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An evaluation of cutting edge and machinability of inclined planetary motion milling for difficult-to-cut materials

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Abstract

Recently, the applications of difficult-to-cut materials (e.g. CFRP and titanium alloy) are increasing in the aviation and automotive industries. Conventional drilling tools occur burr and/or delamination on their materials. The inclined planetary motion milling consists of two independent spindle motions which are tool rotation and revolution. Eccentricity of the tool rotation axis is realized by inclination of few degrees from revolution axis. The movement of eccentric mechanism can be reduced by comparison with that of the orbital drilling. The inclined planetary motion milling reduces inertial vibration and decreases cutting force. According to the geometrical cutting principle, it can be decreased delamination and burr of their materials, comparing to orbital drilling. In the study, the authors revaluated optimum cutting condition for titanium alloy by use of the experimental design and carried out its repeatability test. And the authors developed on measurement and evaluation method for cutting edge profiles and examined the comprehensive discussion of the relationship among change to cutting edge wear and surface texture and circularity on drilling hole, tool rotation torque after based on the practical drilling experiments.

1. Introduction

Recently, the applications of difficult-to-cut materials (e.g. CFRP and titanium alloy) are increasing in the aviation and automotive industries. Conventional drilling tools occur burr and/or delamination on their materials. Field-portable size machine tools utilized in aviation production site have been required. The orbital drilling is one of an effective drilling technique for the industries. However this technique has some disadvantages such as increase of cutting force due to cutting with tool center point, inertial vibration generated by revolution and its high installation cost. In order to improve the disadvantages, the authors have proposed the inclined planetary motion milling.

The inclined planetary motion milling consists of two independent spindle motions which are tool rotation and revolution. Eccentricity of the tool rotation axis is realized by inclination of few degrees from revolution axis. The movement of eccentric mechanism can be reduced by comparison with that of the orbital drilling. The inclined planetary motion milling reduces inertial vibration and decreases cutting force. According to the geometrical cutting principle, it can be decreased delamination and burr of their materials, comparing to orbital drilling.

The author has established a cutting model of the orbital drilling and clarified its machinability and proposed the cutting tools having particular cutting edge for CFRP drilling according to the past studies [3-5]. Delaminations of workpiece and mechanical vibration by the cutting principle of orbital drilling were examined throughout the past studies result. In order to bring solutions to the orbital drilling technique, the authors have modified cutting mechanism principle of the orbital drilling, which named as the inclined planetary milling. Its axis of tool rotation is not parallel to the axis of planetary revolution. The benefit of the inclined planetary milling mechanism is reduction of unbalanced mass of eccentricity from that of the helical milling and it improves revolution speed and drilling quality. It also reduce vibrations by revolution and thrust cutting force,

which is generated on a bottom face of a cutting tool. In previous study, the authors also have tried to verify the availability of drilling into titanium alloy, however the tool wear and tool life time of the inclined planetary motion milling have not been evaluated. Evaluation of tool wear is important for difficult-to-cut materials to improve the machinability and it could be beneficial information for extension of the tool life time.

In the study, the authors revaluated optimum cutting condition for titanium alloy by use of the experimental design and carried out its repeatability test.

In addition, the measurement and evaluation methods for cutting edge profiles were developed and the comprehensive discussion of the relationship among change to cutting edge wear and surface texture and circularity on drilling hole, tool rotation torque after based on the practical drilling experiments were examined.

2. Inclined planetary milling

2.1. Principle

The drilling methodology of the inclined planetary milling is similar to helical milling techniques by use of a machining centre. Both of them consist of a tool rotation spindle and a revolution motion unit. The difference of them is how to realize eccentricity of their mechanisms as shown in figure 1. In the case of helical milling, the axis of tool rotation spindle shifts parallel to the axis of revolution. On the other hand, the tool rotation axis of the inclined planetary milling is inclined from the revolution axis and a tip of a cutting tool is shifted eccentrically. The inclined angle is adjustable from 0 to 3 degrees. In the case of the helical milling, the outermost cutting edges penetrate workpiece and the bottom layer is delaminated. On the other hand, in the case of the inclined planetary milling, penetration is caused by the inner cutting edges not the outermost cutting edges because of inclined tool rotation axis. When penetration occurred, the inner cutting edges penetrate firstly then the outermost edges enlarge the drilled hole and the sequence can avoid generation of delaminations and burrs. The diameter of a target bore is controlled by a tool diameter and the eccentricity, which consists of the inclined angle and the tool length from the centre of inclination as shown in figure 2.

2.2. Inclination angle

Control of inclination is necessary to obtain an arbitrary eccentricity of the inclined planetary milling. Figure 2 illustrates schematics of geometrical milling model of the inclined planetary milling with a square end-mill (a) and a ball end-mill (b) where r: tool radius, D: diameter of hole to be drilled, ϕ: inclination angle and L: distance between tool tip and inclination pivot. For the case of square end-mill, the inclination angle (ϕ) is calculated by eq. (1) considering with the shape of cutting tool, r, and L and eq. (2) represents for the case of ball end-mill.
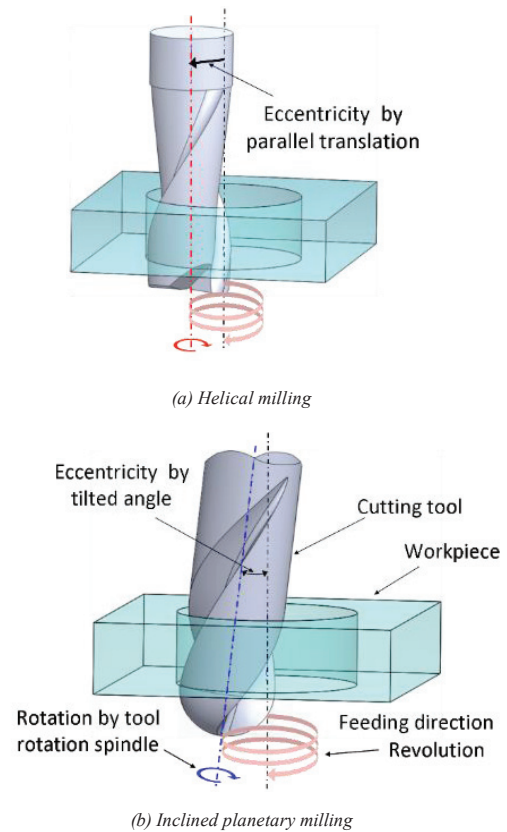

(a) Helical milling

(b) Inclined planetary milling
Fig. 1. Difference of interpolated bore milling method

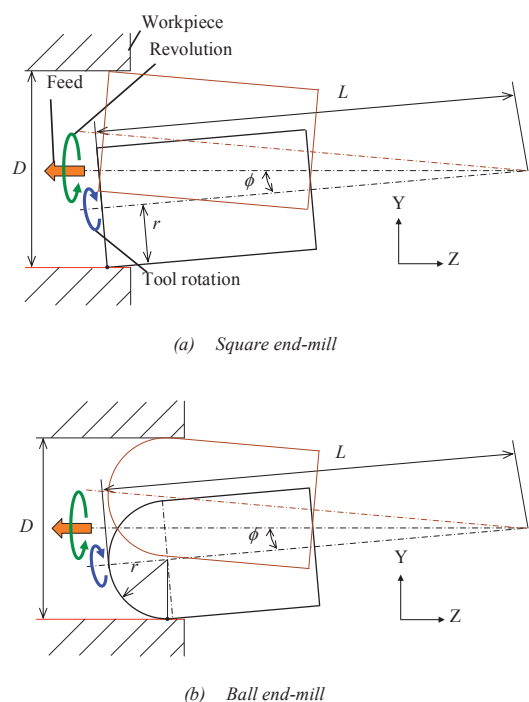*(a)   Square end-mill*

(b)   Ball end-mill
Fig. 2. Schematic of cutting by inclined planetary milling

$$\phi = \sin^{-1}\left(\frac{D}{2\sqrt{L^2 + r^2}}\right) - \sin^{-1}\left(\frac{r}{\sqrt{L^2 + r^2}}\right) \quad (1)$$

$$\phi = \sin^{-1}\left\{\frac{1}{L-r}\left(\frac{D}{2} - r\right)\right\} \quad (2)$$

$$l_{pf} = f_p \cos\phi \quad (3)$$

$$l_{pf} = \sqrt{\left[r\sin\phi - f_p + r\sin\left\{\cos^{-1}\left(\frac{r - f_p\sin\phi}{r}\right) - \phi\right\}\right]^2 + \left\{r(1 - \cos\phi) - Rth\right\}^2} \quad (4)$$

where,

$$Rth = 1000r\left\{1 - \cos\left(\cos^{-1}\left(1 - \frac{f_p}{r}\sin\phi\right) - \phi\right)\right\} \quad (5)$$

2.3. Effective peripheral cutting edge length

The length of peripheral cutting edge depend on the cutting conditions, which restricted according to the cutting principle of the inclined planetary milling. Optimization of the peripheral cutting edge length can improve the bore quality by enlargement of cutting tool stiffness as well as reduce manufacturing cost of the tools. Based on the principle of the inclined planetary milling, end-mill type cutting tools are suitable for bore milling and in the study a square end-mill and a ball end-mill are selected to calculate the effective length. The effective peripheral cutting edge length: l_{pf} of a square end-mill is defined as eq. 3 and l_{pf} of a ball end-mill is defined as eq. 4 where f_p: feed rate per one revolution and Rth: theoretical maximum surface roughness.

3. Evaluation of cutting edge wear

3.1. Instrument and methodology

The edge profile has to be measured precisely without any mechanical contact to avoid its breakage for evaluation of the progress of cutting edge wear. The cutting edge wear by CFRP was measured by use of a laser microscope (Olympus Co.; LEXT OLS4000). The apparatus of cutting edge measurement is shown in figure 3. It consists of a platform, collet chuck and a gonio-stage in order to maintain mounting cutting tools to be repeatable.

A profile of cutting edge to be measured a continuous line from the rake face to the clearance face. The position of the measured edge is located from the center of the cutting tool. The cutting edge wear is evaluated with following values, which calculated from the measured profile.
1) Difference of maximum height of cutting edge
2) Distance of clearance faces between new and worn one
3) Distance of rake faces between new and worn one

3.2. Measurement procedure

First of all, a new cutting tool was measured and a cutting edge profile was obtained for the reference use. Next, CFRP milling was carried out with the cutting tool and then it was mounted the platform again to measure. However the second profile measurement on same position of previous measurement could not be available due to the mounting error, the second profile was fine adjusted by software edit to fit the first profile. The evaluation values for worn cutting edge was calculated by use of image processing of LabVIEW software after the adjustment.
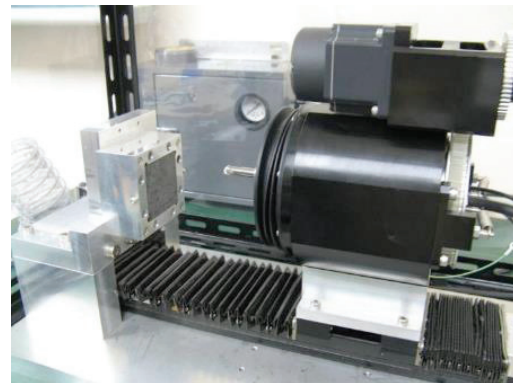

Fig. 3. Measurement setup

Fig. 4.Experimental apparatus

Table 1. Experimental conditions

Cutting speed	565m/min
Feed rate	0.15/rev
Revolution speed	200 rev/min
Inclination	0.92 deg. Eccentricity: 2mm
Cutting tools	2 flutes TiN coated ball end-mill

4. Experiment

4.1. Instrument and procedure

CFRP milling experiments were carried out by use of our own developed inclined planetary milling spindle unit as shown in figure 4. Material of workpieces is fabric CFRP (Fiber: PAN based, 12k) plate of 5mm in thickness. Table 1 shows the cutting conditions, which optimized throughout our previous studies. The surface texture, circularity and tool rotation spindle torque were also measured. Objects to be measured ware sampled from the specimen number 2 to 10 of every 2 specimens and 20 to 100 of every 20 specimens. The cutting tool was a 2 flutes general use TiN coated ball end-mill.

4.2. Experimental result 1 –appearance-

Table 2 is appearances of eye ball observation on exit of the bore. Smooth finishing could be achieved until bore number 6 and after that burrs and delaminations could be observed due to the cutting edge wear.

Table 2.Appearances

Bore #	Appearance	Bore #	Appearance	Bore #	Appearance	Bore #	Appearance
2		4		6		8	
10		20		30		40	
50		60		70		80	
90		100				5mm	

4.3. Experimental result 2 –surface texture, circularity and tool rotation spindle torque -

The bore quality of the workpieces were measured by use of surface roughness measurement instrument (Tokyo seimitsu; surfcom480A), circularity measurement instrument (Tokyo seimitsu; Rondcom46A). The schematic of bore to be measured is shown in figure 5. The torque of tool rotation spindle, which derived from the spindle driver unit was also measured during drilling process. The transition of surface texture, circularity and tool rotation spindle torque through the experiment are shown in figure 6. The tendency of their values are gradually enlarged as the number of bore increasing.

4.4. Experimental result 3 –tool wear-

As same as the tendency of surface texture progression, the cutting edge wear was gradually progressed. A comparative graph of transition of the cutting edge wear is shown in figure

7, 8 and evaluation values are tabled on table 3. The principal wear was occurred on the clearance face of the cutting tool and cutting edge height and edge sharpness were decreasing in accordance with the clearance face wear progression. It seems that a threshold at the bore number 20 could divide the cutting edge life time from the point of view of clearance face wear progression.
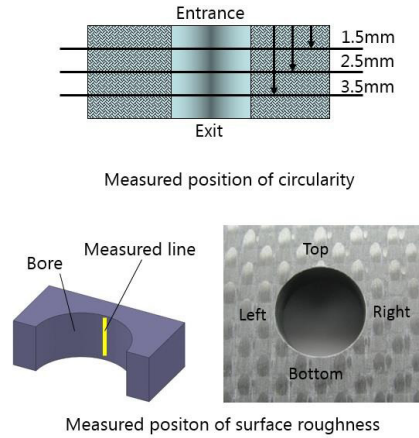

Measured position of circularity

Measured positon of surface roughness

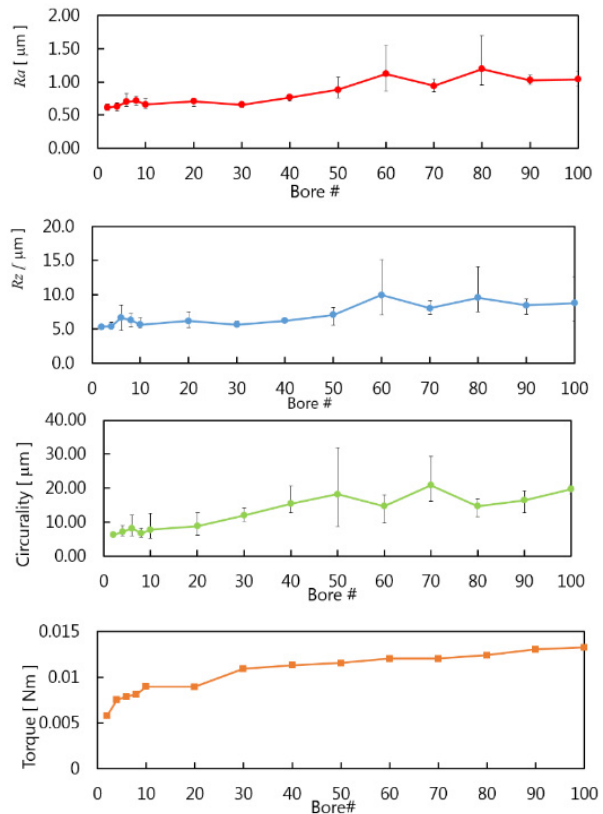*Fig. 5.Schematic of bore measurement*

Fig. 6.Experimental results (Surface roughness, Circularity and Tool rotation spindle torque)

Table 3.Evaluated values of worn cutting edge

Bore #	Height [μm]	Clearance face [μm]	Rake face [μm]
0			
2	4.45	0.368	0.411
4	6.14	-0.278	0.356
6	7.08	0.241	0.241
8	7.65	0.343	0.250
10	8.63	0.286	0.190
20	11.1	0.195	0.293
30	13.5	3.06	0.612
40	16.3	5.37	1.26
50	18.7	8.09	1.29
60	21.0	9.05	3.46
70	23.6	12.5	3.68
80	25.1	13.4	4.72
90	27.3	14.7	6.50
100	27.7	15.2	6.67

Fig. 8.Transition of evaluation values for tool wear

The variability of surface texture and circularity could be occurred by an accidental uncut fiber.

5. Conclusion

Cutting tool endurance test was carried out by use of the inclined planetary milling spindle with CFRP workpieces. The evaluation method for cutting edge wear progression during CFRP cutting was suggested and tendency of the tool wear was declared. It was clarified that there was a positive interaction among surface texture, circularity, tool rotation spindle torque and cutting edge wear progression. The principal factor of cutting edge wear was the abrasion of brush-effect of uncut fibers.
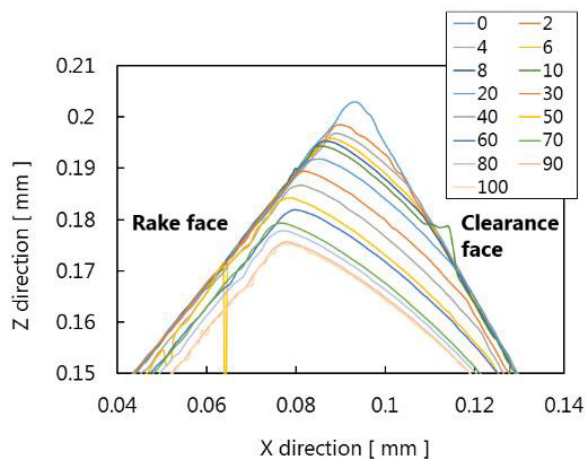
Fig. 7.Transition of tool wear

4.5. Discussion

According to the result of our past study[6-7], thrust force, spindle torque and surface roughness by the inclined planetary milling were lower than the orbital drilling. It seemed that there were positive interactions among surface texture, circularity, tool rotation spindle torque and cutting edge wear progression. The accuracy of circularity was improved comparing to the conventional drilling and helical milling comparing to the result of our past studies. Cutting edge height was gradually decreased due to the clearance face wear. In other words, cutting edge wear on rake was not principal wear in the case of thermos-set CFRP. Thus the clearance face wear was dominative comparing to the rake face. It seems that the principal factor of the clearance face wear could be occurred by the abrasion of brush-effect of uncut fibers.
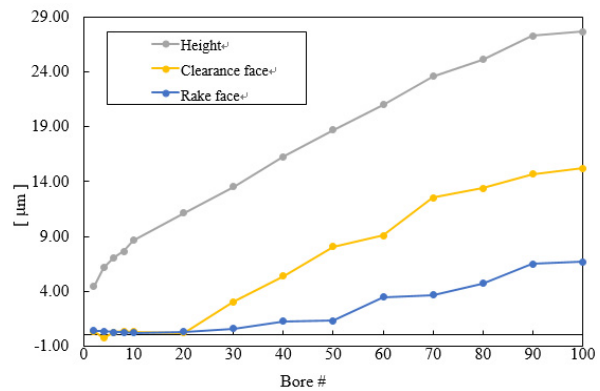
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