

## Estimation of machining error using indirect methods in ball-end milling for inclined surface

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### Abstract

For a cutting process using a low-rigidity end mill, it is very important to be able to estimate the degree of machining error caused by the deflection of the tool. The purpose of this study is to establish a method of estimating, in real time, the machining error caused by the deflection at the cutting point of an end mill. To this end, in this research, a method for estimating the machining error caused by the deflection of the tool used for the ball-end milling for an inclined surface was verified by comparing the estimated deflection of the tool and the measured machining error. As a result, it was found that the machining errors in ball-end milling for an inclined surface could be estimated from the normal force at the moment when the radial direction of the peripheral cutting edge is normal to the feed direction of the tool.

Keywords: Machining error, Deflection of end mill, Cutting force, Ball-end mill, Inclined surface

### 1. Introduction

Metal molds are indispensable to the manufacturing of parts for automobiles, cellular phones, and so on. In recent years, machining centers have been widely used for metal mold manufacturing process because high-speed machining using small-diameter end mills has become practical. However, the use of a long, small-diameter end mill degrades the machining accuracy of the metal mold, because the cutting forces cause the cutting point to deflect considerably at the cutting point. Previously, therefore, a system that minimizes the machining error by compensating the deflection of the end mill at cutting point was proposed [1]. Although this system is unique, it is unfortunately not suitable for practical use, and therefore, there remains a need for a simpler method of compensating for the deflection of the end mill.

researchers have set out to propose cutting models for ball-end milling. Previously, a ball-end milling cutting model using 3D-CAD was reported [2], and a geometrical model for describing the cutting process in ball-end milling with a tilt angle was proposed [3]. Furthermore, a new mathematical model for estimating the deflection of the tool in ball-end milling was also proposed [4].

The purpose of this study was to determine a means of compensating for machining errors caused by the deflection of an end mill at the cutting point. To this end, in this study, an experiment was conducted to determine the relationship between the estimated deflection of the tool and the measured machining error when performing ball-end milling for an inclined surface. In particular, this paper describes how the tool deflection was estimated from the measured cutting force.

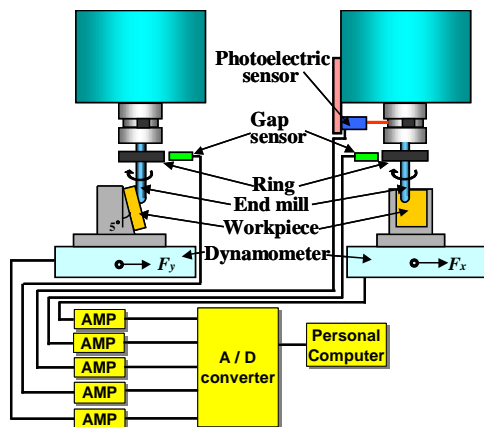


Figure 1. Experimental apparatus

Ball-end mills are useful cutting tool for machining three-dimensional shapes, such as molds and dies. Therefore, many

Table 1. Cutting conditions

Workpiece	Material	JIS S50C
Tool	Type	Indexable Ball-end mill
	Diameter $\phi$ mm	12
	Number of flutes	1
	Helix angle $\psi$ deg.	0
Spindle speed	$N$ min <sup>-1</sup>	1000
Feed rate	$f$ $\mu$ m/rev	20, 40, 60
Pick feed	$P_f$ mm	0.5
Type of cut		Down milling
Feed distance in axial direction	$l$ mm	0~18.0

### 2. Experimental Procedure

The cutting tests were performed in ball-end milling for an inclined surface using a vertical machining centre. The

experimental apparatus used for the experiment is shown in Fig.1, and the cutting conditions are listed in Table 1. In cutting tests, the relation between the cutting forces and tool deflections and the machining error was investigated efficiently in cutting tests by slanting the workpiece at the angle of 5 degrees from the vertical direction. The pick feed was constant.

The cutting forces  $F_x$  and  $F_y$  were measured with a dynamometer. The dynamometer is a piezoelectric quartz force transducer affixed to a table. In addition, two marks were observed every rotation, using a photoelectric sensor fixed to the side of the spindle head of the machining centre (using a magnetic stand), to determine the rotational position of the cutting edge. The preliminary experiment was designed to determine the relationship between the rotational position of the cutting edge and the marks. The cutting forces and the positions of the marks were transmitted to a personal computer via an A/D converter board.

To measure the static stiffness, the workpiece was fixed on the dynamometer. The load was measured using the dynamometer while gradually increasing the deflection of the tool at the cutting point, under NC control. Figure 2 shows the relationship between the load  $F_y$  and the deflection  $\delta_e$  of the tool at the cutting point in the Y direction. The deflection  $\delta_e$  of the tool increases with the load  $F_y$ . Consequently, the relationship between the load  $F_y$  and deflection  $\delta_e$  of the tool at the cutting point can be expressed as follows.

$$\delta_e = K_F \cdot F_y \quad (1)$$

where  $K_F$  is 0.83.

### 3. Experimental Results

Figure 3 shows the concept of the cutting process for the ball-end milling for an inclined surface. Here, point n is the position at the moment when the radial direction of the peripheral cutting edge is normal to the feed direction of the tool. The cutting angle  $\phi$  is the rotational angle relative to point n.

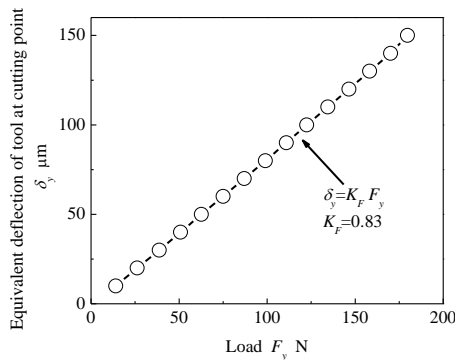


Figure 2. Relationship between load  $F_y$  and deflection  $\delta_e$

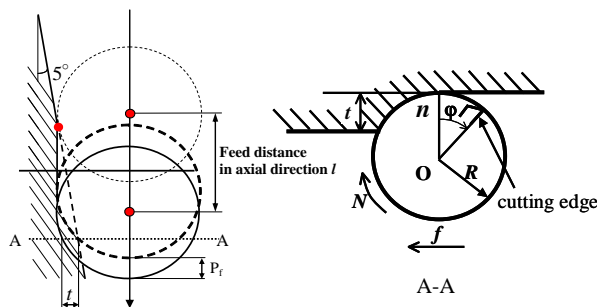


Figure 3. Concept of cutting process

Figure 4 shows the results of estimating the deflection  $K_F F_y$  in detail. Here,  $K_F F_y$  is the deflection of the tool at the cutting point as estimated by equation (1). Here,  $(K_F F_y)_{max}$  is the maximum value of the deflection  $K_F F_y$ , and  $(K_F F_y)_n$  is the deflection  $K_F F_y$  at the moment when the peripheral cutting edge is at point n, as shown in Fig.3.

Figure 5 shows the relationship between the measured machining error  $e_y$  and the estimated deflection  $K_F F_y$ . There is some difference between the machining error  $e_y$  and deflection  $(K_F F_y)_{max}$ . On the other hand, deflection  $(K_F F_y)_n$  closely corresponds to machining error  $e_y$  regardless of the feed rate.

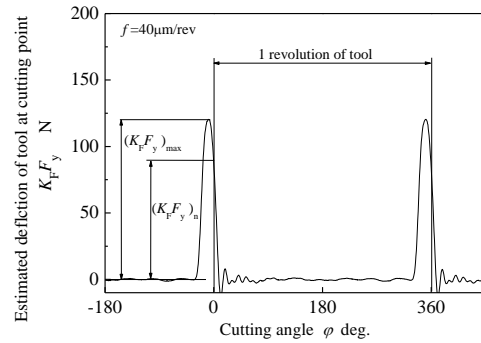


Figure 4. Estimated deflection  $K_F F_y$  at cutting point

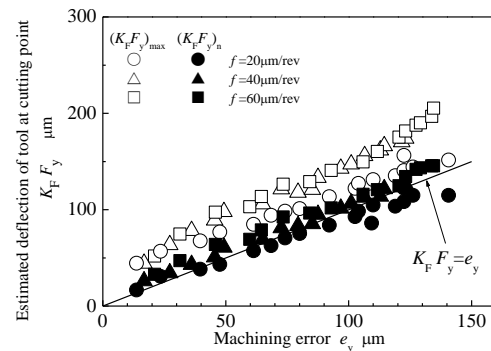


Figure 5. Measured machining error  $e_y$  and estimated deflection  $K_F F_y$

### 4. Conclusions

The results obtained by the ball-end milling for an inclined surface can be summarized as follows.

- 1) The estimated deflection of the tool at the moment when the radial direction of the peripheral cutting edge is normal to the feed direction of the tool closely corresponds to the measured machining error, regardless of the feed rate.
- 2) Using the proposed method, it is thought that machining errors caused by the deflection of the tool in the ball-end milling for an inclined surface can be estimated based on the cutting force.

### References

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