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Novel drill structure for damage reduction in drilling CFRP composites

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ABSTRACT

Drilling holes on CFRP components is inevitable for assembling process in the aviation industry. 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 quality on CFRP components. The article aims to propose a novel drill structure to change the cutting conditions at the drill exit and effectively reduce damages in drilling CFRP. Considering the drilling-exit constraint condition, a unique two-dimensional cutting model is established to represent the axial cutting of the main cutting edge at the drill exit. Based on the model, the effects of point of action and cutting direction on material removal at the exit are investigated, and the result indicates that cutting CFRP in the upward direction has positive effects on deflection limitation and damage reduction. In order to perform the upward cutting, a novel intermittent-sawtooth drill structure is proposed on the one-shot drill. The theoretical and geometrical analyses of the drilling process reveal that the cutting lips of the structure could reverse the cutting direction from downward to upward and thereby, reduce the drill-exit damages. Furthermore, drilling experiments are conducted and the drill structure is proved to be effective to reduce drilling damages as expected.

1. Introduction

Carbon fiber reinforced plastic (CFRP) composites have been widely adopted in the manufacture of aviation parts due to their light weight, high strength and excellent damage tolerance as well as huge reduction on the joints for assembly requirements compared with metallic components [1,2]. Even so, joining is still inevitable for CFRP components in the assembly process. Mechanical joinings to bond CFRP components by bolts and rivets are preferred in many applications [3] where a mass of holes are required. Thus, the drilling operation is the essential process for CFRP parts assembly.

Drilling CFRP composites is not as easy as drilling some metal materials especially for the multi-directional composites with long fibers. The removal mechanism of the composite is different from the metal due to CFRP composites being anisotropic and multi-scale characteristic in nature [4]. Fibers are more difficult to rupture than resins and the bonding strength between fibers and resins is lower than any strength of the reinforced fiber [5]. Thus, in drilling CFRP, damages such as burrs, delaminations and pull-out fibers [6] frequently occur. These damages would lower the load bearing capability of CFRP components and reduce the lifespan of the assemblies [7–9]. In particular, since drilling is usually in the finishing process of assembly and drill-induced damages are hard to be repaired, hence, poor hole qualities account for an estimated 60% of all CFRP part rejections, and part rejections are very costly [10,11]. Therefore, minimizing drilling damages is the key to flight safety and cost reduction.

Great efforts have been made to improve the drilling qualities. Most of the current researches believe that the initial delamination before the drill bit penetrates the last ply is critical and is mainly influenced by the thrust force. Then the critical thrust force leading to the onset of delamination has been analytically calculated based on the popular linear elastic fracture mechanics (LEFM) theory and Mode I fracture [12–14]. Further studies have found that utilizing proper drill bits or optimizing drilling parameters can reduce the drilling thrust force lower than the critical value, and so that the initial delamination can be suppressed. However, the initial delamination is not the final damage in drilling CFRP. After the main cutting edges of drill bits contact the uncut material at the exit, the initial delamination would propagate and other damages such as burrs and pull-out fibers would occur [7,15–17]. The generations of these damages are mainly attributed to unlimited deflection towards outside of the hole when the outside constraints at the drill exit do not exist. Consequently, drilling with the back-up support has also been studied to restrain the

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deflection of material at the drill exit, and it turns out to be an effective way to reduce most of the damages [18,19]. However, it is impractical to add extra back-up support for all of drilling operations in the assembling process. Therefore, a new method of restraining the deflection of the drill-exit material is needed during drilling without any help of extra devices except for drill bits and the workpiece. It is known that, in any cutting process, the geometry of cutting tool determines the cutting condition at tool-workpiece engagement area which includes three basic characteristics, cutting force value, point of action and cutting direction. Current studies on the geometrical influence of CFRP drill bits [14,20–24] mostly focus on how to reduce the maximum thrust force value by utilizing multi-stage structure drill bits such as one-shot drill or step drill. The attempts have only limited effects on reducing drill-exit damages. However, ideas of reversing the cutting direction and changing the point of action have rarely been considered in the design of the drill structure. If these two basic characteristics are changed in drilling CFRP, the deflection of the drill-exit material could be limited and good drilling performance could be achieved.

The article aims to figure out a novel drill structure to change the cutting direction and point of action at drill-exit material, and effectively improve hole qualities. Firstly, the three-dimensional cutting of an elementary edge segment on the main cutting edge is simplified into a two-dimensional cutting model and the model is further developed with the consideration of the drilling-exit constraint conditions. Based on the model, impacts of upward and downward cutting on the material removal mechanisms are fundamentally analyzed, and the damage-free direction is found. Consequently, to fulfill the cutting in the damage-free direction, a novel intermittent-sawtooth structure is proposed on the one-shot drill. The cutting function of the structure acting on the drill-exit material is revealed theoretically and geometrically. Meanwhile, comparative experiments are conducted to verify the effectiveness of the drill structure on the reductions of drilling damages.

2. Cutting model at the drill exit

2.1. Damage analysis at the drill exit

Drilling process is generally comprised of the cutting motions of the chisel edge, the main cutting edge and the minor cutting edge of the drill bit. The material removed and damage induced by those edges are evidently different [25] especially for drilling CFRP as shown in Fig. 1. Before the chisel edge penetrates the last ply, it is found that the CFRP workpiece suffers from the maximum thrust force, and if the thrust force exceeds the critical thrust force, unacceptable initial delaminations could be formed [13,21]. After the chisel edge penetrates, the main cutting edges contribute to the downward cutting motion as well as a peripheral cutting motion on the uncut material at the exit. In the process, there lacks supports on the drill-exit side, and hence, fibers are forced by the main cutting edge to be bended and torn towards the outside. Under the condition, fibers are barely cut off at the expected tool-workpiece engagement area [26]. As a result, delaminations will propagate with drill bits feeding, and severe delaminations are further induced. However, if the damage radius does not exceed the nominal radius of the hole during the penetrating period, the damages could be removed in the subsequent cutting of main cutting edges as illustrated in Fig. 1. Therefore, it is main cutting edges that are the key to determine the final hole quality. The cutting and damage mechanisms of main cutting edges should be further studied in order to come up with some novel structures to improve the final hole quality.

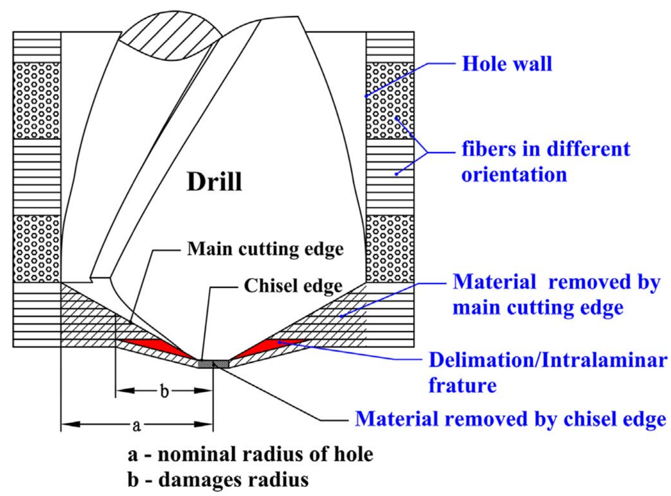

Fig. 1. Schematic diagram of materials removed and damages induced by different cutting edges.

2.2. Modeling the cutting of main cutting edges at the drill exit

Drilling operation of main cutting edges contains complex three-dimensional cutting processes. In the particular case of drilling CFRP composites, the cutting processes are much more complicated due to the laminated structure of plies in sequence of various orientations (Fig. 2(a)). The schematic top view of drilling in Fig. 2(b) illustrates the definition of the fiber cutting angle, θ, in reference to the cutting velocity vector and the fiber orientation. Meanwhile, the main cutting edge will act on several plies laminated in various fiber orientations at the same time as shown in Fig. 2(c), which also means every specific θ is different in cutting each ply. In terms of the cutting motion of the main cutting edge on one ply, θ will continuously change during a half-revolution of cutting and be in cyclical variations as the cutting tool rotates. Cutting modes of the main cutting edge under typical fiber cutting angles are illustrated in Fig. 3 [27]. The instantaneous cutting thickness is affected by the feed rate, and under the same feed rate, the thicknesses are equal in different cutting models.

Basically, the three-dimensional cutting of drill edges can be simplified into a two dimensional cutting model, which properly enables better understandings of material removal mechanism [25]. Therefore, first of all, the simplification is conducted based on the above cutting modes. Taking the mode of $\theta=45°$ for example, Fig. 4(a) depicts the force distribution on an elementary edge segment. With the cutting edge inclination, λ, the infinitesimal cutting contributes to three cutting force components, F_r, F_c and F_t in the oblique coordinate system on the cutting edge. A material coordinate system X–Y–Z is defined in Fig. 4(a) in which X axis is in the same direction of fiber orientation, Z axis is in feeding direction (out-of-plane direction), and Y axis is perpendicular to the X–Z plane under right hand law. Therefore, the cutting forces in the oblique coordinate system can be resolved along the axes of the material coordinate system, and the resultant forces F_x, F_y and F_z are obtained as described in Eq. (1).

$$\begin{cases} F_x = F_{rx} + F_{cx} + F_{tx} \\ F_y = F_{ry} + F_{cy} + F_{ty} \\ F_z = F_{rz} + F_{cz} + F_{tz} \end{cases} \tag{1}$$

Since the critical damages such as delamination are always caused by the force in the out-of-plane direction [28], F_z is the focus in the drilling case. Assuming that F_z is only induced by a cutting motion in the out-of-plane direction, which also induces a cutting force component along X axis, hence, the cutting motion