Cutting Force Mechanism Model of Plain Wove CF/PEEK Milling Considering Size Effect

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KEYWORDS: Cutting force, Size effect; Wove CF/PEEK; Cutting mechanisms

Abstract: *Size effect caused by structural characteristics of workpiece is a new perspective in machining Carbon Fiber Reinforced Polymer (CFRP), as the radius of carbon fibers and cutting edge are in the same order of magnitude. Size effect causes two new cutting mechanisms including impact and workpiece self-action in CFRP machining, especially in wove CFRP. To this end, we presented a cutting force prediction model of high-speed dry (HSD) milling plain wove CFRP considering size effect, since the cutting force is the most direct reaction of cutting mechanism. Firstly, the pseudo-random model of carbon fiber distribution was established to describe the microstructure of the workpiece. Secondly, the main cutting mechanisms including bending, shearing, stretching and delamination, impacting, pressing and bouncing in machining plain wove CFRP were clarified based on size effect, structural characteristics of workpiece and different cutting position of cutting tool. The HSD milling force mechanism model was proofed with a high prediction accuracy of about 90.1%.*

NOMENCLATURE

μ_f = friction coefficient
k_I = correction coefficient of friction cutting force
γ = is rake angle.
ψ = direction of cutting speed
F = cutting force
$F_{I,\ II,\ III}$ =cutting force in position I, II, and III
$F_{I,\ II,\ III\_m,\ f}$= cutting force in position I, II, and III caused by matrix and carbon fiber

1. Introduction (Times New Roman 10pt)

The advanced Carbon Fiber Reinforced Polymer (CFRP) composites have already been widely used in aerospace[1, 2] and aeronautical structures [3, 4], carbodies[5], etc., due to their high specific stiffness and strength, excellent fatigue performance and corrosion resistance. However, CFRP materials are difficult-to-process materials[6] and many manufacturing defects exist in machined surface, including pull-out of the fibers, burning, burrs, fiber-matrix debonding and delamination etc.[7]. Therefore, it is essential to clarify the cutting mechanisms of machining CFRP for reducing manufacturing defects [8] and designing specified cutter. Reasonably predicting force is of great significance to improve the machining quality and the tool life[9], which is also the most direct reaction of cutting mechanisms. So far, many researchers had studied cutting force in milling composites for a higher processing quality.

Su et al. [9] developed a methodology for predicting the plain-wove CFRP milling forces by transforming specific cutting energies derived from the theoretical model of orthogonal cutting. Through the experimental data, the correlation between the cutting force coefficients and the rotation angle was obtained. This methodology was an empirical method, which can provide a reference for the prediction and the control of cutting forces in actual milling of plain-wove CFRP. Xu and Wang [10] studied the variation law of cutting force by milling a woven CFRP. The research found that the increase in tool rake angle played a positive role in reducing the cutting force, while the equivalent cutting area was opposite. Morkavuk et al. [11] immersed plain wove CFRP in cryogenic liquid for slot milling. The results showed that cryogenic machining approach provided less damage formation on the machined surface but increased resulting cutting force.

In this paper, a plain wove CF/PEEK cutting force prediction me chanism model was established considering size effect, as the radius o f carbon fiber and cutting edge are in the same order of magnitude. Ba sed on the size effect, the model proposed that the main cutting mecha nisms of plain wove CF/PEEK processing include bending, shearing, stretching and delamination, impacting, pressing, and bouncing.

2. The cutting force prediction model

2.1 Cutting force prediction generated in position I

Before the cutting is completed, the chip is still connected with the workpiece. Therefore, the chip can be regarded as a simply supported beam. The fulcrum is the rake face of the tool and the fixed point (FP) as shown in Fig. 1 (b). As shown in Fig. 1 (a) and (b), the chip changes from a straight state to a curved state with the move of cutting tool. In order to obtain the cutting force of position I, it is necessary to carry out geometric analysis of chip deformation, and the cutting force of this part is calculated by material mechanics.

Because solids are incompressible and plain wove CF/PEEK cannot form continuous shear plane due to carbon fibers interference, the length of chip surface in base-plane is considered to be constant, as shown in Fig. 1 (b). As the tool moves, the chip geometry features are as follows: i) The chip bends to a concentric arc with a concentric angle 2φ and the center of the concentric circle is O. ii) The chip is an arc tangent to the cutting edge. iii) The length difference of concentric arc is the length difference of the chip part parallel to the rake face, and L_c is the maximum length difference of the chip part parallel to the rake face, as shown in Fig. 1 (b). As shown in Fig. 1 (b)~(d), the coordinates x'O'y' is computational coordinates.

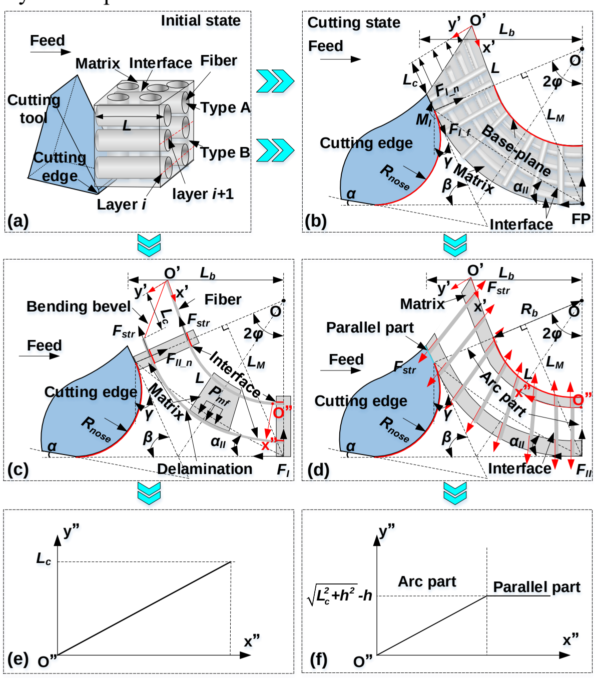

Fig. 1 Analysis diagram of cutting process in position I

In the cutting process, the deformation of the matrix is restricted by carbon fiber. The geometric characteristics of matrix along the axial direction of type A carbon fibers in cutting is shown in Fig. 1 (b). Within the elastic limit, the tensile characteristics of the chip along the axis direction of the type A carbon fibers are shown in the Fig. 1 (e). Based on Hooke's law, the cutting force differential produced by bending of matrix along the axial direction of type A carbon fibers in position I can be obtained as [12].

The geometric characteristics of matrix along the axial direction of type B carbon fibers in cutting is shown in Fig. 1 (b). Within the elastic limit, the tensile characteristics of the chip along the axis direction of the type B carbon fibers are shown in the Fig. 1 (f). Based on Hooke's law, the cutting force produced by bending of matrix along the axial direction of type B carbon fibers in position I can be obtained. The cutting force components of PEEK matrix cutting in position I in the x and y direction are as follows:

$$\begin{vmatrix} F_{I\_my} \\ F_{I\_mx} \end{vmatrix} = \begin{vmatrix} F_{I\_mn} & F_{I\_mf} \\ F_{I\_mf} & F_{I\_mn} \end{vmatrix} \begin{vmatrix} \cos\gamma \\ \sin\gamma \end{vmatrix} = F_{I\_mn} \begin{vmatrix} 1 & 1/k_I\mu_f \\ 1/k_I\mu_f & 1 \end{vmatrix} \begin{vmatrix} \cos\gamma \\ \sin\gamma \end{vmatrix} \tag{1}$$

The elastic range of matrix and carbon fibers are different, so interface delamination usually occurs in deformation process of chip in cutting [13]. As shown in Fig. 1 (c), due to the different deformation coefficients of the matrix and the carbon fiber, the interface produces a force that tends to be delaminated during the cutting deformation process of chip. At the same time, the force from the tool is transmitted to the carbon fiber through the matrix and the interface. Since the carbon fibers conforms to the light rope model, the carbon fibers are subjected to tension from the interface.

Based on [14], the delamination can be calculated only considering interlaminar shear stresses (ILSS). The interface is dependent on the matrix and carbon fibers. In deformation process, the matrix can be damaged when the deformation is too large to make the deformation stress exceed the tensile strength, which leads to carbon fibers cannot be stretched. The maximum number of layers along the axis direction of the type A carbon fibers thcan be expressed by [12]. Based on geometrical relationship in Fig. 1 (c) and elastic-plastic theory, the delamination pressure on the interface of type A carbon fibers and matrix can be calculated.

The cutting force produced by the stretching of type A carbon fibers is caused by elastic-plastic deformation, as shown in Fig. 1 (c), due to the interaction between matrix and fibers, which can be calculated by composite light ropes model and the Hooke's law. The deformation along the axis direction of the type B carbon fibers is small, so the matrix failure in this direction can be ignored. The sum of the cutting force generated by the carbon fibers and the matrix is the total cutting force. Based on Eq. (10) and Eq. (20), the total cutting force in position I in in the x and y direction are as follows

$$\begin{vmatrix} F_{I\_y} \\ F_{I\_x} \end{vmatrix} = \begin{vmatrix} F_{I\_my} \\ F_{I\_mx} \end{vmatrix} + \begin{vmatrix} F_{I\_fy} \\ F_{I\_fx} \end{vmatrix} = \left(F_{I\_mn} + F_{I\_fn}\right) \begin{vmatrix} 1 & 1/k_I\mu_f \\ 1/k_I\mu_f & 1 \end{vmatrix} \begin{vmatrix} \cos\gamma \\ \sin\gamma \end{vmatrix} \tag{2}$$

2.2 Cutting force prediction generated in position II

In the cutting process, the cutting edge is the most important part to complete the separation of the chip and the workpiece, and it is also the most intense position of the cutting process. In position II, the workpiece is pressed, cut in and out in cutting process until the cutting-edge leaves. Because of this, the relative motion and friction force of CFRP and cutting edge can be neglected. Based on the cutting mechanism, the cutting force in position II can be calculated from both pressing and impacting.

The force on the tool in position II due to press include two parts: matrix and carbon fibers are pressed, respectively. The force, which comes from matrix, can be calculated by multiplying the area of the cross-sectional area with the yield strength of matrix σ_{pl}. The direction of the force is same with the direction of cutting speed. The size effect can influence matrix, which lead to that the actual yield strength is greater than that of pure PEEK matrix. So, the σ_{pl} need to be corrected. Based on the Hooke's law, the pressing force can be obtained [12].

For type A, the radius of cutting edge and carbon fibers is in the same order of magnitude and the carbon fibers are surrounded by the PEEK matrix. Based on size effect, the carbon fibers fail by lateral micro-buking due to the axial compression[15]. Based on the Hooke's law, the cutting force caused by micro-bucking can be obtained. The total cutting forces due to pressing in the x and y direction are

$$\begin{vmatrix} F_{II\_py} \\ F_{II\_px} \end{vmatrix} = F_{II\_pm} \begin{vmatrix} \cos\psi \\ \sin\psi \end{vmatrix} + \begin{vmatrix} F_{II\_pf} \\ 0 \end{vmatrix} \tag{3}$$

In position II, the cutting process of the type B carbon fibers is a continuous cut in and out process. The cut in and out is an impact process. The diameter of carbon fiber is very small, which is in the same order of magnitude as the cutting-edge radius. This parts of cutting force can be calculated by [16]. The direction of F_{II_impact} is same with the direction of cutting speed. combined with Eq. (25), the cutting force in position II is

$$\begin{vmatrix} F_{II\_y} \\ F_{II\_x} \end{vmatrix} = \left(F_{II\_impact} + F_{II\_pm}\right) \begin{vmatrix} \cos\psi \\ \sin\psi \end{vmatrix} + \begin{vmatrix} F_{II\_pf} \\ 0 \end{vmatrix} \tag{4}$$

2.3 Cutting force prediction generated in position III

Since the cutting edge is not absolutely sharp, there will be a pressing region during the cutting process. When the tool comes, this part will be pressed, and when the tool leaves, it will bounce with a height of b_c. The relationship of b_c and R_{nose} comes from [15].It is linear distribution as a wedge in contact with a half-space. The cutting force components in position III in the x and y direction can be calculated by

$$\begin{vmatrix} F_{III\_y} \\ F_{III\_x} \end{vmatrix} = b_c a_w E_b/2 \begin{vmatrix} \mu_f k_I + \tan\alpha & 1 \\ 1 & \mu_f k_I + \tan\alpha \end{vmatrix} \begin{vmatrix} \cos^2\alpha \\ \sin 2\alpha/2 \end{vmatrix} \qquad (5)$$

3. Verification of cutting force prediction model

3.1 Experiments

The workpiece in experiments is plain wove CF/PEEK. The average thickness per layer was 0.25 mm and the width of a bundle of fiber was 2.5 mm. plain woven (lay-up in the same direction) for CFRP laminates. The HSD milling experiments are carried out on a five-axis CNC machining center (VARIAXIS j-500/5X, Mazak, Mazak, Japan) with a disk milling tool (BAP400R-100-22-6T, China) whose 6 tool tooth was employed with PCD tip (APKT160404, China). The radius of the disk milling tool is 50mm. The cutting-edge diameter (14 ~16 μm) is measured by super-depth of field microscope (VHX-1000c, Keyence, Japan). The cutting forces are measured by force sensor (9257B, Kistler, Switzerland) with a sampling frequency of 20 kHz. Fig. 2 show the experiments set. The properties of CF/PEEK are obtained by [8].

Fig. 2 Experiment devices of HSD milling operation.

3.2 The verification and analysis of the milling force prediction model

Based on analysis, the experiments in this paper are single tooth cutting. Between two cutting cycles, there will be an empty cutting time. the force signal comes from the vibration of the workpiece after the cutter tooth is cut out [12, 16]. The vibration force can be obtained by fitting, as follows[12]. The correction parameters in the model are obtained by experiments. Two groups of experiments were set up to obtain the error range between the model and the experiment. The used milling parameters for the verification of the model are listed in Table 1. The results of verification is shown in Fig. 3

Table 1 The used milling parameters for verification

No.	v (m/min)	a_w (mm)	a_e (mm)	f_z (mm/z)
1	500	3	0.5	0.02
2	800	3	0.2	0.08

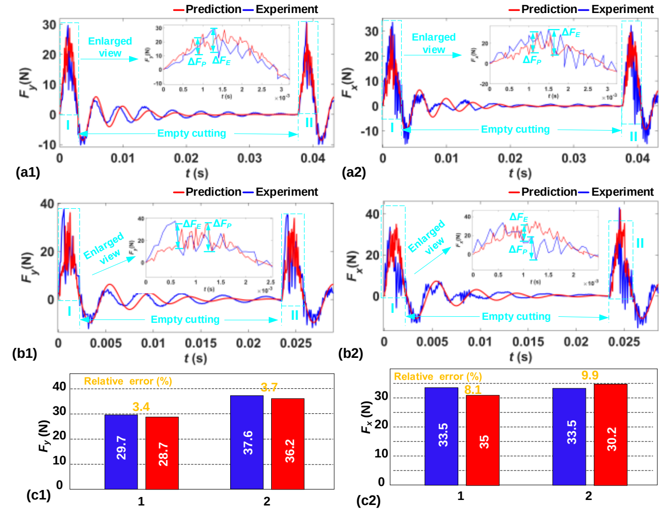

Fig. 3 Verification of the model. (a) ~ (b) are model verification in y-direction and x-direction with EXPs. 1 ~ 2, respectively, and (c) is the relative error of EXPs. 1 ~ 2.

6 Conclusions

We present impacting effect, the specific surface area strengthening effect, workpiece self-action considering size effect to establish cutting force prediction model for revealing cutting mechanisms in HSD milling plain wove CF/PEEK. The main cutting mechanisms of CF/PEEK are mixed by bending, shearing, stretching and delamination, impacting, pressing and bouncing. The proposed model is verified through experiments with high prediction accuracy (maximum relative error 9.9%).

ACKNOWLEDGEMENT

This work was supported by the Science and Technology Research Program of Chongqing Municipal Education Commission (Grant No. KJQN202301147); Scientific Research Foundation of Chongqing University of Technology (Grant No. 2023ZDZ003).

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