Low-Frequency Vibration Drilling of Titanium Alloy

Kiyoshi OKAMURA**, Hiroyuki SASAHARA**, Toshiaki SEGAWA*** and Masaomi TSUTSUMI**

Dry drilling of composite/metallic stacks for aircraft components is extremely difficult to keep sufficient hole quality and efficiency of drilling process. Problems of the dry drilling of those kinds of stacks are chip ejection, chip formation and high temperature especially for titanium alloy. To clear these problems, low-frequency vibration (10–50 Hz) drilling is proposed in this study. Controlled sinusoidal vibration was given in drill axis direction with constant feed motion. The relationship between vibration conditions, such as vibration amplitude, frequency and drill feed rate, and chip formation and drilling temperature were investigated. As a result, low-frequency vibration drilling can control chip formation to reduce chip jamming and can reduce drilling temperature. Temperature measured at the cap burr decreased by 300 degrees C or more when low-frequency vibration was applied compared with the conventional drilling. Also the wear rate of the drill is decreased when the vibration is applied.

Key Words: Low-Frequency Vibration Drilling, Drilling Temperature, Chip Formation, Machining Load, Drill Wear, Exit Burr

1. Introduction

Aluminum alloy, carbon fiber compound material, and titanium alloy are mainly used as structural member of the aircraft such as the body, the main wing, and the tail, etc. It is because the light weight and high strength are required more and more for the next generation aircrafts such as Boeing B787 and Airbus A380(1),(2). Therefore, many hole opening operation for the piled up carbon fiber composites and titanium alloy and/or aluminum alloy is required to assemble the main structure such as body parts and the wings. However, the cutting temperature becomes very high when titanium alloy is machined because the thermal conductivity is very low, and as a result, the tool wear becomes severe(3).

Moreover, the adhesion often occurs easily to the tip of the drill as for the machining of titanium alloy and aluminum alloy. The adhesion leads to the increase in the cutting resistance and chip jamming within the flutes of drill. As a results, it leads to the drill breakage and the decrease of the hole accuracy(4),(5). Those problems are usually avoided due to the use of the cutting oil and the decrease of the cutting speed. However, a dry processing is strongly needed to reduce the cleaning costs of oil in the assembly of the aircraft. On the other hand, many studies of effective coatings on tools to reduce the friction and to give heat resistance are carried out(6),(7). The coated tool is sometimes effective but it is not enough to perform the dry machining of titanium alloy or aluminum alloy.

Then, to clear these problems, low-frequency vibration drilling is proposed in this study. It was reported that the ultrasonic vibration drilling is effective to make fine hole or in drilling of difficult to machine materials(8). However, the vibration amplitude is realized up to several micro meters or so, it restrict the machining efficiency in ultrasonic vibration drilling. On the other hand, in the proposed low-frequency vibration drilling, almost same machining efficiency as the conventional drilling can be realized as the 0.5 mm vibration amplitude in axial direction with 10 to 50 Hz are given. Drilling process becomes an intermittent cutting by low-frequency vibration with enough amplitude. Zhang et al.(9) and Wang(10) and Sakurai(11) investigated the machining force in vibration drilling. Jin(12) et al. also examined the step vibration drilling for difficult to cut materials and showed the capability of the step vibration drilling. But the thermal effect
in vibration drilling on cutting process has not been clarified. As the heating process of drill also becomes intermittent, drill wear rate will possibly be improved. In addition, from the view point of chip exhaust, as the chips are divided into short parts according to the intermittent process, chip jamming is thought to be avoided. In this paper, the relationship between vibration conditions, such as vibration amplitude, frequency and drill feed rate, and chip formation and drilling temperature and tool wear were investigated considering these background.

2. Proposed Drilling Machine and Experiment

2.1 Low frequency-vibration drilling machine

Figure 1 shows the outline of the developed low-frequency vibration drilling machine. Drilling spindle is mounted on two parallel linear guides. One is a linear guide driven by a ball screw for long travel (X-axis), and the other is a linear guide driven by a linear motor for low-frequency vibration (U-axis). This combination of two linear guides realizes the vibrating drilling motion in axial direction. Table 1 shows the specifications of low-frequency vibration drilling machine. Vibrating amplitude and frequency are variable, and the axial vibration amplitude is large enough to realize the intermittent cutting in combination with the setting of feed rate.

2.2 Experimental conditions and measurement method

Table 2 shows the experimental conditions. In this study, Ti-6Al-4V titanium alloy plate of 3.175 mm in thickness was employed. Vibration amplitude and frequency were varied as shown in Table 2 to clarify the influence on drilling temperature, tool wear and the chip formation state, etc. In each condition, drilling temperature, and thrust force were measured.

Drilling temperature was measured by K type thermocouple of 0.3 mm diameter, which was welded on the back side of the workpiece as shown in Fig. 2. The welded point is located on the drilling axis, then the welded point remains as a cap burr after the drilling. Figure 3 shows the cap burr with thermo couple after drilling was carried out. Then temperature at the drilling exit can be measured. In addition, thrust force was measured with load cell located behind the workpiece fixture.

After the drilling, state of the drill wear, chip shape, hole exit burr shape, and the change in color around the hole exit in each condition were observed with CCD camera. We examined five times of drilling tests in each experimental condition in sequence, and the above-mentioned

<table>
<thead>
<tr>
<th>Table 2 Cutting conditions</th>
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</thead>
<tbody>
<tr>
<td>Spindle speed (min⁻¹)</td>
</tr>
<tr>
<td>Feed (mm/min)</td>
</tr>
<tr>
<td>Amplitude (mm)</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>Tool diameter (mm)</td>
</tr>
<tr>
<td>Tool material</td>
</tr>
<tr>
<td>Thickness of Work piece (mm)</td>
</tr>
<tr>
<td>Work material</td>
</tr>
<tr>
<td>Cutting fluid</td>
</tr>
</tbody>
</table>

Fig. 2 Photograph of thermo-couple welding point

Fig. 3 Photograph of cap burr with welded thermo-couple

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**Table 1** Specification of low-frequency vibration drilling machine

<table>
<thead>
<tr>
<th>Travel of each axis</th>
<th>X-axis (mm)</th>
<th>U-axis (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120</td>
<td>40</td>
</tr>
<tr>
<td>Specification of spindle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spindle speed (min⁻¹)</td>
<td>max 10000</td>
<td></td>
</tr>
<tr>
<td>Power (kW)</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>Feed rate (mm/min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spindle speed (min⁻¹)</td>
<td>min 10000</td>
<td></td>
</tr>
<tr>
<td>Power (kW)</td>
<td>3.55</td>
<td></td>
</tr>
<tr>
<td>Vibration specification of linear motor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplitude (mm)</td>
<td>0.24 - 0.4</td>
<td></td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>0, 10, 20, 30</td>
<td></td>
</tr>
<tr>
<td>Maximum electric power usage (kW)</td>
<td>3.55</td>
<td></td>
</tr>
<tr>
<td>Amount of the maximum use (MPa, N/mm²)</td>
<td>0.5, 120</td>
<td></td>
</tr>
</tbody>
</table>
observations were conducted.

3. Relative Movement of Drill and Work Piece

In low-frequency vibration drilling, the relative movement \((X)\) between the drill and the work piece can be shown as the following expressions.

\[
V_v = a \omega \sin(\omega t) \quad (\omega = 2\pi f) \quad (1)
\]

\[
V_r = V_0 + V_v \quad (V_0 = \text{Const}) \quad (2)
\]

\[
X = V_0 t - a \cos(\omega t) \quad (4)
\]

\[
dX = V_0 / f \quad (5)
\]

Where \(a\) and \(f\) are vibration amplitude and frequency, \(V_0\) is constant feed rate of linear motion of a ball screw, \(V_v\) is relative speed between the drill and the work piece in axial direction, and \(dX\) is machining distance at one vibration cycle.

Figure 4 shows the change of the relative distance between the drill and work piece for the case of amplitude 0.4 mm with frequency 10 Hz. In this figure, the term C means the cutting time in one vibration cycle and the term D means non-cutting time. This means the cutting becomes more severe in this cutting time than the case without vibration. Figure 5 shows the average uncut chip thickness in the cutting time. It can be seen that the average uncut chip thickness in the cutting time is three to eight times larger than the case without vibration under the cutting conditions shown in Table 2.

4. Experimental Results and Discussion

4.1 Drilling temperature

Figure 6 shows the change of the maximum drilling temperature at the hole exit against the number of drilled holes. On the case of amplitude 0.4 mm, drilling temperature was lower than the case without vibration in each vibration frequency. On the other hand, on the case of amplitude 0.24 mm, drilling temperature is lower than the case without vibration at first and second holes. But after the third hole with frequency 10 Hz and 20 Hz, drilling temperature became higher than the cases without vibration. However, the case with frequency 30 Hz, drilling temperature kept low even if the number of holes increases. From these results, it seems that large amplitude and higher frequency in low-frequency vibration drilling is effective to decrease drilling temperature.

Moreover, for the case of amplitude 0.4 mm with vibration frequency 30 Hz and the case without vibration, experiments were carried out up to 25 holes, and temperature was measured every 5 holes. Figure 7 shows the change of the maximum drilling temperature. Drilling temperature is kept low even if the number of holes increases when low-frequency vibration is applied. On the other hand, on the case without vibration, drilling temper-
ature rises up to 900 degrees C after 10 holes.

4.2 Thrust force

Figure 8 shows the change of thrust force in the first hole for the case of without vibration, and the case of amplitude 0.4 mm with frequency 10 Hz. The maximum thrust force in vibration drilling was larger than the case without vibration. The reason why thrust force were increased is that the average uncut chip thickness on low-frequency vibration drilling increases to 3 to 8 times larger compared with the case without vibration.

If vibration frequency is very high like ultrasonic vibration (over 20 kHz), measured thrust force will be decreased because the natural frequency of the measurement system consist of dynamometer and workpiece-fixture is much lower than the vibrating frequency\(^{(13)}\). But in this low-frequency vibration drilling, cutting force variation directly appears and acts on the workpiece and tool.

4.3 Drill wear

The transition of the drill flank wear for the case without vibration, and the case of amplitude 0.4 mm with frequency 30 Hz are shown in Fig. 9. As employed cutting conditions are severe, drill wear rapidly progressed especially on the case without vibration. However, the drill wear rate was reduced to about 1/3 when low-frequency vibration was applied. Moreover, the chipping on chisel edge of the drill couldn’t be seen on low-frequency vibration drilling, while some chipping occurred on the case without vibration. As the machining efficiency is same in these two test conditions, the chip load in each cutting time on vibration drilling is larger than the case without vibration. It should be noted that both chipping and tool wear are reduced in vibration drilling. Decrease of drilling temperature is thought to contribute to reduce the chipping and tool wear. In addition, some lubrication effect may be caused when the drill tip apart from the chip/workpiece as mentioned in some vibration cutting processes\(^{(14),(15)}\).

4.4 Chip formation

Figure 10 shows the photograph of the chip for the case without vibration and low-frequency vibration drilling on the first hole drilling. It can be seen that...
the chip is divided into around 10 mm length by low-frequency vibration drilling. As a result, drill breakage by the chip jamming can be avoided.

Figure 11 shows the closeup view of the chip. Folded wavy type chip was mainly observed on both cases. But in the case of low-frequency vibration drilling, conical helix type chip, which is good in chip ejection, was included partly. The chip generated in low-frequency vibration drilling is thought to be effective to reduce of the adhesion to the drill flute and jamming because of the following two points, namely, short chip length and generation of conical helix type chip.

Figure 12 shows the chip under each vibration condition. As the vibration frequency becomes higher, the chip length became shorter. It is because the machining distance \( dX \) becomes shorter with the increase of frequency \( f \) in Eq. (5). Moreover, comparing two cases of amplitude 0.24 mm and 0.4 mm under same vibration frequency in Fig. 12, conical helix type chip appeared more often when amplitude is 0.4 mm. It can be observed the folded wavy type chip often generated when uncut chip thickness becomes thinner than about 0.02 mm. The following two characteristics in vibration drilling are considered as the reasons why the conical helix type chip appeared more often as the amplitude becomes larger. One is that the uncut chip thickness increases as amplitude becomes larger. The other is that the cutting time with uncut chip thickness less than 0.02 mm in one vibration cycle becomes shorter as amplitude becomes larger.

### 4.5 Hole exit burr shape and the change in color around the hole exit

Figure 13 shows the photograph of the hole exit burr shape on the 25th hole drilled without vibration and the case of amplitude 0.4 mm with frequency 30 Hz. Both height and the thickness of the hole exit burr became small on low-frequency vibration drilling. It is considered that the lower drilling temperature contributed to avoid the increase of ductility when low-frequency vibration is ap-
plied. Also, as the smaller tool wear results in small drilling force, it contributes to small exit burr.

Figure 14 shows the photograph of the change in color around the hole exit on 25th hole. Cutting conditions are the same as the case in Fig. 13. It can be seen that the color changes to gold and blue around the hole on the case without vibration. It is difficult to say the actual temperature from the color change of titanium alloy, temperature is thought to over 300 degrees C at least. On the other hand, on low-frequency vibration drilling, those changes in color are hardly seen. From these observations, low-frequency vibration drilling can reduce the thermal influences on not only chip and tool but also the work material.

5. Conclusions

Low-frequency vibration drilling machine is developed and the effect of the vibration conditions, such as vibration amplitude and frequency, on the drilling temperature, force, and chip and burr formation were investigated. The following conclusions were obtained.

(1) Under the experimental condition with amplitude 0.4 mm and vibration frequency 30 Hz in this report, drilling temperature of titanium alloy has decreased greatly by applying low-frequency vibration. As a result, the drill wear rate was suppressed largely, and the hole exit burr height and thickness became small. Also, thermal influences on the work material were largely reduced.

(2) The chip was divided into short length and conical helix type chips were appeared under low-frequency vibration drilling. As the amplitude becomes large and the vibration frequency becomes high, these effects appear more remarkably.

References

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