

## Tool deflections during micro-end milling - Observations of deflection and its effect on processing accuracy-

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### Abstract

This paper discusses the deflection of a micro end-milling cutter and investigated its effects on the accuracy of the milling process. In each experiment, the deflection of the cutting tool used for the small-diameter end milling was measured on the basis of images of the tool captured by a high-speed camera; the machined shape error of the workpiece was also measured. Consequently, The experimental results indicate that the tool with a diameter of 1 mm was deflected by 100–800  $\mu\text{m}$  during the milling and that such deflections represent relatively large deflections. Further, It was found that the deflection occurred when the depth of the cut was less, which allowed the cutting edge of the tool to rubs against the workpiece; the deflection also occurred when the cut was too deep for the tool to remain rigid. Furthermore, a correlation between the deflection of the tool and the milling accuracy was revealed. On the basis of the aforementioned results, we concluded that a preferable finishing surface with less deflection of the tool can be obtained under certain cutting conditions.

Keywords: micro end milling, tool deflection, processing accuracy

### 1. Introduction

In recent years, fine shape milling with high precision has been required because of the demands of downsizing and high precision in the mechanical production field. Consequently, extensive attention has been devoted to micro end milling using small-diameter tools.

During the micro end milling, the tool might be deflected to a greater extent than a tool used in a regular end milling because the tools used for micro end milling are less rigid. Such deflection would negatively affect the accuracy or the surface finish. Even when the influence is minor, it cannot be ignored for fine milling because such processes require greater accuracy than regular milling. Accordingly, improving the accuracy of micro end milling processes necessitates examination of the deflection of the tool.

In this study, an end mill with a diameter of 1 mm was used for each experiment, and video of the tool was captured by a high-speed camera to observe its deflection during the milling; the magnitude of the deflection was simultaneously measured. In addition, the finished surface was observed to investigate how the deflection negatively affected the accuracy of finishing.

### 2. Test device and method

In these experiment, an air spindle (NAKANISHI, Astro-E400) mounted onto an NC milling machine (SHIZUOKA MACHINE TOOL, VHR-AP) was used. This machine is illustrated in Figure 1. The cutting speed, feed, and depth of cut in the axial direction ( $a_d$ ) were set to constant values during a shoulder milling, whereas the depth of cut in the radial direction ( $r_d$ ) was varied. The milling type was an up-cut milling, and 0.5% carbon steel (AISI:1050) was used as the work material. Table 1 shows the milling conditions.

The machining process was captured by a high-speed camera (Nobby Tech, PHANTOM MIRO4). As illustrated in Figure 2, the camera was positioned in the table feed direction (hereinafter referred to as the X-direction) and in the direction vertical to the table feed direction (hereinafter referred to as the Y-direction) to capture deflections of the tool in both directions. Here, the deflection amount  $\delta$  and deflection angle  $\theta_{max}$  are defined as shown in Figure 3. Furthermore, after the machining was finished, chips generated by the milling were collected

and their shapes were observed using a scanning electron microscope (Japan Electronics, JSM-T330A). After the machining, the finished surface was observed using a digital microscope (HIROX, KH-7700) to examine the bottom and sides of the machined surface. In addition, the workpiece was cut using a wire EDM, and the shape error of the cross-section of the material was measured. Shape errors formed by the process are defined as shown in Figure. 4.

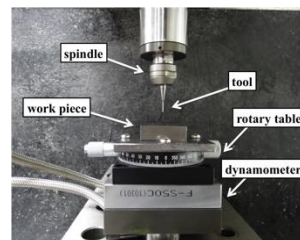


Figure 1. Experimental setup

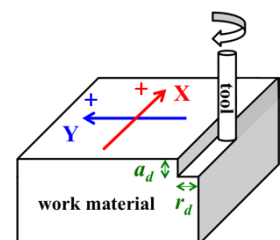


Figure 2. Direction of cutting and deflection

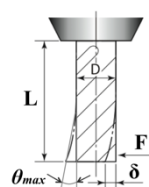


Figure 3. Definition of deflection width

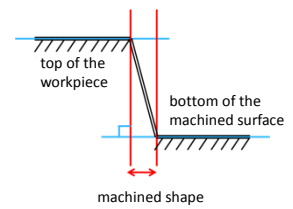


Figure 4. Definition of machined shape error

Tool	Cemented carbide 2 flute, flute length 4mm
Cutting speed	50m/min (15924min <sup>-1</sup> )
feed	10 $\mu\text{m}$
Axial depth of cut	100 $\mu\text{m}$
Radial depth of cut	100, 200, 300, 400, 500 $\mu\text{m}$
Cooling	Dry

### 3. Experimental results and discussion

#### 3.1 Observing deflection behavior

Figure 5 shows the results of the measurements of the deflection width  $\delta$  at the tool, as determined from the images captured by the high-speed camera.

In figure 5, dotted lines show total amount of deflection and solid lines are its each directions. Both the X- and Y-directions were defined to be positive in the direction that extends toward the workpiece, as shown in Figure. 2. As shown in Figure 5, total deflections of 100  $\mu\text{m}$  or more occurred during the cutting under all investigated conditions. When  $rd$  was set to 500  $\mu\text{m}$ , the tool with a diameter of 1 mm total deflected approximately 800  $\mu\text{m}$ . On the basis of this result, it concluded that, during the micro end milling, the tool cut the workpiece while undergoing large deflections. Further, according to Figure 5, the extent of the total deflection gradually increased from  $rd$  100  $\mu\text{m}$  to  $rd$  300  $\mu\text{m}$ , decreased at  $rd$  400  $\mu\text{m}$ , and then increased again.

Furthermore, As shown in Figure, from  $rd$  100  $\mu\text{m}$  to  $rd$  300  $\mu\text{m}$ , relatively large deflections occurred in the negative X-direction, which is opposite to the feed direction. However, a positive deflection in the X-direction occurred at  $rd$  400  $\mu\text{m}$ , and then positive and negative deflections in both the X- and Y-directions occurred at  $rd$  500  $\mu\text{m}$ .

#### 3.2 Influence of tool deflection on milling accuracy

As  $rd$  increases, the extent of deflection first increases, decreases at a certain point, and then increases again. To study the reason for this behavior, we observed machined bottom and side surfaces and chips generated by milling. Figures 6–8 show the observation results at each cutting depth.

Figure 6 shows the observation results at  $rd$  200  $\mu\text{m}$ , where the extent of deflection with increasing cutting depth was relatively large. Both the bottom and side machined surfaces are rough, and no cutter marks are evident. The chips were cut into small pieces. The same rough surfaces and small chips are captured in the results for  $rd$  100  $\mu\text{m}$  and  $rd$  300  $\mu\text{m}$ . Accordingly, it confirms that when the depth is set less than or equal to  $rd$  300  $\mu\text{m}$ , the undeformed chip thickness is substantially thin because  $rd$  is small; consequently, the tooth rubs against and smear the surface. Then, as the  $rd$  increases, the extent of deflection increases. By contrast, at  $rd$  400  $\mu\text{m}$ , a cutter mark of one-stroke cutting is clearly observed on the surface of the workpiece, as shown in Figure 7. Smoothly continued chips are generated at  $rd$  400  $\mu\text{m}$ , as also shown in Figure 7. This result reveals that the tool set at  $rd$  400  $\mu\text{m}$  does not rubbing against the workpiece surface; thus, it properly cuts the workpiece. The extent of deflection increases again at  $rd$  500  $\mu\text{m}$ . As shown in Figure 8, an undesirable tool mark is observed and the shape of chip is uneven. This mark at  $rd$  500  $\mu\text{m}$  is not caused by rubbing; factors that may explain these results are increased cutting force and decreased rigidity of the tool.

Figure 9 shows the results of measurements of machined shape errors on the cross-sections of the machined surface. The error was measured as follows. First, the workpiece was cut using wire electric discharge machining; a stepped-shaped cross-section of the workpiece was then observed using a digital microscope. Figure 9 shows the machined shape error formed on the cross-section at  $rd$  400  $\mu\text{m}$  is the smallest shape error among the investigated samples. Accordingly, although the tool is deflected because of increased cutting force and poor rigidity of the tool, conditions exist under which the extent of tool deflection can be sufficiently reduced to perform a satisfactory milling process.

#### 4. Summary

- (1) The 1-mm cutting tool was greatly deflected during the small-diameter end milling.
- (2) When the radial depth of cut was relatively shallow, the tool rub against the workpiece surface, which caused the deflection of the tool. When the cutting depth was deeper, the cutting force increased; consequently, the tool deflected because it was swinging as it rotated.
- (3) It observed that preferable conditions exist for small-diameter end milling processes to provide high milling accuracy while maintaining a low degree of deflection.

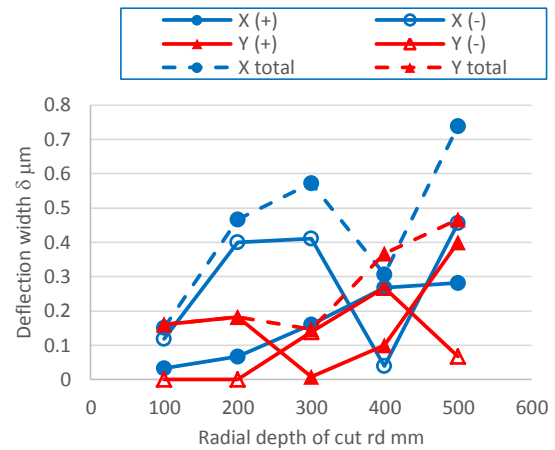


Figure 5. Relationship between radial depth of cut and deflection width

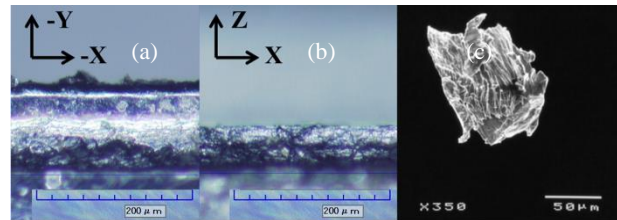


Figure 6. bottom (a) and side (b) view of machined surface and chip (c) on  $rd$  200 $\mu\text{m}$

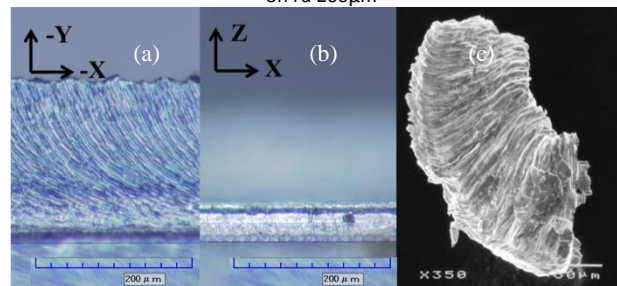


Figure 7. bottom (a) and side (b) view of machined surface and chip (c) on  $rd$  400 $\mu\text{m}$

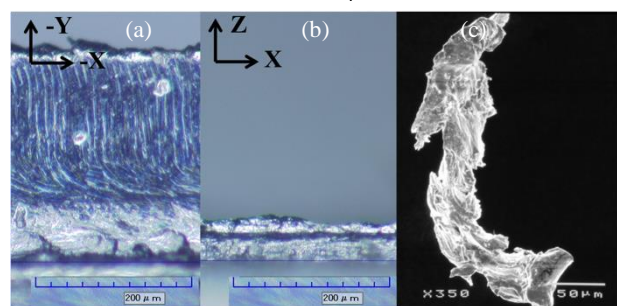


Figure 8. bottom (a) and side (b) view of machined surface and chip (c) on  $rd$  500 $\mu\text{m}$

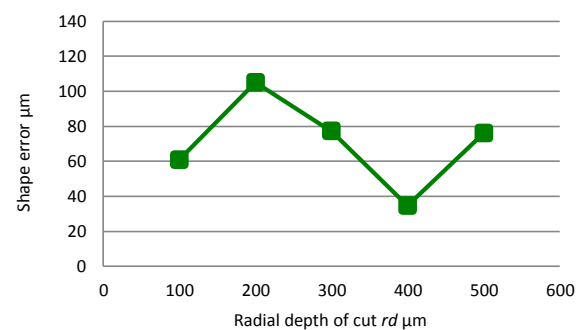


Figure 9. Relationship between  $rd$  and machined shape error