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Experimental Study on Planetary Drilling Machinability for CFRP

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Abstract - **In this study, we express the locus of cutting edge motion on planetary drilling by computer simulating and clarify volume eliminated by bottom face cutting edge and side face cutting edge. Next we have constructed geometric cutting model of planetary drilling and found zero velocity point on bottom cutting edge which is caused by momentary relation among orbital eccentricity, planetary revolution speed and tool rotation spindle speed. In order to evaluate the influence on shapes of the cutting tool during the planetary drilling, we have focus on the shape of the cutting edge. Planetary drilling tools having several kinds of cutting edges are prepared and demonstrated. Considering the drilling load and chips, the appropriate shape of cutting edge was clarified.**

Keywords - **Planetary drilling, CFRP, Counter velocity radius, Cutting edge optimization**

I. INTRODUCTION

Recently, CFRP (Carbon Fiber Reinforced Plastic) are widely used as structural materials in aerospace and aircraft industries. However, those materials are mostly difficult to machine in conventional ways. The planetary drilling is one of the solutions of drilling for CFRP.

Planetary drilling equipment has two axes, which are eccentrically settled each other. The holes, which machined by the planetary drilling has higher roundness than holes machined by helical milling. Furthermore, surface machined by the planetary drilling is enough smooth and requires no finishing process.

In the study, we express the locus of cutting edge motion on planetary drilling by computer simulating and clarify volume eliminated by bottom face cutting edge and side face cutting edge. Next we have constructed geometric cutting model of planetary drilling and found zero velocity point on bottom cutting edge, which is caused by momentary relation among orbital eccentricity, planetary revolution speed and tool rotation spindle speed. In order to evaluate the influence on shapes of the cutting tool during the planetary drilling, we have focus on the shape of the cutting edge. Planetary drilling tools having several kinds of cutting edges are prepared and demonstrated. Considering the drilling load and chips, the appropriate shape of cutting edge was clarified.

II. CUTTING TOOL MOTION

In order to identify control factors on planetary drilling, geometrical model of cutting tool motion is necessary. We focused bottom edge motion on cutting tool, which inferentially affects thrust loading and construct geometric cutting model of planetary drilling

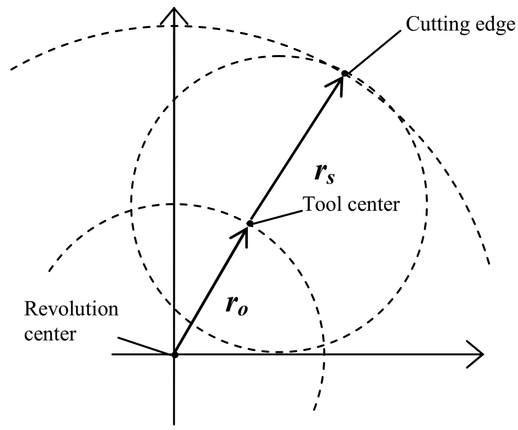


Fig. 1 Geometrical model of planetary cutting.

[2-4]. Cutting edge on bottom face is expressed as 2 positions vectors summation, as show in Fig. 1.

Vector $\boldsymbol{r_o}$ stands for position from planetary center to tool center and center and its value depend on planetary equipment control. Vector $\boldsymbol{r_s}$ stands for position from tool center to cutting edge on bottom face.

III. BOTTOM CUTTING EDGE VELOCITY

The velocity of a cutting edge on bottom face depends on revolution speed (tool speed around revolution center) and tool rotation speed as shown in Fig. 2(a). Therefore the velocity is not constant from speed and direction. An angle between the line for tool center to revolution center and a line for tool center to the cutting edge is named angular difference and it can be also the significant factor. Direction of tool rotation around orbital center is CCW and direction of tool rotation speed on its center axis is CW.

Velocity of the cutting edge by tool rotation (v_s [m/s]) is defined by the Eq. (1) where, r_n [m] stands for counter velocity radius and T_{ss} [s^{-1}] stands for spindle speed.

$$v_s = 2\pi\, T_{ss}\, r_n \tag{1}$$

Velocity of the point by planetary speed (v_o [m/s]) is defined by the Eq. (2) where, r_o [m] stands for eccentricity and N_o [s^{-1}] stands for revolution speed.

$$v_o = 2\pi\, N_o\, (r_o + r_n) \tag{2}$$

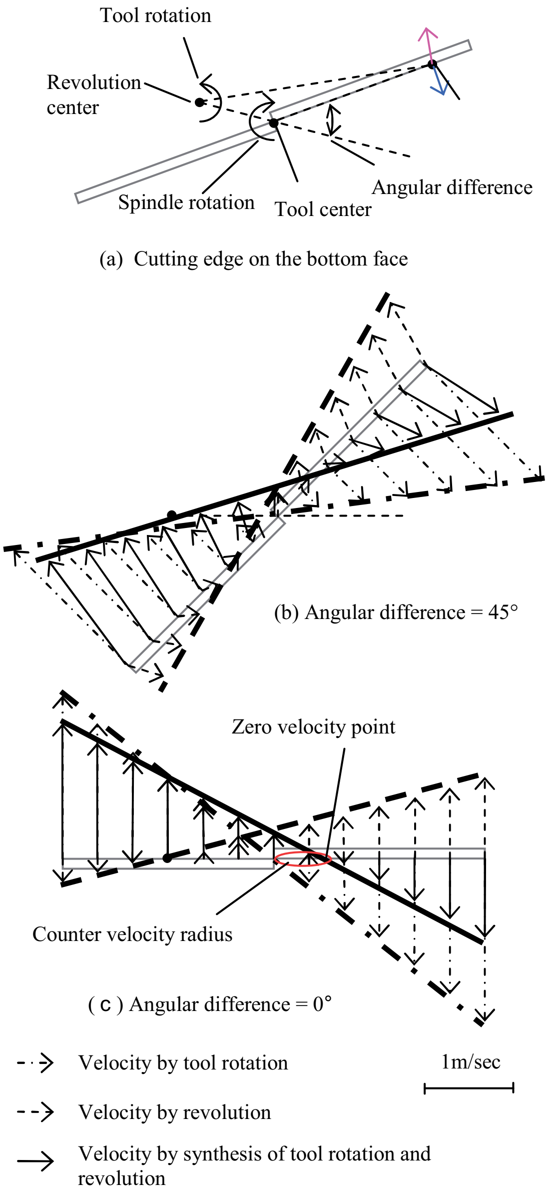


Fig. 2 Velocity components

From Eq. (1) and (2), velocity of cutting edge is calculated by our developed simulation program (with LabVIEW software; National Instrument Co. Ltd.) and the result is showed in Fig. 2. In the case of these parameters, N_o and r_o are larger than actual planetary drilling parameter because of clarifying effect of revolution. Fig. 2(b) shows the result in the case of angular difference = 45° and Fig. 2(c) shows the result in the case of angular difference = 0°. Because v_s and v_o cancel each other when there is no angular difference, zero velocity point on bottom face. It makes thrust loading larger.

IV. Counter Velocity Radius

In the case of typical drilling, drilling resistance become larger in the point of chisel point, where the cutting edge speed theoretically being zero. Beside, the orbital motion made the direction of the cutting edge velocity reversed at the singular point of bottom edge. The radius range where the singular point existing is defined as counter velocity radius (r_n [m]). The counter velocity radius might cause cutting resistance larger and negative effect to the machinability.

Counter velocity radius (r_n) in planetary drilling is defined by revolution speed (N_o [s^{-1}]), eccentricity (r_o [m]) and tool spindle speed (T_{ss} [s^{-1}]).

If v_o becomes equal to v_s in zero velocity point,

$$v_o = v_s \tag{3}$$

$$2\pi N_o(r_o + r_n)= 2\pi T_{ss}\, r_n \tag{4}$$

$$2\pi N_o\, r_n\, (1+r_o / r_n)= 2\pi T_{ss}\, r_n \tag{5}$$

Consequently, the counter velocity radius of bottom edge in orbital drilling is defined by Eq. (6).

$$r_n = r_o /\{(T_{ss} /N_{o)} -1\} \tag{6}$$

The smaller counter velocity radius is significant in machinability. An actual value of the counter velocity radius is 0.01mm calculated by Eq. 6 based on the practical drilling conditions;(r_o=1mm, $\underline{T_{ss}}$=20,000min^{-1}, N_o=200min^{-1}).

V. Peripheral Cutting Edge

In the case of the planetary drilling, machinability of peripheral cutting edge is also important as well as the bottom cutting edge. From the point of view of the motion of the planetary drilling, an interworking of revolution and feeding motions drill objective hole. The cutting tool moves along spiral path though the workpiece and only peripheral cutting edge, which is on tool bottom, can perform drilling. In other words, peripheral cutting edges occupy an intermediate position between tool bottom and tool top do not machine workpiece effectively. Otherwise they may make surface of the drilled hole worse.

From the result of observation and analysis of the planetary drilling process, necessary peripheral cutting edge length (PL) is calculated by Eq. (7),

$$PL = F_s/N_o \tag{7}$$

,where F_s stands for feed speed.

Which indicates necessary length of peripheral cutting edge is equal to the feed rate by one revolution. According to the past studies, practical drilling condition is as follows,

N_o : 200 [min^{-1}]
F_s : 100 [mm/min].

And PL is designated as 1mm considering the drilling condition.

VI. Specialized Tool for Planetary Drilling

We designed and developed three types of specialized cutting tools for CFRP drilling. Shapes of each tool are designed with following common concepts. In order to avoid machining with the cutting edge within the counter velocity radius, the designed cutting tools have appropriate clearance at the bottom edge. And all tools have minimum length of peripheral edge.

A. Drill type

The shape of drill type tool imitates conventional drilling tool. Configuration of the drill type tool is shown in Fig. 3 and Table 1 shows the size of each part of the tool. We expected the shape of the drill type tool might behave effective drilling performance by simple configuration of the tool.

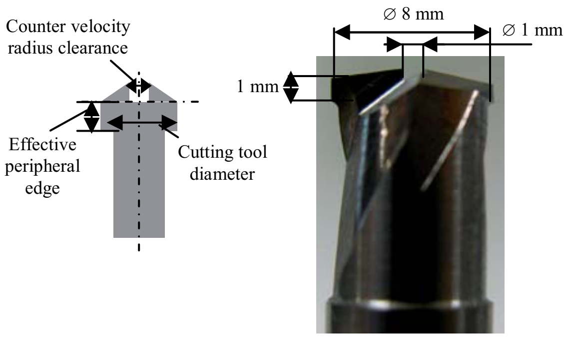


Fig. 3 Drill type tool

TABLE I : SIZE OF DRILL TYPE TOOL

Tool diameter	8.0 mm
Shank diameter	6.0 mm
Number of cutting edge	2
Peripheral edge length	1.0 mm
Point angle	80.0 degree
Clearance width	1.0 mm
Clearance depth	0.5 mm

B. Ball type

The shape of drill type tool imitates conventional ball end-mill. Configuration of the ball type tool is shown in Fig. 4 and Table 2 shows the size of each part of the tool.

The shape of the ball type tool is designed to avoid generation of burrs and delaminations by hemispherical shape cutting edge. Especially, the tool has longest peripheral edge as shown in Fig. 4 and Table 2.

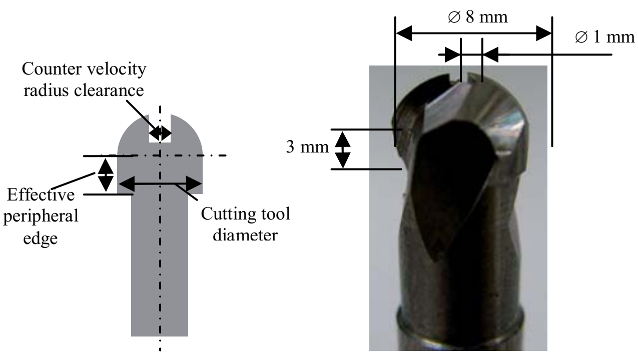


Fig. 4 Ball type tool

TABLE 2 : SIZE OF BALL TYPE TOOL

Tool diameter	8.0 mm
Shank diameter	6.0 mm
Number of cutting edge	2
Peripheral edge length	3.0 mm
Point ball radius	4.0 mm
Clearance width	1.0 mm
Clearance depth	0.5 mm

C. Concave type

The shape of concave type tool is aiming to enhance cutting speed by bottom and peripheral cutting edge. Configuration of the ball type tool is shown in Fig. 5 and Table 3 shows the size of each part of the tool.

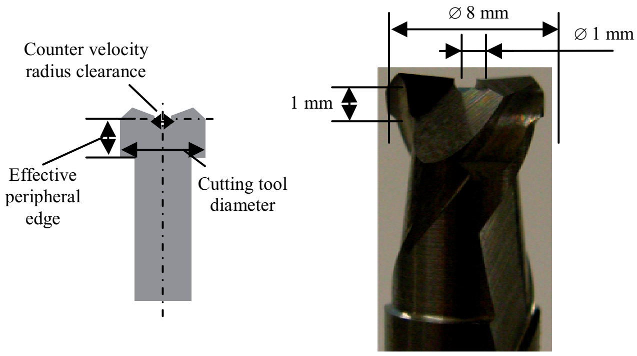


Fig. 5 Concave type tool

TABLE 3 : SIZE OF CONCAVE TYPE TOOL

Tool diameter	8.0 mm
Shank diameter	6.0 mm
Number of cutting edge	2
Peripheral edge length	1.0 mm
Point edge diameter	7.0 mm
Clearance width	1.0 mm
Clearance depth	0.5 mm

VII. DRILLING EXPERIMENT

In order to evaluate machinability of the specialized tools, we carried out drilling experiments by use of our own developed planetary drilling machine. The whole view of the drilling experiment apparatus which consists of a planetary drilling machine and a clamping jig on a 1-DOF stage is shown in Fig. 6. And Specifications of the planetary drilling machine is summarized in Table 4.

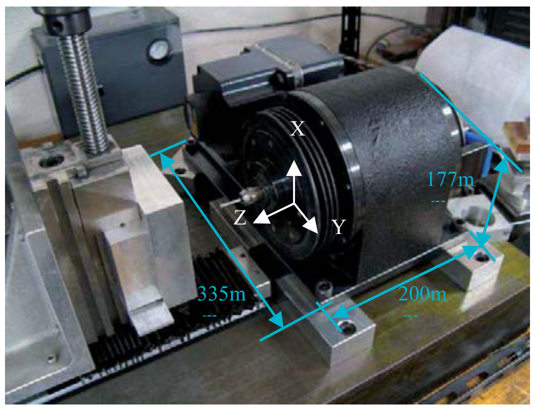


Fig. 6 Drilling experiment apparatus

TABLE 4 : SPECIFICATIONS OF PLANETARY DRILLING APPRATUS

Max rotation speed	60,000 min^{-1}
Max revolution speed	400 min^{-1}
Tool rotation spindle motor output	350W
Revolution spindle motor output	800W
Max eccentricity	3.0 mm
Max drilling depth	4.0 mm
Max speed of 1-DOF stage	600 mm/s

CFRP plate (50mm:square, 5mm:thickness) is chosen as the experimental workpieces. Drilling experimental conditions are shown in Table 5.

TABLE 5 : EXPERIMENTAL CONDITIONS

Drilling hole diameter	10 mm
Drilling hole length	5 mm
Workpiece	CFRP
Orbital rotation Speed (*Os*)	200 min^{-1}
Feed Speed (*Fs*)	100 mm/min
Tool Spindle rotation Speed (*Tss*)	12000 min^{-1}

Table 6 shows pictures of workpieces CFRP machining. In the case of fabricated tool experimental result, no burrs and delaminations are occurred. Table 7 shows the measured results of cylindricity of each drilled hole. Measured results of the cylindricity by all specialized tools are improved by comparison with conventional drilling tool.

TABLE 6 : Pictures of drilled hole

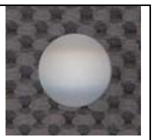
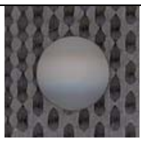
Front side			
Rear side			
Tool type	**Drill**	**Ball**	**Concave**

TABLE 7 : MEASURED RESULT OF CYLINDRICITY

Drill type tool	16.05 μm
Ball type tool	12.23 μm
Concave type tool	11.64 μm
Conventional drill (Reference)	78.34 μm

VIII. SUMMARY

From the analysis and experimental result, following conclusions are obtained.

- The motion of bottom cutting edge of the planetary drilling is analysed. The simulation method can be utilized to identify motion of bottom edge in development of another kinds cutting tool.
- The velocity distribution of bottom cutting edge of the planetary drilling is calculated and existence of the zero velocity point is clarified.
- Availability for CFRP drilling by our developed specialized tools is clarified by the experiments.
- Cylindricity of drilled hole by the concave type tool is improved by comparison with conventional drilling tool.

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