

博士論文（要約）

**Characteristics of Drilling Process on Composite Laminates:  
Understanding Damage Initiation and Progression  
to Improve Final Hole Quality**

（複合材料積層板の穿孔プロセスの評価：  
最終穿孔品質改善のための損傷発生・進展の理解）

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In this dissertation, drilling characteristics of composite materials were investigated, both numerically and experimentally. Composite materials have unique material features not only in-plane direction but also out-of-plane direction. Since composite laminates have weak material property to out-of-plane direction, the mechanics of drilling process which applies direct thrust force to the same direction easily caused machining related damages. There have been a lot of technical advancements both material characteristics and drill tool development on composite machining, therefore this dissertation is more focused on the drilling related damage and failures by considering the current technical improvements.

In chapter 2, drilling induced failure initiation mechanism was investigated by simple experiment as well as numerical analysis. A finite element analysis platform was developed for 2D and 3D modeling configurations. A multi-scale mesh was implemented for detailed failure analysis, especially micro-mesh modeling for failure interested region. The FE analysis code simulated drilling damage initiation mechanism by using elasto-plastic deformation and progressive failure analysis.

1. Failure initiation mechanism for 2D interlaminar toughened CFRP was examined experimentally, and then the result was validated with the developed 2D FE code. The simulation results explain where the damage was initiated and how it progressed to become failure, in-between two long fiber layers and by matrix cracking, respectively.
2. The effects of different chisel sizes, drill point angles, and material characteristics are numerically investigated. The simulation verified sharp chisel edge and low point angle effectively reduced damages. More importantly, how the left over geometrical configuration affects to the final damage was also discussed.
3. From the 3D simulations, cross-ply and quasi-isotropic ply laminates were examined for damage initiation process. The simulation started with 3D configuration and after excessive deformation with matrix cracking failures along long fiber direction, the 3D analysis became close to the 2D analysis. Therefore, the developed 2D model supports the evidences of how and where the drilling damages were initiated and its cracks were progressed.

In chapter 3, element deletion method was implemented into the previously developed 2D FE analysis to simulate material removing process. The FE code is now possible to investigate how initiated damages are further progressed by considering exact geometrical configuration, corresponding to actual drill tip shapes. The feature for updated model is it keeps the previously developed FE platform such as elasto-plastic and progressive failure during element deletion procedures.

1. The material removing simulation, element deletion method, was validated. Thrust response of 2D specimen was measured during drilling experiments, and the response was compared with reaction forces from numerical calculation. The 2D element deletion code successfully calculated thrust responses with respect to ply orientation.
2. The damage initiation mechanism was compared with 2D drilling experiment results. The experiment results showed what the final failure configuration looks like, on the other hands simulation results provided additional explanations of where and how the damage happed. Since the final failure configurations looked similar, the code simulated damage initiation process, reasonably.
3. How the initiated damages are further progressed was investigated. The final failure configuration from numerical results was compared with cross-sectional plane from 3D drilling experiments. The result verified that the initiated failures are very weak, so even small loads can trigger further failure progression. With element deletion method, complete drilling simulation was possible to perform.
4. Finally, the effect of two different thrust load conditions was compared, especially along drill cutting edge regions. Small load increments have resulted different damage progression. From the results, failure initiation is unavoidable; however failure progression can be controllable by the loading condition of drill cutter.

In chapter 4, drilling experiments were performed with high quality drill tools and precise load measurements to investigate how machining conditions affect to the drilled hole quality on composite laminates. Three composite specialized drills were used to understand their featured drilling characteristics. The drills have sharp cutting edges with diamond coating, and they are wildly used at the aerospace industries. Thrust and torque response were recorded, and then they were analyzed to compare the characteristics of twist type and reamer type drills.

1. Machining sensitivity of a twist drill was investigated. 9 different machining conditions were tested, and whole responses were acquired. The result verified higher feeding speed increases thrust increment. A peak load was generated at the beginning of drilling, and it was getting relaxed. Since the peak load was happening much earlier time than damage initiation moment, careful attention is required to estimate delamination size versus measured thrust load.
2. The effect of machining conditions to thrust load distributions was investigated, especially for twist drills. By changing machining conditions, load magnitudes along drill cutters were also changed. Especially, the drill rotation speed resulted significant effect on the load distributions. The results supported that machining conditions are directly related to load distributions, and they are also resulted as different drill hole quality.

3. Machining sensitivity of two reamer type drills was investigated. Both drills required specific machining conditions than twist drills, for example higher feeding speed. R-DRILL showed pure reamer type characteristics, and D-STAD resulted the combined features of reamer and twist types. Both drills became unstable right after the drill tip penetrates materials, so careful attention is required for the reduction of vibration related damages.
4. The machining mechanism of reamer type drills was examined. Like the previous conclusion, reamer types became unstable mostly by machining conditions. When unstable condition occurs, the drill tip started to vibrate and it was getting amplified. The thrust load became almost zero, and most of the thrust loads were transferred to torque. From the result, reamer type drills require minimum thrust load to hold the drill refrain from the vibration, for R-DRILL 50 N.
5. Thrust load distribution for two reamer type drills was estimated. R-DRILL showed a featured load distribution. It applied almost zero thrust at the drill outer corner which verified the most cutting process was performed by torque. The load characteristics for D-STAD were similar to twist types. By comparing the calculated thrust distributions with final failure configurations, how the distribution affect to the final failure patterns and size can be understood.

In chapter 5, precise thrust distributions along drill radial position were estimated to investigate how the exact loading condition affects to the final hole quality. A term, element deletion criterion, is implemented as the same meaning as cutting force distribution required along drill radial position. The developed element deletion finite element code was modified for drilling failure analysis. The FE analysis is possible to consider exact geometrical configurations and precise load distributions.

1. Precise thrust load distributions, element deletion criteria, were estimated for two different materials, T800S/3900-2B and T800H/3631. The calculated load distributions were different by materials as well as machining conditions. The estimated distribution was first validated by using the finite element code, and the calculation resulted what the exact estimation is, for example the angle change on the drill geometry affect sudden load changes on that region.
2. The thrust difference of two T800 rate composites was investigated, numerically. The actual internal characteristics of material configuration were taking into account for comparison. The numerical result verifies that the cutting force for T800 was similar, more precisely; the material contact length between the cutter and material had strong effect to the thrust magnitude.

3. The effect of various drill tip geometries was investigated, numerically. Three different composite special drill shapes were implemented; however the same loading conditions were applied to see the geometric effect, only. The sharp drill tip successfully concentrated its loads near the machining region, and it resulted less residual stress on the other supported region.
4. The effect of two exact thrust load distributions corresponding to the drill tip shapes was investigated. The numerical results compared when and how thrust induced failures were happened. The structural geometries and internal loads were changed drastically right after drill tip penetration which generated high shear forces causing intra-lamina matrix cracking. The damage initiating distribution load was estimated about 30  $N/mm$  from the analysis.