한국정밀공학회지 제 33 권 제 6 호 pp. 447-452 June 2016 / 447
J. Korean Soc. Precis. Eng., Vol. 33, No. 6, pp. 447-452 http://dx.doi.org/10.7736/KSPE.2016.33.6.447
ISSN 1225-9071(Print), ISSN 2287-8769(Online)

◆ 특집 ◆ 탄소섬유복합재 가공시스템

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3-Axis Milling Algorithm Development for Carbon Fiber Reinforced Polymer (CFRP) Composites

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Manuscript received: 2016.5.12. / Revised: 2016.5.25. / Accepted: 2016.5.27.

The simulation of Carbon fiber reinforced polymer (CFRP) machining facilitates the selection of optimal cutting parameter for high machining efficiency and better surface quality. In this study, This paper proposes a dual-dexel model to represent the fiber laminate with computational geometry method to calculate the fiber length removed per revolution and fiber cutting angles. A flat end milling simulation software is developed in C# to simulate and display the CFRP milling process. During simulation, fiber lengths, fiber cutting angle and engaged cutting angle can be displayed in real-time. A CFRP plate with different angles in different layer is used to compare the simulation results.

KEYWORDS: CFRP (탄소섬유복합재), Milling (밀링), Simulation (시뮬레이션), Fiber length (섬유길이)

1. Introduction

Carbon fiber reinforced polymer (CFRP) has been widely used in aerospace, automobile and chemical industries due to the properties of high strength, high stiffness and low weight.[1] Although CFRP composites are usually fabricated to near net shapes,[2] a post machining operation, such as turning, trimming the edge or drilling holes is often necessary. However, machining of CFRPs is more difficult than conventional metals due to the heterogeneous nature of the composite structure. Delamination, matrix fracture and buckling are the principal drawbacks for CFRP machining. Thus, it is important to understand the mechanics of carbon fibers during CFRP machining.

The machinability of CFRP depends on the fiber direction of the laminate, cutting parameters and the tool geometry. There are many researches about the effects of fiber direction to cutting forces and machined surface quality. Lopresto[3] investigates the relations of fiber orientation and cutting forces. The maximum force happens as the fiber direction is 90°, and the minimum

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force occurs between 15° to 30°. Hintze[4] studies the delamination is highly relative on the fiber orientation and the tool sharpness. Machining of CFRP composites has also been studied experimentally[5-7] and through finite element modeling simulations.[8] However, simulations of carbon fiber cutting kinematics such as fiber length calculation have not been considered for CFRP milling operations.

This work aims to develop algorithms to calculate fiber lengths, fiber directions, and chip thickness during machining and investigate the relationship among them. In this paper, 2D simulation approach for CFRP milling operations is presented. The carbon fibers are represented by dexel lines, which are geometrically cut by a milling tool represented as a circle. The number and lengths of fibers cut per revolution of the tool are geometrically obtained and presented.

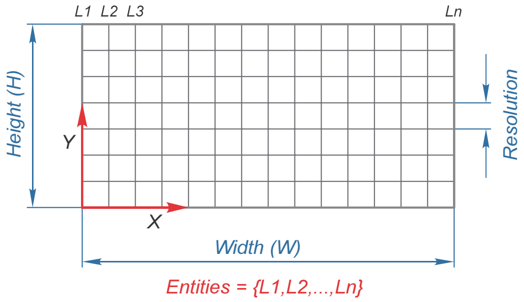
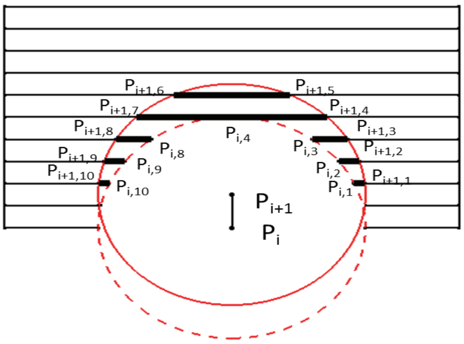
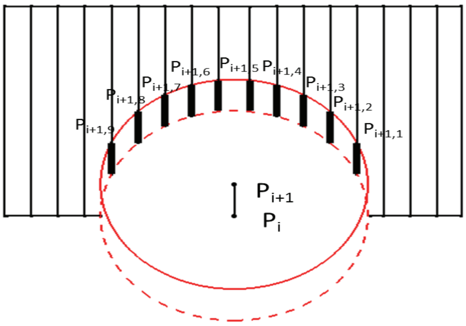


Fig. 1 Workpiece represented with dexels



(a) Fiber direction $\theta = 0°$



(b) Fiber direction $\theta = 90°$

Fig. 2 Dexel trimming and creation of fiber lengths

2. Simulation Software Development

2.1 CFRP Workpiece Representation Model

In order to calculate instantaneous fiber lengths during the two dimensional (2D) simulation of the milling process, the workpiece and material removal need to be represented as geometrical models. Dexel was chosen to represent the workpiece, as it allows for the filling of large areas without requiring data on every section of the area, resulting in highly efficient computation. A new multi-dexel implementation was used, in which there are axes of grids with each axis representing carbon fiber directions. Fig. 1 shows the workpiece represented with dexels. Lines that represent carbon fibers are, for example, added to the Entities array along the X and Y axes at the resolution R that represents fiber spacing, and the workpiece size is determined by the height (H) and width (W) inputs. A circular array Cutter is created to represent the milling tool.

2.2 Fiber Length Calculation Algorithm

During simulation, as the cutter is moved from its current position P_i to the next position P_{i+1}, new intersection points of the current cutter profile and fibers are determined, denoted by $P_{i+1,j}$ as shown in Fig. 2. The machined lengths of fibers are represented by the line segment lengths from the current cutter intersection points $P_{i+1,j}$ along the fiber direction to the previous cutter edge. In Fig. 2, it displays the fibers between the current and previous tool edges are trimmed. Comparing the removed fiber length in the fiber direction of 0° (in Fig. 2(a)) and 90° (in Fig. 2(b)), it can be seen that the fiber length at different intersections depend on the fiber direction. The fiber length at various intersection points in one revolution changes a lot as the fiber direction is 0°; while the fiber length changes stably in the fiber direction of 90°.

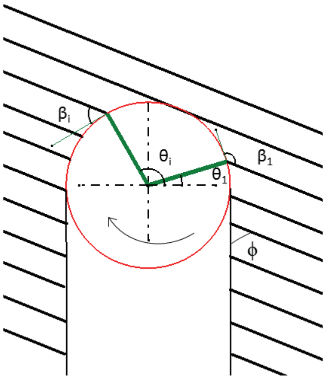


Fig. 3 The relation of fiber cutting angle β, rotation angle θ and fiber direction

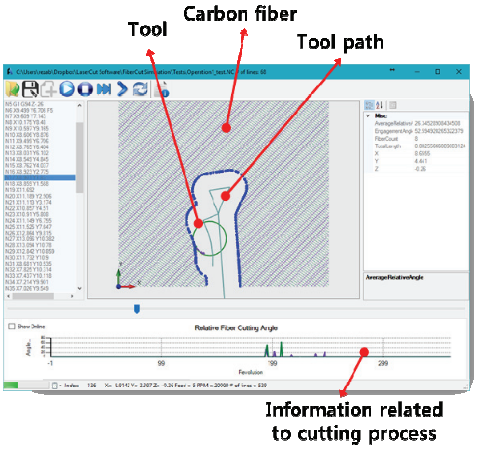
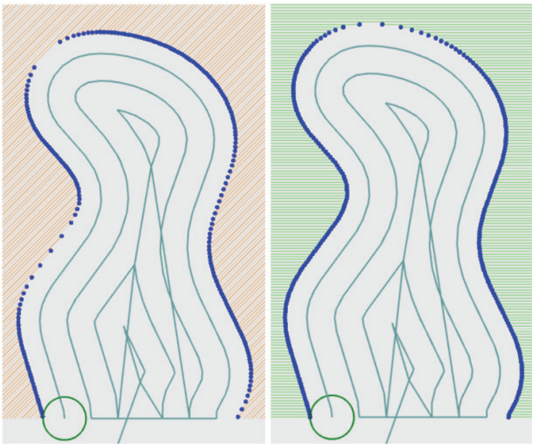


Fig. 4 Fiber milling simulation software snapshot

2.3 Fiber Cutting Angle Calculation Algorithm

Fiber cutting angle can be used to obtain tangential and radial cutting force coefficients through milling tests.[9] In Fig. 3, it shows the fiber cutting angle (β) is relative to the fiber orientation (ϕ) and the tool rotational angle (θ) during milling. The rotational angle is measured counterclockwise from the x axis. The fiber direction angle is also measured counterclockwise. The fiber cutting angle is the angle between fiber direction and the tangential line at the intersection of the cutting tool and the material as shown in Fig. 3. Thus, the fiber cutting angle is related to the tool's rotational angle and the fiber orientation. After some geometric analysis, the fiber cutting angle can be obtained as follows:

$$\beta_i = \theta_i + \phi + 90 \text{ if } \beta_i \geq 180 \text{ then } \beta_i = \text{mod } (\beta_i, 180) \quad (1)$$



(a) (b)

Fig. 5 (a) fiber toolpath at the first layer, fiber direction θ = 45°, (b) fiber toolpath at the second layer, $\theta = 0°$

2.4 Simulation Software Development

In order to implement the method mentioned above, a flat end milling simulation software was developed in C#. For graphical visualization, commercial CAD component Eyeshot, powered by OpenGL, was used. An example of the interface is shown in Fig. 4.

The software simulates a flat end milling operation according to the uploaded G-code. The G-code and its execution are shown on the left side of the interface. Accumulated fiber lengths can be seen at the bottom in real-time during simulation.

3. Case Studies and Results

The simulation has been carried out in a multi-direction laminate plate with 2 alternating layers of fibers. The thickness for each layer is 0.2 mm. The plate size is 6 mm x 8 mm for the width and height. A two-fluted flat-end mill with a diameter of 0.794 mm is used to cut the CFRP. A pocket tool path is generated in the MasterCAM. In the Fig. 5(a), it shows the pocket tool path in first layer of the laminate plate with a fiber direction of 45°. The fiber direction in the second layer is 0° shown in the Fig. 5(b). In this software, different color can be set to represent different layers by user.

Fiber length is an important parameter to know how much fiber can be removed per revolution. In Fig. 2, it can be seen that the fiber length depends on the fiber

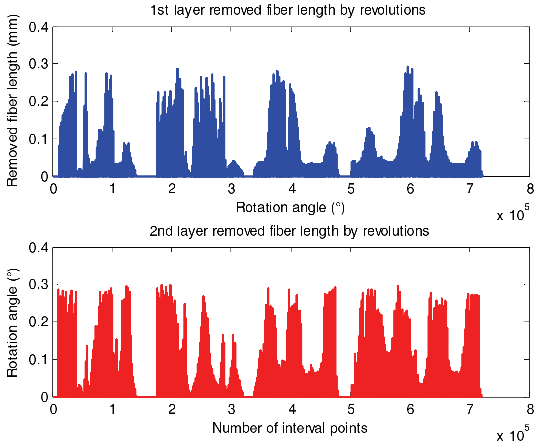


Fig. 6 Removed fiber length changed by rotation angles in the 1st layer ($\theta=45°$) and the 2nd layer ($\theta=0°$)

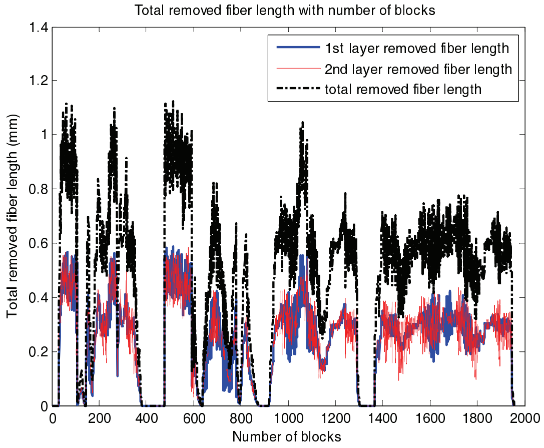


Fig. 7 Total removed fiber length with different number of blocks

direction and the previous and current cutter intersection points. As the fiber direction is 90°, the fiber length at some current cutter intersection points is much longer than that as the fiber direction is 0°. For each revolution, the number of angular integration step is 360. Fig. 6 shows the removed fiber length is changing with rotation angles in the first and second layers for the whole toolpath.

The total fiber length is the sum of fiber length for one revolution. There are around 2000 blocks or NC points for the whole toolpath shown in Fig. 5. Fig. 7 shows the total removed fiber length changed with different number of blocks for different layers. The black center line is the total cutting fiber length, which is the sum of the 1st and 2nd layer total removed fiber length.

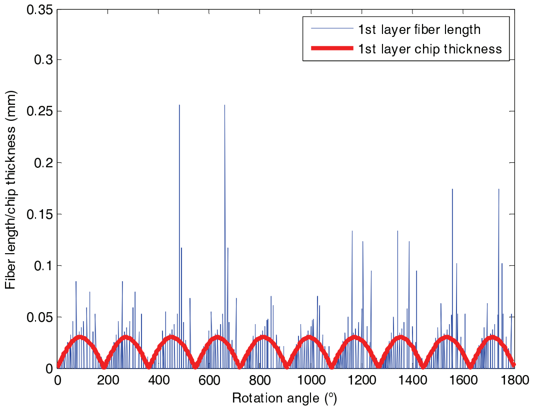


Fig. 8 Comparison of fiber length and chip thickness in 5 revolutions in the 1st layer of the fiber

Chip thickness is an important parameter to calculate chip volume and cutting forces. There are many papers about chip thickness calculation,[10] but no one does the research of fiber length. The typical method to calculate the chip thickness t using a flat-end mill is the sine product assumption.[11]

$$t = f_t \sin\theta \tag{2}$$

where f_t is the feed per tooth, θ is the rotation angle.

To know the difference of fiber length and chip thickness, they are compared in five revolutions in the first layer of the fiber. It can be seen in Fig. 8, the chip thickness is equal or less than the feed per tooth. But the fiber length can be larger than the feed per tooth. That is due to the fiber orientation and the feed direction. For instance, the fiber length of line $P_{i+1,4}\,P_{i+1,7}$ shown in Fig. 2(a) is much longer than the fiber length $P_{i,5}\,P_{i+1,5}$ in Fig. 2(b).

In Fig. 9, it compares the removed fiber length and chip thickness in the first layer of the fiber for the whole toolpath.

The fiber cutting angle is significant to calculate cutting forces. Therefore, it is necessary to predict how the fiber cutting angle changes during the milling process. Fig. 10 compares the fiber cutting angle in different layers for the whole toolpath.

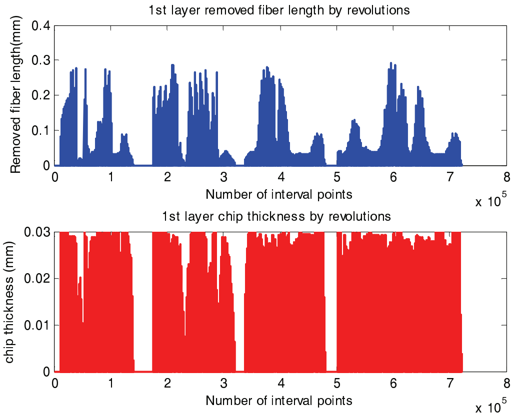


Fig. 9 Comparison of fiber length and chip thickness in the 1st layer of the fiber for the whole toolpath

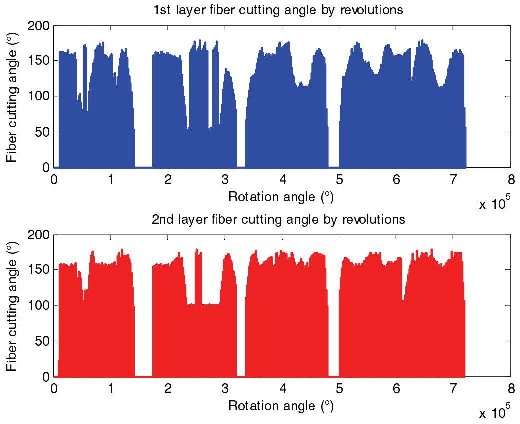


Fig. 10 Comparison of fiber cutting angle in the 1st and 2nd layer of the fiber for the whole toolpath

4. Conclusions

In this work, a milling simulation algorithm for CFRP composite has been developed to simulate and display the CFRP milling process. The software can be used to understand the CFRP cutting process and the effects of carbon fibers. Fiber lengths cut per revolution of the tool is calculated and compared in different layers of the fiber laminate with various fiber directions. The differences of fiber length and chip thickness have been compared in the paper. Variations in the fiber lengths are much larger than the chip thickness. Also simulation shows that the fiber cutting angle varies differently depending on the fiber orientation.

ACKNOWLEDGEMENT

This work was supported by the Technology Innovation Program (10053248, Development of Manufacturing System for CFRP (Carbon Fiber Reinforced Plastics) Machining) funded By the Ministry of Trade, industry & Energy(MOTIE, Korea).

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