Study on the drilling quality in ultrasonic vibration assisted drilling of CFRP/Al alloy Stacks

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Abstract. The mechanism in drilling carbon fiber reinforced plastic (CFRP) and aluminum stack materials differs from that in drilling single material. Aluminum chips evacuation through the hole deteriorate the CFRP hole quality. In this paper, ultrasonic vibration assisted drilling (UVAD) technology is introduced to improve the drilling quality. Then the mechanism of chip formation is studied in UVAD of CFRP/Al. To investigate the quality in drilling of CFRP/Al stacks, orthogonal experiments are designed for analyzing the effects of both vibration parameters and cutting parameters on the drilling performance of hole roughness, burr length and height. The results show that ultrasonic vibration is beneficial to fracture the chip and reduce the damage of hole. Besides, better drilling quality can be obtained with the combination of low feed rate and high spindle speed.

1 Introduction

The use of carbon fiber reinforced plastic (CFRP) in the aeronautical field is growing. In a commercial aircraft such as Boeing 787, 50% of the total weight was composites [1]. For industry applications, CFRP composites were often used by stacking up with aluminum to form stack. Consequently, large numbers of rivet or bolt holes are needed to produce. And drilling is the most common method to manufacture holes, the drilling quality directly affects the strength and fatigue life of the part.

Due to differential mechanical properties and processing mechanisms, drilling of such laminated composite is a challenging task to manufacture engineers. In the traditional drilling, the rapid tool wear, the low processing efficiency and the poor hole quality are major problems [2]. Extraordinarily, the CFRP is prone to delamination, fiber pullout, fiber fragmentation, burrs and other defects. Besides, in the aluminum alloy drilling, built-up edge and burr will occur due to low elastic modulus and melting point [3,4]. A lot of work in drilling of CFRP/Al show that the defect is influenced by the choice of the machining parameters, the tool geometries and types. In the work of Zitoune et al. [5,6], the authors investigated the influence of machining parameters on chip formation, the quality of the holes and tool wear. The experimental results that the size of the chips is strongly influenced by feed rate and the surface roughness in CFRP can be obtained in low fees rate. In addition, the aluminum is usually stacked at the bottom of CFRP in drilling process. The high-temperature and continuous aluminum chips produced during drilling
considerably damage the CFRP hole. Brinksmeie et al. [7] studied the titanium chip passing through CFRP layers deteriorated the quality of the hole. Ramulu et al. [8] showed that the entrance of CFRP holes was obviously damaged in the bonding surface of the CFRP and the titanium alloy due to the high temperature.

In order to reduce the defect of CFRP/Al in the traditional drilling, ultrasonic vibration assisted drilling (UVAD) technology is introduced to improve the drilling quality. It is a hybrid process that combines the material removal mechanisms of conventional drilling and ultrasonic machining. Compared with the traditional drilling, UVAD can effectively reduce the thrust force and tool wear. Pecat et al. [9,10] performed experiments in the drilling of CFRP/Ti under a low vibration frequency. They reported that the cutting temperatures can be reduced by more than 40% in the titanium alloy, and the excellent surface integrity was achieved due to better chip extraction and lower cutting temperatures. The work of Cong et al. [11,12] showed that rotary ultrasonic machining (RUM) resulted in lower cutting force, CFRP surface roughness and longer tool life, compared with other methods for drilling of CFRP/Ti stacks.

According to our survey, the literature related to UVAD of CFRP/Al alloy Stacks is limited. In this paper, the mechanism of chip formation is studied in UVAD of CFRP/Al, and the chip shapes versus machining parameters are discussed. Experimental study on drilling of CFRP/Al stack is carried out. The vibration parameters and the machining parameters influenced on chip shape, hole surface roughness, burr length and burr height are experimentally evaluated.

2 Chip formation analysis

Based on reported literature and our extensive experimental work, the shape and size of the CFRP chip are not influenced by the choice of vibration parameters and the drilling parameters. However, the aluminum chips are greatly influenced by the machining parameters. And drilling with a low feed rate produced continuous chips. While the chips break into little segments when the feed rate is increased [5,6]. Besides, the ultrasonic vibration is beneficial to break the continuous aluminum chips. The mechanism of chip formation in UVAD is different from the traditional drilling. Fig. 1 shows the shape and size of aluminum chips in different machining parameters.

According to the contact condition of drill and workpiece, the drilling can be divided into separation and continuous type in UVAD. It is conspicuous that aluminum chips are discontinuous when the drill was separated from the workpiece. Even, aluminum chips are easier to break under the type of continuous drilling compared with traditional drilling.

By superposing the high-frequency and low-amplitude on the tool, the motion of axial consists of ultrasonic vibration and feed motion in UVAD. Assuming the high-frequency vibration equation is sinusoidal curve, and the axial equation of the cutting lip is shown as follows:
\[ z(t) = x(t) + \frac{v_f}{60} t = A \sin(2\pi Ft) + \frac{v_f}{60} t . \] (1)

For a standard drill, the drill has two cutting lips, the axial equations of the two lips \( a \) and \( b \) can be given as:

\[ z_a(t) = A \sin(2\pi Ft) + \frac{v_f}{60} t . \] (2)

\[ z_b(t) = A \sin \left[ 2\pi F \left( t + \frac{30}{n} \right) \right] + \frac{v_f}{60} \left( t + \frac{30}{n} \right) . \] (3)

Under the type of continuous drilling, the chip thickness is the difference between the two equations. The chip thickness can be written as:

\[ h_d = z_b(t) - z_a(t) = \frac{v_f}{2n} + 2A \cos \left[ 2\pi Ft + \frac{30\pi F}{n} \right] \sin \left( \frac{30\pi F}{n} \right) . \] (4)

where \( v_f \) is the feed rate, \( mm/min \); \( n \) is the spindle speed, \( r/min \); \( A \) is the ultrasonic vibration amplitude, \( \mu m \); \( F \) is the ultrasonic vibration frequency, \( Hz \); \( t \) is the time, \( s \).

From the above analysis, the chip thickness is affected by the feed rate, the spindle speed, the ultrasonic vibration amplitude and the ultrasonic vibration frequency. Moreover, it periodically changes with time. Besides, the dynamic chip thickness is uneven at different times. In practice, the unevenness of chip thickness produced a concentration stress, which makes the chip prone to break.

![Image](image_url)

(a) \( n=5000r/min, v_f=110mm/min, A=6\mu m \) (b) \( n=5000r/min, v_f=110mm/min, A=0\mu m \)

Fig. 1 Influence of the machining parameters on the form of aluminum chip.

3 Experimental setup

3.1 Experimental Conditions.
Carbon fiber reinforced plastic composite of 3.07mm thickness (24 layers) is used
for conducting the experiments. Plain woven fabric of carbon fiber has an orientation of [0°/90°]. The aluminum alloy of 4.1mm thickness is stacked under CFRP. And the mechanical-physical properties of CFRP and aluminum alloy are shown in Table 1. All experiments are carried out on a three-axis CNC machining center (KVC1050N, China) without coolant. The ultrasonic vibration is produced via a vibration device, capable of delivering high frequency vibrations (20 KHz) at various amplitudes (0-8). A carbide twist drill with the diameter of 4.5mm is used in experiments. The surface roughness is measured by a contact surface roughness tester (Surtronic25, Taylor Hobson, British). CFRP entrance burrs and Aluminum exit burrs are detected by laser microscope (KEYENCE, Japan).

<table>
<thead>
<tr>
<th>Mechanical-physical properties</th>
<th>CFRP</th>
<th>Al</th>
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<tbody>
<tr>
<td>Tensile strength [MPa]</td>
<td>3950</td>
<td>572</td>
</tr>
<tr>
<td>Elasticity modules [GPa]</td>
<td>232</td>
<td>71.7</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>1.76</td>
<td>2.81</td>
</tr>
<tr>
<td>Elongation [%]</td>
<td>1.7</td>
<td>12</td>
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</table>

### 3.2 Design of Experiments.

In this study, the parameters affecting the drilling quality and their levels were selected based on our preliminary investigations. Three important parameters, namely, vibration amplitude, feed rate, and spindle speed were selected, and each parameter was investigated at four levels. The designated symbols and their levels are given in Table 2. Besides, the orthogonal experiments are designed for analyzing the effects of these parameters on the drilling quality. It can study the entire space with only a small number of experiments. Therefore, $L_{16}(4^3)$ orthogonal array is used.

<table>
<thead>
<tr>
<th>Factor code</th>
<th>Parameters</th>
<th>levels</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>Vibration amplitude[μm]</td>
<td>0 4 6 8</td>
</tr>
<tr>
<td>B</td>
<td>Feed rate [mm/min]</td>
<td>110 130 150 170</td>
</tr>
<tr>
<td>C</td>
<td>Spindle speed [r/min]</td>
<td>2000 3000 4000 5000</td>
</tr>
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</table>

### 4 Result and Discussion
4.1 hole surface roughness.

Fig. 2 illustrates the surface roughness of the holes in all \((L_{16})\) tests. According to experimental data, the surface roughness values of aluminum alloy holes vary slightly, and all the values can be controlled within 1.6\(\mu\)m. However, vibration amplitude and feed rate have a significant effect on the surface roughness values of CFRP holes. In Fig. 2a, the surface roughness of CFRP holes exceeded 3.2\(\mu\)m in traditional drilling (vibration amplitude is 0\(\mu\)m). However, the ultrasonic vibration can reduce CFRP surface roughness, and the values are significantly decreased to less than 1.6\(\mu\)m (the regulations of the industry \(Ra\leq3.2\mu m\)). Besides, it also decreases with the increase of the vibration amplitude. On the other hand, Fig. 2b shows the effect of the feed rate on the CFRP surface roughness. It can be seen that the increase of feed rate leads to the value of the surface roughness increase. The reason is that the cutting force and the cutting temperature increase as the feed rate increases. Then, the fiber is easily set aside from matrix and remains on machined surface, which increases the CFRP surface roughness. Influence of spindle speed on the roughness of machined surface is shown in Fig. 2c. Experimental results show that the spindle speed has less effect on the CFRP surface roughness.

![Fig. 2 Measured results of hole surface roughness.](image)

4.2 CFRP entrance burrs and aluminum exit burrs detection

The burrs of CFRP and aluminum are formed in different ways. The topography of the hole burrs are shown in Fig. 3. The CFRP burrs are mainly at the entrance of the hole, while the aluminum burrs are at the exit. Therefore, the length of CFRP entrance
burrs and the height of aluminum exit burrs are measured and analyzed. Their values are detected by laser microscope, and using the maximum value to evaluate burrs length and height.

Fig. 3 The topography of the hole burrs.

(a) The length of CFRP entrance burrs.

(b) The height of aluminum exit burrs.

Fig. 4 shows the effect of vibration parameters and machining parameters on hole burrs. Obviously, the length of CFRP entrance burrs and the height of aluminum exit burrs have a similar tendency. It can be seen that the ultrasonic vibration can reduce the burr length of CFRP and the burr height of aluminum. In addition, the burr length of CFRP decreases with the increase of the ultrasonic vibration amplitude, while the burr height of aluminum is only reduced at a small vibration amplitude (vibration amplitude is 4μm). When the vibration amplitude increases, the burr length of CFRP increases. Besides, the feed rate has a major effect on the burrs of hole. With the
increase of feed rate, the length of CFRP entrance burrs and the height of aluminum exit burrs rapidly increase. It can be seen that there is a approximate linear relationship between the burrs of hole and feed rate. For the spindle speed, the trend is decreased first and then increased. Experimental result (spindle speed is 4000 r/min) shows that the value of burrs are lowest. When the speed continues to increase, the length of CFRP entrance burrs and the height of aluminum exit burrs increase.

Fig. 4 Measured results of burr length and height.

5 Conclusions

This paper presents the mechanism of chip formation and the results of a study on holes quality in UV AD of CFRP /Al alloy Stacks. Three input variables (vibration amplitude, feed rate and spindle speed) in UVAD are studied. In the following, the most important findings and hypothesis are listed:

1. The mechanism of chip formation in UVAD is different from the traditional drilling. Effect of ultrasound vibration and the feed rate have a great effect on aluminum chip breakability. The chip extraction could be significantly improved by the application of UVAD.

2. Ultrasonic vibration can improve the drilling quality of the hole. The hole roughness, burr length and height are reduced in UVAD of CFRP /Al alloy Stacks. The feed rate has a significant impact on drilling quality compared with the spindle speed. Using a low feed rate and high spindle speed can get better drilling quality.
Acknowledgments
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References


