A prediction model of thrust force for drilling of bidirectional carbon fiber–reinforced carbon matrix composites

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Abstract
Carbon fiber–reinforced carbon matrix composites have been widely used for the manufacturing of thermostructural parts for several industries such as the aerospace and automotive. Drilling is an extremely common method used in the machining of carbon fiber–reinforced carbon matrix composites before assembly. However, their non-homogeneous, anisotropic, and brittle nature make difficult to guarantee the hole quality in drilling. Some severe drilling defects, such as burrs, delamination, and tear, usually occur. In this regard, it is necessary to accurately predict the thrust force in drilling of carbon fiber–reinforced carbon matrix composites. Therefore, in this article, based on the cutting theory of fiber-reinforced polymer composites, an alternative thrust force prediction model for drilling of bidirectional carbon fiber–reinforced carbon matrix composites is proposed. The cutting force of the cutting lips is established by dividing the cutting deformation zone into three regions according to the machined material structure based on the Zhang’s model in cutting of fiber-reinforced polymer. The periodic variation of fiber orientation is considered in detail. The experimental results show that the relative deviations of the predicted and experimental values of the thrust force are less than 14.36%.

Keywords
Carbon fiber–reinforced carbon matrix composites, thrust force, drilling, fiber orientation

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Introduction

Carbon fiber–reinforced carbon matrix (C/C) composites are the only hyper high-temperature materials that can maintain mechanical properties at room temperature over 2000°C.\(^1\) They present some excellent properties, such as low thermal expansion coefficient, high heat resistance, high specific stiffness, and high resistance to corrosion. Due to these special features, they have been widely applied in a great number of fields for several decades, especially in the aeronautic, aerospace, sports, and automotive industries.\(^2\) The preform of bidirectional C/C composites is commonly formed with bidirectional fibers. The chemical vapor infiltration technique is applied to generate the carbon matrix in the preform.

In conventional manufacturing, drilling with a twist drill bit is one of the most commonly used methods in the machining of holes required for the composite assembly, accounting for about 40% of all removed materials. However, their non-homogeneous and brittle nature make difficult to guarantee the hole quality in drilling of C/C composites. The most commonly defects are burrs, delamination, and tear in drilling of C/C composites. In order to overcome these problems, it is very necessary to develop suitable methods to gain appropriate cutting parameters in drilling of C/C composites.

It is well known that the cutting force is the most important factor in reducing drilling defects of composites. There are extensive literatures about the influence of cutting force (thrust force) in drilling of composites. In 1990, Ho-Cheng and Dharan\(^3\) first studied the concept of critical thrust force in drilling of composite laminates. Chen\(^4\) found that it was possible that drilling method suppressing delamination could be gained by selecting suitable tool geometries and drilling parameters in drilling of carbon fiber–reinforced polymer (FRP) composites. Tsao\(^5\) reported that the delamination induced by the thrust force in drilling at the exit of hole could be avoided if the thrust force could be controlled below a critical thrust force. Rubio et al.\(^6\) investigated that high speed machining could reduce defects during drilling of glass FRPs by experiments. Kerrigan and Scaife\(^7\) found that dry drilling could reduce torque and make more holes than drilling with any cutting fluid in the cutting tests of carbon FRPs. Shan et al.\(^8\) reported that rotary ultrasonic drilling could improve the hole quality compared with high speed drilling and conventional twist drilling methods in the drilling tests of C/C composites within their selected cutting parameter range.

There have been a large amount of efforts developing prediction models of cutting force and investigating the cutting mechanism of drilling. One of the models for the prediction of cutting force in drilling of composites is the empirical equation model using test data. Langella et al.\(^9\) proposed a mathematical prediction model for thrust force and torque in drilling of composites. The coefficients in their model must be recalculated by a simple linear relation equation once the tool geometries or materials were changed. To analyze the influences of cutting parameters on delamination factor, Karnik et al.\(^10\) established an artificial neural network prediction model with point angle of twist drill bit, feed rate, and spindle speed as the input parameters. They reported that high speed machining was helpful to control the
delamination during drilling. By assuming that the distributions of cutting force along the chisel edge and the cutting lips of a drill bit is continuous, Wang and Zhang\textsuperscript{11} presented a cutting force prediction model incorporating tool geometries and cutting process parameters. In their model, the cutting lips and the chisel edge were taken as oblique cutting and orthogonal cutting, separately. Zhang et al.\textsuperscript{12} presented an analytical mechanical model for drilling of carbon FRPs based on composites mechanics, linear elastic fracture equations, and classical bending thin plate theory.

Cutting simulation has become a very effective method to optimize tool geometries and cutting parameters for controlling hole quality and analyzing the evolution of tool wear.\textsuperscript{13} Taking the workpiece as an equivalent homogeneous anisotropic material, He et al.\textsuperscript{14} constructed a three-dimensional (3D) macro finite element (FE) model for drilling of carbon FRPs using the ABAQUS software tool. Usui et al.\textsuperscript{15} proposed a FE method using a large deformation, nonlinear Lagrange equation with an explicit integration for orthogonal cutting and drilling of unidirectional carbon FRPs. Based on the Shokrieh–Lessard’s model\textsuperscript{16} and the Hashin’s failure criteria, Shan et al.\textsuperscript{17} presented a damage initiation model and a 3D progressive failure model in the FE simulation for drilling of 2.5 dimensional (2.5D) C/C composites.

In summary, although the empirical modeling method has a certain practical value, it requires a experiments and data accumulation. Once the cutting parameters, tools, or process equipment are changed, the prediction accuracy of the empirical formula will definitely decrease, and the test and data accumulation have to be repeated. Compared with the costly empirical modeling method, as an alternative method, the FE method can offer a visible of cutting process and is a reliable method for defects prediction.\textsuperscript{18} However, its calculation process is complicated and time-consuming. And the simulations for composites drilling are mostly concentrated on composite laminates (such as carbon FRPs), but few studies on C/C composites.

In this article, an improved mechanistic prediction model of thrust force in drilling of bidirectional C/C composites using a carbide twist drill bit is proposed. The effects of fiber orientation and cutting parameters are considered in this model. Experimental cutting tests are carried out and results are compared with the predicted results to verify the validity of the proposed model.

**Modeling of thrust force**

Generally, in the modeling of the thrust force for a twist drill bit, the chisel edge and the cutting lips of the twist drill bit are always analyzed as two distinct separate zones, then summing them up to obtain the total thrust force.

The influence of cutting temperature is not included in the model. Bidirectional C/C composites are anisotropic and can be regarded as a brittle material without plastic formation during the drilling process according to the literature reviews. The variation of the friction between the tool, chip, and workpiece during the
drilling process is neglected. The filled chopped carbon fiber felts between fiber plies of bidirectional C/C composites are considered to have the same properties as carbon matrix.

**Cutting force on chisel edge**

Many years ago, Kachanov\(^{19}\) and Langella et al.\(^{9}\) reported that a small region all-round the center point of a drill bit does not cut, but only extrude the material, which is then cut off by the main cutting lips. Hence, the chisel edge is commonly regarded as orthogonal cutting with negative rake angle by many researchers.\(^{4,11,20–22}\) However, to be precise, it is not enough to describe the cutting force trend of chisel edge satisfactorily.

During drilling process, the chisel edge is pushed into the workpiece primarily like a wedge, and then the cutting lips begin to cut materials. Figure 1 shows the relevant geometries and cutting force components in the section plane of the chisel edge. According to the theory of contact mechanics,\(^{23}\) the average stress \(\kappa\) generated when a rigid wedge is push into a workpiece could be expressed as

\[
\kappa = \frac{dP}{2adr} = 2\tau_s(1 + \psi_s)
\]

where \(dP\) is the elemental load acting on the rigid wedge, \(dP = dF_c\), and \(dF_c\) is the elemental force of the chisel edge. \(\tau_s\) is the maximum yield stress value of the workpiece material in pure shear. \(\psi_s\) is the sector angle of the slip line field of the extruded material, \(2a\) is the contact length of the chisel edge, and \(dr\) is the elemental axial length perpendicular to the section plane, as shown in Figure 1. On the one hand, the wedge angle \(\gamma_w\) of the chisel edge could be calculated by Johnson\(^{23}\) as

\[\gamma_w = \frac{2a}{dr}\]
\[
\gamma_w = \frac{1}{2} \left[ \arccos \left( \frac{\cos \psi_s}{1 + \sin \psi_s} \right) + \psi_s \right]
\]  

(2)

On the other hand, the wedge angle \( \gamma_w \) of the chisel edge could be calculated by

\[
\tan \gamma_w = \tan p \sin \psi
\]

(3)

where \( p \) is the half of the twist drill bit point angle, and \( \psi \) is the chisel edge angle as shown in Figure 1.

In the beginning, the cutting lips of the twist drill bit would not start cutting the workpiece until the chisel edge has penetrated into the workpiece to a cutting depth \( g \) equal to \( f_r/2 \) (two cutting lips). \( f_r \) is the feed rate per revolution of the twist drill bit. Then the contact length \( 2a \) can be expressed by

\[
2a = 2g \tan \gamma_w = f_r \tan \gamma_w
\]

(4)

As shown in Figure 1, the resultant cutting force \( dF_c \) acting on the chisel edge can be decomposed to the cutting force \( dF_{cv} \) along the thrust direction and the cutting force \( dF_{ch} \) along the velocity \((v_c)\), then

\[
\tan \gamma_d = \frac{f_r}{2\pi r}
\]

(5)

where \( \gamma_d \) is the total cutting speed angle and can be calculated by Wang and Zhang\textsuperscript{24}

Then

\[
\begin{align*}
\{ dF_{cv} &= dF_c \cos \gamma_d \\
 dF_{ch} &= dF_c \sin \gamma_d
\end{align*}
\]

(6)

Then according to equations (1) and (6), the total cutting force acting on the chisel edge is

\[
F_{cv} = \int_{-d/2}^{d/2} 2f_r \tan \gamma_w \tau_s (1 + \psi_s) \cos \gamma_d dr
\]

(7)

**Cutting force on cutting lip**

**Mechanics model of cutting lip.** Bidirectional C/C composites are made by alternating 0° and 90° unidirectional carbon fiber plies as shown in Figure 2(a). According to Zhang et al.\textsuperscript{25} the mechanics model at a certain point \( p \) can be treated as three cutting deformation regions, namely, chipping, pressing, and bouncing regions, separately.

**Region 1.** The first cutting deformation region is a chip formation zone. Due to the structure characteristics of bidirectional C/C composites, the shear strength of
carbon fiber is much larger than carbon matrix. Because of the poor bonding performance of the carbon fiber and the carbon matrix of C/C composites, the interlaminar shear strength becomes very low, resulting a near step-like shear plane formed in drilling as shown in Figure 2(b).

As shown in Figure 3, the cutting force $F$ of the drill bit acting on the chip can be resolved into two components. One is the pressure force $F_n$ against the chip, and the other is the friction force $F_f$. The reaction force $F'$ of the workpiece acting on the chip can be resolved into the pressure force $F_n$ and the shear force $F_s$. The shear force $F_s$ can be resolved into $F_{s1}$ and $F_{s2}$ components. The cutting force $F_{s1}$ is perpendicular to the fiber orientation. The cutting force $F_{s2}$ is parallel to the fiber orientation. $F$ and $F'$ are equal with each other in magnitude and in opposite directions.

As shown in Figure 3(a), the elemental length $dl$ is a small segment on the main cutting lip. The elemental shear forces $dF_{s1}$ and $dF_{s2}$ in the section plane perpendicular to the main cutting lip can be expressed as

\[
\begin{align*}
  dF_{s1} &= \frac{\tau_1 a_p}{\tau_2 \cot(\theta - \phi) \sin \theta - \cos \theta} dl \\
  dF_{s2} &= \frac{\tau_2 a_p}{\sin \theta - \frac{\tau_2}{\tau_1} \tan(\theta - \phi) \cos \theta} dl
\end{align*}
\]

where $\tau_1$ and $\tau_2$ are the shear strength of carbon fiber and carbon matrix, respectively, $\theta$ is the fiber orientation angle, $\phi$ is the shear angle, and $a_p$ is the cutting depth.

Then, the elemental shear force $dF_s$ can be given as

\[
dF_s = \frac{\tau_2 a_p}{\sin \theta \cos(\theta - \phi) - \frac{\tau_2}{\tau_1} \cos \theta \sin(\theta - \phi)} dl
\]

According to the geometrical relationship in Figure 3(a)
Where $\beta$ is the friction angle on the rake face of the tool, and $\gamma_n$ is the rake angle of the tool.

Then the tangential force $F_{C1}$ and the feed force $F_{T1}$ can be given as:

$$
\begin{align*}
    dF_n &= dF_s \tan(\phi + \beta - \gamma_n) \\
    dF_{C1} &= dF_n \sin \phi + dF_s \cos \phi \\
    dF_{T1} &= dF_n \cos \phi - dF_s \sin \phi 
\end{align*}
$$

The shear angle $\phi$ can be expressed by

$$
\phi = \tan^{-1}\left( \frac{r_c \cos \gamma_n}{1 - r_c \sin \gamma_n} \right)
$$

where $r_c = a_p/a_c$, $a_c$ is the chip thickness. In light of the brittle nature of C/C composites, $r_c = 1$ in this article.

Then
\[
\left\{ \begin{array}{l}
\frac{dF_{C1}}{dl} = \frac{\tau_2 a_p}{2} \left[ \tan(\phi + \beta - \gamma_n) \sin \phi + \cos \phi \right] \\
\frac{dF_{T1}}{dl} = \frac{\tau_2 a_p}{2} \left[ \tan(\phi + \beta - \gamma_n) \cos \phi - \sin \phi \right]
\end{array} \right.
\tag{13}
\]

Region 2. A simplified diagram of region 2 is shown in Figure 3(b). According to contact mechanics, the tool nose can be treated as a cylinder rolling on a plane, and the acting load \(dF_{N2}\) can be expressed as

\[
dF_{N2} = \frac{\pi r_e E_2}{8} \sin \theta
d\theta
\tag{14}
\]

where \(r_e\) is the radius of the tool nose, and \(E_2\) is the effective elastic modulus of the workpiece material in the second deformation zone and can be given by

\[
E_2 = \frac{E}{1 - \nu^2}
\tag{15}
\]

where \(E\) and \(\nu\) are the elastic modulus and Poisson’s ratio of the bidirectional C/C composite, respectively.

Due to the elastic deformation of the second cutting deformation zone, the effective pressure force \(F_{N2}'\) is a function with respect to the pressure force \(F_{N2}\) and the fiber orientation angle \(\theta\)

\[
F_{N2}' = KF_{N2} = f(\theta)F_{N2}, \quad K = 0.5 \tan^{-1} \left( \frac{30}{\theta} \right)
\tag{16}
\]

As shown in Figure 3(b), the friction force \(f_2\) can be obtained by

\[
f_2 = \mu F_{N2}'
\tag{17}
\]

where \(\mu\) is the friction coefficient of the bidirectional C/C composite.

Thus, the tangential and feed elemental cutting forces, \(dF_{C2}\) and \(dF_{T2}\), in region 2 can be expressed by equation (18) in terms of the effective pressure force \(F_{N2}'\), the friction force \(f_2\), and the fiber orientation angle \(\theta\)

\[
\left\{ \begin{array}{l}
\frac{dF_{C2}}{dl} = \frac{\pi r_e E_2}{8(1 - \nu^2)} [\sin \theta + \mu \cos \theta] \sin \theta \\
\frac{dF_{T2}}{dl} = \frac{\pi r_e E_2}{8(1 - \nu^2)} [\cos \theta - \mu \sin \theta] \sin \theta
\end{array} \right.
\tag{18}
\]

Region 3. The third cutting deformation region is a rebound zone. It is caused by the interaction of the clearance face of the tool and the machined surface of the workpiece. In order to simplify the calculation, it is assumed that the bouncing back height is equal to \(r_e\).

According to contact mechanics, the pressure force \(F_{N3}\) can be calculated by
where \( a \) is the contact length between the clearance face of the tool and the machined surface, \( \alpha_0 \) is the clearance angle of the tool. \( E_3 \) is the effective elastic modulus of the workpiece material in the third deformation zone. \( E_3 \) is set to \( K_E \) times of \( E \), and \( K_E \) is set to 0.35 in this article.

The frictional force \( f_3 \) between the workpiece and the tool shown in Figure 3(c) can be decomposed into two components \( f_{3C} \) and \( f_{3T} \) in the horizontal direction and the vertical direction, respectively. Hence, the elemental cutting forces \( dF_{C3} \) and \( dF_{T3} \) in horizontal and vertical directions in the third deformation zone can be expressed as

\[
\begin{align*}
    dF_{C3} &= \frac{1}{2} aE_3 \tan \alpha_0 dl \\
    dF_{T3} &= \frac{1}{2} E_3 \ln 1 - \frac{1}{v^2} dl (1 - \mu \cos \alpha_0 \sin \alpha_0)
\end{align*}
\]  

Figure 4. Illustration of fiber orientation angle.

The total cutting forces, \( dF_C \) and \( dF_T \), can be expressed as

\[
\begin{align*}
    dF_C &= dF_{C1} + dF_{C2} + dF_{C3} \\
    dF_T &= dF_{T1} + dF_{T2} + dF_{T3}
\end{align*}
\]  

Fiber orientation angle. As shown in Figure 4, it is assumed that the 0° fiber ply is parallel to MN, and the 90° fiber ply is perpendicular to MN. Point \( H \) is an arbitrary point on the cutting lip in the cross section of a twist drill bit. The fiber orientation angle \( \theta \) is defined to be the angle between the 0° fiber ply and the cutting speed direction of point \( H \). At the beginning, it is assumed that the fiber orientation angle \( \theta \) of point \( H \) is \( \theta_0 \) at time \( t_0 \). At time \( t \), the point \( H \) moves to \( H' \), and the fiber orientation angle of point \( H \) comes to be \( \theta(t) \). Hence, for the 0° fiber ply, the rotation angle \( \theta(t) \) can be expressed by
For the 90° fiber ply, the fiber orientation angle $\theta'(t)$ can be gained by

$$\theta'(t) = \pi - \theta(t)$$

Total thrust force. As shown in Figure 5, there is an inclination angle $i$ between the normal direction of the cutting lip and the cutting speed, which can be expressed as

$$i = \arcsin(\sin \alpha \sin p)$$

where $\alpha$ is the angle between the cutting speed $v$ and its $x$ direction component, which is related to the radius $r$ of point $Q$, and can be obtained by

$$\alpha = \arcsin \frac{w}{r}$$

where $w$ is the half of the drill bit web thickness.

In the normal plane perpendicular to the cutting lip at point $Q$ in Figure 5, the projection vector of cutting speed $v$ in the normal plane can be resolved into two components: the component perpendicular to the cutting lip and the component parallel to $v_x$. The angle $\xi$ between the two velocity components can be calculated by

$$\xi = \arctan(\tan \alpha \cos p)$$

According to the geometrical relationship in Figure 5, the normal rake angle $\gamma_n$ can be expressed as
\[
\gamma_n = \gamma_f - \xi
\]  
(27)

where \(\gamma_f\) is the reference rake angle, which can be calculated according to the calculation formula proposed by Armarego\(^27\)

\[
\tan \gamma_f = \frac{\tan \delta \cos \alpha}{\sin p - \tan \delta \sin \alpha \cos p}
\]  
(28)

where \(\delta\) is the local helix angle of point \(Q\).

Assuming that the helix angle of the drill bit is \(\delta_0\), the local helix angle \(\delta\) of point \(Q\) can be calculated by

\[
\delta = \tan^{-1}\left(\frac{r}{R} \tan \delta_0\right)
\]  
(29)

The length \(l\) of cutting lip can be obtained as

\[
l = \frac{1}{\sin p} \sqrt{r^2 - w^2} - \frac{d}{2} \cos(\pi - \psi)
\]  
(30)

where \(d\) is the chisel edge length, then

\[
dl = \frac{r \, dr}{\sin p \sqrt{r^2 - w^2}}
\]  
(31)

Then \(dF_R\) can be expressed as

\[
dF_R = \sqrt{(dF_C^2 + dF_T^2)} \sin \beta \tan \eta
\]  
(32)

where \(\eta\) is the chip flow angle.

According to Stabler,\(^28\) the chip flow angle \(\eta\) can be approximately equal to the inclination angle \(i\). According to the geometrical relationship in Figure 5 and Altintas\(^29\)

\[
\begin{align*}
    dF_{Ci} &= dF_C \cos i + dF_R \sin i \\
    dF_{Ti} &= dF_T \\
    dF_{Ri} &= dF_R \cos i - dF_C \sin i
\end{align*}
\]  
(33)

Then

\[
dF_{lip} = dF_{Ti} \cos \xi \sin p - dF_{Ri}(\cos i \cos \varphi + \sin i \sin \xi \sin p)
\]  
(34)

Then the total cutting force \(F_{lip}\) of the two cutting lips can be expressed by

\[
F_{lip} = 2 \int_{d/2}^{R} dF_{lip} \frac{r}{\sin p \sqrt{r^2 - w^2}} \, dr
\]  
(35)
The total thrust force, $F_Z$, are the summation of the cutting forces of the cutting lips and the chisel edge, that is

$$F_Z = F_{lip} + F_{cv}$$  \hspace{1cm} (36)

According to Altintas,\textsuperscript{29} shear angle, average friction angle, average friction factor, shear strength of C/C composites, and other values can be obtained by orthogonal cutting tests.

Similarly, the total torque is the summation of the torque of the cutting lips and the chisel edge. The calculation method of torque can be found in Wang and Zhang,\textsuperscript{11} which is not discussed in this article.

**Experimental procedure**

To validate the developed model, a group of cutting experiments is conducted. The experimental equipment is a JOHNFORD-VMC850 four-axis control numerical control (CNC) machine tool with a FANUC-OI-MB NC unit. Its maximum spindle speed is 8000 r/min and its maximum power is 22 kW. The workpiece, which is cut from a part, is a bidirectional C/C composite thin plate composed of about seven plies and with thickness equal to 6 mm, as shown in Figure 6. First, the preform of the part is prepared by laminating unidirectional carbon fiber plies one over another in a $90^\circ$ cross and filling chopped carbon fiber felts between adjacent plies. Then, the chemical vapor infiltration technique is used to generate the carbon matrix in the preform.

Four conventional two-lip cemented carbide twist drill bits of 6 mm in diameter with a $118.8^\circ$ angle are used, which is shown in Figure 7. The cutting force signal acquisition system consists of a Kistler 9255B type three-component dynamic dynamometer, a Kistler 5080A multi-channel charge amplifier, a Dewesoft

![Figure 6. Bidirectional C/C composite thin plate.](image)
DEWE3010 data collector, and DEWESoftX software. The experimental setup is shown in Figure 8. Because the cutting forces in three directions of X, Y, and Z can be acquired by the three-component dynamic dynamometer, the cutting force measured in the Z-direction is exactly the thrust force. However, because of the limitation of the equipment conditions, the torque cannot be directly measured in these experiments by the three-component dynamic dynamometer. Hence, the torque is not compared with the prediction value in this article.

The geometrical parameters of the twist drill bit and the material properties of the workpiece are shown in Tables 1 and 2, respectively. The cutting parameters used in the experiments are shown in Table 3. The experiments are conducted using a single factor method without coolant. The average thrust force obtained from three repeated experiments is adopted as the experimental result. Hence, each twist drill bit is used 12 times at the same spindle speed for four different feed rates.

Results and analysis

Figure 9 shows the measured thrust force signals under the cutting parameters of \( n = 1000 \text{ r/min} \) and \( v_f = 150 \text{ mm/min} \). The drill bit begins to cut at time B. In
the beginning, as the twist drill bit advances, the thrust force increases quickly. From time B to C, the thrust force is mainly caused by the chisel edge of the drill bit. From time C to D, the chisel edge has immersed into the workpiece and the

Table 1. Geometrical parameters of the twist drill bit.

| Parameter                  | Value     |
|----------------------------|-----------|
| Point angle                | 118.8°    |
| Helix angle                | 30°       |
| Chisel length              | 0.6 mm    |
| Twist drill bit radius     | 3 mm      |
| Clearance angle            | 13.4°     |
| The chisel edge angle      | 120°      |
| Cutting lip radius         | 3.5 µm    |

Table 2. Material properties of the workpiece.

| Property                                  | Value     |
|-------------------------------------------|-----------|
| Tensile strength (X, Y)                   | 47.35 MPa |
| Tensile strength (Z)                      | 20.98 MPa |
| Compressive strength (X, Y)               | 119.44 MPa|
| Compressive strength (Z)                  | 182.6 MPa |
| Shear strength of carbon fiber             | 91.53 MPa |
| Shear strength of carbon matrix            | 21.95 MPa |
| Shear strength of C/C composite            | 54.68 MPa |
| Average friction factor                    | 0.75      |
| Elastic modulus (XY)                       | 16.41 GPa |
| Elastic modulus (Z)                        | 5.51 GPa  |
| Poisson’s ratio                            | 0.026     |

Table 3. Cutting parameters used in the experiments.

| No. | Spindle speed, n (r/min) | Cutting speed, v_c (m/min) | Feed rate, v_f (mm/min) |
|-----|--------------------------|----------------------------|-------------------------|
| 1   | 1000                      | 18.85                      | 60                      |
| 2   | 1000                      | 18.85                      | 90                      |
| 3   | 1000                      | 18.85                      | 120                     |
| 4   | 1000                      | 18.85                      | 150                     |
| 5   | 2000                      | 37.7                       | 60                      |
| 6   | 2000                      | 37.7                       | 90                      |
| 7   | 2000                      | 37.7                       | 120                     |
| 8   | 2000                      | 37.7                       | 150                     |
| 9   | 3000                      | 56.54                      | 60                      |
| 10  | 3000                      | 56.54                      | 90                      |
| 11  | 3000                      | 56.54                      | 120                     |
| 12  | 3000                      | 56.54                      | 150                     |
| 13  | 4000                      | 75.4                       | 60                      |
| 14  | 4000                      | 75.4                       | 90                      |
| 15  | 4000                      | 75.4                       | 120                     |
| 16  | 4000                      | 75.4                       | 150                     |
cutting lips of the drill bit begin to cut. From time D to E, the thrust force increases slightly, mainly because the friction force between the tool and the work-piece increases a bit with the increasing of cutting depth. From time E to F, the thrust force quickly drops to near zero with the twist drill bit coming out of the workpiece.

The experimental and predicted values of the thrust force are compared in Table 4. It can be seen from it that the maximum relative deviation of the thrust force is about 14.36%, and the minimum value is about 1.67%.

Figure 10 shows the variation trends of the experimental values of the thrust force versus spindle speed. It can be seen that the experimental values of the thrust force fall gradually with the rising of spindle speed from 1000 to 4000 r/min. These trends are similar for different feed rates from 60 to 150 mm/min. Figure 11 shows the variation trends of the experimental values of the thrust force versus feed rate. It can be seen that the experimental values of the thrust force rise approximately linearly with the rising of feed rate. These trends are also similar for different spindle speeds from 1000 to 4000 r/min. Moreover, the rising trends of the thrust force gradually slow down as the spindle speed increases. As the feed rate increases from 60 to 150 mm/min, the thrust force rises approximately 85% when \( n = 1000 \) r/min; however, the thrust force only rises about 40% when \( n = 3000 \) r/min.

Figure 12 shows the comparison of the experimental and predicted values of the thrust force for different spindle speeds as the feed rate increases from 60 to 150 mm/min. The predicted values show a good agreement with the experimental results especially when \( n = 2000 \) and 3000 r/min.

Figure 13 shows the comparison of the experimental and predicted values of the thrust force for different feed rates as the spindle speed rises from 1000 to 3000 r/min. The predicted values show a good agreement with the experimental results especially when \( v_f = 60 \) and 90 mm/min. Therefore, the thrust force can be reduced by increasing spindle speed and decreasing feed rate in the selected cutting parameter range. In order to reduce the defects in drilling of C/C composites, higher spindle speeds and lower feed rates should be selected in low speed machining.
The prediction of thrust force is very important for controlling the defects of composites in drilling process. An analytical mechanical model for predicting the thrust force is presented in drilling of bidirectional C/C composites. The cutting force of the cutting lips is established by dividing the cutting deformation zones into three regions based on the Zhang’s model in cutting of FRPs. The cutting force on chisel edge is established according to the theory of contact mechanics and orthogonal

Table 4. Experimental and predicted values of the thrust force.

| $n$ (r/min) | $v_f$ (mm/min) | Experimental $F_{exp}/N$ | Predicted $F_p/N$ | Relative deviation (%) |
|-------------|----------------|--------------------------|------------------|-----------------------|
| 1000        | 150            | 47.721                   | 51.504           | 7.93                  |
| 120         | 39.518         | 35.286                   | 35.949           | 1.88                  |
| 90          | 30.098         | 27.937                   | 7.18             |
| 60          | 22.209         | 18.721                   | 9.765            | 5.58                  |
| 2000        | 150            | 33.751                   | 25.893           | 2.56                  |
| 120         | 33.751         | 25.339                   | 19.765           | 4.17                  |
| 90          | 25.893         | 20.578                   | 3.95             |
| 60          | 17.292         | 17.283                   | 14.36            |
| 3000        | 150            | 21.606                   | 20.463           | 6.65                  |
| 120         | 21.606         | 20.463                   | 12.83            |
| 90          | 17.283         | 15.684                   | 5.58             |
| 60          | 14.692         | 14.692                   | 2.56             |
| 4000        | 150            | 25.231                   | 25.231           | 2.56                  |
| 120         | 21.823         | 19.765                   | 14.36            |
| 90          | 19.765         | 17.696                   | 12.83            |
| 60          | 17.003         | 15.616                   | 5.58             |

Figure 10. Experimental values of the thrust force versus spindle speed.

Conclusion

The prediction of thrust force is very important for controlling the defects of composites in drilling process. An analytical mechanical model for predicting the thrust force is presented in drilling of bidirectional C/C composites. The cutting force of the cutting lips is established by dividing the cutting deformation zones into three regions based on the Zhang’s model in cutting of FRPs. The cutting force on chisel edge is established according to the theory of contact mechanics and orthogonal
Figure 11. Experimental values of the thrust force versus feed rate.

Figure 12. Comparison of the predicted and experimental values of the thrust force for different spindle speeds: (a) $n = 1000 \text{ r/min}$, (b) $n = 2000 \text{ r/min}$, (c) $n = 3000 \text{ r/min}$, and (d) $n = 4000 \text{ r/min}$.
cutting. The function of fiber orientation at different drilling times is developed considering its periodic change. The total thrust force is the summation of the cutting forces of the cutting lips and the chisel edge. The model is verified by a series of experiments. The experimental results show that the maximum deviation of the predicted and experimental values of the thrust force is about 14.36%, and the minimum deviation is about 1.67%. Hence, it indicates that the proposed model can be used to predict the thrust force in drilling of bidirectional C/C composites when the requirements are not high. Moreover, to reduce the defects in drilling of bidirectional C/C composites, higher spindle speed and lower feed rate should be selected because the thrust force can be reduced by increasing spindle speed and decreasing feed rate in low-speed machining.

**Declaration of conflicting interests**

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Appendix 1

Notation

- $a_p$: cutting depth
- $a_c$: chip thickness
- $2a$: contact length of the chisel edge
- $d$: chisel length
- $dP$: elemental load on a wedge
- $dr$: elemental axial length
- $dF_c$: elemental resultant force on the chisel edge
- $dF_{cv}$, $dF_{ch}$: elemental cutting force along the thrust direction and the velocity, respectively
- $dl$: elemental length on the cutting lip
- $dF_{N2}$: elemental acting load in region 2
- $E$: elastic modulus of composites
- $E_2$: effective elastic modulus in the second deformation zone
- $E_3$: effective elastic modulus in the third deformation zone
- $f_r$: feed rate per revolution
- $F_n$: pressure force on the chip
- $F_f$: friction force
- $F'$: reaction force
- $F_s$: shear force on the chip
- $F_{s1}$: shear force perpendicular to the fiber orientation in region 1
- $F_{s2}$: shear force parallel to the fiber orientation in region 1
- $F_{C1}$, $F_{T1}$: tangential force and feed force in region 1, respectively
- $F_{C2}$, $F_{T2}$: tangential force and feed force in region 2, respectively
- $F_{C3}$, $F_{T3}$: tangential force and feed force in region 3, respectively
- $f_2$: friction force in region 2
- $F'_{N2}$: effective pressure force in region 2
- $F_{N3}$: pressure force in region 3
- $F_{lp}$: total cutting force of the two cutting lips
- $F_Z$: total thrust force
- $g$: cutting depth of the chisel edge in the beginning
- $i$: inclination angle
- $K$: average stress caused by a wedge
- $n$: spindle speed
- $2p$: point angle of the drill bit
- $r$: radius of an arbitrary point on the cutting edge of a drill bit
- $r_c$: radius of the tool nose
- $R$: twist drill bit radius
- $2w$: drill bit web thickness
$\alpha_0$ clearance angle of the tool
$\beta$ friction angle on the rake face
$\tau_s$ maximum shear yield stress
$\gamma_w$ wedge angle of the chisel edge
$\gamma_d$ cutting speed angle
$\gamma_n$ rake angle of the tool
$\gamma_f$ reference rake angle
$\delta_0$ helix angle of the drill bit
$\eta$ chip flow angle
$\tau_1, \tau_2$ shear strength of the carbon fiber and the carbon matrix, respectively
$\theta$ fiber orientation angle
$\phi$ shear angle
$\nu$ Poisson’s ratio of composites
$\mu$ friction coefficient
$\Psi$ chisel edge angle
$\psi_s$ sector angle of the slip line