The International Journal of Advanced Manufacturing Technology (2019) 103:1977–1988
https://doi.org/10.1007/s00170-019-03571-y

ORIGINAL ARTICLE

A mechanistic prediction model of instantaneous cutting forces in drilling of carbon fiber-reinforced polymer

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Received: 1 July 2018 / Accepted: 11 March 2019 / Published online: 16 April 2019

Abstract

Drilling of carbon fiber-reinforced polymer (CFRP) is one indispensable machining operation to produce holes for final assembly of structural parts. Excessive cutting forces during drilling processes will lead to machining defects, such as fiber breakage, burrs, micro cracks, and plies delamination within laminate. This paper aims to simulate the variation of instantaneous cutting forces in CFRP drilling considering the influences of fiber orientation, machining parameters, and tool geometries. The cutting edges are split into infinitesimal elements; the instantaneous cutting forces are obtained by the accumulation of elemental forces exerted on all engaged elements. The overall cutting forces are the combination of forces contributed by the cutting lips and chisel edge using different machining mechanisms; oblique cutting and mechanistic modeling approaches are applied to the cutting lips while the principle of contact mechanics is adopted for the chisel edge. An integrated artificial neural network (ANN) and genetic algorithm (GA), ANN-GA is developed especially for predicting the specific cutting force coefficients, which are functions of the fiber orientation and can account for the variation of cutting forces. Meanwhile, the change of geometrical parameters along the cutting lips is analyzed, and the effects of fiber orientation and tool geometries are integrated in the model. Results showed the proposed model is able to predict the instantaneous cutting forces in CFPR drilling. Model predictions agree well with experimental data and are beneficial for optimizing the machining processes of CFRP composite laminates.

Keywords Carbon fiber-reinforced polymer (CFRP) · Mechanistic modeling · Cutting forces · Fiber orientation · Tool geometries

1 Introduction

Carbon fiber-reinforced polymer (CFRP) is used extensively in aeronautical and aerospace structures due to its superior mechanical properties such as high stiffness, corrosion resistance, and excellent fatigue strength [1, 2]. Large numbers of structural parts are fastened together by bolting or riveting in assembly; this makes drilling a key post machining process for CFRP [3]. Compared to metals, CFRP is anisotropic and inhomogeneous; different machining damage occurs during operations like milling and drilling. Fiber pull-out, fiber fragmentation, fiber-matrix de-bonding and plies delamination are observed under inadequate machining conditions and significantly affect the hole quality [4]. Therefore, the mechanism of material removal and the kinematics of machining process should be understood to overcome the machining damage [5].

Delamination at the exit of drilled hole, namely exit-ply delamination, appears to be the most problematic one in CFRP drilling, which significantly damages the structural integrity and causes performance deterioration. According to relevant experimental observations and theoretical analyses, exit-ply delamination is closely related to thrust force, which strongly depends on the tool geometries and cutting conditions for a given combination of work-piece and cutting tool material [6–9]. Cutting forces are intermediate variables linking up process parameters with hole quality; thus, they can be analyzed

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conveniently and feasibly to evaluate the whole drilling process. As a consequence, accurate prediction of cutting forces can be used for developing appropriate machining schemes and selecting process parameters to implement damage-free machining.

Experimental research showed that machining parameters, tool geometries, and material properties contribute considerably to cutting forces in CFRP machining. Zenia et al. [2] designed orthogonal cutting experiments to identify the most important cutting factors affecting cutting forces and the interactions among these factors. They found that the interactions among some factors are negligible, the fiber orientation and depth of cut have greater impact on cutting forces than the tool rake angle and tool edge radius. Chen et al. [6] conducted experiments of drilling unidirectional and multi-directional CFRP laminates to examine the effects of tool geometries and machining parameters upon cutting forces and delamination. The results indicated that delamination can be effectively avoided through the appropriate combination of tool geometries and machining parameters. Ameur et al. [10] experimentally investigated the cutting conditions of CFRP drilling and applied the statistical analysis of variance (ANOVA) to analyze experimental data. Their research revealed that parameters (feed rate, spindle speed, tool material) can significantly affect the output (thrust force, torque, exit delamination factor).

In addition, a lot of attempts have been made to develop mathematical prediction models of cutting force to reflect the machining mechanisms in CFRP drilling. Stephenson et al. [11] presented a model to calculate the torque and thrust force on the main cutting edges during drilling of gray cast iron; a parametric method is used to characterize point geometries and the radial force distribution is revealed. The main cutting edges are split into small segments and thus elemental force can be calculated by multiplying the specific pressure on each segment and chip area. One fatal disadvantage of the model is that it neglects the contribution of chisel edge in force prediction. It was indicated by previous studies of Su et al. [12] and Qi et al. [13] that machining of CFRP is governed by different physical laws compared to the plastic deformation of metals during machining processes. Their theoretical analyses and experimental observations in orthogonal cutting of CFRP showed that chip formation mechanisms change along with the fiber orientation. The intrinsic characteristics of CFRP (such as fiber orientation and laminate structure) could severely decrease its machinability and make drilling a more challenging task, which is still not fully understood until now. Langella et al. [14] calculated cutting forces in composite materials drilling assuming that orthogonal cutting occurs both on the cutting lips and chisel edge over an infinitesimal instant. The model has limited application, for the reason that the coefficients of empirical equations in orthogonal cutting need to be re-determined if the tool or work-piece material changes. Meng et al. [15] established an analytical prediction model with emphasis on simulating the fluctuation of thrust force in the drilling process of unidirectional CFRP composites. The cutting lips perform orthogonal cutting while the impact of chisel edge is insignificant and thus is neglected. Chandrasekharan et al. [16] integrated cutting forces on the whole cutting edges for force prediction; oblique cutting is assumed for the cutting lips and orthogonal cutting is applied for the chisel edge. Nevertheless, large errors are found between model predictions and experimental results; an additional mechanism of material removal may act at the chisel edge area and account for this as suggested by the authors. Guo et al. [17] proposed an analytical model of cutting forces and investigated the influences of machining parameters, tool geometries, and fiber orientation on thrust force and torque. Oblique cutting is applied to the cutting lips containing three distinct deformation regions. Whereas the same chip formation mechanism is adopted over the entire range of fiber orientation, which is inconsistent with actual situations occurred in the machining processes as pointed out by related research [12, 13]. Feed rate and tool geometries are the two most important input parameters which directly affect cutting forces and further affect machining quality, but the influence of drilling speed is shown to be minimal [18].

The existing prediction models of cutting forces for CFRP drilling involve some preconditions and assumptions, and some need a large number of experiments to determine the relevant coefficients. The limitations of these models are apparent, so there is a need to propose a model which can account for the special material properties of CFRP in drilling process. A twist drill comprises of cutting lips and chisel edge; cutting speed and inclination and rake angles vary along the cutting lips. The machining action of cutting lips in the drilling process is three-dimensional and oblique [14], whereas the chisel edge performs in a different machining mechanism compared to the cutting lips. Moreover, the chip formation mechanisms continuously change along with the fiber orientation as the drill rotates. As a result, it is of great necessity to develop an appropriate model which could reflect the specific machining mechanisms occurred at different contact areas considering the complexity of tool geometries and the anisotropy of CFRP.

Given all these considerations, this paper proposes a mechanistic prediction model for the instantaneous cutting forces in the drilling of CFRP. Different methods are presented separately for the cutting lips and chisel edge owing to the different machining mechanisms existing in these two areas. The cutting lips are divided into infinitesimal elements, and oblique cutting is suggested for each elemental cutting edge. Mechanistic modeling approaches are utilized for the cutting lips integrating the influences of fiber orientation, feed rate, and geometrical parameters. Meanwhile, analytical modeling techniques are applied to the chisel edge and the principle of contact mechanics is adopted to reflect the extrusion action. Section 2 describes the mechanistic modeling of orthogonal cutting and geometric transformation of orthogonal cutting to oblique cutting. An integrated artificial neural network (ANN) and genetic algorithm (GA), ANN-GA, is employed to generate the cutting force coefficients covering the whole range of fiber orientation incorporating the variation of rake angle along the cutting lips. Section 3 calculates the total cutting forces (thrust force and torque) on the drill; the variations of tool geometries and fiber cutting angle are analyzed in detail. Section 4 validates the proposed model by making comparisons with experimental data. The discussion and conclusions are provided in Section 5.

2 Mechanistic model for the cutting lips

For the sake of addressing the complexity of tool geometries, the cutting lips could be split into infinitesimal elements which are small enough to be treated as straight cutting edges. The instantaneous cutting forces are continuously distributed along the cutting lips and can be obtained through the accumulation of instantaneous elemental forces on all engaged elements.

Feed rate is one significant factor affecting the drilling process and thus cause the variation of cutting forces [19, 20]. Moreover, tool geometries also have a decisive impact on the interaction of tool and work-piece in the contact zone. Except for these influences, it was also noted that the fiber orientation is the main reason for different cutting mechanisms occurred in CFRP machining and has a key influence on cutting forces [20–24]. In consideration of relevant research results, the effects of fiber orientation, feed rate, and tool geometries should all be incorporated in the mechanistic modeling for reflecting the machining mechanisms of CFRP drilling.

2.1 Model architecture

In the drilling process, the cutting lips expand the hole by removing the material as the drill feeds into the work-piece. Because of the offset caused by the chisel edge and varying diameter, the helix, rake, and inclination angles all vary from the chisel-lip to lip-flute intersection [25].

The geometric model of twist drill is shown in Fig. 1 to explain the oblique cutting operation of elemental cutting edges.

The cutting width of one infinitesimal element is denoted as Δb, the projection of Δb can be given by a function of the normalized radial coordinate ρ [14], then

$$dx = dr \cdot \cos(\varphi(\rho)) \tag{1}$$

where $\varphi(\rho)$ represents the angle between the projection of cutting lips and the radial direction at point Q in the plane ($z = 0$), and

$$\cos(\varphi(\rho)) = \frac{\sqrt{r^2 - w^2}}{r} \tag{2}$$

where w is the half thickness of chisel edge, and r is the perpendicular distance from the point Q to the drill axis.

The normalized radial distance is expressed as:

$$\rho = r/R \Rightarrow dr = R d\rho \tag{3}$$

therefore

$$dx = \frac{\sqrt{\rho^2 R^2 - w^2}}{\rho} d\rho \tag{4}$$

So, the cutting width of one element could be obtained by

$$\Delta b = \frac{dx}{\sin k_t} = \frac{\sqrt{\rho^2 R^2 - w^2}}{\rho \sin k_t} d\rho \tag{5}$$

where k_t is the taper angle.

Infinitesimal elements performs oblique cutting during drilling and an extra inclination angle i exists between the cutting edge and the normal to the cutting direction as shown in Fig. 1. The presence of inclination angle generates a third force component referred to as lateral force component dF_{rc}.

As for oblique cutting action of all engaged elements, the mechanistic modeling approaches from metal cutting are utilized to predict the elemental tangential (dF_{tc}) and radical (dF_{fc}) forces, which can be calculated by multiplying the cutting force coefficients (cutting pressure) in each direction and chip area dA as follows:

$$\begin{cases} dF_{tc} = K_{tc} dA \\ dF_{fc} = K_{fc} dA \end{cases} \tag{6}$$

where K_{tc} and K_{fc} are the cutting force coefficients in tangential and radial directions, which are strongly dependent on cutting conditions (machining parameters, tool geometries, and material properties).

$$dA = \Delta b \cdot h' \tag{7}$$

the uncut chip thickness h' is an expression of the feed per revolution f and geometrical parameters,

$$h' = \frac{f}{2} \sin k_t \cos\gamma_d \tag{8}$$

where γ_d is the angle between the two velocity components and

$$\gamma_d = \arctan\left(\tan\varphi(\rho)\cos k_t\right) \tag{9}$$

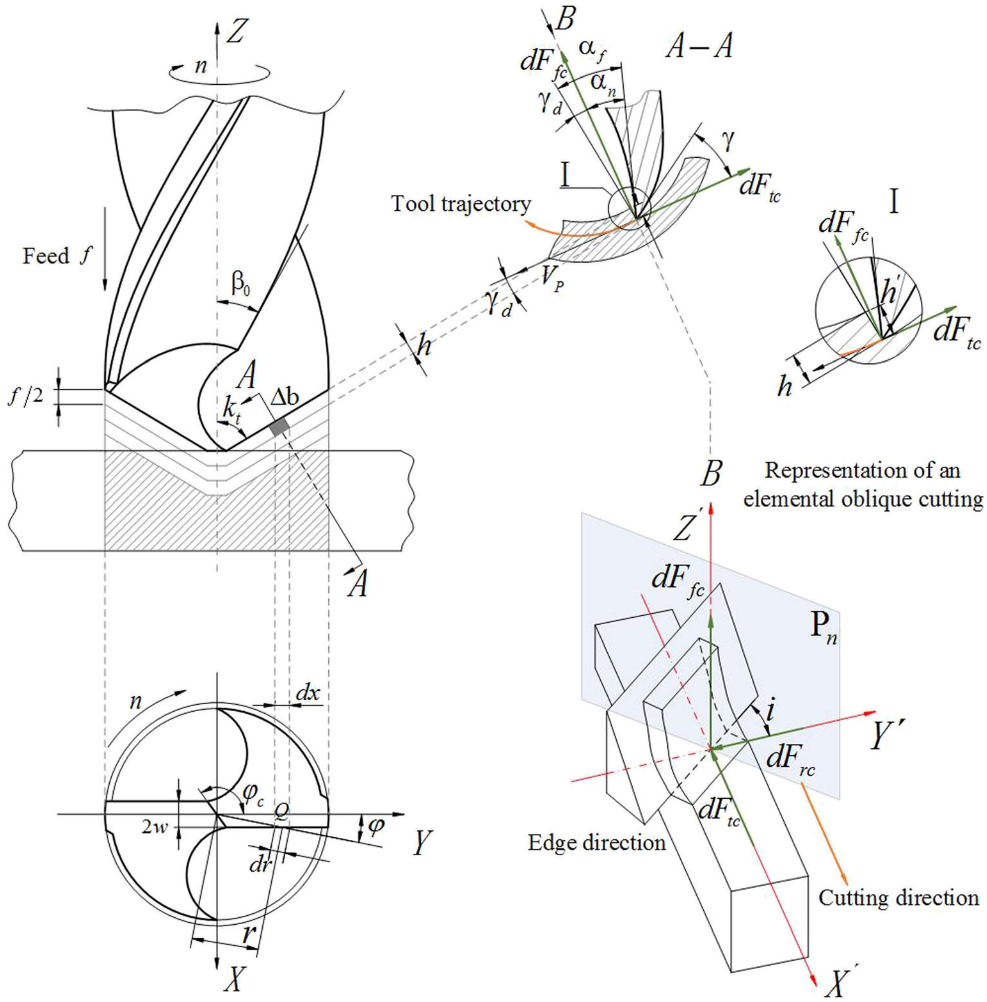

Fig. 1 The geometry and elemental cutting forces of twist drill [25]

The lateral force dF_{rc} is calculated using the semi-empirical method proposed by Lin et al. [26] in expression of:

$$dF_{rc} = \frac{dF_{tc}(\sin i - \cos i \sin\alpha_n \tan\eta) - dF_{fc}\cos\alpha_n \tan\eta}{\sin i \sin\alpha_n \tan\eta + \cos i} \tag{10}$$

where α_n is the normal rake angle and η is the chip flow angle on the rake face (η and i have the same value based on Stabler's rule). The values of geometric parameters change continuously along the cutting lips.

The cutting forces (thrust force and torque) on one oblique cutting element could be obtained by geometrical transformation:

$$dF_{th} = dF_{fc}\cos\gamma_d \sin k_t - dF_{rc}(\cos i \cos k_t + \sin i \sin\gamma_d \sin k_t) \tag{11}$$

$$dF_{to} = dF_{tc}\rho R \tag{12}$$

The cutting forces on one cutting lip are calculated by the integral of elemental forces

$$F_{th} = \int_{\tau}^{1} dF_{th} d\rho \tag{13}$$

$$F_{to} = \int_{\tau}^{1} dF_{to} d\rho \tag{14}$$

where

$$\tau = \frac{w/\sin\varphi_c}{R} = \frac{w}{R\sin\varphi_c} \tag{15}$$

2.2 GA-ANN for cutting force coefficients

The cutting force coefficients represent the amount of energy needed to remove a unit volume of material in machining processes. They are key coefficients for force prediction in mechanistic model and can be expressed as functions of material-dependent terms (shear stress and angle), tool geometries (rake angle), and friction angle between tool's rake face and moving chip in metal cutting. However, brittle chip formation occurs in machining of CFRP in opposite to plastic deformation of metals. Those basic quantities applied for metals are nonexistent or difficult to measure in machining of CFRP [27]; so the cutting force coefficients can not be calculated using the same method applied for metals and they need to be evaluated to reflect the different characteristics of CFRP machining. CFRP owns peculiar material properties and displays different responses to manufacturing in comparison with metals, this makes the modeling of its drilling process more difficult and trickier. Soft computing techniques have been successfully used to analyze and model the machining processes, and could yield complete, accurate and reliable results [28]. Design of experiments (DOE), response surface methodology (RSM), and artificial neural network (ANN) are frequently employed with soft computing techniques to explore and describe the complex behavior observed in the machining processes.

DOE refers to carry out experiments by statistically designed tests and it can efficiently reduce the number of experiments required in the experimental research. The Taguchi orthogonal array design is one methodology which calculate the average value of experimental response and its corresponding signal-to-noise (S/N) ratio of each test to investigate the influences of individual machining parameters [29]. RSM is widely used to obtain an empirical model from experimental data for evaluating the effects of several variables on the response of interest. A mathematical model can be developed to establish a relationship for multi-variable and multi-response systems with only a few experiments [28, 30]. ANN is an artificial intelligence approach which could offer an effective and efficient way to capture the ambiguous input–output relationships from limited data for process modeling. Consequently, it is a helpful tool to model the machining processes in which huge experimental data is difficult and expensive to obtain [31]. The cutting force coefficients to be calibrated are closely related to one specific variable (the fiber cutting angle), this one-on-one relationship makes the application of DOE and RSM less valuable and meaningful. Due to the complexity and ambiguity of the relationship between these two variables, ANN is a more desirable tool to simulate the behavior of machining processes for CFRP with the advantage of minimizing the necessary experiments.

In the proposed model, ANN and genetic algorithm (GA), ANN-GA is developed to produce the specific cutting force coefficients. A feed-forward multi-layer ANN architecture trained with error back propagation learning algorithm is employed, which comprises of one input layer with one neuron (corresponding to the fiber cutting angle), two hidden layers with 12 neurons in each, and one output layer with one neuron (corresponding to K_{tc} or K_{fc}). The fiber cutting angle θ (the angle measured anticlockwise from cutting velocity vector to fiber orientation as shown in Fig. 2) has a crucial influence on the cutting force coefficients for CFRP machining. GA is especially used to optimize the initial weights and biases of ANN in order to accelerate the learning convergence of the established ANN.

A series of slot milling experiments are conducted under dry cutting conditions as described in Table 1. By changing the milling direction on two unidirectional laminates (0° and 45° fiber orientations), tests on laminates of four fiber orientations (0°, 45°, 90°, 135°) can be accomplished. Thus the cutting data can be obtained for the whole range of fiber cutting angle from 0° to 180°. The change rule of fiber cutting angle with fiber orientation angle ϕ (the angle measured in anticlockwise from Y-axial to the longitudinal direction of fiber) and tool rotation angle ψ is illustrated in Fig. 2 and can be expressed by:

$$\theta = 90^{\circ} + \phi + \psi \text{ if } \theta \geq 180^{\circ} \textit{ then } \theta = \text{mod}\left(\theta, 180^{\circ}\right) \quad (16)$$

Owing to the fact that process parameters vary along the normalized radial distance of cutting lips and the fiber cutting angle also keeps changing in a drilling cycle, the cutting force

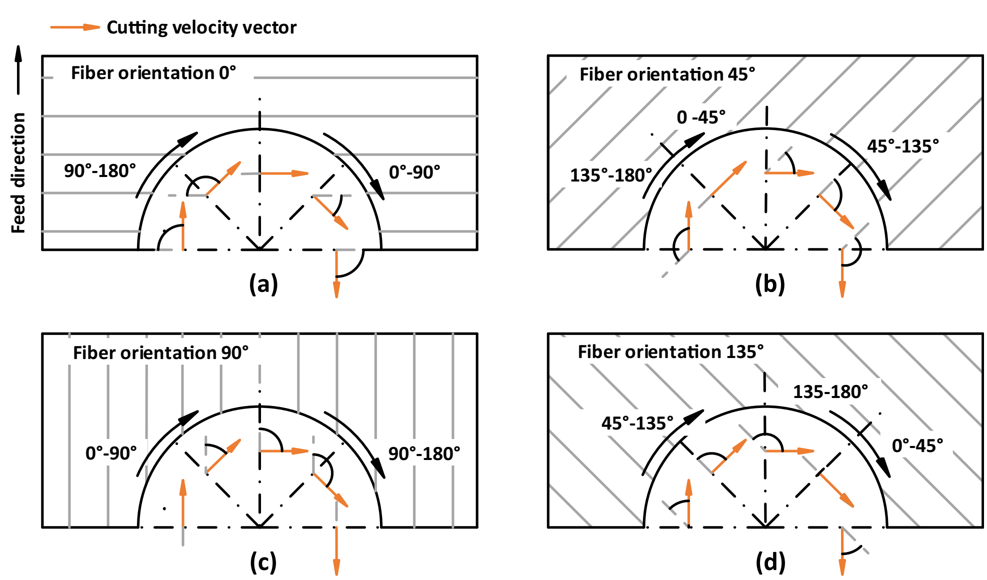

Fig. 2 The fiber cutting angle in slot milling experiments

Table 1 Cutting parameters used for slot milling experiments

Parameters	Milling
Spindle speed (rpm)	2000
Feed speed (mm/min)	160
Depth of cut (mm)	3
Laminate orientation	0°, 45°
Tool diameter (mm)	6
Number of flutes	2
Helix angle (°)	0°
Rake angle (°)	0°

coefficients are considered to be variable. During the immersion of tool in slot milling for different fiber orientations (0°, 45°, 90°, 135°), the fiber cutting angle repeats at some points by the different combinations of tool rotation angle and fiber orientation angle. Therefore, the cutting force coefficients calibrated with experimental data are the average values determined by those repeating values at the same fiber cutting angle. At the entry and exit regions during slot milling experiments, the uncut chip thickness is very small and radial cutting force increases drastically due to rubbing effect. In order to remove the rubbing effect, only experimental data at the tool rotation range ($45^{\circ} < \omega < 135^{\circ}$) are used for the calculation of cutting force coefficients with the expression in mechanistic model as:

$$\begin{cases} K_{tc}(\theta) = F_{tc}(\theta)/A_c \\ K_{fc}(\theta) = F_{fc}(\theta)/A_c \end{cases} \tag{17}$$

The experimentally calculated K_{tc} and K_{fc} are further used as the input-output data to train and test ANN. First of all, GA is used to optimize the initial weights and biases of ANN, the training results of average and best fitness of GA for K_{fc} vs. the number of generations are represented in Fig. 3. The training

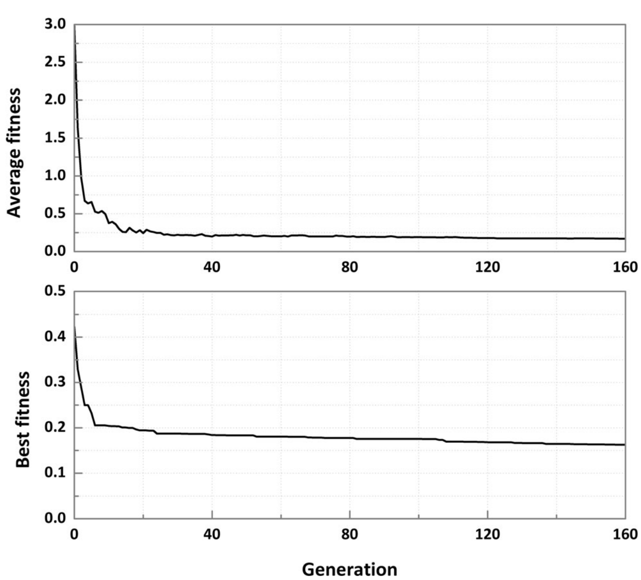

Fig. 3 The training results of GA for K_{fc}

performance of ANN-GA for K_{tc} and K_{fc} are shown in Fig. 4; predictions match well with experimental results. The cutting force coefficients change with the fiber cutting angle θ, K_{fc} in the radial direction have considerably higher values compared to K_{tc} in the tangential direction.

The cutting force coefficients (cutting pressure) determined by ANN-GA are then used in combination with tool geometries to predict cutting forces in drilling of multi-directional CFRP composite laminates. One distinct advantage of this methodology lies in that it aims to produce the specific cutting force coefficients under certain machining conditions integrating the effect of fiber orientation, so the calibrated coefficients can also be applied to other processes in which different tool geometries and fiber orientations are involved as long as the material properties of tool and work-piece remain the same.

3 Numerical simulation of instantaneous cutting forces

The chisel edge is modeled as a rigid wedge indenting a brittle material in this analysis. The principle of contact mechanics is adopted and the indentation force and torque generated by the extrusion action are calculated by

$$F_{chi\_th} = \int_{-\tau}^{\tau} \frac{E}{1-\nu^2}\left(K_c w + \frac{f}{2}\right)\tan k_t \sin\alpha_c \cos\left(\arctan\frac{f}{2\pi\rho R}\right) R d\rho \tag{18}$$

$$F_{chi\_to} = \int_{-\tau}^{\tau} \frac{E}{1-\nu^2}\left(K_c w + \frac{f}{2}\right)\tan k_t \sin\alpha_c \sin\left(\arctan\frac{f}{2\pi\rho R}\right) R\rho R d\rho \tag{19}$$

where E is the Young's modulus in the direction perpendicular to the laminates, ν is the Poisson's ratio, α_c is the rake angle of chisel edge, and K_c is the coefficient of chisel edge which is related to tool geometries.

For a laminate composite, superposition principle is used for the prediction of cutting forces [32]. It is assumed that the adhesive strength between different plies has negligible effect on the machining process as if each ply could be treated as a single one. For each ply within the laminate, the instantaneous cutting forces are the accumulation of forces contributed by the elemental cutting edges acted within the ply. Then, the total cutting forces could be obtained by superposition of forces independently exerted on each ply. The flow chart for the prediction of instantaneous cutting forces during the whole drilling process is outlined in Fig. 5.

3.1 Inclination angle effect

The cutting lips of a twist drill are made up of infinitesimal elements and each element is regarded as an oblique cutting

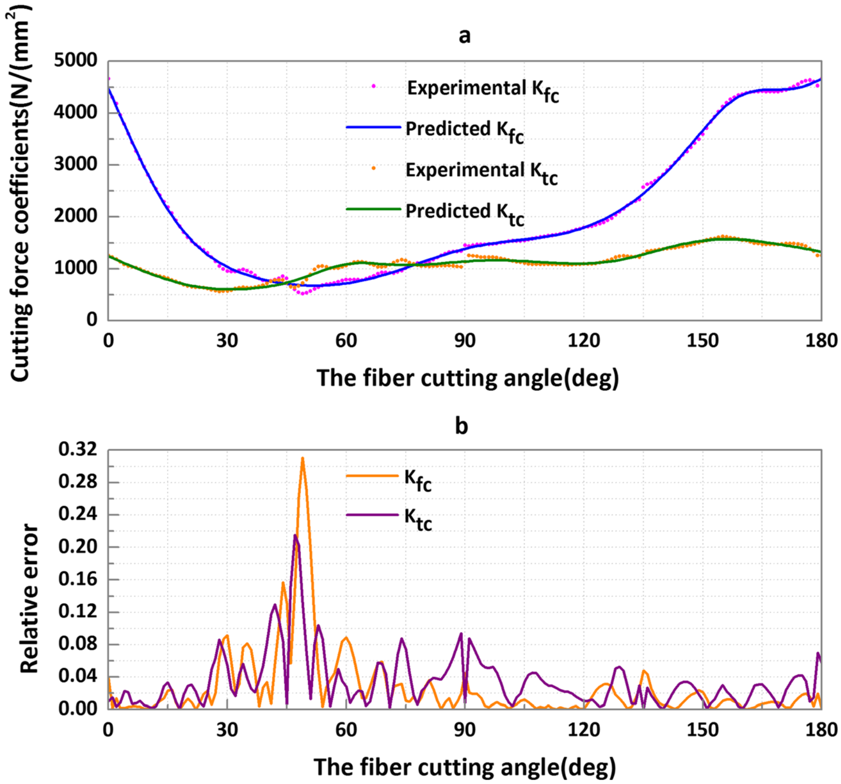

Fig. 4 **a** The experimental and predicted cutting force coefficients. **b** The relative error of the predicted cutting force coefficients

edge. For one elemental cutting edge, the inclination angle could be given by

$$i = -\arcsin(\sin\phi \sin k_t) \tag{20}$$

where

$$\phi = \arcsin\left(\frac{w}{\rho R}\right) \tag{21}$$

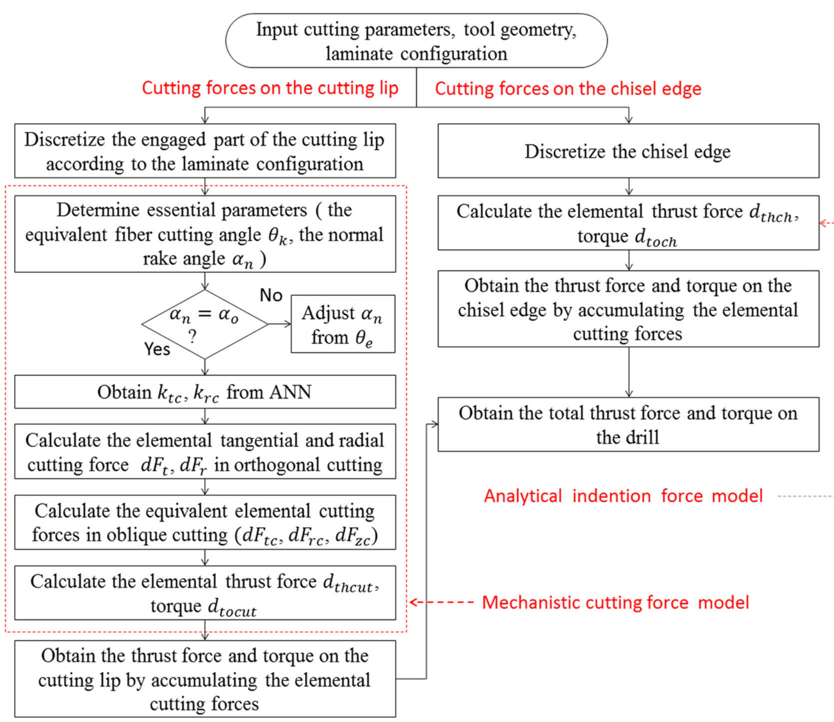

Fig. 5 Flow chart for drilling force prediction model

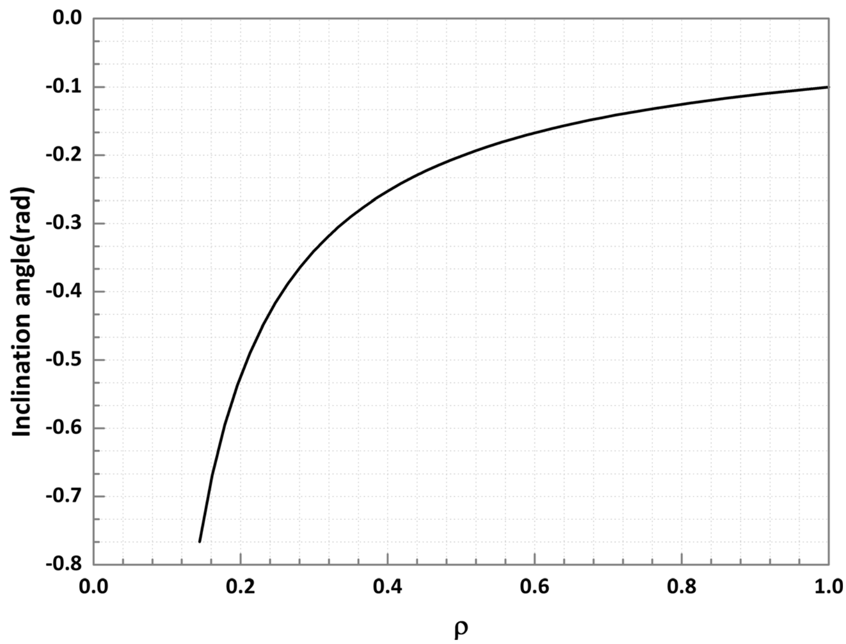

Fig. 6 The inclination angle along the normalized radial distance

The inclination angle varies along the normalized radial distance of cutting lips, decreasing continuously from maximum value at the lip-flute intersection to minimum value at the chisel-lip intersection, as shown in Fig. 6.

3.2 Fiber orientation effect

The cutting forces fluctuate in the drilling process due to the anisotropy of CFRP caused by fiber orientation. Multi-directional composite laminates have different fiber orientations in certain plies, the fiber cutting angle θ is the combined result of fiber orientation, tool geometries, and tool rotation. For an elemental orthogonal cutting edge, it could be calculated using the expression

$$\theta = arccos\left(\frac{\cos\omega}{\sqrt{\cos^2 k_t + \sin^2 k_t + \cos^2\omega}}\right) \quad (22)$$

$$\omega = 2\pi nt + \varepsilon + \phi \quad (23)$$

where ε is the initial angle measured in clockwise from the cutting lip to *Y*-axial, ε and ϕ could be any value between 0 and π.

A special case ($\varepsilon = 0$, $\phi = 90^\circ$) for an elemental cutting edge is shown in Fig. 7 to explain the change rule of fiber cutting angle as tool rotates.

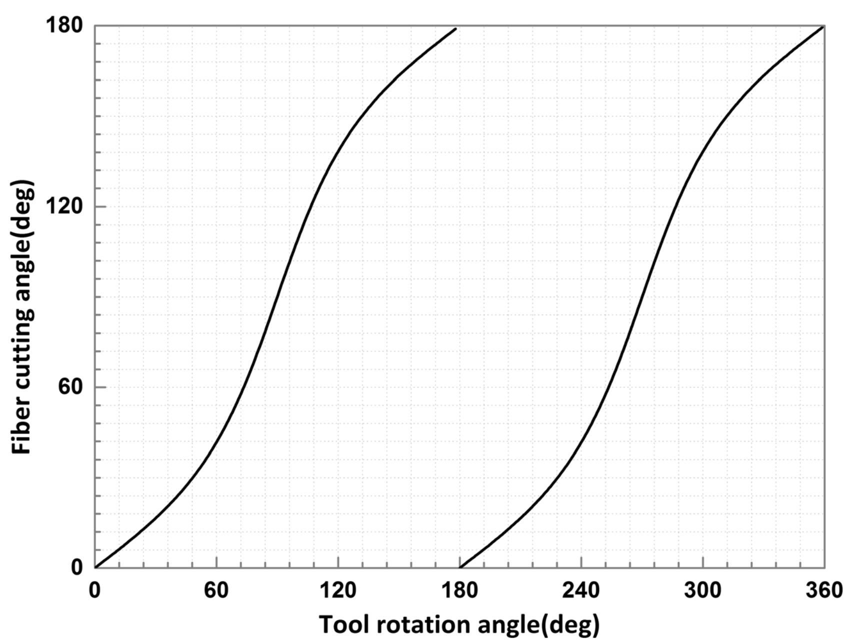

Fig. 7 The change rule of fiber cutting angle as tool rotates

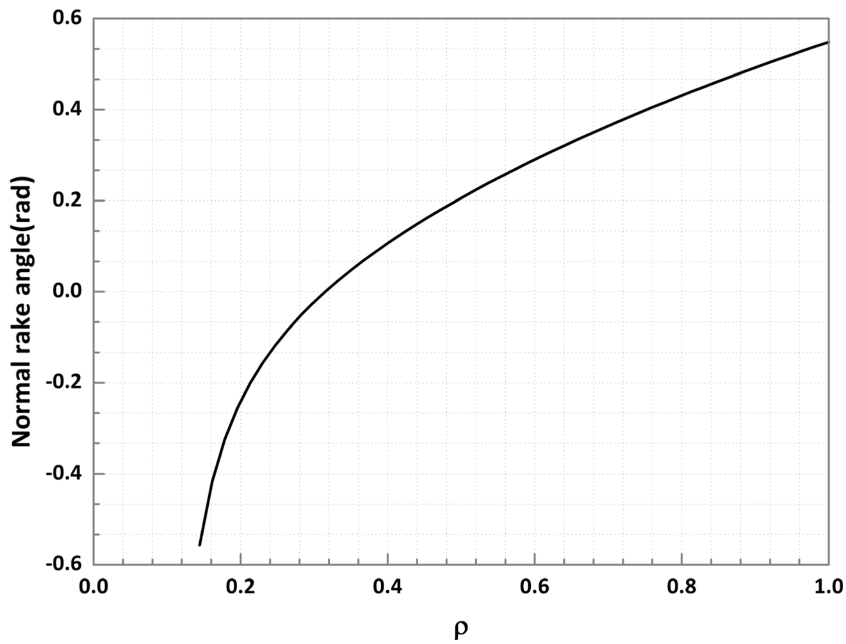

Fig. 8 The normal rake angle along the normalized radial distance

Considering the effect of γ_d as shown in Fig. 1, the fiber cutting angle θ should be adjusted as

$$\begin{cases} \theta = \theta + \gamma_d & \text{if } \theta \geq \gamma_d \\ \theta = \gamma_d - (\pi - \theta) & \text{if } \theta < \gamma_d \end{cases} \tag{24}$$

3.3 Rake angle effect

The normal rake angle of cutting elements on the cutting lips is variable, decreasing continuously from positive value at the lip-flute intersection to negative value at the chisel-lip intersection, as shown in Fig. 8. The specific cutting force coefficients are generated from slot milling using a special tool with a certain rake angle of $\alpha = 0^\circ$. In order to apply these coefficients in drilling processes which involve variable normal rake angle, some adjustments are made following the procedure introduced by Ramulu et al [33]. The variation of normal rake angle could be integrated into the coefficients with the introduction of effective fiber orientation angle assuming that the cutting mechanisms would be the same as long as the effective fiber orientation angles are the same [27].

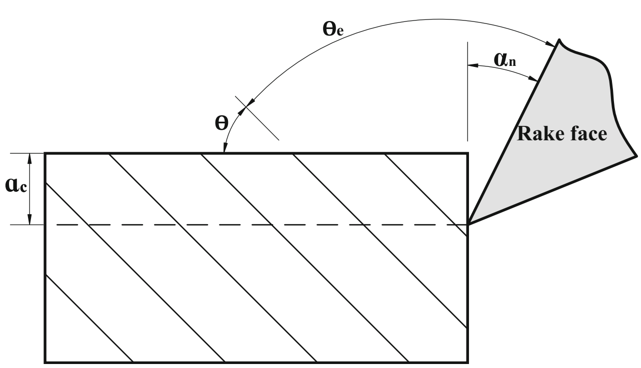

Fig. 9 The effective fiber orientation angle [27]

The effective fiber orientation angle θ_e is the angle between the rake face of cutting edge and the longitudinal direction of fiber as illustrated in Fig. 9:

$$\theta_e = 90^\circ + (\alpha_n - \theta) \tag{25}$$

Let α_n represents the normal rake angle of one elemental cutting edge on the cutting lips, α is the rake angle of cutter used in orthogonal milling experiments. If $\alpha_n = \alpha$, the cutting force coefficients can be directly produced by ANN-GA with the original fiber cutting angle as input. In cases that these two angles are different, the cutting force coefficients corresponding to the same θ_e should be produced by ANN-GA with the adjusted fiber cutting angle as input [27].

For instance, for an elemental cutting edge with a normal rake angle α_n, when the instantaneous fiber cutting angle is θ, the effective fiber orientation angle θ_e should be:

$$\begin{cases} \theta_e = 90^\circ - (\theta - \alpha_n) & \alpha_n \geq 0 \\ \theta_e = 90^\circ - (\theta + \alpha_n) & \alpha_n < 0 \end{cases} \tag{26}$$

Table 2 Cutting parameters used for drilling tests

Parameters	Drilling
Spindle speed (rpm)	2000
Feed rate (mm/min)	80,120
Diameter (mm)	6
Point angle (°)	118°
Chisel width (mm)	0.7

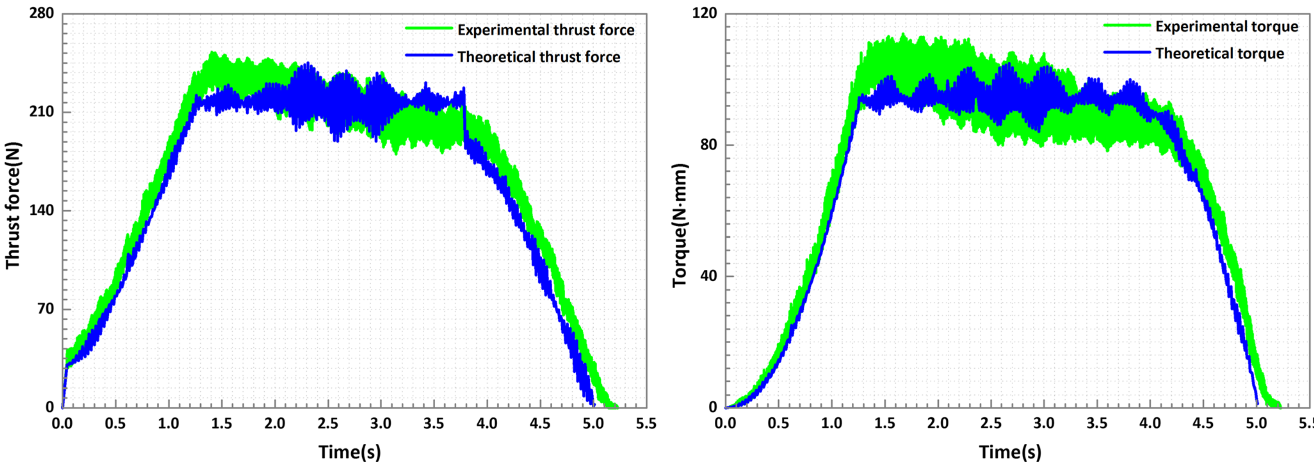

Fig. 10 Comparison of thrust force and torque between experimental results and model predictions with n = 2000 r/min, f = 0.04 mm/r

For the milling cutter with a certain rake angle $\alpha(\alpha \geq 0)$, when the instantaneous fiber cutting angle is $\theta^{'}$, the effective fiber orientation angle $\theta^{'}_{e}$ can be given by

$$\theta^{'}_{e} = 90^{\circ} - \left(\theta^{'} - \alpha\right) \tag{27}$$

The fiber cutting angle $\theta^{'}$ in orthogonal milling which can result in the same θ_e for the elemental cutting edge can be calculated by

$$\begin{cases} \theta^{'} = \alpha - \alpha_n + \theta & \alpha_n \geq 0 \\ \theta^{'} = \alpha + \alpha_n + \theta & \alpha_n < 0 \end{cases} \tag{28}$$

The machining mechanism in orthogonal milling of laminates (fiber cutting angle equals to $\theta^{'}$ with a rake angle α) is equivalent to that in elemental edge cutting of laminates (fiber cutting angle equals to θ with a normal rake angle α_n), the specific cutting force coefficients should be produced by ANN-GA with the adjusted $\theta^{'}$ as input.

4 Experimental validation

To verify the proposed model, a series of drilling operations are conducted on a three-axis CNC machining center with a twist drill. Since cutting speed has an insignificant influence upon cutting forces [34], all tests are performed at a constant cutting speed under dry cutting conditions as represented in Table 2. Multi-directional long carbon fiber-reinforced epoxy composite laminates with the stacking sequence of $[0°/-45°/90°/45°]_{5s}$ are used in the drilling tests. The thickness of laminates is 5 mm with each ply 0.125 mm. Kistler Dynamometer 9125A and Kistler 5073 charge amplifier are used to measure the thrust force and torque; experimental data are recorded by a HBM GEN2i data recorder. The same facilities and instruments are used in slot milling experiments for the calibration of cutting force coefficients.

Model predictions of the thrust force and torque with experimental results for multi-directional laminate drilling are shown in Figs. 10 and 11.

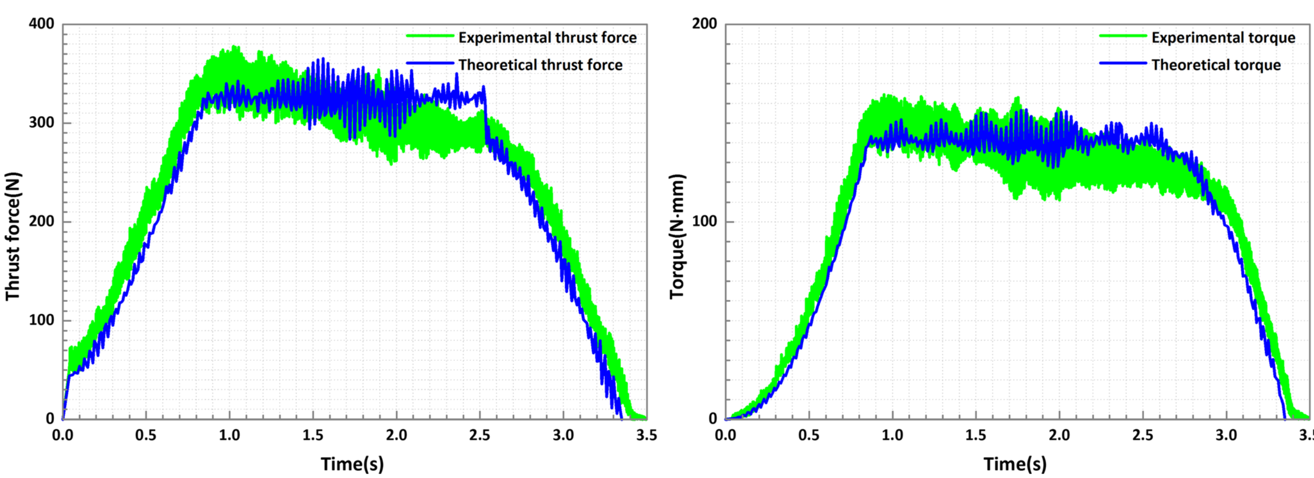

Fig. 11 Comparison of thrust force and torque between experimental results and model predictions with n = 2000 r/min, f = 0.06 mm/r

Comparisons showed that predictions are in a reasonable agreement with experimental results in the whole drilling processes of multi-directional laminates. The change trends of predictions and experimental data are coincidental, and the fluctuation of thrust force and torque is likely caused by the anisotropy of CFRP and the excitation of force measuring system.

5 Conclusions

A mechanistic prediction model is presented for the instantaneous cutting forces during the drilling processes of CFRP composite laminates. The cutting edges of drill are split into infinitesimal elements and oblique cutting mechanism is assumed for the cutting lips. Elemental forces on the cutting lips are calculated using the cutting force coefficients of mechanistic approaches and oblique transformation technique. Meanwhile, the theory of contact mechanics is adopted in the force modeling for the chisel edge. The overall cutting forces are obtained by superposition of forces exerted on all engaged elemental cutting edges on the drill. The proposed model is capable of accounting for the changes in axial feed rate, drill geometries, and stacking sequences of CFRP in drilling operation.

The following conclusions are drawn from this work:

1. The normal rake angle, inclination angle of each point on the drill, keep changing along the cutting lips; the fiber cutting angle also varies under the comprehensive influence of laminate structure, tool geometries, and tool rotation.
2. The cutting force coefficients generated by ANN-GA are functions of the fiber cutting angle. The impact of fiber cutting angle upon cutting forces is effectively shown by the variations of cutting force coefficients. As a consequence, the cutting forces are the result of combined effects exerted by the anisotropy of CFRP composites, tool geometries, and kinematics of drilling process.
3. ANN-GA is trained based on the experimental data obtained in orthogonal milling with a special cutter (helix angle equals to 0°), in which the fiber cutting angle continuously changes during one experiment. So, only a few milling experiments are sufficient to calculate the cutting force coefficients covering the whole range of fiber cutting angle.
4. Combined with the adjustments of normal rake angle, ANN-GA can produce cutting force coefficients fulfilling the needs of modeling for CFRP drilling in which different tool geometries, stacking sequence of laminate, and feed rate are involved. The calibrated cutting force coefficients can also be applied to simulate other processes (like milling) in which different tools and fiber orientations are involved as long as the material properties of tool and work-piece remain the same.

Compliance with Ethical Standards

Conflicts of Interest The authors declare that they have no conflict of interest.

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