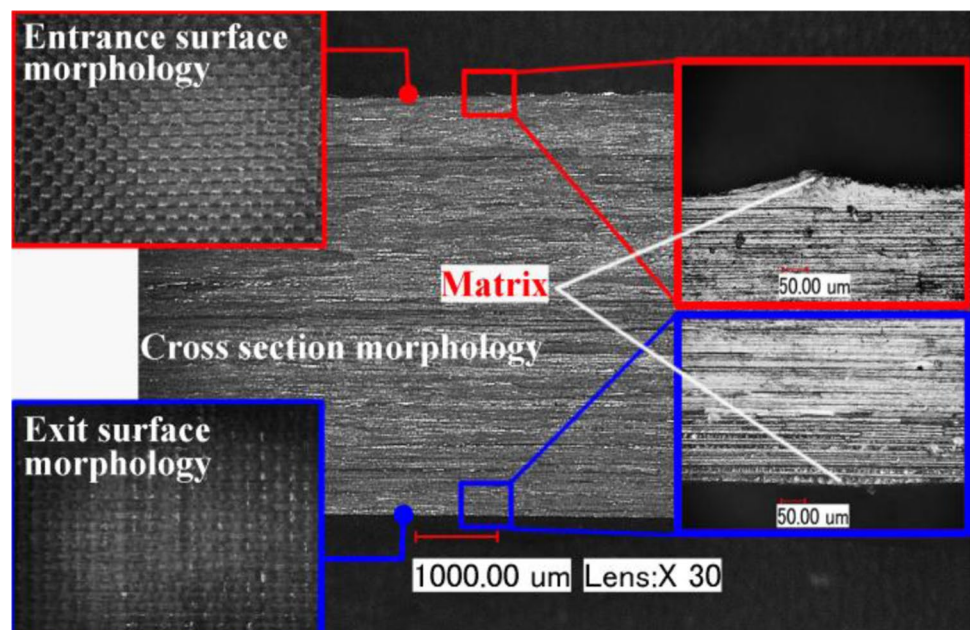
2.1 Experiment Details

The workpiece is a CFRP unidirectional plate with a thickness of 5 mm. The reinforcing fiber is Toaray-T800S, and the epoxy matrix is

Toray 250F. All fibers are in the same direction (see Fig. 1).

In order to reveal the forming process of the damage, holes were machined at different drilling depths. The hole drilling depth (h) of the dagger drill is 0.5, 5, 5.2, and 20 mm, respectively. The spindle speed is 3500 rev/min, and the feed rate is 0.02 mm/rev. The hole drilling depth (h) of the double point angle drill and the candle stick drill is 0.5, 5, 5.2, and 7 mm, respectively. Tests were conducted on a KVC800/1 Vertical Machining Center without back plate. The experimental setup and drills are shown in Fig. 2. The dagger drill, the double point angle drill, and the stick drill were used to drill the CFRP plate. Table 1 shows the information of the drills. The cutting force was measured by using a Kistler 9253B23 force dynamometer and a Kistler 5080A charge amplifier. The force signals were sampled by a 32-bit PC based on a data acquisition system. A digital microscope system (Keyence VHX-500FE) was used to observe the hole entry and exit morphology.

Fig. 1 Workpiece (T800S/250F) features



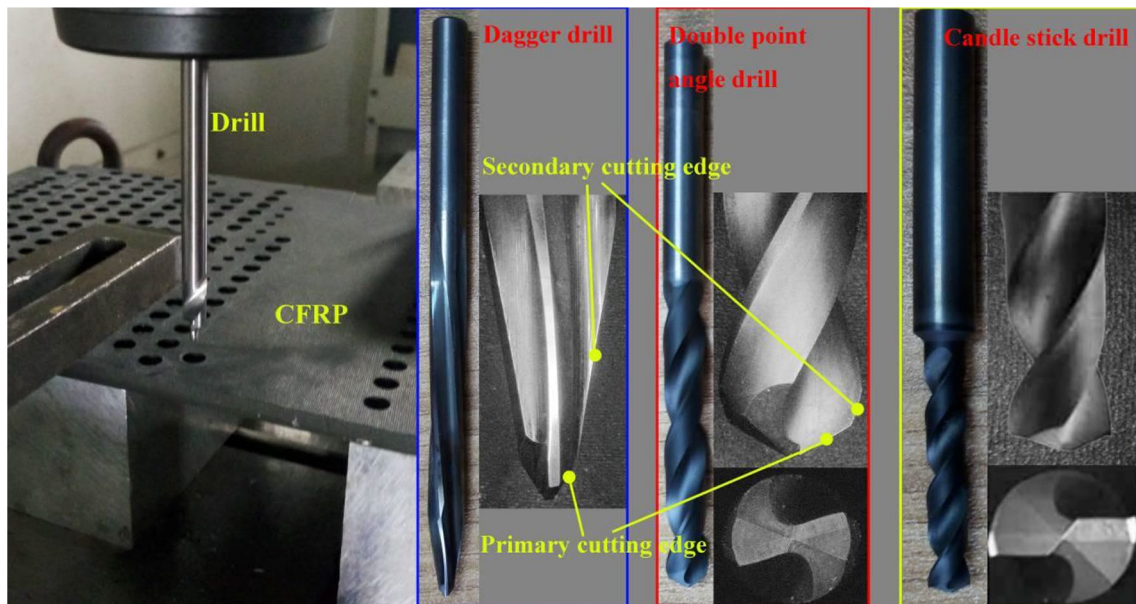


Fig. 2 Experimental setup and drills

Table 1 Tools information

No.	Name	Diameter (mm)	The first point angle (°)	The second point angle (°)
T1	Dagger drill	6	118	–
T2	Double point angle drill	6	120	40
T3	Candle stick drill	6	130	–

2.2 Thrust Force

Figure 3a shows the thrust force time-varying curve of the dagger drill. In the A1 stage, the thrust force drastically reduced due to the chisel edge and the primary cutting edge cut out of the plate. The A2 stage is the process of the secondary cutting edge that gradually drilled out of the

plate bottom. The dropping speed of thrust force is small (6.6 N/s), and leading a small impact on the outermost layer. Figure 4a shows the force diagram at the hole exit of the dagger drill. The thrust force at the hole exit can be considered as the sum of the linear loads of the four cutting edges while in contact with the wall of the hole, which is beneficial to obtain a larger critical thrust force at the beginning of delamination. The longer secondary cutting edge of the dagger drill makes the outer layer material to bear smaller thrust force.

Figure 3b shows the time-varying curve of the thrust force of the double point angle drill. In the B stage, the thrust force dropping speed is great (36 N/s), and leading a large impact on the outermost layer. The thrust force of the double point angle drill can be assumed as a concentrated load P1 (see Fig. 4b).

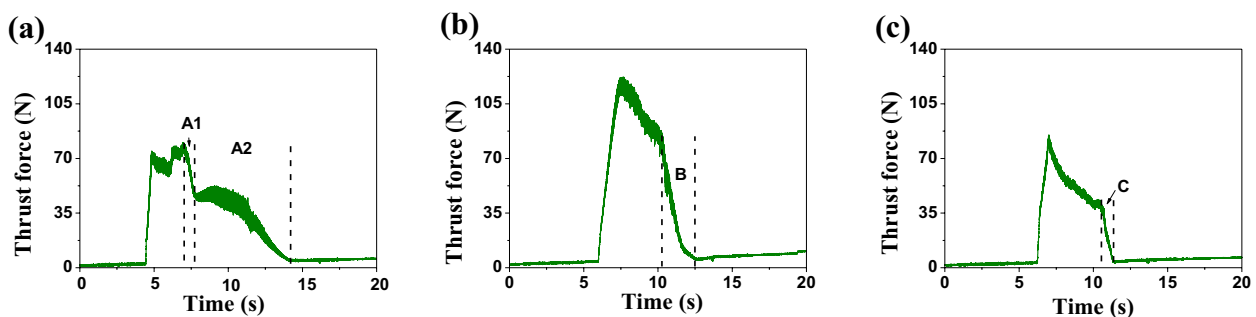


Fig. 3 The time-varying curve of the thrust force for $n=3500$ rev/min, $f=0.02$ mm/rev, a Dagger drill, b double point angle drill, c Candle stick drill

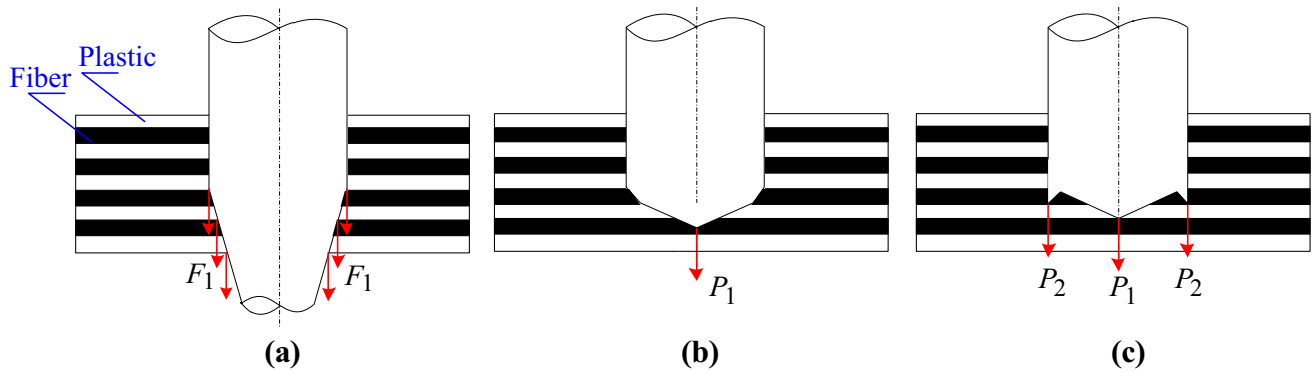


Fig. 4 The force diagram at the hole exit, **a** dagger drill, **b** double point angle drill, **c** candle stick drill

Figure 3c indicates the time-varying curve of the thrust force of the candle stick drill. The stage C is the final hole formation stage. The thrust force dropping speed is great (28 N/s), and leading a large impact on outermost layer. The thrust force of the candle stick drill can be viewed as the sum of a central concentrated load P_1 and a circumferential distribution load P_2 (see Fig. 4c), which is beneficial to obtain a larger critical thrust force at the beginning of delamination.

2.3 Damage Analysis

2.3.1 Hole Entry Damage

Figure 5 shows the hole entry morphology of the dagger drill at $n=3500$ rev/min and $f=0.02$ mm/rev. It can be seen from Fig. 5a, that burrs and tear present at the hole entry before the secondary cutting edge of the dagger drill cut the workpiece. As the depth of drilling increases, the diameter of the cutting portion of the secondary cutting edge increases, and the length of the burr and the range of the tear are also increased. It can be seen from Fig. 5b, c that the secondary

cutting edge has no ability to cut off the burrs but extends the tear range along the direction of the burrs.

θ is the angle between the cutting speed and the fiber direction (see Fig. 6a). As is can be seen from Fig. 6, it can achieve that:

$$F_s^2 = F_x^2 + F_y^2 + F_z^2, \quad (1)$$

$$\begin{cases} F_x = F_s \cdot \cos \beta \cdot \sin \theta \\ F_y = F_s \cdot \cos \beta \cdot \cos \theta \\ F_z = F_s \cdot \sin \beta \end{cases}, \quad (2)$$

where θ is the angle between the cutting speed and the fiber direction, β is the helix angle.

Burrs exist at θ in the range of 0° – 90° . When the cutting position of the tool changes from $\theta=90^\circ$ to $\theta=0^\circ$ (see Fig. 6b), F_x will gradually decrease. So, the deformation degree of the cutting material is decreased, which results in forming burrs. When the cutting position of the tool changes from $\theta=180^\circ$ to $\theta=90^\circ$ (see Fig. 6c), F_x will gradually

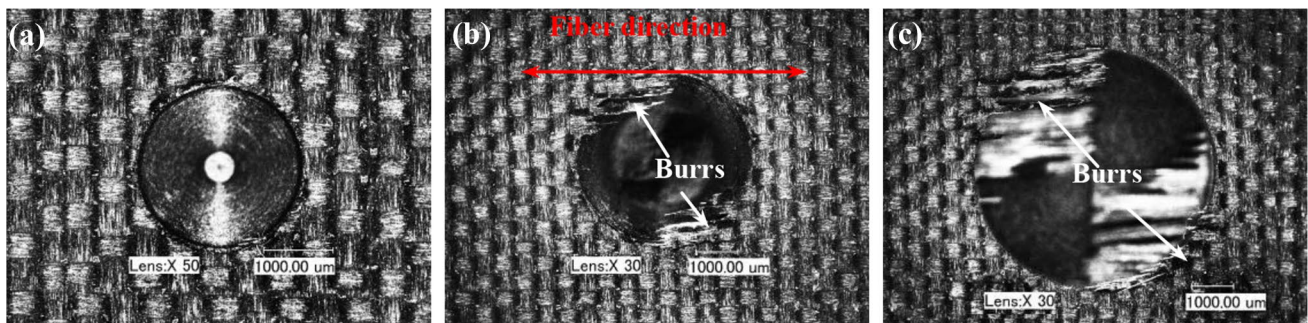


Fig. 5 The hole entry morphology of the dagger drill at $n=3500$ rev/min, $f=0.02$ mm/rev, **a** $h=0.5$ mm, **b** $h=5$ mm, **c** $h=20$ mm

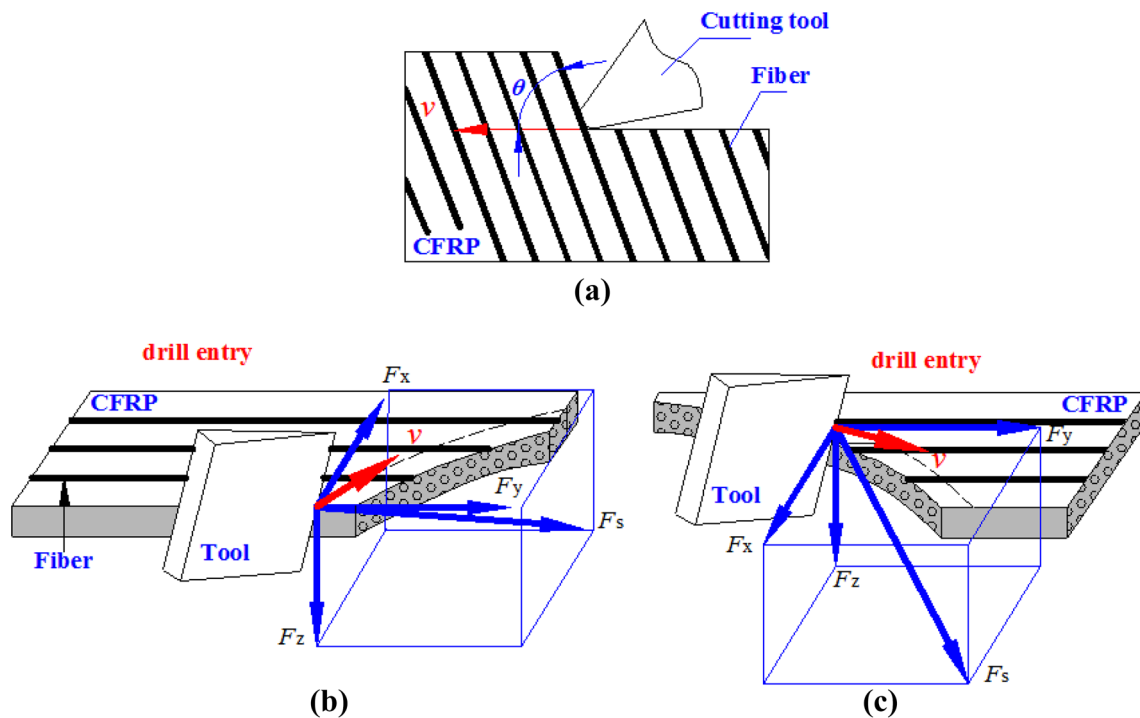


Fig. 6 The force model of the secondary cutting edge of the dagger drill, a a diagram of θ , b $0^\circ < \theta < 90^\circ$, c $90^\circ < \theta < 180^\circ$

increase, the degree of deformation of the cutting fiber is larger, and the fiber can be easily cut off.

Figure 7 shows the hole entry morphology of the double point angle drill. In the primary cutting edge drilling stage, no damage appeared at the hole entry (see Fig. 7a). It can be seen from Fig. 7c, there are less burrs exists at $\theta = 0^\circ - 90^\circ$; and delamination appeared at $\theta = 90^\circ - 180^\circ$. For the uncut material for θ in the range of 90° to 180° , it can be inferred that the peel-up delamination is formed at the cutting stage caused by the secondary cutting edge.

Compared the hole entry of the double point angle drill with that of the dagger drill, burrs exist in the same condition ($\theta = 0^\circ - 90^\circ$), but the burrs number and length are more significant. The hole entry of the double point angle drill

shows a peel-up delamination for θ in the range of $90^\circ - 180^\circ$, while the hole entry of the dagger drill shows no delamination. The main reason is that the dagger drill is a left-helical angle drill, while the double point angle drill is a right-helical angle drill. When the main cutting edge of the double point angle drill cuts into the workpiece, the topmost layer is subjected to an upward force component F_z (see Fig. 8), which is the root reason for peel-up delamination. However, the direction of the force component F_z (see Fig. 6) of the dagger drill is downward, the peel-up delamination is not easily produced.

Figure 9 shows the hole entry morphology of the candle stick drill. The hole entry is very integrity. As can be seen in Fig. 10, the surface fibers bear an upward thrust force F_{z1}

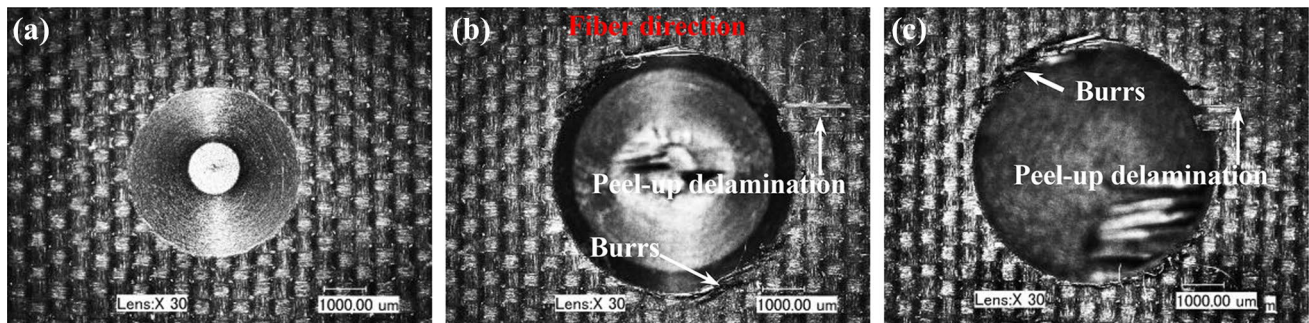


Fig. 7 The hole entry morphology of the double point angle drill at $n = 3500$ rev/min and $f = 0.02$ mm/rev, a $h = 0.5$ mm, b $h = 5$ mm, c $h = 7$ mm

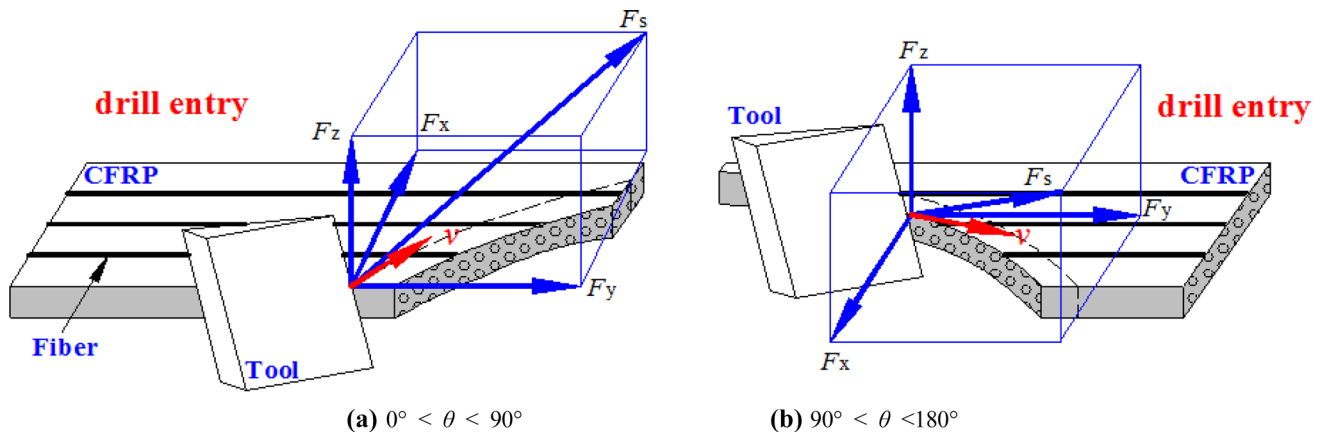


Fig. 8 The force model of the main cutting edge of the double point angle drill

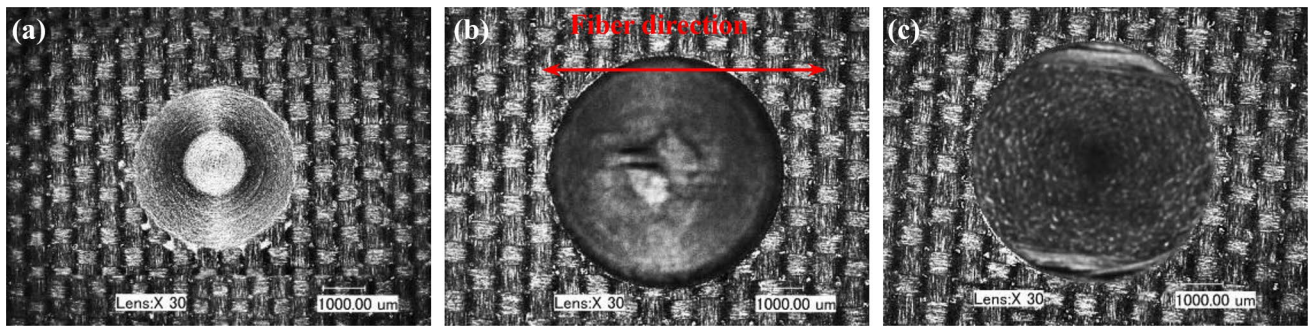


Fig. 9 The hole entry morphology of candle stick drill at $n=3500$ rev/min and $f=0.02$ mm/rev, a $h=0.5$ mm, b $h=5$ mm, c $h=7$ mm

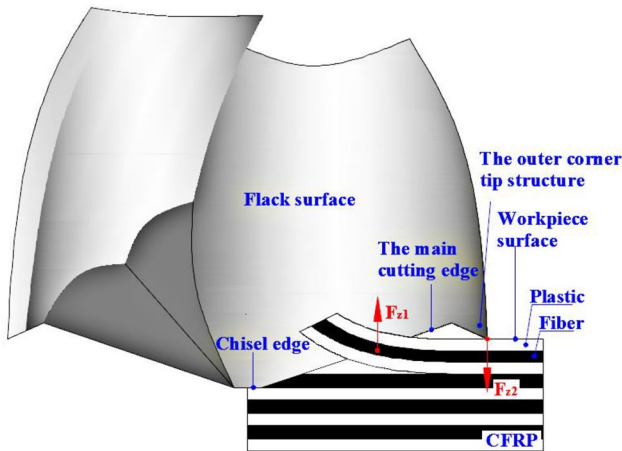


Fig. 10 The drilling model of the candle stick drill at hole entry

at the main cutting edge, but bear a downward thrust force F_{z2} at the outer corner tip structure. The fibers can be easily cut off by the tip structure of the outer corner, which makes it difficult to damage the hole entry for the primary cutting edge and the side edge.

2.3.2 Hole Exit Damage

In order to study the drill bit drilling characteristics, the cross-sectional morphology of the hole was observed by grinding half of the hole in the fiber direction. Figure 11 shows the hole morphology features of the dagger drill at different drilling depths. It can be seen from Fig. 11 that the deformation area at the bottom of the plate increases as the drilling depth increases. Due to the smaller diameter of the dagger drill tip, the diameter of the deformation ring did not exceed the diameter of the drill ($d=6$ mm). Most of the deformation material was cut by the secondary cutting edge. However, some fibers were not cut off at the hole exit, but forming a large number of burrs. From Fig. 11e, delamination appears at the hole exit after the whole hole is formed.

Figure 12 shows the hole morphology features of the double point angle drill at different drilling depths. The corner material produces less deformation, so the delamination area is small at the hole exit (see Fig. 12d), with a large amount of burrs (see Fig. 12e) at the hole exit.

Figure 13 shows the hole morphology features of the candle stick drill at different drilling depths. At the corner of the

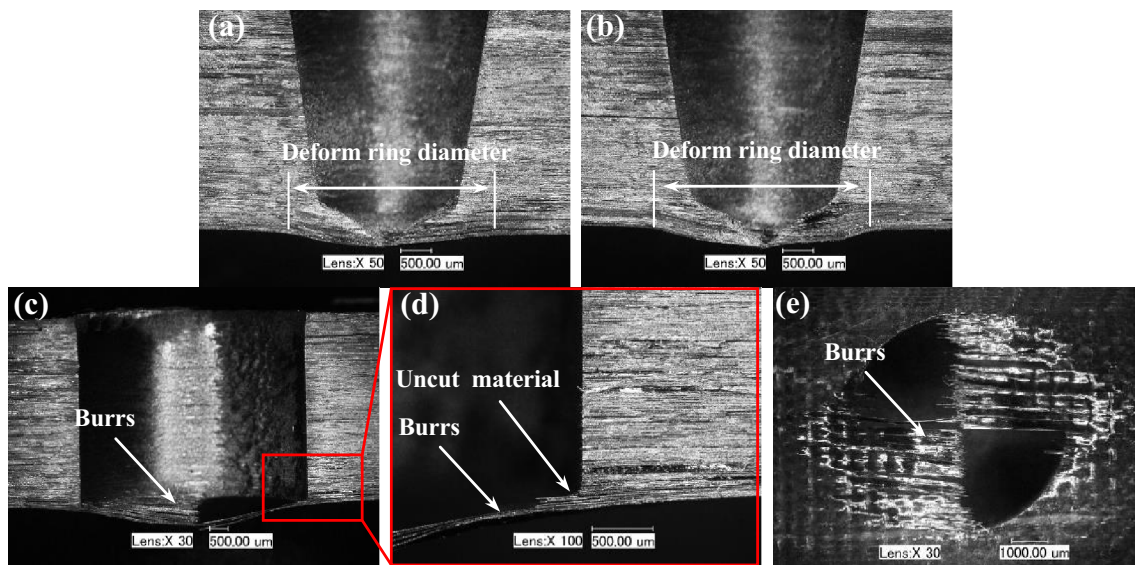


Fig. 11 The hole morphology features of the dagger drill at $n=3500$ rev/min and $f=0.02$ mm/rev. **a** $h=5$ mm, **b** $h=5.2$ mm, **c** $h=20$ mm, **d** $h=20$ mm (Lens: X100), **e** Hole exit morphology

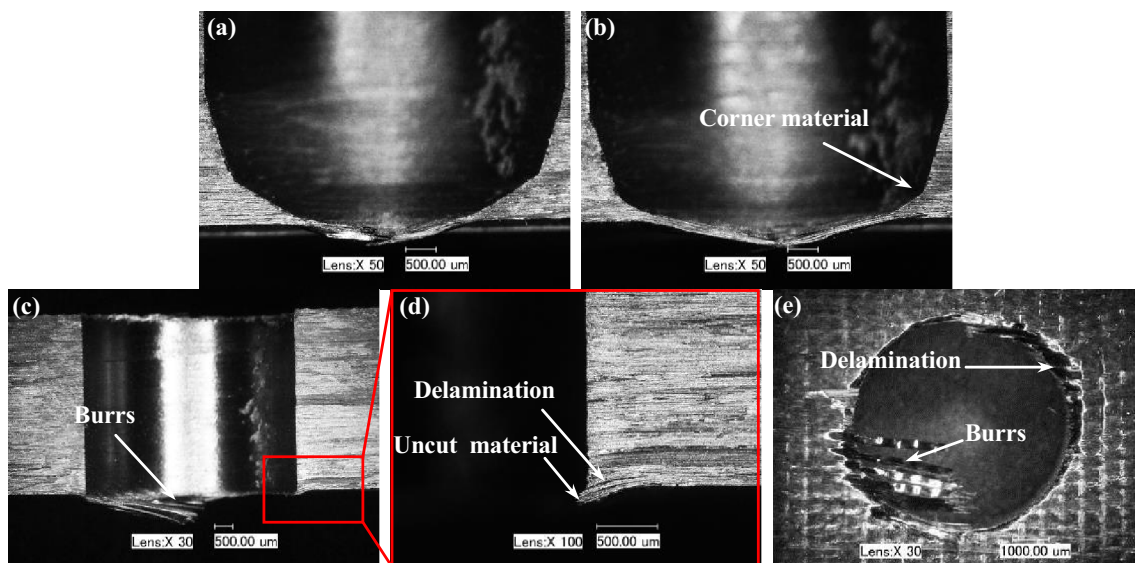


Fig. 12 The hole morphology features of the double point angle drill at $n=3500$ rev/min and $f=0.02$ mm/rev, **a** $h=5$ mm, **b** $h=5.2$ mm, **c** $h=7$ mm, **d** $h=7$ mm (Lens: X100), **e** Hole exit morphology

drill bit, the material is less deformed (see Fig. 13a, b), leading to a small delamination (see Fig. 13d). However, there are uncut fibers at the position when θ is 0° . The reason is that the tip structure of the outer corner is too small, which cannot effectively remove the fiber.

Dagger drill is characterized by a small tip diameter and a long secondary cutting edge, leading a large delamination range at the hole exit and a large number of burrs at both hole entry and exit. The drilling features of the double point angle drill are that the peel-up delamination

exists at the hole entry, burrs and a large delamination range appear at the hole exit. The candle stick drill is characterized by a good hole entry and small delamination at a hole exit, but the tiny tip structure of the outer corner cannot effectively remove the fiber around $\theta=0^\circ$.

In summary, it can infer that the side edge has a poor ability to remove burrs, but the tip structure of the outer corner of the candle stick drill can greatly reduce the hole entry damage. However, the small tip structure of

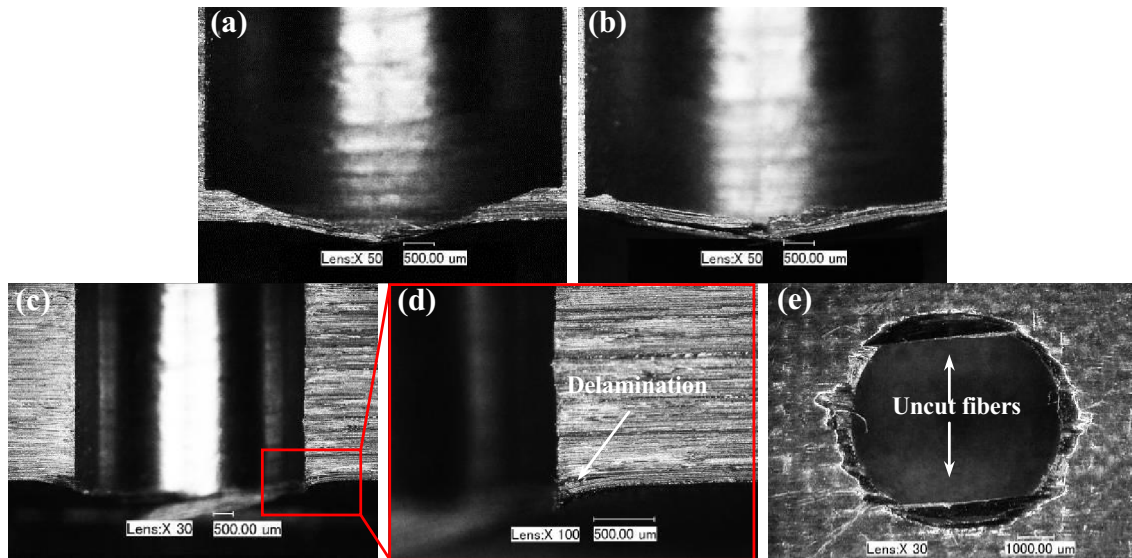


Fig. 13 The hole morphology features of the candle stick drill for $n = 3500$ rev/min and $f = 0.02$ mm/rev. **a** $h = 5$ mm, **b** $h = 5.2$ mm, **c** $h = 7$ mm, **d** $h = 7$ mm (Lens: X100), **e** Hole exit morphology

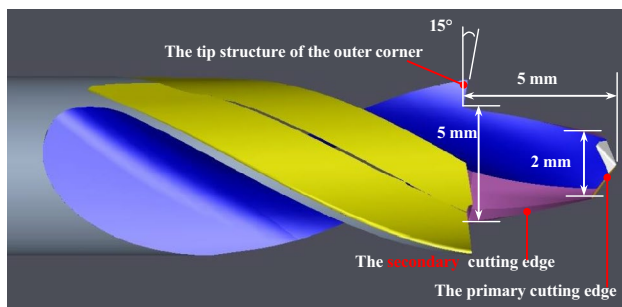


Fig. 14 New compound drill structure

the outer corner of the candle stick drill cannot effectively remove the uncut fiber at the hole exit of $\theta = 0^\circ$.

3 Tool Design and Experimental Verification

3.1 New Compound Drill Bit Design

Based on the advantages of the three types of drill bits, a new compound drill bit is developed that has a long secondary cutting edge, a small tip diameter and a small tip structure of the outer corner. The specific structure of the new compound drill bit is shown in Fig. 14, and its structure parameters are listed in Table 2.

Table 2 New compound drill structure parameters

Name	Diameter	Drill tip diameter	Point angle
New compound drill	6 mm	2 mm	120°

3.2 Experimental Details

The ANCA ToolRoom software was used to create the new tool model, and the new tool was grind on the ANCA RX7. The drill material is ultrafine crystal carbide (the WC grain size is 0.2–0.3 μm). The workpiece material is in accordance with the above. In addition, the diameter of the drill is 6 mm. The spindle speed is fixed at 3500 rev/min, the feed rate are 0.01, 0.02, 0.03, 0.04, and 0.05 mm/rev, respectively.

3.3 Thrust Force Analysis

Figure 15 shows the thrust force time-varying curve of the new compound drill bit. In the A–B stage, the chisel edge squeezes the workpiece and the primary cutting edge cuts the workpiece, resulting in a rapid increasing in the thrust force. In the B–C stage, the secondary cutting edge gradually cuts into the workpiece while the thrust force slowly increases. In the C–D stage, the tip structure of the outer corner cuts into the workpiece, resulting in a rapid increase in the thrust force. When the tip structure of the outer corner completely participates in the drilling action, the thrust force reaches a maximum value. In the D–E stage, when the chisel edge and the primary cutting edge cut off the laminate bottom, the thrust force reduced rapidly. The E–F stage is the

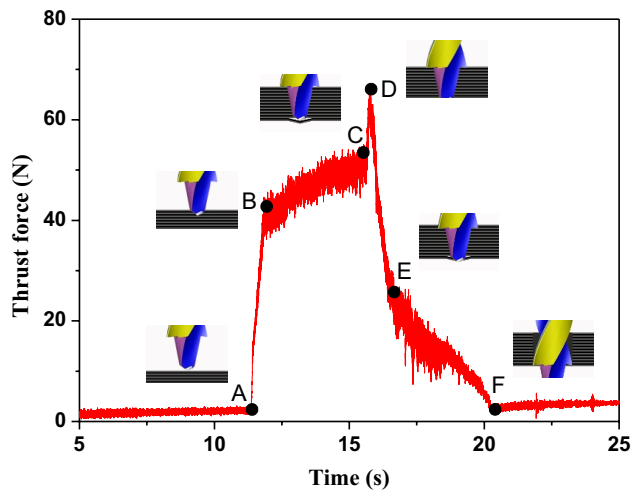


Fig. 15 The time-varying curve of the thrust force of the new compound drill bit at $n=3500$ rev/min and $f=0.02$ mm/rev

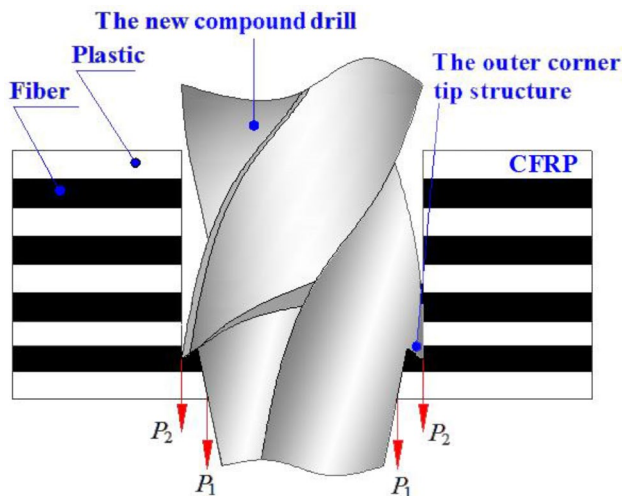


Fig. 16 The force diagram at the hole exit

final stage of the hole formation. In this stage, as the secondary cutting edge gradually cuts off the laminate bottom, the thrust force slowly decreases to zero.

Figure 16 shows the force diagram at the hole exit of the new drill. The thrust force at the hole exit can be considered as the sum of a load P_1 of the secondary cutting edge, which contacts with the wall of the hole, and a circumferential distribution load P_2 , which is beneficial to obtain a larger critical thrust force at the beginning of delamination. The thrust force dropping speeds for both the dagger drill bit and the new compound drill bit at drilling decline stage are very fast first (see Fig. 15, D–F stage). However, the thrust force dropping speeds are small at the hole final formation stage (see Fig. 15, E–F stage). Therefore, the outermost layer of the plate at the hole exit is less affected by the thrust force.

Meanwhile, the tip structure of the outer corner can remove part of damage produced at the secondary cutting edge drilling stage.

3.4 Comparative Analysis of Damage

3.4.1 Hole Entry

Figure 17 shows the entry morphology of the four drill bits at $n=3500$ rev/min and $f=0.02$ mm/rev. Because the holes entry morphology features of the each drill are consistent under the selected machining parameters, so only one of the hole entry morphology is selected for analysis. The hole entry of the dagger drill exists burrs, and the damage is the most serious. Because of the drills have a small tip structure of the outer corner, both the candle stick drill and new compound drill bit have good holes entry quality.

3.4.2 Hole Exit

3.4.2.1 Burrs Table 3 shows the hole morphology of the four types of drills at different cutting conditions. Burr of the dagger drill is the most serious at the hole exit, and it exists mainly at θ in the range of 0° – 90° . This shows that the side edge of the dagger drill is not conducive to the removal of burrs. Burrs also appear at the hole exit of the double point angle drill, but the number is less than that of the dagger drill. The hole exit of the candle stick drill has few burrs and uncut fibers at $\theta=0^\circ$. The tiny tip structure of the outer corner of the candle stick drill cannot effectively remove the uncut fibers. The new compound drill bit obtains an intact hole exit that proves that the tip structure of the outer corner of the new drill can remove the fibers effectively and create burr-free holes.

Figure 18 shows a two end constrain cutting model. In this model, the fibers are cut off in the middle because they are constrained by the inner ring and the hole wall. One side of the fiber that have been cut off remains in inner ring, and the other side remains at hole wall (see Fig. 18b, c). The fiber in inner ring doesn't affect the hole quality in the subsequent cutting process, which causes less damage.

3.4.2.2 Delamination The delamination factor (F_d) is used to evaluate the push-out delamination that is defined as the ratio of the maximum diameter, D_{max} , of the delamination area to the hole nominal diameter, D_{norm} , and described as the following equation.

$$F_d = D_{max} / D_{norm} \quad (3)$$

The delamination diameter is measured with a digital microscope system (Keyence VHX-500FE), and the schematic diagram is shown in Fig. 19.

Fig. 17 The morphology of the hole entry, **a** dagger drill, **b** double point angle drill, **c** candle stick drill, **d** new compound drill

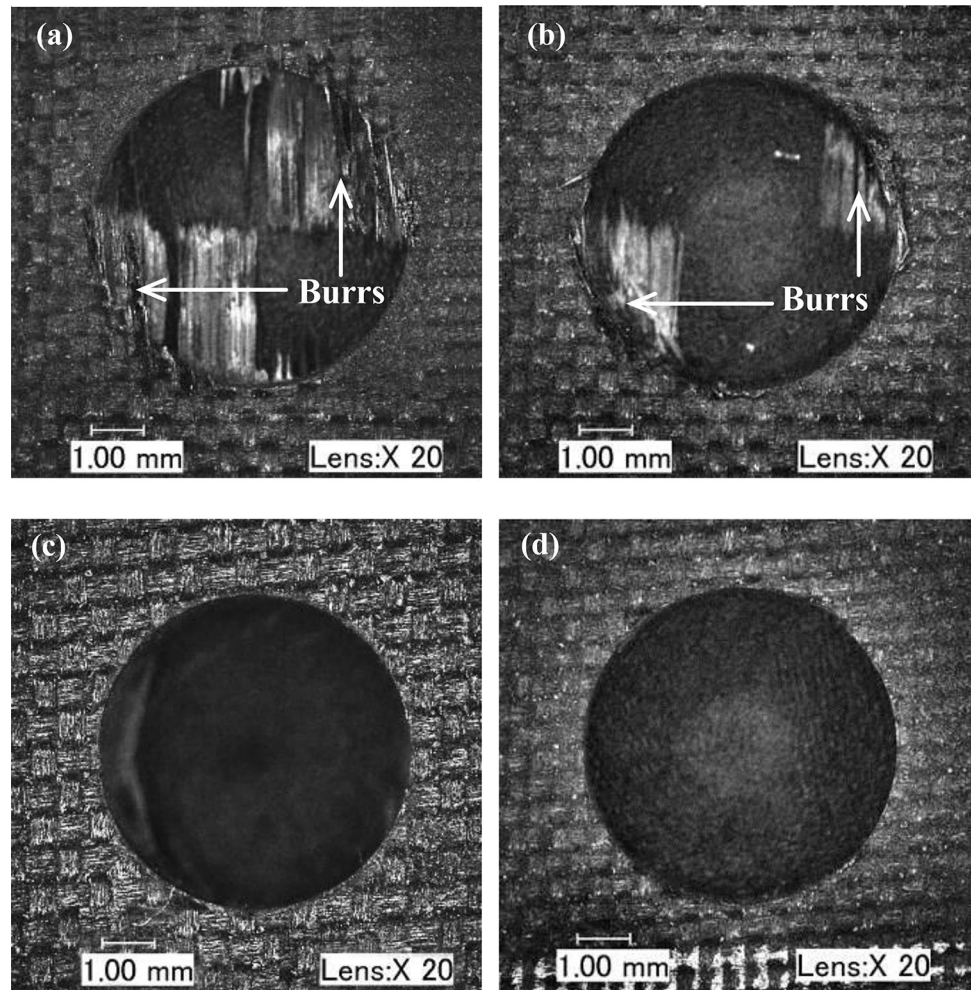


Figure 20 shows the comparison of the delamination factor among the four drills. When the feed rate (f) is less than 0.03 mm/rev, the delamination factor of the hole drilled by the dagger drill is the largest. When the feed rate is bigger than 0.03 mm/rev, the delamination factor of the hole drilled by the double point angle drill is the largest. The delamination factor of the hole drilled by the new compound drill bit is the smallest for all cases. And, the average delamination factor of the new drill is 15.7%, 23.7% and 29.3% lower than that of the candle stick drill, double point angle drill and dagger drill, respectively. Therefore, the new compound drill bit has a large advantage in reducing the damage. There are two main reasons attributing such behaviors: one is that the tip structure of the outer corner of the new compound drill bit can remove the fibers effectively and create burr-free holes, and the other is that the new compound drill bit has a small thrust force at the drilling exit stage (see Fig. 15, E–F stage).

4 Conclusions

In this paper, drilling characteristics of the dagger drill, the double point angle drill, and the candle stick drill were studied. Then, a new tool was designed for drilling CFRP based on the advantages of the three types of drill bits, and its drilling quality was compared with other drills. A two end constrain cutting model has been found to reduce the hole damage. The following conclusions can be defined from the experiments.

1. The long secondary cutting edge of the dagger drill makes a small thrust force at the drilling exit stage and reduces the dropping speed of the thrust force, leading a lower impact on the outermost layer.
2. The left-handed small helix angle and the long secondary cutting edge of the dagger drill cannot effectively

Table 3 The hole exit morphology of the four types of drill

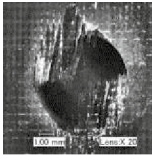
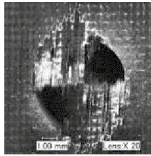
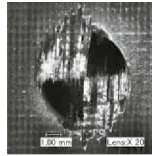
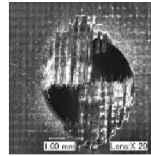
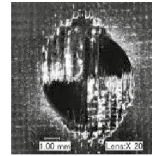
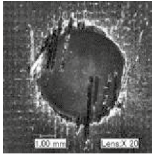
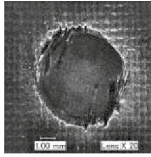
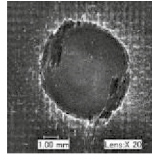
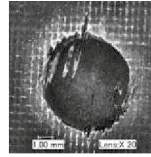
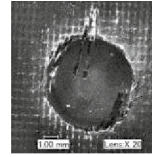
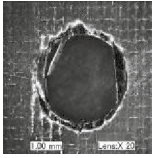
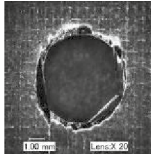
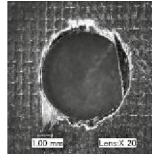
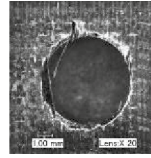
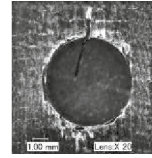
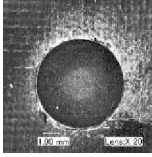
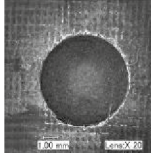
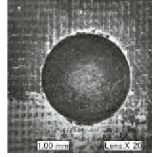
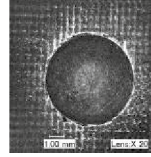
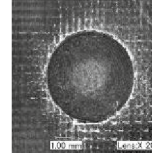
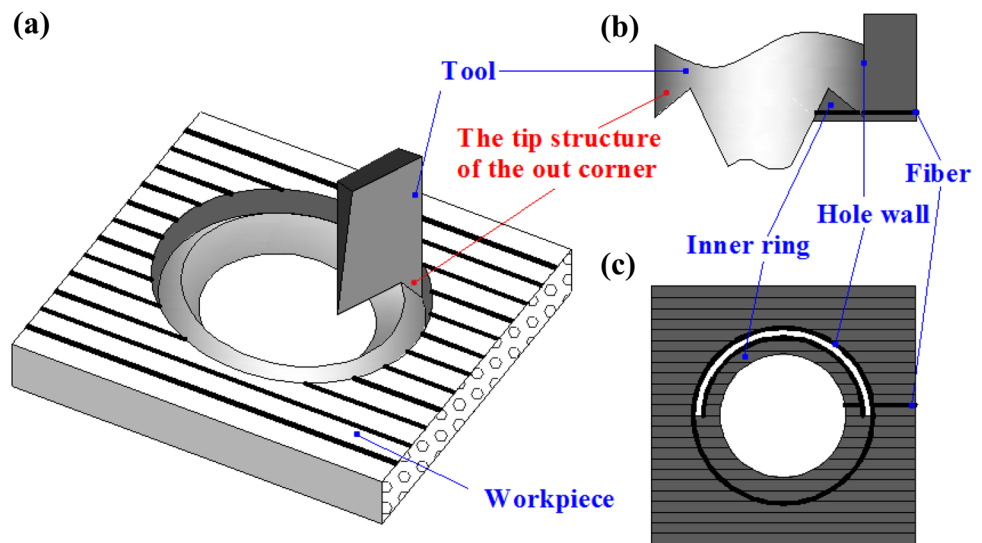
	$f=0.01$ mm/rev	$f=0.02$ mm/rev	$f=0.03$ mm/rev	$f=0.04$ mm/rev	$f=0.05$ mm/rev
Dagger drill					
Double point angle drill					
Candle stick drill					
New compound drill					

Fig. 18 Two end constrain cutting model **a** 3D view, **b** cross section view, **c** top view



remove the hole burrs. The hole exit of the double point angle drill that produces a peel-up delamination, and little burrs at the hole exit. The tip structure of the outer corner of the candle stick drill can prevent the generation of burrs and form an intact hole entry, but the small tip structure of the outer corner cannot effectively remove the uncut fiber at the position of $\theta=0^\circ$.

3. A new compound drill bit that has a long secondary cutting edge, a small tip diameter and a tip structure of the outer corner was designed to reduce the hole damage in drilling CFRP. In the absence of back plate, the new compound drill bit can effectively reduce the hole damage. The verification experimental results show that the long secondary cutting edge and the larger tip struc-

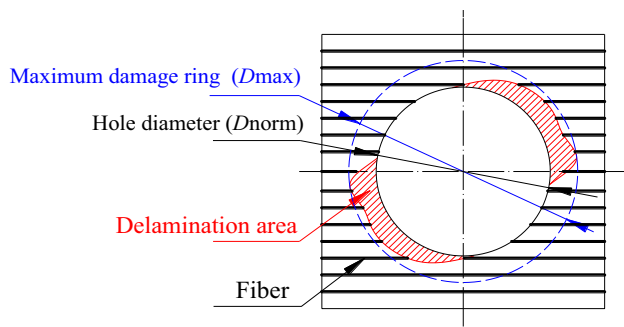


Fig. 19 Schematic diagram of measured diameters

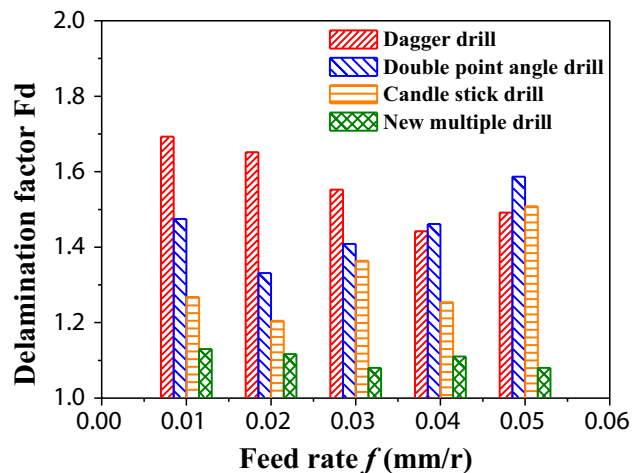


Fig. 20 The comparison of the delamination factor between the four drills

ture of the outer corner can effectively remove the burr, reduce the thrust force and obtain better quality holes. The average delamination factor of the new compound drill is 15.7%, 23.7% and 29.3% lower than that of the candle stick drill, double point angle drill and dagger drill, respectively. Therefore, the developed tool has less defects compared to the above drills and that result less wastes.

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References

- Doh Roh, H., Lee, H., & Park, Y.-B. (2016). Structural health monitoring of carbon-material reinforced polymers using electrical resistance measurement. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 3(3), 311–3216.
- Kumaran, S. T., Ko, T. J., & Kurniawan, R. (2018). Grey fuzzy optimization of ultrasonic-assisted EDM process parameters for deburring CFRP composites. *Measurement*, 123, 203–212.
- Mishra, R., Malik, J., Singh, I., & Davim, J. P. (2010). Neural network approach for estimate the residual tensile strength after drilling in uni-directional glass fiber reinforced plastic laminates. *Materials and Design*, 31(6), 2790–2795.
- Zitoune, R., Krishnaraj, V., Sofiane, A. B., Collombet, F., Sima, M., & Jolin, A. (2012). Influence of machining parameters and new nanocoated tool on drilling performance of CFRP/aluminium sandwich. *Composites Part B Engineering*, 43(3), 1480–1488.
- Islam, M. M., Li, C. P., & Ko, T. J. (2017). Dry electrical discharge machining for deburring drilled holes in CFRP composite. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 4(2), 149–1541.
- Knashaba, U. A. (2013). Drilling of polymer matrix composites: A review. *Journal of Composite Materials*, 47(15), 1817–1832.
- Kumaran, S. T., Ko, T. J., Li, C. P., Yu, Z., & Uthayakumar, M. (2017). Rotary ultrasonic machining of woven CFRP composite in a cryogenic environment. *Journal of Alloys and Compounds*, 698, 984–993.
- Rubio, J. C., Abrao, A. M., Faria, P. E., Correia, A. E., & Davim, J. P. (2008). Effects of high speed in the drilling of glass fiber reinforced plastic: Evaluation of the delamination factor. *International Journal of Machine Tools and Manufacture*, 48, 715–720.
- Tsao, C. C., & Hocheng, H. (2007). Parametric study on thrust force of core drill. *Journal of Materials Processing Technology*, 192–193, 37–40.
- Xu, J. Y., An, Q. L., Cai, X. J., & Chen, M. (2013). Drilling machinability evaluation on new developed high-strength T800S/250F CFRP laminates. *International Journal of Precision Engineering and Manufacturing*, 14, 1687–1696.
- El-Sonbaty, I., Khashaba, U. A., & Machaly, T. (2004). Factors affecting the machine-ability of GFR/epoxy composites. *Composite Structures*, 63(3-4), 329–338.
- Chen, W. C. (1997). Some experimental investigation in the drilling of carbon fiber-reinforced plastics (CFRP) composite laminates. *International Journal of Machine Tools and Manufacture*, 37, 1097–1108.
- Fernandesa, M., & Cook, C. (2006). Drilling of carbon composites using a one shot drill bit. Part I: Five stage representation of drilling and factors affecting maximum force and torque. *International Journal of Machine Tools and Manufacture*, 46(1), 70–75.
- Shyha, I. S., Aspinwall, D. K., Soo, S. L., & Bradley, S. (2009). Drill geometry and operating effects when cutting small diameter holes in CFRP. *International Journal of Machine Tools and Manufacture*, 49(12–13), 1008–1014.
- Jia, Z. Y., Fu, R., Niu, B., Qian, B. W., Bai, Y., & Wang, F. J. (2016). Novel drill structure for damage reduction in drilling CFRP composites. *International Journal of Machine Tools and Manufacture*, 110, 55–65.
- Abrão, A. M., Faria, P. E., Rubio, J. C. C., Reis, P., & Davim, J. P. (2007). Drilling of fiber reinforced plastics: a review. *Journal of Materials Processing Technology*, 186(1-3), 1–7.
- Su, F., Wang, Z., Yuan, J., & Cheng, Y. (2015). Study of thrust forces and delamination in drilling carbon-reinforced plastics (CFRPs) using a tapered drill-reamer. *The International Journal of Advanced Manufacturing Technology*, 80(5-8), 1457–1469.
- DiPaolo, G., Kapoor, S. G., & DeVor, R. E. (1996). An experimental investigation of the crack growth phenomenon for drilling of fiber-reinforced composite materials. *Journal of Engineering for Industry*, 118(1), 104–110.
- Tsao, C. C., & Hocheng, H. (2005). Effects of exit back-up on delamination in drilling composite materials using a saw drill and a core drill. *International Journal of Machine Tools and Manufacture*, 45(11), 1261–1270.

20. Qi, Z., Zhang, K., Li, Y., Liu, S., & Cheng, H. (2014). Critical thrust force predicting modeling for delamination-free drilling of metal-FRP stacks. *Composite Structures*, *107*(1), 604–609.
21. Phadnis, V., Makhadmeh, F., Roy, A., & Silberschmidt, V. (2013). Drilling in carbon/epoxy composites: experimental investigations and finite element implementation. *Composites: Part A*, *47*, 41–51.
22. Islam, M. M., Li, C. P., Won, S. J., & Ko, T. J. (2017). A deburring strategy in drilled hole of CFRP composites using EDM process. *Journal of Alloys and Compounds*, *703*, 477–485.

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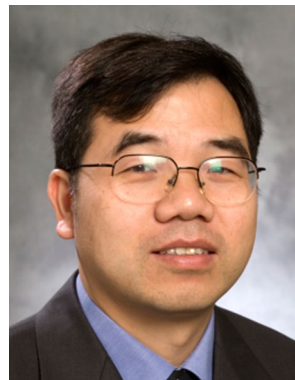
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