

Formation Mechanisms and Suppression Strategies of Delamination Defects in Drilling of Carbon Fiber Composite Materials

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Abstract: The delamination defects in the drilling of carbon fiber composite materials are the key problem restricting the hole-making quality of these materials. Systematically studied on the geometric characteristics, formation mechanism and suppression strategy for delamination defects. In terms of geometric characteristics, established a morphological classification system and characteristic parameter description method of delamination defects; revealed the spatiotemporal evolution laws of delamination defect during the drilling process; clarified the dominance of ply structure and material anisotropy in delamination morphology. In terms of formation mechanism, found out the axial force was the main driving force of interlaminar crack initiation, correlated the interlaminar stress field distribution with crack propagation path, built a prediction model of delamination critical conditions based on linear elastic fracture mechanics. In terms of suppression strategy, gave suppression approach from three aspects: process parameters' optimization, cutting tool's geometric structure design, and assisted machining technologies. It indicates that the delamination morphology is mainly decided by the stiffness distribution of the laminated layers, the exit delamination size is related to the relative relationship between the peak axial force and the critical value, and can effectively suppress delamination defects by controlling axial force under the threshold combined with assisted machining methods.

Keywords: carbon fiber composite materials; drilling; delamination defects; axial force; fracture mechanics; ultrasonic vibration-assisted drilling

Introduction

Carbon fiber composite materials with high specific strength and specific modulus are widely used in aerospace and other fields; drilling is vital for component assembly and connection. Due to their inherent features (heterogeneity, anisotropy, low interlaminar bonding strength) the delamination defect easily occurs during drilling that will greatly reduce the load-bearing capacity and fatigue life of components. Some researches were carried out regarding axial force action, interlaminar stress distribution or fracture mechanics but there has no systematic description about the whole physical process of delamination from initiation to propagation and the intrinsic relation between geometric characterization and mechanical models need to be deepened. Process control, cutting tool development, and assisted technologies all have achieved progresses for suppression strategies, however, the boundary of applicability among them lacks clear mechanical criteria. From the geometric characterization of delamination, we analyzed its spatiotemporal evolution laws and ply dependence, established a critical condition model based on fracture mechanics, proposed suppression strategies from three aspects including parameter control, cutting tool design, and assisted machining.

1. Geometric Characterization and Evolution Laws of Delamination Defects in Drilling

1.1 Morphological Classification and Geometric Characteristic Parameters of Delamination Defects

Delamination defects produced from drilling carbon fiber composite materials are divided into entry-side delamination or exit-side delamination according to their location, which differ essentially in their geometric morphologies (entry-side delamination has a circular distribution, and is relatively

smaller in size compared to one at the exit where it has a complicated morphology--several surface layers on the exit side have an elliptic form while the deep delamination still keeps a circular shape reflecting differences in the interlaminar stress state at different depth positions during drilling for unidirectional carbon fiber reinforced composite materials, whose delamination shape at the exit is almost elliptical and there is a definite functional relation between the direction of its major axis and the principal stiffness direction of the laminated layers); the delamination shape of plain woven CFRP is basically approximately circular because of the relative uniformity of the stiffness distribution of the woven structure in two orthogonal in-plane directions.

The geometric features of delamination defects are usually described by some parameters such as the delamination factor, delamination area, and delamination shape. The delamination factor represents a ratio of maximum diameter of delamination area over nominal drilling diameter which could intuitively represent the severity level of delamination defect. Direction of maximum stiffness in the laminated layers is where the largest delamination defects will be produced, functional relationship between bending stiffness in the principal stiffness direction of laminated layers with major axis angle of elliptical delamination can be obtained mechanically derived. Whole bundle fiber tearing is very likely to happen on principal stiffness direction when feed rate increases, the increase in delamination size can reach up to 0.81mm, and there will be an abrupt change in delamination shape along this direction. These geometric feature parameters lay foundation for the qualitative analysis of delamination formation mechanism and formulating suppression strategy^[1].

1.2 Spatiotemporal Evolution Process of Delamination Defects During Drilling

The evolution process of Delamination defects goes through the stages of Drill Bit Entry, Cutting, Exit; there are clear sequences. In the entry stage, the dominant mode is push out delamination. The initiation happens when the chisel edge contacts the material first. The tensile effect of the chisel edge on carbon fibers is the main cause of tearing. Because the material on the entry side has a relatively sufficient constraint, the size of delamination in this stage is usually small. In the intermediate cutting stage, the cooperation between the chisel edge and the main cutting edge cuts materials, and the interlaminar stress state changes continuously during the feed of the drill bit. With increasing drilling temperature, the elastic modulus of the matrix material and interlaminar bonding strength decrease, reducing the critical axial force for delamination, aggravating the tendency of damage of the interlaminar interface.

The most important stage during delamination defect's evolution: Generally, the delamination size achieves its maximum at this stage. When approaching the exit, the thickness of the layer being cut gradually reduces along with decreasing the constraining ability of the material on the drill bit. The axial force has dramatic changes when breaking through the exit causing severe push-out delamination at the exit. Dynamic fluctuation characteristics of axial force occur throughout the drilling process, and its peak appears mostly in the drill-out stage. Controlling the drilling axial force so that it doesn't exceed the critical axial force for exit delamination to avoid or reduce delamination defects is of great importance. A good positive correlation exists between how fast the axial force drops down to zero and the exit delamination factor, which can be used to describe the effect of drill geometry on the degree of delamination as a reference for process optimization.

1.3 Influence of Ply Structure and Material Anisotropy on Delamination Morphology

The heterogeneity and anisotropy of carbon fiber composite materials determine the morphological features of delamination defects inherently. In forming CFRP, carbon fibers were stacked together with resin as a bond between layers; however, the interlaminar bonding strength was only about 2.2% of the fiber-direction strength. This large difference renders the interlaminar interface the weakest link susceptible to damage during drilling. Ply stacking sequence affects the interlaminar bonding strength and stiffness distribution of the laminate. Different ply stacking sequences change the mechanical response characteristics of each layer interface which in turn influence the propagation path and final morphology of delamination defects—the direction of maximum stiffness within laminated layers is also the direction of the largest delamination defects being produced. That's why delamination at the exit of multidirectional laminates has an elliptical distribution^[2].

The influence of fiber orientation angle on the material removal process; for the fiber orientation angle ranging from 0° to 90°, carbon fibers experience shear fracture with better surface quality but for the fiber orientation angle ranging from 90° to 180°, carbon fibers experience bending fracture

with worse surface quality. It results from different interaction mode between the cutting edge and fibers. Increasing feed rate of unidirectional CFRP plates, whole bundle fiber tearing is extremely prone to happen along the principal stiffness direction, and there will be an abrupt change in delamination shape at this direction. Due to the combined effect of the helical flute peeling force and the drill axial force during entry and exit in drilling of CFRP tubes, severe push-out delamination and peel-up delamination are prone to occur. The influence of ply structure and material anisotropy on delamination morphology reveals the essence which distinguishes the drilling of composite materials from that of isotropic materials as well as being a key constraint condition should consider when developing delamination suppression strategies.

2. Mechanical Formation Mechanisms of Delamination Defects in Drilling

2.1 Mechanism of Axial Force-Driven Interlaminar Crack Initiation

Initiation of delamination defects due to axial force: The axial force consists of two parts – axial part of the force exerted from the chisel edge rake face onto the CFRP and axial part of the force exerted from the main cutting edge. The axial forces created by the chisel edge and the main cutting edge during drilling act upon uncut layers causing opening mode stress concentration at the interlaminar interface when the interlaminar normal tensile stress exceeds the interfacial bonding strength — Mode I crack initiates between the layers. In case of multidirectional laminates, the influence of axial force on the interlaminar interface at the exit side has great significance because as the drill bit approaches the exit, the thickness of the layer being cut gradually reduces, the support stiffness provided by the material to the drill bit also decreases and the axial force causes an impact effect at the exit prompting cracks to initiate and propagate rapidly at the interfaces of the bottom several layers.

The critical state for interlaminar crack initiation is determined by the ratio between the axial force amplitude versus the interlaminar fracture toughness. If the actual axial force falls within certain range, then it can completely suppress delamination. The critical axial force positively related to interlaminar fracture toughness GIC of the material and has definite function relation with the thickness of the uncut layer. Inversely proportional to the spindle speed and proportionally depending on the feed rate, there exists a theory foundation that allows us to adjust the axial force according to the change of process parameters. As the drill point angle increases, the axial force tends to increase; however, chisel edge regrinding can effectively reduce the peak axial force at the initial drilling stage which reduces the initiation probability of entry-side delamination^[3].

2.2 Interlaminar Stress Field Distribution and Crack Propagation Path

The spatial distribution of the interlaminar stress field determines both the direction of crack propagation and the shape of the delamination region that are affected together with the drill geometric parameters and cutting conditions. Load distributions vary greatly depending on the structure of drills — stress concentrates in the area between the chisel edge and the main cutting edge of a conventional drill bit but a multi-point drill can make the interlaminar stress distribution more uniform because of the change of the load distribution mode of the cutting edges during drilling. Normal tensile stress and shear stress borne by every layer interface has a non-uniform distribution along the radial direction, and there exists a stress peak at the location corresponding to the outer diameter of the drill bit which makes delamination cracks grow preferentially towards outside along this region. Tool wear will affect the geometric angles of the cutting edge increase the axial force and change the position where the force acts, thereby disturbing the stress field distribution.

However, it cannot be ignored that the influence of drilling temperature on the interlaminar stress field: because of drilling heat, the elastic modulus of the matrix material decrease, under the same axial force, the real stress borne by the interlaminar interface increases greatly. From the prediction results of delamination morphology considering temperature effects, we find large deviation as compared to those without consideration of temperature effects. Under Mode I loading, interlaminar cracks present mainly opening-mode propagation, where the delamination region has a symmetric distribution, whereas for Mode II loading, the crack propagation presents the shear mode, which exhibits asymmetry characteristics for the delamination shape. The determination of the crack propagation path not only depends on the current stress field distribution but also is restricted by the ply stacking sequence and interlaminar bonding strength—cracks tend to propagate along the interfaces with lower bonding

strength, and there are obvious differences in the propagation speed at different interlaminar interfaces^[4].

2.3 Delamination Critical Condition Model Based on Fracture Mechanics

The Delamination critical condition model based on linear elastic fracture mechanics can quantify the axial force threshold: it assumes that the uncut material in front of the drill bit is a laminated layer and derives the formula of critical axial force for delamination initiation and propagation through elastic foundation beam theory. Function of bending stiffness in the principal stiffness direction of the laminated layer regarding the delamination size could be deduced mechanically and value of the major axis angle of elliptical delamination was acquired by differentiating the function. If the delamination propagation is dominated by Mode I loading, there exists a closed form analytical relationship between critical axial force, interlaminar fracture toughness GIC, bending stiffness of the laminated layer and thickness of the uncut layer which gives the maximum allowable axial force ensuring no delamination damage occurs.

Cohesive elements coupled with quadratic stress criterion can well simulate the initiation and evolution process of interlaminar damage; the numerical method simulates the entire process mechanical behavior of interlaminar interface: linear elasticity to damage initiation, then complete failure. By comparing the axial force curve obtained through simulation with the critical axial force we can predict the occurrence and severity of delamination defects. We find that the critical axial force declines sharply as the thickness of the uncut layer decreases (when the drill bit is about 0.5 mm away from the exit) where the critical axial force has dropped to less than 30% of its original value – explaining why the delamination at the exit is the worst. The delamination critical condition model not only reveals the quantitative relationship between axial force and delamination size but also provides a theoretical boundary for determining the process parameter window in suppression strategies.

3. Multidimensional Suppression Strategies for Delamination Defects in Drilling

3.1 Optimization and Regulation of Drilling Process Parameters

Another approach of process parameter optimization to suppress delamination defects by maintaining the axial force under the critical delamination value through adjustment of spindle speed and feed rate. Axial force in drilling has inverse proportionality with spindle speed and direct proportionality with feed rate according to the mechanical law which offers a way to adjust parameters to control delamination. Increase spindle speed when feed rate keeps constant will be able to effectively decrease the load per unit cutting thickness thus decreasing the exit delamination factor. Reduction in feed rate helps reducing delamination defects too; however, if the feed rate is too low then the drilling time increases and tool wears worsen, whereas too high spindle speed causes an increase in matrix temperature leading to thermally induced delamination. Constraint boundary for parameter regulation requires process optimization considering not just suppressing axial force but also machining damage control^[5].

The essence of parameter optimization is balancing axial force control with machining efficiency; the balance point requires comprehensive consideration based on the actual situation of material system and drill bit structure. Quantitative mapping out the relation among process parameters and delamination factor by response surface methodology via experimental designs (e.g., central composite design) for typical T700-grade carbon fiber composite materials have a relatively low delamination factor in the range of spindle speed ranging from 4000 – 8000 r/min and feed rate ranging from 0.02 – 0.08 mm/r. Strongly dependent upon material – recalibrate optimization interval according to different fiber systems, ply stacking sequences, and laminate thicknesses. Diameter of tool and laminated layer thickness will affect the optimal parameter region – the larger diameter drill bit has a lower critical axial force and more conservative feed rate needed. Back-calculate the maximum allowable axial force under the delamination critical condition model using this method to determine the upper limit of feed rate which provide theoretical constraint for parameter optimization.

3.2 Geometric Structure Design of Dedicated Drilling Tools

The geometric structure of tool plays an important role in suppressing the defect of delamination via changing the space arrangement of cutting edges and load distribution mode: The drill bit with smaller

point angle can greatly reduce the axial drilling force since a small point angle makes the cutting edge gentle which leads to decreasing the load per unit length of the cutting edge; Chisel edge is one of the major source of axial force during drilling, grinding the chisel edge would be effective to decrease the peak axial force at the beginning of drilling process and weakening the driving force of push-out delamination on the entry side. A reasonable match between chisel edge width and regrinding angle will decrease the axial force by 15% – 30%; Double-point-angle drill bit has advantages of small point angle (reducing axial force), large point angle (improving chip removal). It shows relatively good overall performance when making holes in CFRP.

Even multi-point drill spreads the drilling load in circumferential direction by increasing number of cutting edges and optimizing spatial distribution makes interlaminar stress field tends toward isotropic, avoid delamination's preferential propagation in the principal stiffness direction of unidirectional laminates; Step drill cuts the material in several steps, thinning out the uncut layer for each step, weakening the push-out effect on the exit side. This structure is suitable for hole-making in thick laminates, stepwise cutting will also weaken the temperature accumulated from one cut, reduce thermal – mechanical coupling damage. Adding a backup plate on the exit side gives additional support reducing the free deformation space of the material at the exit. The supporting effect depends on the rigidity of the backup plate material and the friction characteristic of the contact interface. Optimization of tool geometric structures follows the delamination critical condition model, separating parameter matching needs to be done according to different diameter specifications and length-to-diameter ratio.

3.3 Delamination Suppression Effect of Assisted Machining Technologies

Ultrasonic vibration-assisted drilling technology gives the drill bit with high-frequency axial vibration which make the cutting process has an intermittent character. The intersection path of adjacent cutting edges satisfy a certain phase difference so that the tool and the material are periodically separated. Intermittent cutting character breaks the continuous accumulation process of axial force and keeps the interlaminar stress low—there exists a clear nonlinear correlation between the amplitudes and frequencies of ultrasounds and the delamination suppression effect – the higher the amplitude, the better the separation effect but too large amplitude will lead to greater waviness on the hole wall surface, thus it needs a compromise between amplitude and surface quality. Chips discharge under ultrasonic vibration as fine fragments, reduce chip entanglement and friction heat accumulation, produce multifaceted suppression effects on delamination defects.

Alternative hole-making method: Helical milling moves the tool along a helix path and cuts layers of materials through an eccentric motion; it reduces the peak axial force up to 40% – 60%, relative to conventional drilling, and is suitable for machining large diameter holes. Low-temperature cold air assisted machining offers a cooling medium into the cutting zone, effectively suppressing the temperature rise during drilling such that the elastic modulus of the matrix material and the interlaminar bonding strength are not reduced due to thermal softening, thus indirectly enhancing the resistance of the interlaminar interface against delamination crack propagation. In hole making of stacked structures, there exists a lower metal material offering exit side support for the upper composite material, whose constraint effect greatly decreases the exit delamination factor (confirmed in the assembly hole-making of aluminum alloy/CFRP stacked components). There exist different applicability range and process cost for every assisted technology, they should be chosen or combined according to the material system, hole quality requirement and production condition.

Conclusion

The formation mechanisms and suppression strategies for delamination defects were studied systemically in CFRP drilling. There exist two types of delamination defect including entry-side delamination and exit-side delamination. The morphology depends on the stiffness distribution of the laminated layers with a principal stiffness direction corresponding to the maximum delamination size. Delamination evolves throughout the whole drilling process, where the dominant mode of delamination in the entry stage is push-out delamination due to chisel edge tensile action but due to reduced constraint, axial force impact makes the delamination size reaching its peak at the exit stage. Axial force plays the main role initiating Mode I interlaminar cracks. The non-uniformity of the interlaminar stress field decides the crack propagation direction, reduction drilling temperature reduces the critical axial force. According to the critical model derived from linear elastic fracture mechanics, when approaching 0.5 mm away from the exit, the critical axial force drops down less than 30% compared to

its original value which explains the reason why the most serious delamination happens at the exit. Suppression strategies adopt axial force control as the basic principle. Balance parameter optimization between spindle speed and feed is needed. Small point angle and chisel edge regrinding can effectively reduce the load. Ultrasonic vibration-assisted drilling interrupting axial force accumulation. Helical milling could reduce the peak axial force. We will do further research focusing on online monitoring and adaptive control of delamination defects, refined constitutive models under three-dimensional complex stress states, and collaboration matching of intelligent tool systems.

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