Fundamental Investigation on the tilt helical milling of carbon fiber reinforced plastics (CFRP)

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Abstract. Carbon fiber reinforced plastics (CFRP) are widely used in various aircraft structural components. However, it is difficult for conventional methods such as drilling and helical milling to meet the requirements on high quality and efficient holes creation. Hence a so-called tilt helical milling (THM) method has been proposed. This new method is performed by replacing the revolving motion of the tool in conventional helical milling (CHM) with conical pendulum motion, in which the tool axis is tilted towards the hole axis at a certain angle. As a step toward the establishment of the new method, in this work, the fundamental drilling characteristics of CFRP by the THM is elucidated by experimentally investigating the effects of tilt angle on thrust force and delamination factor. The obtained experimental results demonstrated that the thrust force was considerably lower in THM than in CHM. The delamination is effectively suppressed by this new method.

Introduction
Carbon fiber reinforced plastics (CFRP) is a class of extremely strong and light-weight carbon fiber reinforced polymers, and used for various mechanical structures [1]. However, it is difficult for conventional methods, such as drilling, helical milling and so on, to meet industrial requirements [2-3]. Against these problems, the authors proposed a novel method for drilling holes in CFRP products [4]. This new method is performed by replacing the revolving motion of the tool in conventional helical milling with conical pendulum motion, in which the tool axis is tilted towards the hole axis at a certain angle, so it is called tilt helical milling (THM).

In conventional helical milling (CHM) process, the tool proceeds a helical path while rotates around its own axis, where the tool axis is constantly parallel to the hole axis. In contrast, the THM technique is performed by tilting the tool against the hole at a small angle. So that, the tool rotates around its own axis and exhibits conical pendulum motion around the hole axis. That is, the kinematic difference of the two methods is due to the tool attitude. In addition, the delamination is a major problem during drilling of CFRP, which tends to reduce hole-making quality. The thrust force has a critical influence on the fiber delamination and tool wear [5-6]. Therefore, as a step toward the establishment of the hole drilling technique by THM, it is important to elucidate the effects of the tilt angle on the thrust force and the delamination factor and to reasonably select the processing parameters for ensuring the dimensional accuracy, the tool working life and the productivity.

In this paper, the effects of the tilt angle on the thrust force and the delamination factor are experimentally investigated. Proposals for the basic understanding of the machining process are presented.

Processing principle and experimental setup
Figs. 1 (a) and (b) schematically show the processing principles of hole creation by CHM and THM, respectively. In CHM (Fig. 1 (a)), the axis of the tool, usually an end mill with a diameter of \( D_t \),
positioned parallel to that of the hole. During processing, the tool rotates around its own axis at a speed of \( n \) and has planetary motion around the hole axis at a speed of \( n_o \), and is simultaneously fed downward along the hole axis at a feed rate of \( v_f \). Eventually, the tool proceeds a helical trajectory to generate a hole with a diameter of \( D_b \).

In contrast to CHM where the tool axis is constantly parallel to the hole axis, the tool attitude in THM is adjusted momentarily so that the tool axis is always tilted against the hole axis with the tilt angle, \( \theta \), due to the conical pendulum motion (Fig. 1 (b)). That is, the tool rotates around its own axis at the speed \( n \), and exhibits conical pendulum motion around the hole axis at a speed of \( n_o \). Simultaneously it is fed downward along the hole axis at a feed rate of \( v_f \). Hence, a point, \( O_{HT} \), on the hole axis, where the tool axis crosses the hole axis, moves downward as the tool is fed downward along the hole axis. As an end mill with a diameter of \( D_t \) is used as the tool, the unwanted materials in the wall and at the bottom of the hole are cut off with the side and end of the tool at the same time. Eventually, the tool moves along a helical path to generate a hole with a diameter of \( D_b \).

In order to experimentally validate the capacity of the proposed THM in the hole creation of CFRP, an experimental apparatus is constructed by installing a work holding unit produced in house onto a 3-axis NC milling machine as show in Fig. 2 (a). The work-holding unit mainly consists of a workpiece holder, a rotary table, a motor, and a wedge-shaped tilt base for tilting the workpiece at the given tilt angle (Fig. 2 (b)). A dynamometer is fixed below the unit to measure the drilling force. If the wedge-shaped tilt base is replaced with a flat plate, the hole drilling by CHM could be performed. In experiments, plate-shaped CFRP samples with dimensions of L80xW40xH2.8 mm are used as the workpiece and dry drilling operations without coolant are performed.
Experimental conditions and procedure

For the purpose of investigating the fundamental machining characteristics of the new method, the CHM is also performed for comparison, and the experiment is carried out at the same hole-making efficiency and the cutting speed of the tool as those in THM. During drilling process, the through-hole is created once the end face of the tool has penetrated through the workpiece with thickness of \( H \).

According to helical milling kinematics, the stock tool feeds \( s \) (mm) required for completing the hole-making as expressed in Eq. (1). The total time, \( T \), required for completing the hole drilling is determined as in Eq. (2).

\[
s = H + D \sin \theta + v_f / n_o \quad (1)
\]
\[
T = s / v_f \quad (2)
\]

Combining Eqs. (1) and (2), the experimental parameters were set which ensure the same hole-making efficiency and the cutting speed of the tool during drilling process, as shown in Table 1. As the cutting tool, a commercial cemented carbide cross cutter (BC4114 by Minitor Co., Ltd., Japan) was employed (Fig. 3).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CHM</th>
<th>THM₁</th>
<th>THM₂</th>
<th>THM₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool rotational speed, ( n ) (rpm)</td>
<td>2000</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Tool revolution speed, ( n_o ) (rpm)</td>
<td>153</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Axial feed speed, ( v_f ) (mm·min⁻¹)</td>
<td>11.81</td>
<td>13.56</td>
<td>15.30</td>
<td>17.04</td>
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<tr>
<td>Tilt angle, ( \theta ) (°)</td>
<td>0</td>
<td>2.5</td>
<td>5.0</td>
<td>7.5</td>
</tr>
<tr>
<td>Hole diameter, ( D_b ) (mm)</td>
<td>12</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Experimental conditions

Results and discussion

Thrust force during drilling. Drilling experiments were conducted at different tilt angles. Fig. 4 exhibits a typical experimental result, i.e., the variations of thrust force \( F_z \) during drilling both in CHM (\( \theta = 0° \)) and THM (\( \theta = 5.0° \)), showing that the thrust force in CHM is about twice the value in THM. It is also can be seen that the variation of the thrust force in CHM is heavier than that in THM. This implies that the THM process is better for lowering and stabilizing the thrust force than the CHM process.

Fig.5 shows the effect of the tilt angle \( \theta \) on the maximum thrust force \( F_{z,max} \). Obviously, as the \( \theta \) increases from 0° to 7.5°, the \( F_{z,max} \) decreases from 109.6 N to 51.3 N, showing the \( F_{z,max} \) is quickly
decreased with the increase of the tilt angle $\theta$. It is in particular worthy to note that the $F_{z,max}$ is decreased by 53.2% at $\theta=7.5^\circ$ compared with those in CHM ($\theta=0^\circ$).

**Appearance of hole edge.** Fig. 6 and Fig. 7 show the photographs of the inlet and outlet sides of holes created by CHM ($\theta=0^\circ$) and THM at different tilt angles, $\theta$, respectively. In CHM, many chippings and burrs appeared on the hole edges at both sides (Fig. 6 (a) and Fig. 7 (a)). In particular, a large delamination occurred at the outlet side of the hole (Fig. 7 (a)). By contrast, as can be seen from Figs.6(b), (c), (d) and Figs. 7 (b), (c), (d) in THM ($\theta=2.5^\circ$, 5.0$^\circ$, 7.5$^\circ$), although burrs and chippings can be still observed on the hole edges at both sides, the number of burrs and the chipping area are much smaller compared with those in CHM. It is especially worthy to note that no large delamination occurred at the exit side of the hole by THM at different tilt angles.

For evaluating the hole quality, the delamination factor $F_d$ was introduced which is defined as in Eq. (3).

$$F_d = \frac{D_m}{D_i}$$  \hspace{1cm} (3)

where $D_m$ is the maximum diameter of the damaged zone and $D_i$ is the ideal diameter of the hole (Fig.8) [7].
The effect of the tilt angle on the delamination factor is plotted in Fig. 9. At a tilt angle of 2.5°, the delamination factor of inlet side and the delamination factor of outlet side are reduced by 9% and 18%, respectively, relative to their CHM values (measured at a tilt angle of 0°). This reduction may be attributable to the small thrust force and the tool attitude. In THM at different tilt angles (θ=2.5°, 5.0°, 7.5°), the $F_d$ of both sides was nearly in the same level.

Summary

The tilted helical milling (THM) technique was developed for high quality hole drilling of CFRP. In order to investigate the fundamental machining characteristics of the the new method, the conventional helical milling (CHM) was also performed for comparison, and the experiments was carried out on the same hole-making efficiency and the cutting speed of the tool. The obtained results are drawn as followings.

- The thrust force in THM was considerably lower than in CHM. They also decreased with increasing tilt angle, θ. The measured thrust drilling force in THM (θ=5.0°) was approximately half of that in CHM (θ=0°).
- The THM process is better for lowering and stabilizing the thrust force than the CHM process.
- Similar to the thrust force, the delamination factor was considerably lower in THM than in CHM. But in THM at different tilt angles (θ=2.5°, 5.0°, 7.5°), the delamination factor of both sides was nearly in the same level.

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References