Chip Formation Mechanism in Machining of Carbon Fiber Reinforced Plastic

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Keywords: Machining of CFRP, Finite element model, Dynamic cutting process, Chip formation mechanism, Damage.

Abstract. Machining of carbon-fiber-reinforced plastic (CFRP) is still a challenging due to its inhomogeneous and anisotropic properties, which often lead to damage such as the delamination and the fiber pullout. The chip formation mechanism in machining of CFRP is completely different from the mechanism in metal cutting. In this paper, a two-dimensional macro equivalent homogeneous finite element model is established to simulate the dynamic cutting processes of unidirectional CFRP (UD-CFRP). The anisotropic material constitutive, the initial failure criterion and the damage evolution rule are defined in this model to investigate the material responses under the cutting load. Furthermore, the specific stiffness degradation variables are set to calculate the residual stiffness in cutting process. Failure mechanisms in chip formation in machining of CFRP for 0°, 45°, 90° and 135° fiber orientations are investigated by this model. And the effect of rake angle and the depth of cut on the chip formation are also analyzed. Cutting experiments of CFRP are obtained to observe the chipping process by microscopic observation accordingly. Finally, the chip formation mechanisms in machining of CFRP are summarized as the debonding-bending type and the cutting type. There is serious sub-surface damage in machining of CFRP for 135° fiber orientation.

Introduction

Composed of carbon fiber and matrix, CFRP gain wide applications in many industries such as aerospace, robotic[1], sport equipment[2], transportation[3] due to the high specific strength and high specific stiffness properties. In the aerospace industry, more and more CFRP materials are used in manufacturing the large-scale structures, such as main wing, central wing, horizontal tail and vertical tail. The utilization of CFRP materials become an important performance indicator of the modern aircrafts. CFRP components are often manufactured as a whole by laying and curing[4], but most of them need post processing such as milling and drilling, to meet the dimensional tolerance, surface and assembly requirements[5].

Due to the inhomogeneity and anisotropic nature of CFRP, its chip formation in machining of CFRP is completely different from those isotropic metals. Various damage tends to occur during machining of CFRP including delamination and fiber pullout, which inevitably lead to the poor quality[6]. The material removal mechanism in machining of CFRP is not clear[7]. Machining of CFRP has recently attracted a lot of attention from the academia and industry, and a number of relevant researches study the effects of the fiber orientation, machining parameters, tool geometries and materials nature[8-11] by the experiment, theory and simulation methods. Experiments are rather time-consuming and costly, and it is hard to test all different process parameters, especially for the material difficult to machining. In addition, CFRP dusts are poisonous which bring threat to the health of the testing staff[12]. Therefore, the finite element model has become an effective tool which can describe the cutting process intuitively and quickly[13]. Arola et al.[14] establish a quasi-static model to simulate the chip formation of UD-CFRP, and the model assumes two fracture processes: the maximum stress and the Tsai–Hill criteria. Mahdi et al.[15] develop the quasi-static model by considering chip breaking without predefined separation plane, which results in greater sensitivity.
and accuracy. Based on a similar model, Bhatnagar et al.[16] then simulate the initial instant of the cutting process to predict the depth of the induced damage. Santiuste et al.[17] use a model to simulate the induced damage during the single chip formation process. Hashin, Maximum stress and Hoffman criteria are compared. Results show that it would be better to predict the failure modes and the induced damage of matrix and fiber by the Hashin criteria. Most of these macro model analyzes the chip initiation phenomena without the continuous evolution of cutting. Furthermore, Calzada et al.[18] establish a micro model to describe the fiber failure occurring throughout the chip formation. Rao et al.[19] establish a two-dimensional, two-phase micromechanical model with the elastic fiber, elastic-plastic matrix and cohesive zone to simulate the debonding of the interface between the fiber and the matrix. These micro models are capable to simulate the local single fiber and surrounding matrix failure process, but it will take much higher computational cost.

This paper builds a finite element model which based on the anisotropic linear elastic constitutive, the Hashin failure criteria and the damage evolution rule. The dynamic cutting processes in machining of CFRP which include four types of failure modes are simulated. Furthermore, the orthogonal cutting experiments are conducted to investigate the chipping process and the cutting force. Chip formation mechanisms are discussed both experimentally and numerically for a range of fiber orientations (θ), depths of cut (ap), and rake angles (α).

Finite Element Model of Orthogonal Cutting

The UD-CFRP is defined as a two-dimensional model with an anisotropic linear elastic constitutive. Hashin failure criteria is taken into this model as the initial criteria of material failure, and a specific maximum stiffness degradation coefficient obtained by experiments is defined in order to accurately describe the failure initiation and evolution process of elements in cutting process.

Geometries and Boundary Conditions

Figure 1 shows a schematic diagram of the experimental test bed used for model validation. The workpiece is constrained at the bottom while the left and right sides are under the free boundary condition. Figure 2 shows the geometry and the boundary condition of the orthogonal cutting model. The cutting tool is defined as a rigid body represented by a reference point. The cutting speed is applied by an amplitude curve as shown in Figure 3, smoothly increasing from zero to the maximum, and then keeping as constant. Considering the calculation accuracy and efficiency, quadrilateral plane stress elements are used in the whole mesh, and the refining mesh elements are applied in the local contact area.
Materials Model

The orthogonal anisotropic linear elastic constitutive is defined in the UD-CFRP material model. The anisotropic nature of the material for different fiber orientations are fully considered, and the elastic property under the cutting load is maintained. The anisotropy nature of the material is represented by specifying material principal directions: 1st direction represents the orientation along the fiber and 2nd direction represents the direction perpendicular to the fiber. The material properties are shown in Tables 2. After the initial failure, the stiffness of CFRP will fall with increasing of the damage. The following linear elastic constructive model is obtained by linking the elastic property to the failure modes and damage level.

\[
\begin{bmatrix}
  1 & 0 & 0 \\
  \frac{-\nu_{12}}{E_1} & 1 & 0 \\
  0 & 0 & 1 \\
  \frac{1}{1-d} & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
  \sigma_{11} \\
  \sigma_{22} \\
  \tau_{12} \\
\end{bmatrix}
= 
\begin{bmatrix}
  \frac{1}{E_1} \\
  \frac{-\nu_{12}}{E_1} \\
  0 \\
  \frac{1}{G_{12}} \\
\end{bmatrix}
\begin{bmatrix}
  \varepsilon_{11} \\
  \varepsilon_{22} \\
  \gamma_{12} \\
\end{bmatrix}
\]  

(1)

where \(d\) is a variable of the stiffness degradation of CFRP, which is initially set to 0, and once one value of the four failure modes (as shown in Table 1) exceed 1. It means the failure starts.

<table>
<thead>
<tr>
<th>Failure modes</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal tensile fracture of fiber</td>
<td>(F'<em>l = \left(\frac{\sigma</em>{11}}{E_1}\right)^2 + \alpha \left(\frac{\tau_{12}}{S_1}\right)^2)</td>
</tr>
<tr>
<td>Longitudinal compressive fracture of fiber</td>
<td>(F'<em>c = \left(\frac{\sigma</em>{11}}{E_1}\right)^2)</td>
</tr>
<tr>
<td>Transverse tensile fracture of fiber</td>
<td>(F'<em>m = \left(\frac{\sigma</em>{12}}{Y}\right)^2 + \alpha \left(\frac{\tau_{12}}{S_1}\right)^2)</td>
</tr>
<tr>
<td>Transverse compressive fracture of fiber</td>
<td>(F'<em>n = \left(\frac{\sigma</em>{12}}{2S}\right)^2 + \left(\frac{Y}{2S}\right)^2 - 1 \left(\frac{\sigma_{12}}{Y}\right) + \left(\frac{\tau_{12}}{S_1}\right)^2)</td>
</tr>
</tbody>
</table>

Contact Model

Given the continual and dynamic contact relationships between the tool and the materials, surface-surface contact is defined between the materials and the tool. As the cutter has a higher stiffness than CFRP, the contact face of the cutter is defined as the first surface and the contact face of the workpiece is defined as the second surface. The force in normal direction will be transferred when pressure occurs between the cutter and the workpiece. The contact behavior along the normal direction is defined as hard contact. Two contact areas are formed: one is between the tool’s rake face and the chips and the other is between the tool’s clearance face and the machined surface. Suppose the
K-C law applies to both areas, and the friction coefficients are defined as 0.3, 0.6, 0.8 and 0.6 for fibers in 0°, 45°, 90° and 135° respectively[20].

Material Failure Model

CFRP composites cutting is a process that the materials gradually fail under the pushing of the cutting tool. The key part of the process is the chip formation and separation. To simulate the process, Element failure model is adopted in this paper. The element failure model is to describe the element stiffness degradation: when the elements based on the specific constructive model fail, the element stiffness degrades regularly until the bearing capacity completely disappears. As shown in Figure 4, the process of elements’ failure contains three stages: A-B represents the material respond curve; B point represents the initial failure which is determined by the Hashin criteria[21,22] as shown in Table 1; B-C represents the damage evolution curve.

![Figure 4. The stress-strain curve used in simulation.](image)

When reaching the initial destruction point (B), the element stiffness begins to degrade. The variable of stiffness degradation is introduced to describe the degree of the destruction. After the initial destruction, the elastic modulus of the UD-CFRP composites can be described in the following equation:

\[ E = (1 - D)E_0 \]

when D=0.7, the material loses the bearing capacity and the elements will be deleted from the model.

Numerical Simulation and Validation

The finite element model is validated through a number of experiments in which different sets of process parameters are applied in planning CFRP materials with varied fiber orientations as shown in Table 3.

Definition of Fiber Orientation

CFRP is anisotropic material. Fiber orientations will have a direct influence on the failure mechanisms. As shown in Figure 5, fiber orientation (θ) is measured clockwise from the cutting direction to fiber direction. θ is varied between 0° and 180° in 45° steps.

![Figure 5. The definition of fiber orientation.](image)

Experiment Setup

Unidirectional carbon fiber (T800) prepregs are used. The specimens are laid-up by 24 plies with ply thickness of 125μm, solidified in autoclave under pressure of 0.62MPa. The fiber volume fraction
of the specimen as found to be 65% by Ignition Loss Method (ASTM D 2584). Using an NC slot saw and diamond impregnated wheel, the panels are fabricated into test specimens of desired fiber orientations: 0°, 45°, 90°, 135° and desire dimensions 100mm×30mm×3mm.

The experiments are conducted on a VGM210 five-axis NC machining center, as shown in Figure 1. A special single-edge cutting tool is designed using YG8 material for the orthogonal cutting, and the tool is clamped on the spindle. The spindle is locked, and the specimens move with the travelling table while processing. The minimum resolution of the NC machining center is 0.1m.

Table 3 lists the machining parameters as shown in Figure 1, the cutting forces are collected using 6-component Kistler 9257B dynamometer, and the cutting process images are captured by a video recording device which is composed of PHOTRON SA5 high-speed camera, VH-Z50L microscope and a single-hole halogen light.

Table 3. Operation condition.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>UD-CFRP</td>
<td></td>
</tr>
<tr>
<td>Specimen dimension</td>
<td>100×30×3</td>
</tr>
<tr>
<td>Rake angle (γ°)</td>
<td>25, 10</td>
</tr>
<tr>
<td>Clearance angle (α°)</td>
<td>10, 5</td>
</tr>
<tr>
<td>Edge radius (r/m)</td>
<td>7</td>
</tr>
<tr>
<td>Depth of cut (a, /m)</td>
<td>50, 100, 150</td>
</tr>
<tr>
<td>Tool geometries</td>
<td></td>
</tr>
<tr>
<td>Machining parameters</td>
<td></td>
</tr>
<tr>
<td>Fiber orientation (°)</td>
<td>0, 45, 90, 135</td>
</tr>
<tr>
<td>Cutting speed (Vc/m/s)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Simulation Set-up

The simulation process of machining CFRP contains continual dynamic contact relationship and dynamic material failure process. These processes are highly nonlinear. Thus, the simulation is carried out using ABAQUS/EXPLICIT software which is expert in solving nonlinear problems. Models of different fiber orientations are established to simulate the continual dynamic cutting process in machining of UD-CFRP. Same machining conditions are applied to both simulation and experiment for validation as shown in table 3.

Results and Discussions

Chip Formation

Figure 6 shows the simulation results in machining 0° fiber orientation CFRP. When the tool contacts the workpiece, compress and shear failure occurs to the matrix along the fiber orientation, and the materials bend forward. Then the tensile and shear failure occurs to the fiber perpendicular to the fiber orientation. Finally, the chips form at certain point in front of the tool.

The images captured during the experiment are shown in Figure 7 in cutting 0° fiber orientation CFRP. It can be observed that the materials buckling along the fiber orientation, bending forward and finally separated from the workpiece. This is consistent with the simulation results. The chip formation mechanism of the 0° fiber orientation is the debonding-bending type.
Figure 7. Micro observation images of chip formation for 0° fiber orientation.

Simulation results of cutting 45° fiber orientation CFRP are shown in Figure 8. Under the compress of the tool, the crush fracture with the tensile and shear failure first occurs in the direction perpendicular to the fiber. Then the failure of compress and shear occurs to the matrix along the fiber direction. Finally, the materials are separated from the workpiece, and then the chips are formed. Figure 9 shows the images of the cutting process of 45° fiber orientation CFRP. It can be observed that the material buckles along the fiber orientation. Then, chips fly off the workpiece. This is consistent with the simulation results. The chip formation mechanism of the 45° fiber orientation is the cutting type.

Figure 8. Simulation results of chip formation for 45° fiber orientation.

Figure 9. Micro observation images of chip formation for 45° fiber orientation.

Figure 10 shows the simulation results of 90° CFRP. Under the pressure of the tool, the failure of tensile and shear occurs perpendicular to the fiber orientation. As the tool moves forward, the contact area of the material and the rake face increases, and the push force upward from the tool increases. Then the failure of tensile and shear, compress and shear occurs to the matrix along the fiber orientation. Finally, the material is separated from the workpiece at a certain point in front of the tool.

Figure 11 shows the results from cutting experiment for 90° fiber orientation. After the tool contacts the workpiece, the cracks propagate forward perpendicular to the tool. As the tool moves forward, the matrix bucks along the fiber orientation ahead of the tool, finally, the material separate from the workpiece and form the chips. The chip formation mechanism of the 90° fiber orientation is the cutting type.

Figure 12 shows the results from 135° fiber orientation cutting simulation. The material deforms under the stress of the rake face. As the tool move forward, the deformation of the material continues increase, and then the failure of tensile and shear, compress and shear occurs to the matrix due to the excessive elastic deformation. And the failure of the matrix propagates deep into the surface. As the tool continues to move forward, the press from the tool’s rake face continues increase, and then the failure of tensile to the fibers and the failure of compress and shear occurs at the same time. Finally, the separated materials form the chips of blocks.
Figure 10. Simulation results of chip formation for 90° fiber orientation.

Figure 11. Micro observation images of chip formation for 90° fiber orientation.

Figure 12. Simulation results of chip formation for 135° fiber orientation.

After the tool contact the workpiece in experimental observation as shown in Figure 13, the material bend forward under the press of the tool, and at the same time, the matrix crack along the fiber orientation. As the tool move on, the cracking and the bending of the material continues to increase and finally the failure of bending occurs to the fiber and forms the chip of blocks.

Figure 13. Micro observation images of chip formation for 135° fiber orientation.

As it is an equivalent homogeneous model, we cannot directly observe the procession of matrix cracking. But the failure of tensile occurs to the matrix from the simulation results can reflect it. The failure mechanisms of 135° fiber orientation is that the fibers bend under the push of the tool and induces the bulking of the matrix, and then the fibers bend to break and the matrix fail at a point under the surface, leading to the formation of the chips. The chip formation mechanism of the 135° fiber orientation is the debonding-bending type. The results from both simulations and experiments show that fiber orientation is the main influence factor of the failure mechanisms of the CFRP composites. As shown in Figure 14 and 15, the failure mechanism can be concluded into two types: debonding-bending and cutting.

Figure 14. Chip formation of the debonding-bending type.
Effect of the Depth of Cut and Rake Angle

Figure 16 and 17 show simulation and experimental results in the case of 45° fiber orientation, at 50μm and 100μm cutting depths, 25° rake angle, 10° clearance angle and 0.5 m/min cutting speed. It is observed that the cutting depths have little effect on the failure mechanisms, but the chip sizes decrease as the cutting depth increases.

Figure 16. 135° simulation results under different depths of cut.

Figure 17. 45° simulation results under different depths of cut.

Figure 18 shows force analysis in cutting 45° CFRP. The main forces applied to the materials are along the direction of the cutting speed. The cutting force ($F_c$) is divided into two parts: the force along the fiber orientation ($F_{c1}$) and the force perpendicular to the fiber orientation ($F_{c2}$). Figure 19 shows the average cutting forces from the results of simulations and experiments. It is observed that as the depth of cut increases, the cutting forces increase. Thus, the force along the fiber orientation also increases. However, for the certain material, the ultimate strength of the matrix is specific. Consequently, in the case of large depth of cut, shear failure along the interface will occur to generate smaller chips.

Figure 18. Chip separation for 45° fiber orientation.

Figure 19. Cutting forces under different depths of cut.

In the case of 45° fiber orientation, the effects of the rake angle on the failure mechanism are as shown in Figure 20. With the change of rake angle from 10° to 25°, there is no influence on the failure
mechanism, but has a significant influence on size of the chip. Fig. 21 shows that the chips’ sizes decrease as the rake angles increase.

![Figure 20. 45° simulation results of different rake angles.](image1)

![Figure 21. 45° simulation results of different rake angles.](image2)

As shown in Figure 22, in the case of 45° materials in the contact area cracks under the pressure of the tool, and then slides along the rake face. As the tool advances, the crispation of the chip occurs. Meanwhile, the cracking of the interface and the matrix along the fiber orientation would come into being leading to the chip separation. It is easily to crack due to the excessive deformation under the pressure of rake face, and the chip size decreases with the increase of the rake angle.

![Figure 22. Chip formation of different rake angles for 45° fiber orientation.](image3)

As shown in Figure 23, the cases of -5°, 0°, 15° and 20° rake angles are conducted through the simulation. Results show that the failure mechanism in the cases of 15° and 20° rake angles is very similar to that of the 10° and 25° cases. So at specific fiber orientation, the failure mechanism will not change if the stress state of the material does not change. In the case of negative rake angle, the stress state of the material changes from push-forward to push-downward, and the failure mechanism change from cutting into crushing accordingly.

![Figure 23. Simulation results under varied rake angles for 135° fiber orientation.](image4)

In the case of >90°, the change of the rake angle will also influence the failure mechanism. If + <180° and >0°, the rake face firstly contacts the material and then the tool nose contact the material, so that the failure mechanism is the bending dominate fracture. If + >180° and >0°, the crushing dominate fracture occurs which is same as the case of 90° fiber orientation as shown in Figure 24.
Summary

Both experiment and simulation are conducted on orthogonal cutting of UD-CFRP. The following conclusions can be drawn from this work.

Fiber orientation has the main effect on the failure mechanisms in machining of CFRP. In case of the 45° and 90° fiber orientations, the type of the chip formation is cutting. In the case of 0° and 135° fiber orientations, the type of the chip formation is debonding-bending.

The depth of cut has little effect on the failure mechanisms in range of 50µm to 150µm, but has a large effect on the size of chips. As the depth of cut increases, the chip decrease in case of 45° fiber orientation.

When rake angle is positive, it has little effect on the chip formation mechanism, but has a large effect on the size of chips. As rake angle increases, the size of chips decreases in case of 45° fiber orientation. However, there is a significant influence on the chip formation mechanism in case of 135° fiber orientation. In case of negative rake angle, the failure mechanism in chip formation changes from the cutting to the crushing.

Acknowledgement

This research was financially supported by the Scientific Research Foundation of NINGXIA UNIVERSITY (grant number ZR1705).

References


