THE EFFECT OF INTERACTION BETWEEN TITANIUM ALLOY AND CFRP ON THE INTERFACE DAMAGE IN CUTTING TI/CFRP STACK COMPOSITE

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ABSTRACT

In modern aircraft industry, machining CFRP/Ti stack composite in one shot drilling is still a challenging task due to the disparate nature of each stacked constituents and their poor machinability. The current research on the CFRP/Ti stack composite machining is mostly based on the experimental studies, which exhibits high cost, time consuming and can't reveal the cutting process accurately. In this paper, a 3D oblique cutting model is developed to simulate the chip formation process when the cutting edge machining two stacked constituent simultaneously. Different constitutive models and failure criteria are implemented to construct the entire machining behavior of the stacked material. Special concentration is made on revealing the regulation of the sub-surface damage of CFRP under the constraint of the titanium. The numerical results emphasize the pivotal role of stacking-sequence strategy on the interface damage of the CFRP.

1 INTRODUCTION

Carbon fiber reinforced plastics (CFRPs) exhibit excellent mechanical properties, such as high specific stiffness and strength, which result in increasing application in aerospace structures [1]. As structural material, CFRP combined with titanium alloy is a typical stacked composited configuration. The key benefit of the stacked composites usually arise its enhanced mechanical properties and improved structural functions of each stacked constituent [2, 3]. With the development of aircraft industry, the stacked composite is widely used in key load-bearing components. The typical application is the use of the wing-fuselage connection in the new generation Boeing 787 Dreamliner [4].

CFRP/Ti stacked composites are usually jointed by bolting and riveting. In order to assemble preciously, the fastener holes are often drilled through composite-metal stacks instead of drilling composite and metallic material separately. However, machining such CFRP/Ti stacked composite still represents a most challenging task in aircraft industry because of the disparate properties of each stacked constituent and the complex interaction in the interface region. For instance, the CFRP laminate shows anisotropic behavior, and abrasive nature, which may cause poor machined surface quality and severe induced damage in machining [5-7] The titanium alloy exhibits low thermal conductivity and strong chemical affinity, which results in high force/heat generation and serious tool wear in machining operation [8-10]. The practical process of drilling of CFRP/Ti stacked composite can be considered as an oblique cutting process, due to the feed movement in the axial direction. When the tool cut two stacked materials, the CFRP in the interface region is restrained by the titanium alloy, which could cause the removal mechanism and the extent of sub-surface damage of the CFRP vary obviously.

In recent decades, many scholars have paid attention to the problem of machining such composite/metal stacked composite. Many experimental studies have been conducted to address various aspects involved in CFRP/Ti stacked composites machining such as machinability assessment, tool wear study, and hole quality evaluation [11-14], etc, which have benefits on the comprehension of the machining physics and the improvement of the machined quality. However, for reasons that the kind of the stacked composite is various and the interaction between stacked constituent is complicated, only experimental research concerning machining of CFRP/Ti stacked composite is time-consuming, expensive and can not reveal the cutting process accurately. In contrast, to some extent, the numerical simulation is a high-efficient and low-costing method, which could offer sufficient capabilities to overcome the limitations arising from the experimentation. However, for numerical study on CFRP/Ti stacked composite, there are still very limited researches can be found in the open literature compared to tremendous scientific works dealing with the single composite and single titanium alloy cutting model. Nearly rare publications are reported to analyze the influence of the interaction between two stacked materials on the induced damage in the interface region. Lack of the integrated researches on the sub-surface damage of CFRP in the interface region when drilling of stack composites. As a result, the sub-surface damage can't be predicted accurately. This is the key incentive that motivated this research to address the mentioned issues.

On the basis, the present work is thus dedicated to predict the sub-surface damage of CFRP with the constraint of the titanium. To this aim, a 3D finite element macro oblique cutting model is established to simulate the process that the cutting edge cut two stacked materials simultaneously in drilling CFRP/Ti stack. This model can realize the goal of chip formation at the same time for different laminated materials. Several aspects of the cutting phenomena activated in different stacking-sequence strategies when cutting CFRP/Ti stacks are studied. This paper highlights the significant role of the cutting-sequence strategy in affecting the subsurface damage of CFRP in the interface region.

2 NUMERICAL MODEL FOR CFRP/TI CUTTING

2.1 Description of oblique cutting model

In the present contribution, a 3D finite element oblique cutting model is developed by using the Abaqus/Explicit code to simulate the CFRP/Ti stack composite continuously dynamic cutting process. The established oblique cutting model consists of four basic parts, the Ti part, the CFRP part, the interface part and the tool part. The basic geometries, dimensions and boundary conditions of the numerical model were depicted in Fig. 1.

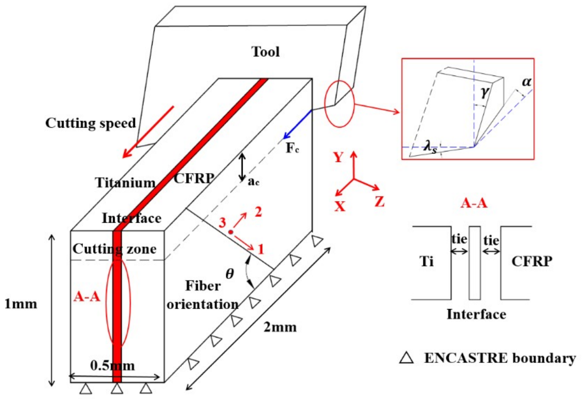


Fig.1 Schematic illustration of the established oblique cutting model

The size of the workpiece was , the sufficient cutting length is 1mm in order to attain the steady cutting condition and to fulfill the complete chip separation. Displacements of the workpiece bottom are restrained in cutting direction, perpendicular direction and the out-of–plane direction (X, Y, and Z directions). The left and right edge of the stack composite under the cutting zone are also restraint in the three directions. The tool is simplified as a rigid body with the defined geometries of rake angle (γ=20°), clearance angle (α=10°), tool edge radius (r_e=2μm) and inclination angle (λ_s=20°). The CFRP phase is modeled as an equivalent homogeneous material (EHM) with anisotropic property by using 8-node linear brick elements with reduced integration (C3D8R). For Ti phase, it is modeled as a fully isotropic and homogeneous material, and C3D8R type element was used in the Ti phase. The interface phase connecting the Ti phase and the CFRP phase is modeled by using the 8-node 3D cohesive element (COH3D8) as a transition zone available in the Abaqus/Explicit code. Friction properties ruled in tool-work contact pairs are described by using Coulomb criterion with a constant friction coefficient equal to 0.3.

2.2 Failure damage criteria

In finite element modelling, failure damage criteria plays a pivotal role in rupture phenomena of the simulated material and determining the separated chip morphology during the cutting process. The Ti phase and CFRP phase are required to implement different damage criteria to fulfil the chip separation process controlling the hybrid stack cutting. In this contribution, the material of Ti phase is Ti6Al4V, the material properties are summarized as follows: Density (4430kg/m3), Young's modulus (113GPa), Poisson's ratio (0.342), Thermal expansion coefficient (9.1×10^{-6}C$^{\circ-1}$), Melting temperature (1680C°), Room temperature (25C°), Thermal conductivity (7.0*W/m·℃*),Specific heat (546*J/Kg·℃*).The metal is assumed to suffer high plastic deformation, plane stress, strain rate and pronounced temperature effects during the cutting operation. In this case, Johnson-Cook (JC) constitutive model and JC damage criteria [15-16] are employed in this study. The input parameters for JC constitutive model and JC damage criteria are summarized as follows: A=1098 (MPa), B=1092 (MPa), C=0.014, m=1.1, n=0.93, D_1=-0.09, D_2=0.25, D_3=-0.5, D_4=0.014, D_5=3.87, respectively [17].

For CFRP phase, it is modeled as a macro EHM with the anisotropy of the material relative to the fiber orientation. The constitutive behavior and damage criteria of the composite are defined by using Hashin damage criteria [18]. The material of CFRP phase is T800 laminate and its material properties are summarized as follows: Longitudinal modulus (E_{11}=195GPa), Transverse modulus (E_{22}=8.6GPa), Shear modulus in 1-2 plane (G_{12}=6.3GPa), Shear modulus in 1-3 plane (G_{13}=6.3GPa), Shear modulus in 2-3 plane (G_{23}=4.2GPa), Major Poisson's ration (υ_{12}=0.25, υ_{23}=0.34), Longitudinal tensile strength ($\sigma_{11}{}^{T}$=2843MPa), Longitudinal compressive strength ($\sigma_{11}{}^{c}$ =1553MPa), Transverse tensile strength ($\sigma_{22}{}^{T}$ =166MPa), Transverse compressive strength ($\sigma_{22}{}^{c}$=600MPa), Shear strength (80MPa), density (ρ=1530 Kg/m^3).

The interface phase is modeled as a transition region linking the CFRP phase and the Ti phase. The interface phase plays a key role in controlling the contact management and reproducing the induced damage in the interface region when machining of the CFRP/Ti stack composite. However, it should be noted that the interface phase do not exist in real CFRP/Ti configuration. The interface phase is modelled by using cohesive interaction. The traction-separation cohesive law with linear softening is adopted to reproduce the mechanical responses of the interface phase. Damage initiation and evolution are controlled by using BK damage law available in Abaqus/Explicit. The relevant parameters are as follows: K_{nn}=2.0GPa, K_{ss}=K_{tt}=1.5GPa, $\boldsymbol{t}_n^f$ =60MPa, $\boldsymbol{t}_s^f = \boldsymbol{t}_t^f$ =80MPa, $\boldsymbol{G}_n^c$ =0.78N/mm and $\boldsymbol{G}_s^c = \boldsymbol{G}_t^c$ =1.36 N/mm [19].

2.3 Validation of the oblique cutting model

In this study, the validation of the CFRP/Ti model is conducted based on an oblique cutting experiment. The oblique cutting experiment is carried out on a high-speed linear motor and a micro-displacement platform. The cutting process is implemented on the manner that the tool is fixed and the workpiece moved. The cutting force is recorded by a Kistler 9257B three-component dynamometer. Experiment setup is shown in Fig 2. During the validation work, the experiment cutting conditions are selected the same as used in the simulation (v_c=50mm/s, a_c=20μm).The result shows that the predicted force magnitudes yields strong correlation with the experimental results, and the error of the force magnitude is less than 10% of the experimental results, as shown in Fig. 3. The cutting force results confirm the credibility of the developed CFRP/Ti oblique cutting model.

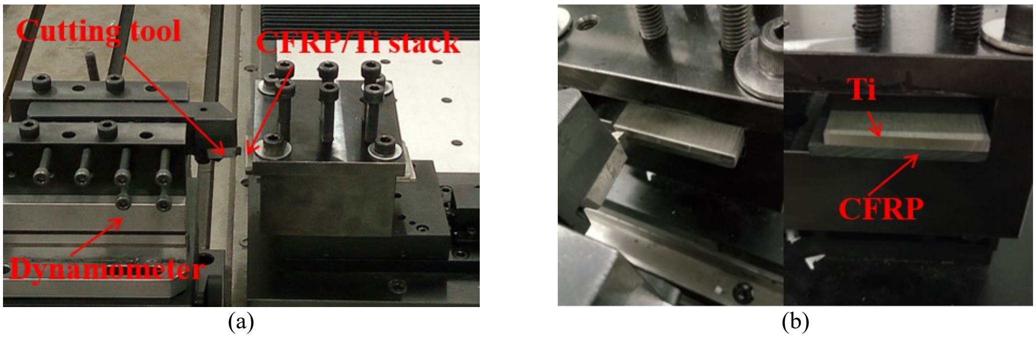


Fig.2 Experiment setup of machining CFRP/Ti stack composite. (a) the entire experimental setup. (b) the close-up of the clamped workpiece

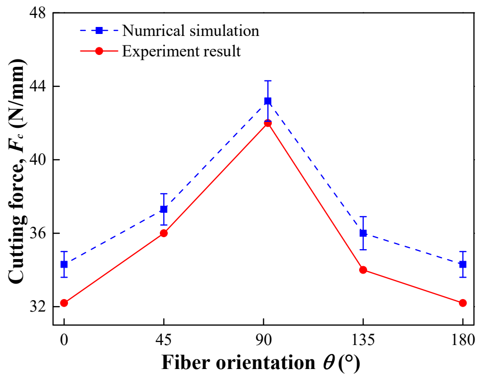


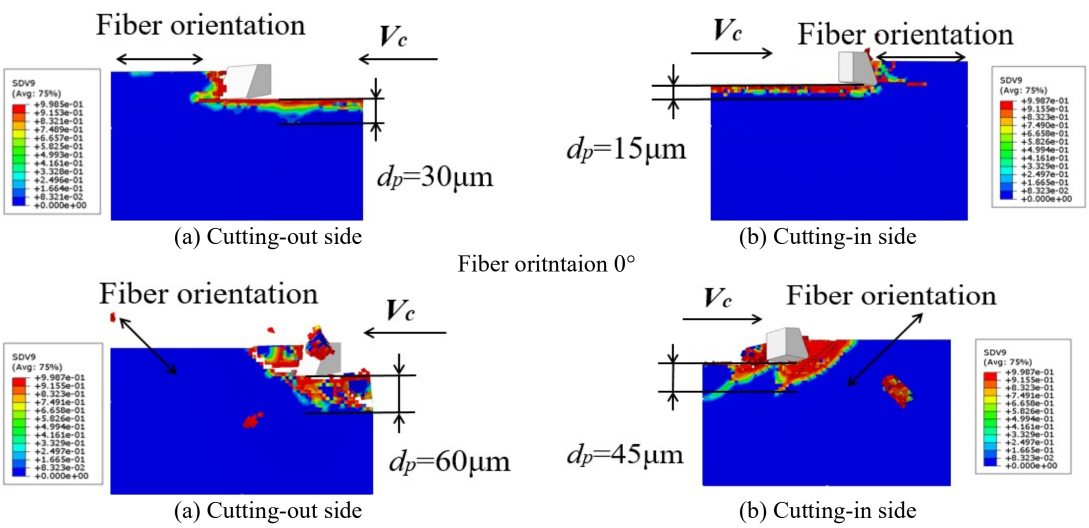
Fig. 3 Comparison of the simulated and experimental force generations in CFRP/Ti oblique cutting

3 NUMERICAL RESULT AND DISCUSSION

In CFRP/Ti stack machining, the stacking sequence is a key factor affecting the interaction of the stacked constituent which could have a significant influence on the interface damage of CFRP.

In this contribution, the stacking sequence Ti to CFRP means that the tool contacted the Ti first, in the direction of the out-of-plane. The stacking sequence CFRP to Ti means that the tool contacted the CFRP firstly, in the direction of the out-of-plane. The cutting-in side means that the side of the workpiece that the tool contact first in the direction of the out-of-plane. The cutting-out side mean that the side of the workpiece that the tool leave finally, in the direction of the out-of-plane.

The numerical simulation result of the sub-surface damage is revealed through SDV9 code. Sub-surface damage of the CFRP is shown in Fig. 4 and Fig. 5.



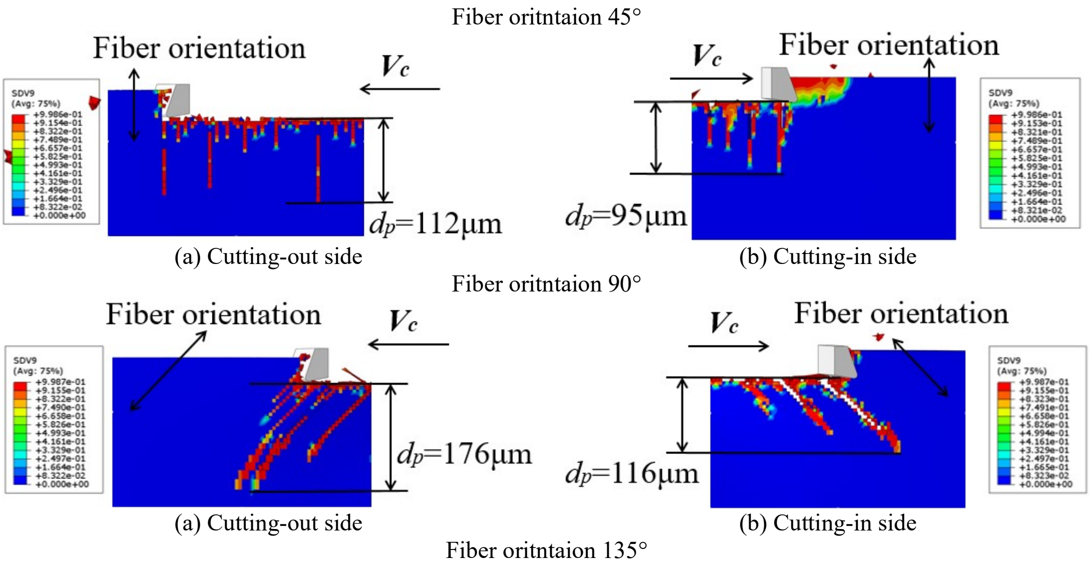


Fig.4 sub-surface damage of CFRP (stacking sequence Ti to CFRP, vc=50mm/s, ac=40μm)

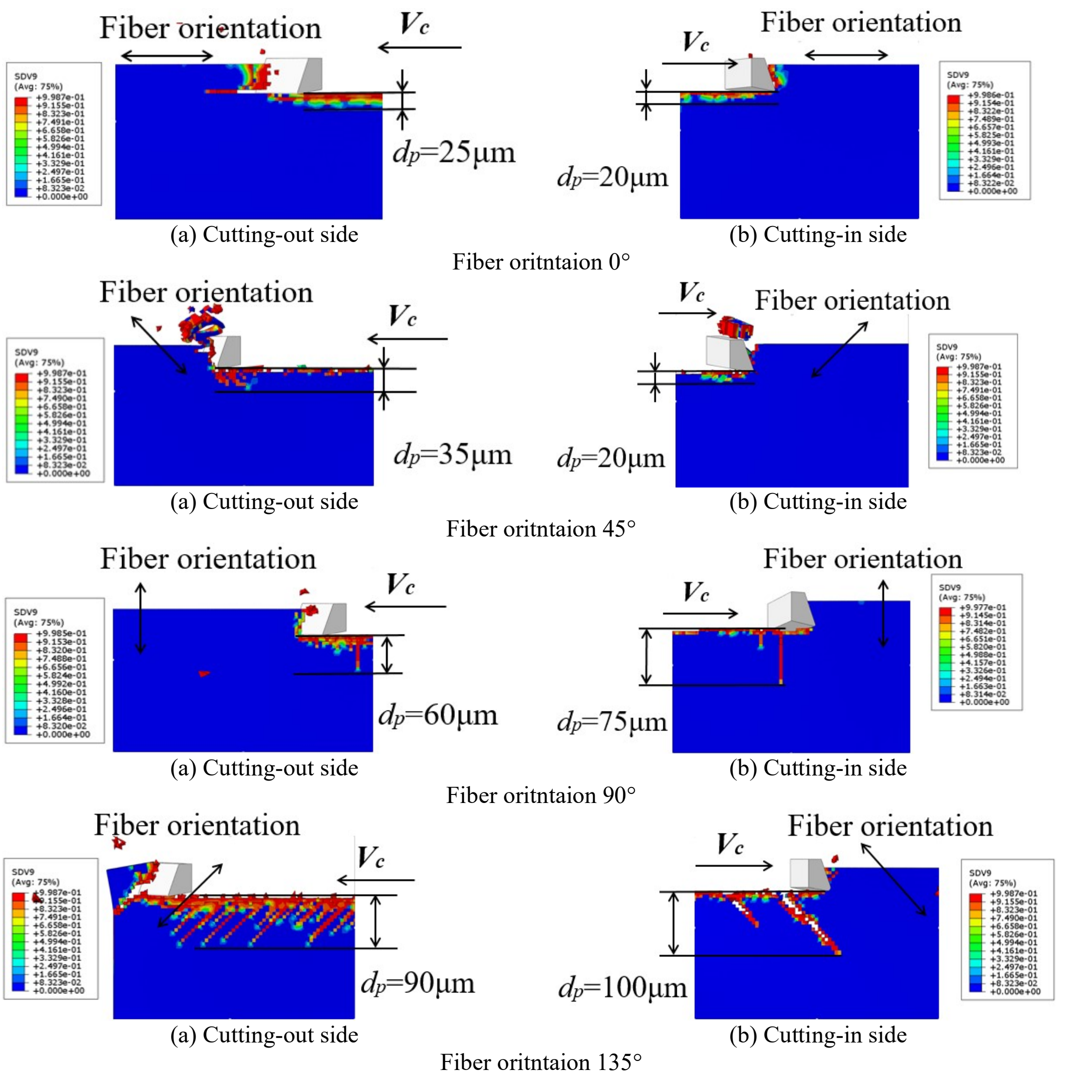


Fig.5 sub-surface damage of CFRP (stacking sequence CFRP to Ti, vc=50mm/s, ac=40μm)

It could be found that the interaction between titanium alloy and the composite has a significant influence on the formation of the sub-surface damage in the interface region. When the stacking sequence is Ti to CFRP, deformation of the titanium in the interface region is occurred in the direction of the out-of-plane. The deformed titanium squeezes the CFRP which could aggravate the sub-surface damage of the CFRP. When the tool cut-out the CFRP, the CFRP in the cutting-out side is under weak constraint. In this condition, the effect of the out-of-plane force on the CFRP in the cut-out side is enormous, which could cause the deformation of the CFRP in the cut-out side and elevate the sub-surface damage. However, when the stacking sequence is CFRP to Ti, the CFRP is supported by the titanium, which could reduce the deformation of the CFRP in the cutting-out side along the out-of-plane direction and minimize the sub-surface damage. Fig. 6 presents the predicted sub-surface damage depth versus the effect of the titanium.

Besides, it can be found that the effect of the interaction between titanium and CFRP on the variation of sub-surface damage depth in the interface region is distinct in two stacking sequences, as shown in Fig. 7. When the stacking sequence is Ti to CFRP, the CFRP of the interface region is in the cutting-in side. In this circumstances, CFRP of the interface region is supported by the unmachined CFRP laminate in the direction of the out-of-plane. Due to the existence of the supporting, the influence of the titanium squeezing on the CFRP is counteract partly. In contrast, when the stacking sequence is CFRP to Ti, the CFRP of the interface region is in the cutting-out side. In this condition, the CFRP of the interface region only sufferes the supporting of the titanium. As a consequence, the effect of the titanium on the sub-surface damage of the CFRP of the interface region in the condition of stacking sequence Ti to CFRP is smaller than that in the condition of stacking sequence CFRP to Ti. Meanwhile, it is found that in the case of stacking sequence CFRP to Ti, the variation of the sub-surface damage depth increase gradually when fiber orientation ranged from the 0° to 135° and dropped drastically for θ above 135°.

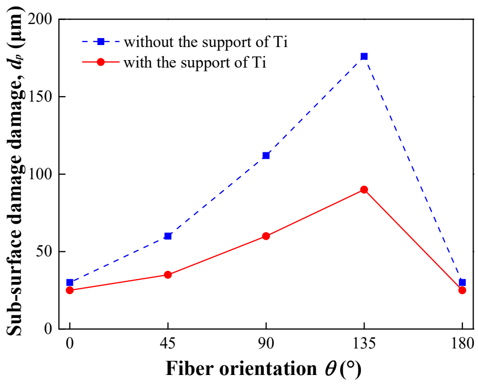


Fig. 6 The effect of the titanium on sub-surface damage depth (vc=50mm/s, ac=40μm)

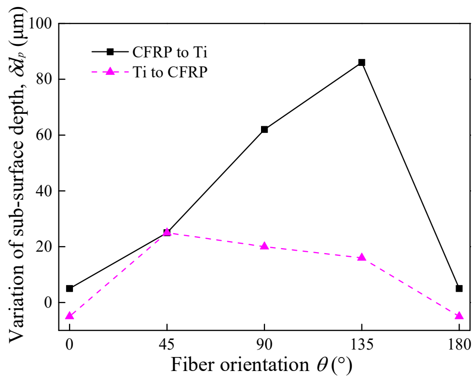


Fig. 7 Variation of the sub-surface damage depth (vc=50mm/s, ac=40μm)

4 CONCLUSION

In this paper, a 3D finite element model is developed to simulate the continuously dynamic chip formation process with oblique cutting of CFRP/Ti stack composite. Special FE analysis are made focused on the comparative studies of different stacking sequence on the interface damage on the CFRP. Based on the acquired FE results, some key conclusion can be drawn as follows:

(1) Sub-surface damage of the CFRP in the interface region is affected by the interaction between titanium and CFRP. The CFRP to Ti cutting sequence is confirmed to minimize the sub-surface damage in the interface region due to the supporting of the titanium. In contrast, the Ti to CFRP cutting sequence is verified to aggravate the sub-surface damage of CFRP in the interface region on account of the squeezing of the titanium.

(2) The variation of the sub-surface damage depth caused by the constraint of titanium is influenced by stacking sequence and fiber orientation. The Ti to CFRP cutting sequence is confirmed to have little influence on the variation of the sub-surface damage depth, and in this stacking sequence, the fiber orientation has little impact on the variation of the sub-surface damage depth. In contrast, it is prominent for the variation of sub-surface damage of the CFRP in the interface region with the fiber orientation in CFRP to Ti stacking sequence. Besides, the magnitudes of the variation increases as θ ranged from 0° to 135°, and decreases as θ above 135°.

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