DESIGN OF A NEW TOOL WITH INTERMITTENT-SAWTOOTH STRUCTURE FOR DAMAGE REDUCTION IN DRILLING OF CFRP COMPOSITES

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Keywords: Drill, CFRP, Cutting Model, Intermittent-sawtooth Structure, Damage Reduction

Abstract

Drilling pilot holes on CFRP components is inevitable for assembling process in manufacuting industries. However, the drilling-induced damages frequently occur and affect not only the load carrying capacity of components but also the reliability. Therefore, it is of great urgency to enhance drilling performance of CFRP components for manufacturers. In the article, the defect mechanism at the exit during drilling CFRP is analyzed associated with drill geometries. Cutting fibers at the exit by the main cutting edge in the axial direction is modeled into a unique two-dimensional cutting model with the side support from the machined hole wall based on the elastic foundation beam theory. Moreover, orthogonal cutting mechanisms of fibers are analyzed in two directions in terms of the fiber deformation and fracture as well as the debonding between the fiber and the matrix. Then damage-free cutting direction is revealed. According to the damage-free cutting direction, a novel one-shot drill is proposed with the intermittent-sawtooth structure on its secondary and minor cutting edges. The effect of the intermittent-sawtooth structure on the damage reduction was presented theoretically and geometrically. The verification experiment was also conducted, and encouraging reductions on drilling damages were successfully achieved with the novel drill.

1. Introduction

Carbon fiber reinforced plastic (CFRP) composites have been widely adopted for the manufacture of aviation parts due to their light weight, high strength and excellent damage tolerance [1, 2]. CFRP components are usually assembled by bolts and rivets [3], thus the drilling operation is the most essential process in the final production process. However, the removal mechanism of CFRP material is greatly different from that of metal [4] in terms of its properties of being anisotropic and multi-scale characteristic. Especially for parts in aviation applications made of the long fiber composite material, the laminates and fibers are bonded solely by the resin matrix. In particular, the bonding force of interface and intraface is far smaller than that in longitudinal direction of the reinforced fiber. When the cutting tip of the drill bit reaches the drill exit, the uncut fibers are largely influenced by the thrust force, and the delaminations, fiber pullouts, etc. are easily generated as the thrust force surpass its threshold [5-7]. Meanwhile, fibers are bended as the drill punches the last laminate, which will aggravate delaminations and lead to subsequent burrs [8, 9]. The machining damages above of CFRP parts will definitely weaken the mechanical performance and service durability for the aircrafts [4, 8, 10], and therefore, it is necessary to carry out high quality hole-drilling to guarantee flight safety.

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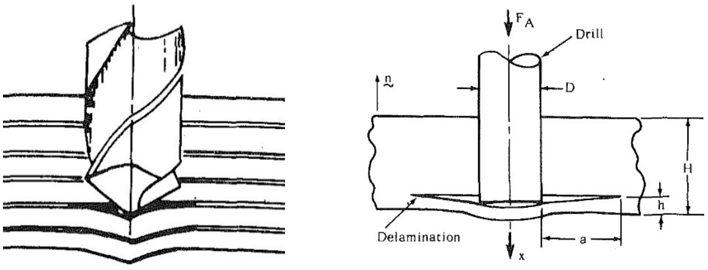
Previous studies have found that the back-up support minimized the exit delaminations [11, 12], and as a result, increasing stiffness at the drill exit could be seen as an effective way to reduce the chance of delaminations. However, it is quite difficult to add extra back-up support for drilling during the practical assembling. Besides, it is known that the geometry of a drill bit determines the loading condition at tool-workpiece engagement area. Therefore, according to the comprehensive analyses of damages at the exit in drilling CFRP, it is possible to design a new geometry of drill bit to change the loading condition at the exit and achieve the damage-free hole. Currently, studies about CFRP drill bits [7, 13, 14] suggest the maximum thrust force before penetrating could be reduced by utilizing one shot drill and step drill to complete a multi-stage drilling process. Then delaminations, thereby, appear to be eliminated. However, as a matter of fact, the main cutting edges of drills would cause delaminations at the exit as well [15]. Even employing the one shot drill, after penetrating the workpiece, the main cutting edges involve in gradually removing the left material. And in the process, there lacks supports in the hole-exit side, therefore, the fibers are deformed and hard to be cut off at the tool-workpiece engagement areas. As a result, the main cutting edges exert normal force on the uncut fibers, then delaminations and other defects could be generated [8, 16].

The present article aims to figure out a new geometrical drill bit to eliminate most of the defects caused by the main cutting edge in CFRP drilling. On the basis of comprehending damage mechanism and the elastic foundation beam theory [17], a two-dimensional orthogonal cutting model with one side support was proposed to simplify the drill exit machining process of main cutting edges. Based on the model, the impacts of machining direction on the removal of fibers are analyzed. Furthermore, a novel intermittent-sawtooth structure is presented and used to make the modification of the one shot drill. The effect of the intermittent-sawtooth structure on the damage reduction is presented theoretically and geometrically. Meanwhile, it was verified experimentally that the novel drill was effective on reducing the drilling damage.

2. Damage Analysis and Modeling the Cutting at the Drill Exit

2.1 Damage Analysis at the Drill Exit

The drilling process is generally comprised of the material removals by the chisel edge, the main cutting edge and the minor cutting edge. The cutting mechanisms and induced damages of those edges are evidently different [18]. Fig.1(a) shows the schematic diagram of drilling CFRP, and it is believed that the thrust force primarily contribute to damages such as delaminations at the drill exits. The present studies[6, 14] simplified drilling CFRP before penetrating as a circle plate model in Fig.1(b), and employed linear elastic fracture mechanics (LEFM) theory to analytically solve the threshold inducing I mode fracture. The threshold is known as the critical thrust force which could be applied to determine the onset of delaminations. After delamination, the interlaminar crack would propagate with the drill tip feeding, and if damages marked as *b* do not exceed the nominal radius, *a*, during that period, the damages could possibly be removed in the subsequent cutting by main cutting edges as illustrated in Fig.2. Meanwhile, no matter how complex the drill geometry are, the removal of the material at the drill exit mainly depends on cutting action of main cutting edges. As a consequence, it is main cutting edges that are the key to determine the final hole quality.



(a) (b)

Figure 1. Drilling damage analysis at the exit (a) Push-out delamination, (b)Circular plate model for delamination analysis

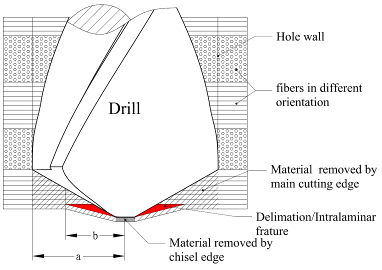


Figure 2. Stock removals and damages by different cutting edges

2.1 Modeling the Cutting at the Drill Exit

Damages at the drill exits are commonly mode I fractures caused by drilling movement in drill axial direction. Once mode I fractures occur, the circumferential drilling movement which makes the spalls tear and twist can also result in mode III fracture [15] and particularly, the mode I fracture is the most critical for the CFRP composite [19]. Therefore, the cutting motion in the axial direction is considered to be detrimental in drilling of CFRP when damages induced by main cutting edges are concerned. Drilling operation contains three-dimensional complex machining processes, and however, it can be simplified into a two dimensional cutting model, which properly enable better understandings of material removal mechanism of separate cutting edges[18]. A simplified free body diagram of drill is depicted in Fig.3 to represent the three-dimensional drilling process [20]. The cutting motion of the main cutting edge on the infinitesimal material would always contribute to F_{zdr} along the drill axis, F_{xdr} and F_{ydr} perpendicular to the drill axis. A motion component which only induces F_{zdr} acting in the critical direction of drilling CFRP, and F_{xdr} in the X-Z cutting plane can be decomposed from the above infinitesimal cutting. Thereby, that cutting can be altered to two-dimensional orthogonal cutting to study the impact of main cutting edges on material removal along the drilling axis. Meanwhile, although CFRP composite consists of various fiber orientations in different laminates, the cutting movement along the drilling axis is always perpendicular to each laminates as well as the fibers which overcomes the bonding force between the fibers and resin, and would be rarely affected by the fiber orientation. Thus, fibers in 90° orientation are considered in the two-dimensional orthogonal cutting. Moreover, in terms of constraints between the fibers and resin, the deflection of the fibers in the article, is modeled as a beam on an elastic foundation [17], which reflects the constraint effects of the composite surrounding the fibers. The model is close to the real machining process of CFRP [21]. In particular, there is no resin and fibers supporting the uncut material at the hole exit from the outside in drilling. As a result, the uncut material at the exit is modeled as a two-dimensional model with one side support in Fig.4.

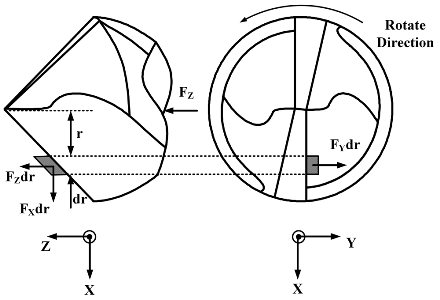


Figure 3. A simplified free body diagram of drill

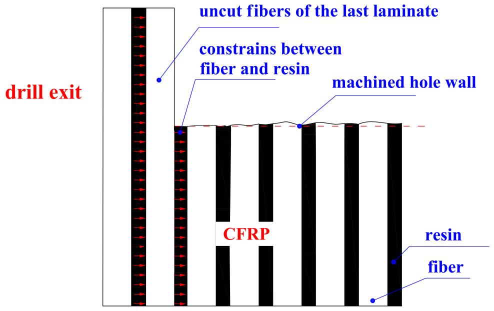


Figure 4. Modelling of uncut material at the exit

According to the knowledge of modeling at the exit, for the ordinary drill, the axial cutting of drill-exit material by main cutting edges was simplified into the orthogonal cutting process shown in Fig.5(a). The cutting motion of the tool is from the machined hole wall to the exit, which generates cutting force, F_c , in the same direction and the thrust force, F_t, perpendicularly to F_c, and the uncut fibers of the last laminate are pushed and stretched. Under such loadings, owing to the lack of back supports at the exit, the constraints of the uncut material are from the weak bonding force in the transverse direction of the material and the small supporting force from the back material. Then, in terms of basic mechanical properties of CFRP, the transverse tensile strength and transverse shear strength of the fiber are much higher than the bonding strength between the fiber and resin. As a result, in Fig.5(a), the loadings at the engagement area will force the bonding between fibers and resin to reach the ultimate strength before fibers break, and lead to debonding and intralaminar damages. The fibers would probably break under the cutting plane as illustrated in Fig.5(b) when the transverse tensile strength or transverse shear strength reaches the breaking point, and delaminations or fiber pull-outs are formed in macroscopic at the exit. Besides, if the debonding fibers are too flexible to break, then, burrs would remain at the exit. In the contrast, when the cutting motion is reversed as shown in Fig.5(b), it

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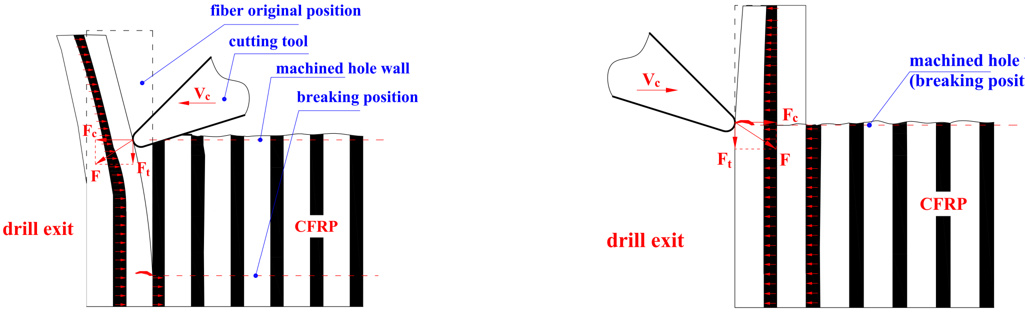
generates F_c from the drill exit to the machined hole wall and F_t, perpendicularly to F_c. In that case, the deflection of fibers is strongly restrained by the large supporting force of the machined hole wall, due to the high transverse compressive strength of the fiber, consequently, debondings are almost eliminated. Meanwhile, as the transverse shear strength is much smaller than the transverse compressive, during cutting operation, the fibers are easily squeezed to shear and rapture nearby the cutting edge before they experience the bending break, which helps to minimize intralaminar damages. Therefore, a reverse cutting from the exit to the machined hole wall at the drill exit is definitely a good approach to avoid exit damages for drilling CFRP.



(a) (b)

Figure 5. Cutting models (a) towards the drill exit, (b) towards the machined hole wall

3 Tool Geometry Design and Experiments

Previous studies have presented various multi-stage drilling tools such as one shot drill, stepped drill, etc. The thrust force was effectively reduced by the multi-stage drilling process and drill-exit quality was improved. Hence, this article employs the one type of the popular multi-stage drilling tools, one shot drill, which is widely utilized in the industry, and makes geometric modifications on its cutting edges to accomplish a further improvement.

The one shot drill Fig.6 normally has two stage main cutting edges, named as the primary cutting edge and the secondary cutting edge with two different point angles. The drilling process of a one shot drill at the exit is divided into four stages as shown in Fig.6. In Stage I, the chisel edge pushes the last laminates at the exit before penetration. After the chisel edge penetrates the last piles of CFRP, the removal of rest material at the exit in Stage II is conducted by the primary cutting edges. In Stage III, the secondary cutting edges with a small point angle involve in the removal of material, and following that, in the last stage, the secondary cutting edges gradually drill out, and the minor cutting edges begin to cut the material until the hole is finished. In terms of the above four drilling stages of one shot drill, there is possibility that the damages are removed in the subsequent drilling stage if they are not so severe and do not exceed the normal diameter of the hole. However, the damages induced in Stage IV cannot be eliminated, and become final damages of the machined hole together with the residual damages in the previous stages.

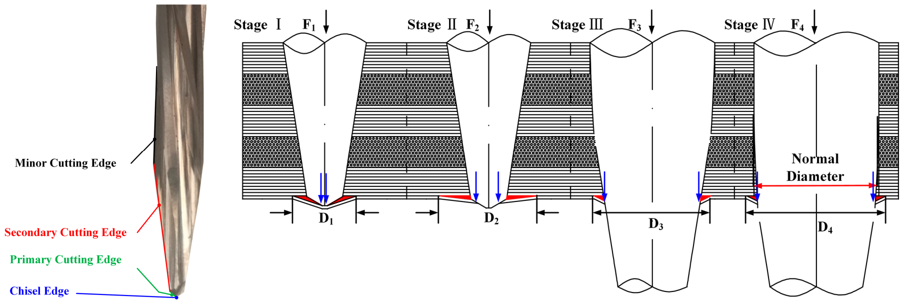


Figure 6. One shot drill and the drilling process at the hole exit

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3.2 Intermittent-Sawtooth Structure on One Shot Drill

Reducing the final damages at the exit is always the top priority in drilling process, however, even if a one shot drill is applied, damages are inevitable. Based on analysis of the two dimensional orthogonal cutting in Section 2, the cutting force contributed by the main cutting edges is always in the direction to the drill exit, which leads to drill-exit damages. To minimize the drilling damages at the exit, the cutting force direction should be reversed to machined hole side from the drill-exit side. Since the drill bit geometry has directly influence on loading condition at the tool-workpiece engagement area at the exit, a new drill geometry can be effective to achieve the goal of reversing the cutting direction of some cutting edges at the drill exit. The article presents a novel drill geometry, in Fig.7, with the intermittent-sawtooth structure added to the secondary and minor cutting edges of one shot drill to bring the reverse cutting to the drilling process at the exit. The sawteeth have a large right-hand helix angle, and are arranged intermittently. The width of each sawteeth and the gap between each two sawteeth are designed to guarantees enough strength of sawtooth and interval space respectively. The cutting lip of the sawtooth (CLS) is normally on the left of a sawtooth in the view of Fig.7.

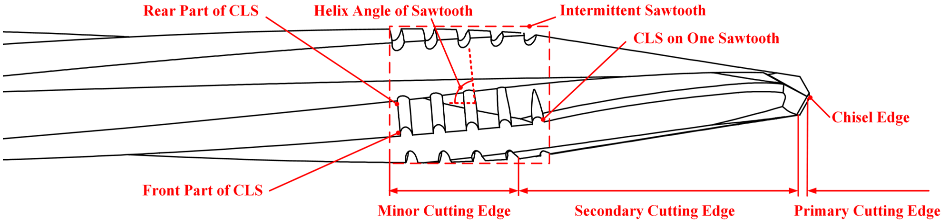
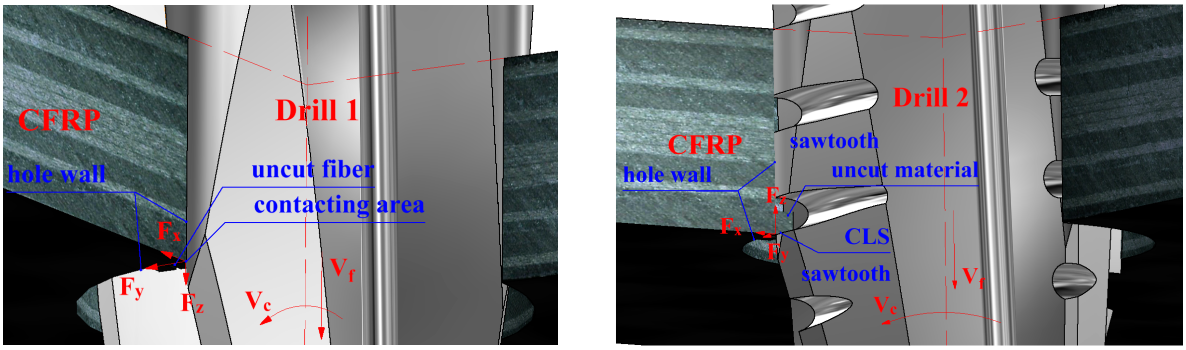


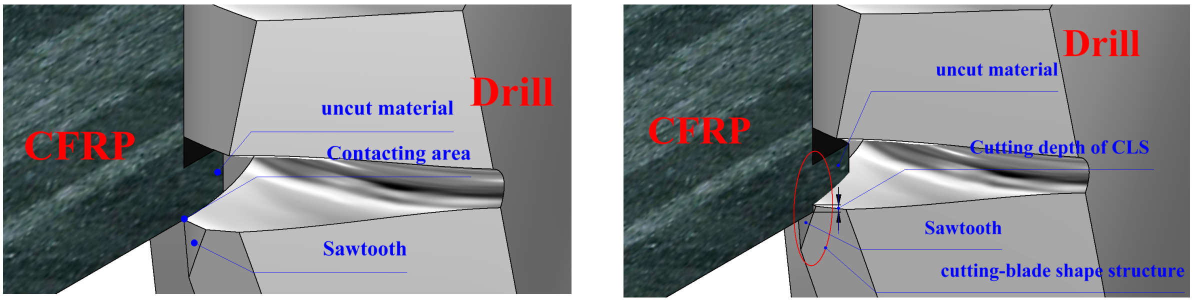
Figure 7. Schematic of the novel one shot drill with intermittent-sawtooth structure

Fig.8(a) shows drilling CFRP by the ordinary one shot drill in Stage IV, and supposing that the uncut material has no pre-deformation, the cutting force induced by the secondary cutting edge is distributed on the infinitesimal uncut material as illustrated. The rotating and feeding cutting motion generate F_z in the axial direction, and F_x in the normal direction. The decomposed cutting motion of the drill in the X-Z cutting plane can be described as the two-dimensional cutting model with direction from the machined surface to the drill exit in Section 2. Thus, the uncut material at drill exit will be bended, and delaminations and burrs are probably formed. In comparison, Fig.8(b) shows the drilling status with the intermittent-sawtooth structure on one shot drill in similar axial position to that in Fig.8(a). The uncut material falls into the groove between two adjacent sawteeth, and the position is named as Position On in Fig.8(b) and Fig.9(a) for the convenience of analysis. The front part of the CLS begins contacting the uncut material after the material falls into the groove. In drilling CFRP, low feed rate and high spindle speed are always recommended to help reduce thrust force and cut off fibers. Under the condition that the rotating speed is much higher than the feed rate, the CLS would experience a large motion in the circumferential direction but a small motion in the axial direction. Due to the right-hand helix angle of the sawtooth structure, the rear part of CLS is higher than the front part in Fig.7 in drilling process. As a result, it would move towards the machined hole, and induce the cutting force in the normal direction of the rear part of the CLS, and similarly, the cutting force is decomposed in three directions. In X-Z cutting plane shown in Fig.8(b), the cutting force has a large component force, F_z, in the axial direction due to the large right-helix angle, which turns the machined hole wall into the back support for uncut material. The uncut material are pushed towards the machined hole wall with the CLS approaching. Consequently, in the X-Z cutting plane, the reverse cutting mentioned in Fig.5(b) is realized by the cutting motion of the CLS, and the uncut material is theoretically squeezed to shear and rapture at the exit. After the drill rotates from Position 1 in Fig.9(a) to Position 2 in Fig.9(b), CLS has moved a large distance in tangential direction and a small distance in the feed direction and the rare part of CLS cut into the uncut material as shown in Fig.9(b). Thus, there forms a scissor-like structure between the cutting edge and the machined hole wall, and fibers should be cut off at the engagement area geometrically. In the whole drilling process at the exit, all the intermittent sawteeth perform continuous cutting and, thereby, drill-exit damages are effectively reduced. Therefore, compared with the ordinary one shot drill, the novel drill theoretically have a better material removal capability.



(a) (b)

Figure 8. Geometrical analysis of cutting in Stage IV (a) one shot drill , (b) one shot drill with intermittent-sawtooth structure



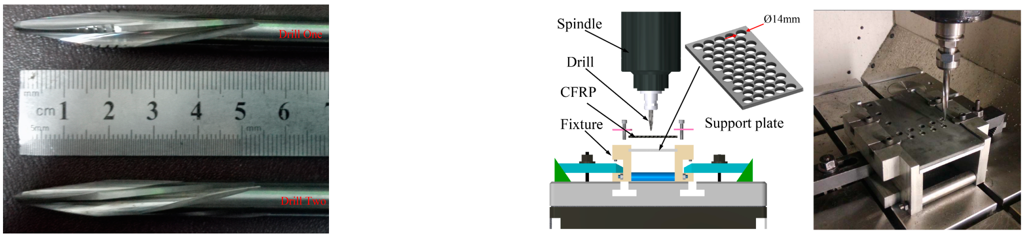
(a) (b)

Figure 9. Geometrical analysis of cutting by CLS (a) Position One, (b) Position Two

3.3 Experimental Verification of Intermittent-Sawtooth Structure on Damage Reduction

3.3.1 Experimental Details

In order to verify the practical effectiveness on the damage reduction of the design, a 7.94 mm one shot drill with the intermittent sawtooth structure was made of tungsten carbide in Fig.10(a). It has 4 left-hand helix flutes. The sawteet are on each of the secondary cutting edges and the minor cutting edges. Meanwhile, an ordinary one shot drill with the same geometrical parameters except for the intermittent-sawtooth structure is added for drilling performance comparisons. The CFRP workpiece used in the experiments was laminated by 20 layers of P2352 prepregs in $[(-45/0/45/90)_2/0/0]$s, and after curing under high temperature and pressure condition, the workpiece had the thickness of 4mm. A series of drilling operations was carried out on the Micron 3-axis machine center. The drill passed through a support plate, which guaranteed the identical supporting stiffness. The experimental setup is shown in Fig.10(b). Drilling parameters of 3000 rpm (Vc=75.36m/min) in spindle speed and 150mm/min (f=0.05mm/r) in feed rate were adopted in the experiments.



(a) (b)

Figure 10. Experimental details (a) drills, (b) experimental layout

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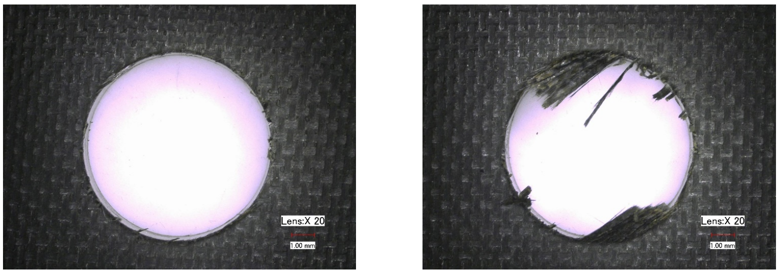
3.3.2 Experimental Results

The Keyence digital microscope was utilized to examine the machining quality of the drill-exit area. Fig.11 presents morphologies of the exits drilled by Drill One and Drill Two respectively. It was noted that few burrs were founded at the exit of the first hole for both drill. After drilling several holes, the drill bits was worn and the cutting force would increase which may induce cutting damages. Severe burrs occurred on the ninth hole drilled by Drill Two as expected. However, burrs were still rare on the ninth hole drilled by Drill One. Meanwhile, the delamination was also evaluated by applying delamination factor(F_d)[22] which is a one-dimensional factor defined as the ratio of the maximum diameter (D_{max}) of the delamination area to the hole nominal diameter (D_{norm}), described as the following equation (Eq. 1) :.

$$F_d = D_{max}/D_{norm} \tag{1}$$

The delamination damage around the holes was also measured by using the Keyence digital microscope, following the schematic diagram in Fig.12. And the results showed that F_d of the ninth hole drilled by Drill One was 1.049, smaller than 1.107 by Drill Two. Therefore, it is proved that the intermittent-sawtooth structure has great effect on burrs and delamination reductions.



(a) (b)

Figure 11. Drilling qualities at the exit (a) Drill One, (b) Drill Two

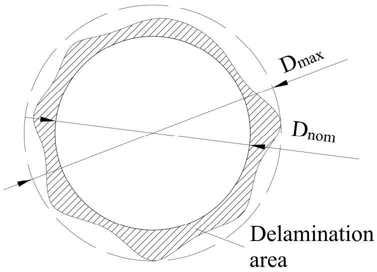


Figure 12. Schematic diagram of delamination factor

3. Conclusions

Main cutting edges have great influence on the drill-exit qualities, and their axial cutting motions are dominant in inducing the final damages. The axial cutting of the main cutting edges on the last ply in various fiber orientation can be simplified into a two dimensional orthogonal cutting in 90° fiber orientation with one side support, which is modeled based on elastic foundation beam theory and the constraint condition at the exit. Referring to the two dimensional cutting model, it is figured out that cutting from the drill exit to the machined hole surface can alter the machined hole surface as back supports for uncut fibers, which helps to cut fibers off and minimize the possibilities of burrs and intralaminar damages. A novel one-shot tool design was proposed with intermittent-sawtooth structure on the secondary and minor cutting edges, and the cutting motion of CLS of the novel drill is from the drill exit to the hole machined surface. Drilling damages at the exit is supposed to be eliminated by CLS theoretically and geometrically. Through experimental verification, burrs and delaminations induced by the novel drill are much smaller than that by the ordinary one shot drill. The intermittent sawteeth of the novel drill is proved to be effective to modify the loading conditions at the drill exit and provide good solutions to the damage-free drilling of CFRP composites.

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References

[1] D. Che, I. Saxena, P. Han, et al. Machining of carbon fiber reinforced plastics/polymers: A literature review. *Journal of Manufacturing Science and Engineering*, 136: 1588-1594, 2014.

[2] W.J. Cantwell, J.Morton. The impact resistance of composite materials—a review. *Composites*, 22: 347-362,1991 .

[3] I.S. Shyha, D.K. Aspinwall, S.L. Soo, et al. Drill geometry and operating effects when cutting small diameter holes in CFRP. *International Journal of Machine Tools and Manufacture*, 49: 1008-1014, 2009.

[4] J. P. Davim. *Machining of composite materials,* ISTE and Wiley, London, 2010.

[5] H. Saghizadeh, C.K.H. Dharan. Delamination fracture toughness of graphite and aramid epoxy composites. *Journal of Engineering Materials and Technology*, 108: 290-295, 1986.

[6] H. Ho-Cheng, C.K.H. Dharan. Delamination during drilling in composite laminates. *Journal of Engineering for Industry*, 112: 236-239, 1990.

[7] A.T. Marques, L.M. Durão, A.G. Magalhães, et al. Delamination analysis of carbon fibre reinforced laminates: evaluation of a special step drill. *Composites Science and Technology*, 69: 2376-2382, 2007.

[8] Y. Turki, M. Habak, R. Velasco, et al. Experimental investigation of drilling damage and stitching effects on the mechanical behavior of carbon/epoxy composites. *International Journal of Machine Tools and Manufacture*, 87: 61-72, 2014.

[9] R. Zemann, J. Sacherl, W. Hake, et al. New Measurement processes to define the quality of machined fibre reinforced polymers. *Procedia Engineering*, 100: 636-645, 2015.

[10] E. Persson, I. Eriksson, L. Zackrisson. Effects of hole machining defects on strength and fatigue life of composite laminates. *Composites Part A: Applied Science and Manufacturing*, 28: 141-151, 1997.

[11] C.C. Tsao, H. Hocheng. 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: 1261-1270, 2005.

[12] Z. Qi, K. Zhang, Y. Li, et al. Critical thrust force predicting modeling for delamination-free drilling of metal-FRP stacks. *Composite Structures*, 107: 604-609, 2014.

[13] M.B. Lazar, P. Xirouchakis. Experimental analysis of drilling fiber reinforced composites. *International Journal of Machine Tools and Manufacture*, 51: 937-946, 2011.

[14] H. Ho-Cheng, C.C. Tsao. Comprehensive analysis of delamination in drilling of composite materials with various drill bits. Journal of Materials Processing Technology, 140:335–339, 2003.

[15] H.J.Zhang. Study on the drilling technology of CFRP. Beijing University of Aeronautics and Astronautics, 1998.

[16] A.M. Abrao, P.E. Faria, J.C.C.Rubio, et al. Drilling of fiber reinforced plastics: A review. *Journal of Materials Processing Technology*, 186: 1-7, 2007.

[17] F. Zhaohua, R.D. Cook. Beam elements on two-parameter elastic foundations. *Journal of Engineering Mechanics*, 109: 1390-1402, 1983.

[18] R.A. Williams. A Study of the Drilling Process. *Journal of Engineering for Industry*, 96: 1207–1215, 1974.

[19] E.S. Greenhalgh. *Failure Analysis and Fractography of Polymer Composites.* Crc Press, 2009.

[20] V.P. Astakhov. *Geometry of single-point turning tools and drills: fundamentals and practical applications*. Springer Science & Business Media, 2010.

[21] Bin Niu, Rui Yang. Micro-mechanical model and material removal mechanism of machining carbon fiber reinforced polymer composite. *Proceedings of the 20th International Conference on Composite Materials ICCM-20, Copenhagen, Denmark,* July 19-24 2015.

[22] W.C. Chen. Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates. *International Journal of Machine Tools and Manufacture*, 37: 1097–1108, 1997.

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