Hole Making Machine based on Double Eccentric Mechanism for CFRP/TiAl6V4 Stacks

H.Yagishita
Numazu National College of Technology
3600 Ooka, Numazu-city, Shizuoka-pref. 410-8501
JAPAN

J. Osawa
OSG Corporation
149 Miyamae, Ichinomiya-cho, Toyokawa-city, Aichi-pref., 441-1231
JAPAN

ABSTRACT
Construction parts consisting of 2-layer composite materials made of carbon fiber reinforced plastic (CFRP) laminates and TiAl6V4 still need to be machined, whereby drill holes are frequently manufactured. Recently, it is well-known that Orbital drilling, which is also called Circular milling, Planetary drilling or Spiral drilling, is superior to conventional drilling for hole making of CFRP/TiAl6V4 stacks. The author newly developed hole making machine based on Double Eccentric Mechanism so that a cutting tool driven by one built-in air motor can rotate clockwise on its own axis at high speed, simultaneously can revolve counter-clockwise on eccentric axis at low speed (Yagishita, 2012). The driving mechanism of the machine is entirely different in that respect both high speed rotation and low speed revolution of cutting tool can be created by one built-in air motor from Novator’s mechanism (PCT/SE2008/050719) which needs two driving sources.

The purpose of this paper is that by replacing a built-in air motor used in the previous hole making machine with a built-in AC motor it is achieved to lighten the weight of the machine and also to be handy by applying electric control device. After that hole making tests are executed to CFRP/TiAl6V4 stacks by using a new type cemented carbide endmill having 6 blades.

Keywords: Hole making machine, Double eccentric mechanism, Orbital drilling, Circular milling, Planetary drilling, Spiral drilling, CFRP/TiAl6V4 stacks.

1 Introduction
Modern composite materials combining carbon fiber fabrics with a polymer matrix are attractive for use in structures for aviation and automotive applications due to their high strength-to-weight
ratios. In a wide range of applications dissimilar material stack-ups of composites and titanium alloys are used for wing or tailplane structures, door-frame and window-frame. These structures contain holes for various purposes such as bolts holes. The machining characteristics of these composites introduce a unique set of machining problems. Machining these materials induces intense tool wear, diameter deviation caused by dissimilar elastic moduli of the materials, hole defects, delaminations, and erosion as major problems. Apart from the intense tool wear caused by the high mechanical and thermal loads during the processes, the abrasion in the CFRP laminates layer is also a critical factor in aerospace fabrication (Yagishita, 2006). In addition, industrial demands such as the avoidance of cooling lubrication require a highly efficient machining technology and an optimized machining process.

Previously, the author compared the three processes for the hole making of 6 mm diameter to the CFRP laminates, which are conventional drilling, specific drilling assisted by ultrasonic torsional mode vibration cutting and circular milling. As a result it was ascertained that the circular milling process is superior to the other drilling processes from these aspects such as tool wear, hole diameter, roundness and peripheral zone defects, as well as operating efficiency (Yagishita, 2007). Continuously, the author applied the circular milling process and drilling one for the hole making of 6 mm diameter into CFRP/ TiAl6V4 stacks. As a result, it was ascertained that circular milling process is superior to drilling one in bore hole accuracy, tool life and outlet burr (Yagishita, 2008).

Recently, a new hole making machine was developed based on double eccentric mechanism so that a cutting tool can rotate clockwise on its own axis at high speed, simultaneously can revolve counterclockwise on eccentric axis at low speed which was driven by one built-in air motor, and hole making tests of CFRP/TiAl6V4 stacks were executed (Yagishita, 2012).

The purpose of this paper is that by replacing a built-in air motor used in the previous hole making machine (Yagishita, 2012) with a built-in AC motor it is achieved to lighten the weight of the machine and also to be handy by applying electric control device. After that hole making tests of 15 mm diameter are executed to CFRP/TiAl6V4 stacks by using a new type cemented carbide endmill having 6 blades. Hole diameter, roundness, tool life and outlet burr are measured and evaluated.

2 Principle of Double Eccentric Mechanism and Hole Making Machine

2.1 Principle of Double Eccentric Mechanism

Figures 1 (a) and (b) show the principle of double eccentric mechanism (Yagishita, 2012). In Fig. 1 (a) C1 is the first axis (center of rotation, i.e. central axis of the shaft portion 1). C2 is the second axis (center of revolution, i.e. central axis of the outer cylinder 2). C3 is a central axis of the inner cylinder 3. e1 is the amount of eccentricity of the central axis C3 of the inner cylinder 3 from the central axis C2 of the outer cylinder 2. e2 is the amount of eccentricity of the central axis C1 of the shaft portion 1 from the central axis C3 of the inner cylinder 3. θ is a phase angle of C1’ from the reference line, where the three centers of C2, C3 and C1 are positioned in line, when the center C1 of shaft portion 1 is shifted to C1’ by turning inner cylinder 3.
In Figure 1 (b) C1’ is a center of rotation of shaft portion 1 at a phase angle $\theta$. $t$ is a distance (amount of eccentricity) between the central axis C2 of the outer cylinder 2 and the center C1’ of the shaft portion 1 and can be calculated by the following equation (1).

$$t = [(e_1)^2 + (e_2)^2 + 2 \cdot (e_1) \cdot (e_2) \cdot \cos \theta]^{1/2} \quad (1)$$

When $(e_1)$ and $(e_2)$ are equal to 1.5mm, equation (1) is changed to equation (2).

$$t = [1.5^2 + 1.5^2 + 2 \cdot 1.5 \cdot 1.5 \cdot \cos \theta]^{1/2} \quad (2)$$

Accordingly,

- when $\theta = 0^\circ$, $t = 3.00$mm;
- when $\theta = 45^\circ$, $t = 2.77$mm;
- when $\theta = 90^\circ$, $t = 2.12$mm;
- when $\theta = 120^\circ$, $t = 1.50$mm.

When a cutting tool (endmill) attached to the shaft portion 1 rotates at high speed clockwise on its own axis simultaneously revolves slowly counterclockwise on the central axis C2 of the outer cylinder 2, down-cut milling is executed. If the diameter of endmill is $d$, the diameter of machined aperture $D$ is determined by the equation of

$$D = d + 2 \cdot t$$

Although during machining the inner cylinder 3 is fastened rigidly to the outer cylinder 2, when amount of eccentricity $t$ is adjusted, after being unfastened the inner cylinder 3 is turned on its own axis and the phase angle $\theta$ is changed.

### 2.2 AC Motor built-in Type Hole Making Machine based on Double Eccentric Mechanism

Figure 2 shows an AC motor built-in type hole making machine based on double eccentric mechanism (Yagishita, 2012, 2013, 2014). In Fig.2 an AC motor (0.45kw, max. 4,000 rpm) is built-in at the middle of the shaft portion 1. The left side output of the AC motor is connected to the shaft portion 1 and an endmill attached to shaft portion 1 is rotated clockwise at max.4,000 rpm. On the other hand, the right side output of the AC motor is reduced to max.40 rpm by a harmonic drive. Since the output of the harmonic drive is connected to the outer cylinder 2, the endmill revolves counterclockwise at max.40 rpm on the central axis C2 of the outer cylinder 2. At this time the revolving radius of the endmill is $t$ (amount of eccentricity) between the central axis C2 and the center C1’ of the endmill. $t$ can be changed by shifting the phase angle $\theta$ shown in Fig. 1 (a) and (b).

In Fig. 2 the feed mechanism generates an axial feed of the endmill. The rotation of an AC servo motor (0.3 kw) is connected to the timing pulley and belt device. A driven pulley is connected to a ball screw (P=5mm). Since a ball nut is fixed to the double eccentric mechanism, the axial feed of endmill is executed by rotating the ball screw.
A straightness of the feed motion is guaranteed within a high precision by using two pairs of slide guide consisting of one guide rail and two guide blocks. The heat generated by the built-in AC motor is carried away by air flow between shaft portion 1 and inner cylinder 3.

The specifications of the hole making apparatus are shown in Table 1. By replacing 1.0 kw air motor and 0.4 kw reversible air motor with 0.45kw AC motor and 0.3 kw AC servo-motor the weight of machine is reduced from 18 kgf to 13.5 kgf. Moreover, by using electric control device machining conditions such as start and end position of feed, rotational speed (rpm), revolution speed (rpm), feed rate (mm/min) and back feed rate (mm/min) are set by pushing keyboard on the control box of the machine shown in Fig.3(a).

### Table 1: Specifications of the hole making machine.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC motor built-in type</td>
<td>Max. 0.45 kw</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>1500～4000 rpm</td>
</tr>
<tr>
<td>Revolution speed</td>
<td>15～40 rpm</td>
</tr>
<tr>
<td>Stroke</td>
<td>Max. 45 mm</td>
</tr>
<tr>
<td>Feed rate</td>
<td>Max. 50 mm/min</td>
</tr>
<tr>
<td>Amount of eccentricity</td>
<td>0～3 mm</td>
</tr>
<tr>
<td>Tool diameter</td>
<td>φ 3mm～φ 10mm</td>
</tr>
<tr>
<td>Hole diameter</td>
<td>φ 3mm～φ 16mm</td>
</tr>
<tr>
<td>Weight of machine</td>
<td>13.5 kgf</td>
</tr>
</tbody>
</table>

### 3 Experimental Setup and Procedure

Figure 3 (a) shows an appearance of AC motor built-in type hole making machine based on double eccentric mechanism, (b) shows a helical nurlock adapter screwed to the end of taper flange and (c)

(a) Appearance of new hole making machine based on double eccentric mechanism.

(b) Helical nurlock adapter.

(c) Fitting jig for apparatus to be installed.

**Figure 3:** New hole making machine, helical nurlock adapter and fitting jig.
shows a fitting jig having four sets consisting of a pair of two nurlock clamps for one liner bushing. After the bush at end of helical nurlock adapter shown in Fig.3(b) is inserted into the liner bushing shown in Fig.3(c), the apparatus is fixed rigidly to the fitting jig shown in Fig.3(c) by turning the apparatus slowly so that the two taper surfaces of helical nurlock adapter may contact to the two taper surfaces of two nurlock clamps. In Fig. 3 (a) a white pipe attached to the taper flange is used to suck up a lot of small chips by air.

3.1 Material Systems

CFRP was consolidated from the laminates of prepreg, which were combined carbon fiber clusters with epoxy-resin matrix, using the autoclave method to create a strong high temperature composite. The experiments were carried out on CFRP/TiAl6V4 stacks shown in Fig.4 as workpiece. The workpiece consists of a CFRP laminates (10 mm) and a TiAl6V4 plate (4 mm). Most of cases in aerospace fabrication, CFRP laminates are used at outer side and TiAl6V4 at inner one.

3.2 Experimental Method and Machining Conditions

A diamond coated cemented carbide square endmill of 11 mm diameter having 6 blades shown in Fig.5 (a) and (b) is chosen for all hole making tests. In Fig.5 (a) 6 blades are composed of two pairs of three different shape’s blades. Hole making tests are executed at the amount of eccentricity of 2.0 mm. Therefore, the hole diameter machined is 15.0 mm. The summary of hole making conditions for CFRP/TiAl6V4 stacks is listed in Table 2.

After a series of hole making tests are executed by employing the hole making machine and fitting jig shown in Fig. 3(a), (b) and (c), hole diameter and roundness of CFRP laminates and TiAl6V4 are measured by a three coordinate measuring machine. The wear of cutting edges and the burr at inlet and outlet of CFRP’s hole and TiAl6V4’s hole are observed by a microscope.

Table 2: Summary of hole making conditions

<table>
<thead>
<tr>
<th>Hole diameter</th>
<th>15 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endmill used</td>
<td>11 mm× 85mm, R0.6, 6 cutting edges</td>
</tr>
<tr>
<td>Amount of eccentricity</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>2400 rpm</td>
</tr>
<tr>
<td>Revolution speed</td>
<td>24 rpm</td>
</tr>
<tr>
<td>Feed rate ( go )</td>
<td>24 mm/min</td>
</tr>
<tr>
<td>Feed rate ( back )</td>
<td>40.0 mm/min</td>
</tr>
<tr>
<td>Machining time per one hole</td>
<td>3 min 32 sec</td>
</tr>
</tbody>
</table>

Figure 5: Appearance of diamond coated cemented carbide square endmill used.
4 Results and Discussion

After hole making tests, hole diameter and roundness of CFRP and TiAl6V4 are measured at every four holes interval. For CFRP laminates the measuring is executed at two middle positions of the upper and lower CFRP, and for TiAl6V4 at one middle position within the thickness.

4.1 Hole Diameter in relation to Number of Hole Machined

Figure 6 shows the relationship of hole diameter in relation to number of hole machined. In Fig.6 from 1st to 12th hole, the hole diameter of both CFRP and TiAl6V4 decreases gradually as the number of hole machined increases. Within the following extent from 12th hole to 40th hole, the hole diameter of CFRP (Upper) and CFRP (Lower) are almost constant except for 32nd hole and 40th hole. On the other hand, the hole diameter of TiAl6V4 decreases gradually and the hole diameter of 32nd hole and 40th hole show smaller value than others similarly to those of CFRP (Upper) and CFRP (Lower).

Within the whole extent from 1st hole to 40th hole, the hole diameter of CFRP (Upper) is large, that of CFRP (Lower) is middle and that of TiAl6V4 is small, where the difference between CFRP (Upper) and CFRP (Lower) is about 0.18 mm and the difference between CFRP (Lower) and TiAl6V4 is also about 0.18 mm.

Table 3 shows mean value and standard deviation (S.D.) of hole diameter for CFRP (Upper), CFRP (Lower) and TiAl6V4.

<table>
<thead>
<tr>
<th>Material (position)</th>
<th>Mean (mm)</th>
<th>S.D. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP (Upper)</td>
<td>14.979</td>
<td>0.0777</td>
</tr>
<tr>
<td>CFRP (Lower)</td>
<td>14.856</td>
<td>0.154</td>
</tr>
<tr>
<td>TiAl6V4</td>
<td>14.711</td>
<td>0.189</td>
</tr>
</tbody>
</table>

Table 3: Mean value and S.D. of hole diameter.

![Figure 6: Relationship of hole diameter in relation to number of hole machined.](image-url)
4.2 Roundness in relation to Number of Hole Machined

Figure 7 shows the relationship of roundness in relation to number of hole machined. In Fig.7 the roundness of CFRP (Upper), CFRP (Lower) and TiAl6V4 increases gradually as the number of hole machined increases. Scattering width of roundness for CFRP (Lower) is the least value of about 120 \( \mu \) m, that for CFRP (Upper) is the largest value of about 150 \( \mu \) m and that for TiAl6V4 is middle.

Table 4 shows mean value and standard deviation (S.D.) of roundness for CFRP (Upper), CFRP (Lower) and TiAl6V4.

<table>
<thead>
<tr>
<th>Material (position)</th>
<th>Mean (mm)</th>
<th>S.D. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRP (Upper)</td>
<td>0.102</td>
<td>0.0434</td>
</tr>
<tr>
<td>CFRP (Lower)</td>
<td>0.104</td>
<td>0.0328</td>
</tr>
<tr>
<td>TiAl6V4</td>
<td>0.0980</td>
<td>0.0386</td>
</tr>
</tbody>
</table>

4.3 Wear of Cutting Edge

Figure 8 (a) shows top view of endmill having 6 blades used. In Fig.8 (a) Blade 1, Blade 2 and Blade 3 have different shapes respectively, and the other three blades have the same shapes as the opposite blade. Figure 8 (b) and (c) show the comparison between ① Before milling and ② After 40th hole milling for Blade 1, Blade 2 and Blade 3, where (b) is Flank surface and (c) is Rake surface respectively.

Blade 1, Blade 2 and Blade 3 in ② After 40th hole milling in Fig. 8 (b) show narrow flank wears as white lines at the end cutting edges. Although slight abrasion is seen at the outer cutting edges of Blade 1, Blade 2 and Blade 3, micro chipping is not seen at all.

Blade 1, Blade 2 and Blade 3 in ② After 40th hole milling in Fig. 8 (c) show slight abrasion at outer cutting edges, however, crater wear is not seen at all on the rake surface and micro chipping is not seen at all similarly to those in Fig 8 (b).
4.4 Edge Quality of Hole

Figure 9 (a) and (b) show inlet and outlet of CFRP’s hole at 1st hole, 20th hole and 40th hole. As shown in Fig. 9 (a) and (b) all edges at inlet and outlet of 1st hole, 20th hole and 40th hole are sharp without delaminations and edge quality is excellent at even 40th hole although violent chippings occurred at inlet and outlet of CFRP’s hole machined by previous hole making machine driven by air motor [1].

Figure 10 (a) and (b) show inlet and outlet of TiAl6V4’s hole at 1st hole, 20th hole and 40th hole.

Figure 9: Edge quality of inlet and outlet of CFRP’s hole.

Figure 10: Edge quality of inlet and outlet of TiAl6V4’s hole.
As shown in Fig. 10 (b) burr is not seen at all at outlet of 1st hole, 20th hole and even 40th hole. Such sharp edge is the result that cutting temperature is restrained at low level because of intermittent cutting by this hole making machine.

5 Conclusions

(1) By replacing built-in air motor and reversible air motor with built-in AC motor and AC servo-motor the weight of hole making machine is lightened to 13.5 kgf and by applying electric control device the machine becomes handy on the occasion of setting hole making conditions.

(2) This hole making machine enables to do hole making of CFRP/TiAl6V4 stacks without trouble besides with high efficiency and high accuracy at aircraft assembly site.

(3) Since there is no burr at all inlet and outlet of both CFRP’s hole and TiAl6V4’s hole, de-burring operation is not necessary. Therefore, the combination of this hole making machine and new type cemented carbide endmill having 6 blades is effective to execute hole making operation of CFRP/TiAl6V4 stacks. However, to satisfy thoroughly hole quality requirement a lot of hole making tests must be executed by changing kind of endmill and machining condition.

(4) Since the chips of CFRP and TiAl6V4 can be sucked up entirely by air, operators can execute hole making work under clean environment.

(5) Since cutting temperature is restrained at low level by this hole making machine, the machine enables to execute high quality hole making for difficult-to-cut materials having insufficient heat conductivity or heat sensitive materials.

References