

Laminated CFRP Cutting Area Deformation Analysis and Sub-surface Damage Control

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Abstract: Carbon fiber-reinforced polymer (CFRP) has been used in many aspects. During machining of CFRP damages are always brought in. Due to the brittleness property, the damages are closely related to the deformation in cutting area. In this study, a three-dimensional finite element model was established to study the deformation transformation in cutting area and the interactions of the deformation between two adjacent plies. An experiment was also conducted to measure cutting area deformation and sub-surface damage. The simulation results and experimental data were combined to analyze the correlation between cutting area deformation and sub-surface damage. The sub-surface damage was found have a positive relation with cutting area deformation. Based on the analyzing, a stacking strategy was proposed to reduce the damages in sub-surface. Then the optimization was verified in both numerical and experimental way.

1. Introduction

Carbon Fiber-reinforced Polymers (CFRP) has gained wide application in aero and aviation industries. The high durability and long service life of products require the machining of CFRP parts with extraordinary high precision and least defects. During mechanical machining, however, though the dimensional precision may meet design requirements, when examining the sub-surface burr, delamination and fiber-matrix interface debonding occur frequently [1]. The micro-scale damages accumulate and propagate to form the macro-scale cutting area deformation. The cutting area refers to the area that deforms under the cutting load applied by cutting edge. Due to the brittleness property of CFRP, even a tiny deformation may lead to irreversible damages in fibers and matrix. Therefore, investigating the cutting area deformation is of great importance to reveal the formation and propagation of damages, and to propose methods for minimizing the damages. In literature, the relation between damages and cutting area deformation is not well explained. Ref. [2-6] established FEM models to simulate CFRP cutting responses. Equivalent homogeneous material (EHM) was used to characterize CFRP and Hashin criteria was used to describe failure initiation. The models were used to study sub-surface damage [2], delamination [3], chip formation [4-5] and cracks propagation [6]. The deformation in the whole cutting area are not paid enough attention. When refers to cutting area deformation measurement, digital image correlation (DIC) method is commonly used. The exterior surface deformation in cutting area can be measured using DIC method. The interior deformation or damage, however, are not able to measure using DIC method. In this study, a novel experiment was conducted to specify the interior sub-surface damage. Based on the numerical and experimental results, a damage control strategy is present.



2. Cutting area deformation simulation

In order to simulate the propagation and interaction of the deformation in inter-ply, an FEM model was built using Abaqus/Explicit according to ref. [3]. The properties of EHM were offered by the manufacturer (Weihai Guangweicompanies Co.Ltd) as shown in Table 1. The Hou criteria presented in ref. [3] was implemented by VUMAT to describe materials failure. Two plies were extracted to run the simulation. Figure 1 shows the cutting regime and boundary condition of the FEM model. The two plies were tied together. Fiber orientation angle (FOA) was defined as the angle between cutting direction and fiber direction, as shown in Figure 1. By changing the principal direction in each ply, the cutting area deformation for any FOA can be simulated. When investigating the interaction of adjacent plies, the FOA of the two plies were set 45 °and 135 °respectively. The rake and clearance angle of the cutting tool were both 10°. The cutting depth was 100 μ m. The cutting tool was selected as analytical rigid body and a reference point was set on it. The velocity load was acted on the reference point to simulate real cutting speed. The mesh of local cutting area was refined to increase computing accuracy. The element type was 8-node brick elements with reduced integration (C3D8R). The element size was 4 μ m in refined zone. The interaction between rake face and elements was surface-to-node contact. The friction coefficients of the two surfaces were 0.3, 0.8, 0.49 and 0.6 respectively when FOA=0 °, 45 °, 90 °and 135 °.

Table 1. Properties of EHM

Properties	value
Elastic modulus (Gpa)	$E_{11}=120, E_{22}=8$
Poisson's ratio	$\nu=0.25$
Longitudinal/transverse tensile strength (Mpa)	$X_T=1800/Y_T=55$
Longitudinal/transverse compressive strength (Mpa)	$X_C=1200/Y_C=200$
Shear strength (Mpa)	$S_L=100/S_T=80$

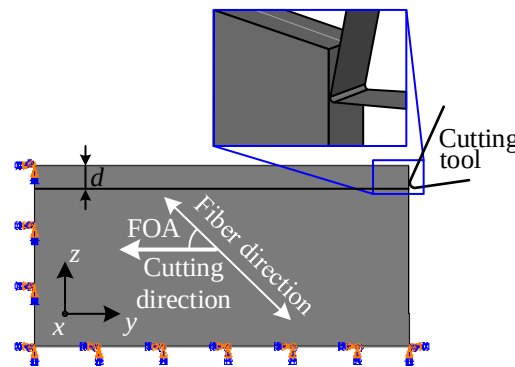


Figure 1. The scheme of FEM model

3. CFRP cutting experiment

CFRP cutting experiment was conducted to measure cutting area deformation and the damage propagation in sub-surface. The CFRP used in experiment was T300/7901. The thickness of each ply was 0.2mm with 56.3% fiber volume fraction. Two types (T_u and T_m) of workpieces were made. The stacking sequence of the T_u type was $[0]_{20}$, while the stacking sequence of the T_m type was $[45^\circ_{10}/-45^\circ_{10}]$. Both the dimension of T_u and T_m were 60 $\times$ 60 $\times$ 4mm. By aligning the workpieces in different direction, the FOA of T_u type can be 0 °, 45 °, 90 ° or 135 °, and the FOA of T_m type was a combination of 45 ° and 135 °. T_u type workpieces were used to measure the cutting area deformation when only one FOA was involved, while T_m type workpiece was used to investigate the deformation of the orthogonal stacking plies with two different FOAs. For T_u cutting, digital image correlation (DIC) method was used to measure the deformation. Random spots were sprayed on the surface which facing to the camera, as shown in Figure 2. The deformation was measured by calculating the movement of the

spots [7]. For T_m cutting, the sub-surface in the adjacent area of the two plies was examined to qualify the transverse transfer of deformation. A small cube which contained the adjacent area was taken out for the purpose of inspection.

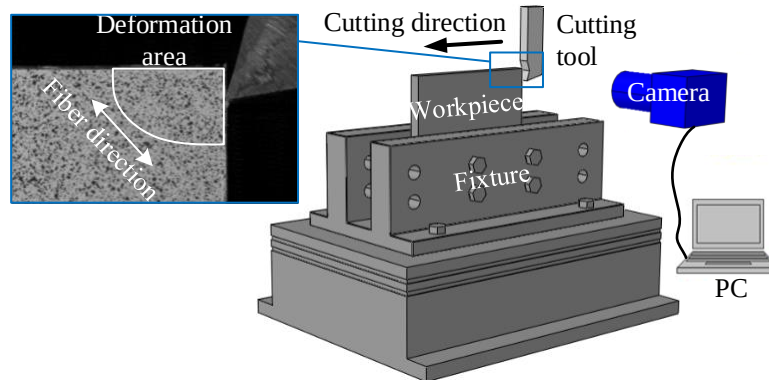


Figure 2. Scheme of experimental setup

4. Results and discussion

Figure 3 shows the comparison of the numerical and experimental results. The experimental results were obtained using T_u type workpiece. A deformation area forms in front of the cutting tip as the tool contacts the workpiece. The propagation of the deformation varies according to FOA and its trend is observed propagating along fibers direction in both numerical and experimental results. When $FOA=0^\circ$; as shown in Figure 3 (a) and (e), the deformation occurs not only in the materials to be removed but also in sub-surface. According to the DIC results in Figure 3 (e), the cracks propagate exactly in front of the cutting tip. The deformation, however, occurs not only in the materials to be removed, but also transfers to the sub-surface. When examining the sub-surface, as shown in Figure 3, no damage was observed. As FOA increases to 45° , the deformation in cutting area was found transferring along fibers direction. This can be seen from both numerical and experimental results, as shown in Figure 3 (b) and (f). The largest deformation occurred in front of the cutting tip and then it decreased gradually in fibers direction. The sub-surface damage was about $20\mu\text{m}$ (shown in Figure 3 (i)), which is much larger than that in $FOA=0^\circ$. The cracks were not observed in the experiment since the fibers and matrix around the cutting tip were crushed into powder-like chip.

When FOA reached 90° , more fibers and matrix involved in the deformation. The deformation transferred deeply into sub-surface, as shown in Figure 3 (c) and (g), leading to severe sub-surface damage. This is because the fibers and matrix tended to be bended towards lateral side to avoid the cutting tip. After experiencing out-of-plane deformation, extensive fiber-matrix interface debonding occurred in the cutting area. The damage length in sub-surface reached $235\mu\text{m}$ in this situation (shown in Figure 3 (k)).

When FOA is 135° , the fibers were raised to slide on the rake face as contacting the cutting tool. The role of cutting tip was weakened to a large extent. Larger out-of-plane deformation and severer fiber-matrix debonding were observed. The deformation in cutting area transferred deeply in the sub-surface, as shown in Figure 3 (d) and (h). The damage length in sub-surface reached $590\mu\text{m}$, which is the largest in the four situations.

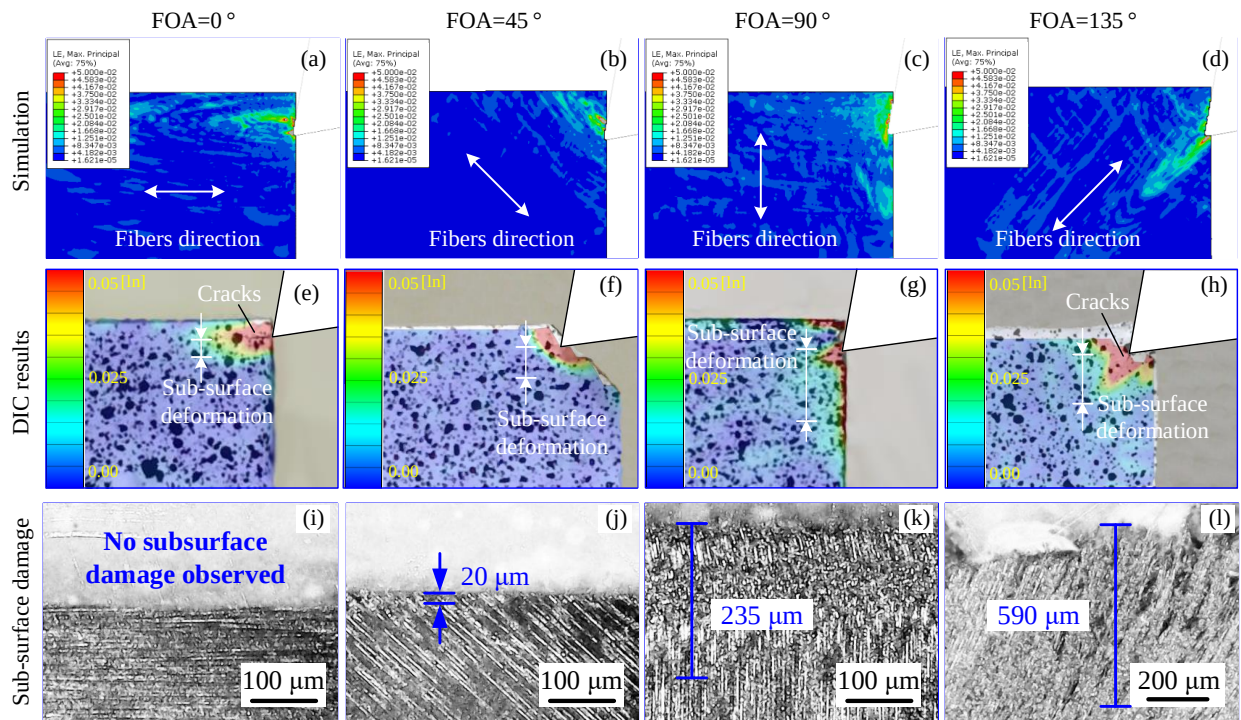


Figure 3. Comparison of cutting numerical and experimental results

According to the simulation and experimental results, the sub-surface damage has a positive correlation with the deformation in cutting area. One potential way to diminish sub-surface damage is to control the deformation in cutting area. For this purpose, an orthogonal stacking strategy was proposed in this study. Figure 4 shows the stress distribution in cutting area when the fibers in two adjacent plies are parallel and perpendicular. As can be seen, the stress in orthogonal stacking plies is not as concentrate as that in non-orthogonal stacking plies. This means the deformation in cutting area is reduced after the interaction of the two orthogonal stacking plies. In order to examine the sub-surface damage, a cutting experiment was conducted using T_m type workpiece. A small cube was taken from the workpiece. Surface 1-2-3-4 was the machined surface, while surface 3-4-5-6 was a cross-section in the cutting area. After polishing the cube, it can be seen an obvious boundary between the two orthogonal stacking plies. The damages cannot be judge from the machined surface. When examining surface 3-4-5-6, however, it was found that there was almost no damage for $FOA=45^\circ$ but a severe damage for $FOA=135^\circ$. The damage reduced gradually from the middle to the right side, as shown in Figure 5. This means the deformation can be controlled by adjusting stacking sequence since the deformation in two adjacent plies interacted with each other.

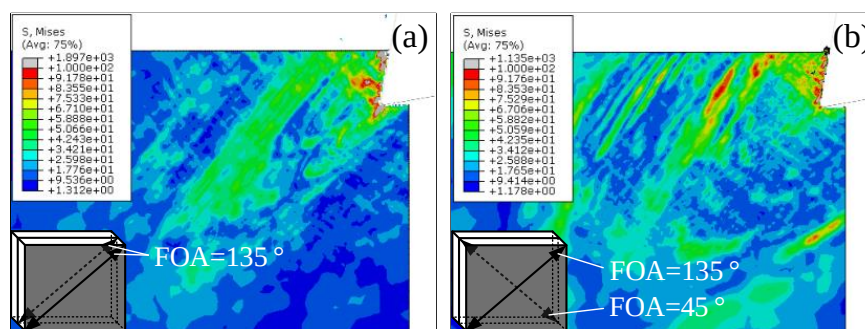


Figure 4. The stress distribution in cutting area: (a) non-orthogonal stacking; (b) orthogonal stacking

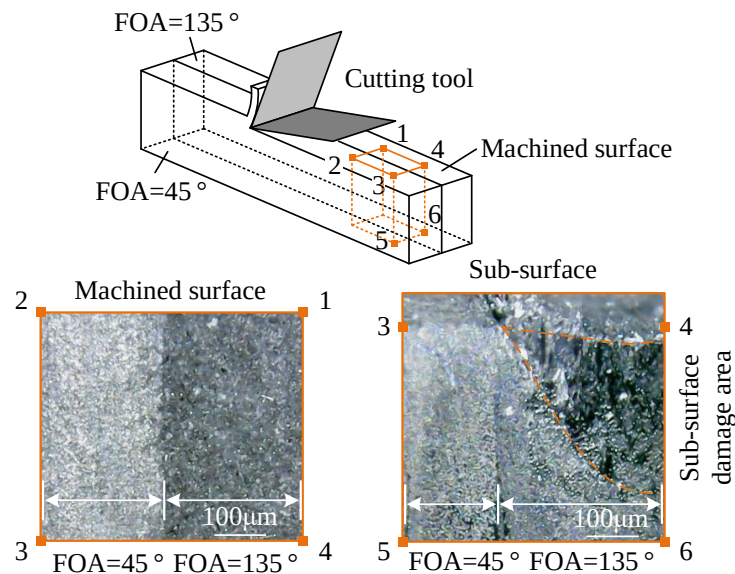


Figure 5. Machined surface and sub-surface damage

5. Conclusions

A numerical CFRP cutting model was built to simulate the stress distribution and an experiment was conducted to measure deformation in cutting area. According to numerical and experimental results, it can be concluded that the deformation in cutting area transfers along the fibers direction. The sub-surface damage has a positive correlation with the deformation. The interaction between two orthogonal adjacent plies can be used to control sub-surface damage. By applying the strategy in this study, the damage during machining of CFRP will be reduced to a large extent.

6. References

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