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Behavioral analysis of tool deflections during micro-end milling

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Abstract
This paper discusses the behavior of deflection in tools during micro end milling. In the experiment, the behavior and cause of the deflection that occurs while the tool is rotating was investigated by measuring the cutting force and performing observations using a high-speed camera. At the results, it was made clear that the lack of rigidity in the tools during micro end milling resulted in deflection in two axial directions as the processing continued.

micro end milling, tool deflection, machining accuracy

1.Introduction

The significant developments in cutting tool producing techniques and overall improvements in operation precision of the machine tool have made it possible to perform cutting processing with a level of detail and high precision unlike that seen in processing thus far. There are higher precision demands with respect to micro end mill processing than that found normally because of the high detail associated with the machined shape. However, due to the small diameter of the tools used in micro end milling, these tools have extremely low tool rigidity and are thought to deflect when cutting. This tool deflection may lead to abnormal tool wear, tool fracture, lower machined surface quality, and lower dimensional accuracy. Moreover, tool tilted method is often used in general end mill process to keep the cutting speed. However, it has possibility that this method increase above problems in micro end milling due to the low rigidity of tool. Therefore, it is important to have a thorough understanding of tool deflection incurred during micro end milling. Based on this background, we previously clarified that an extremely large deflection is incurred by the tool during micro end milling through using a high-speed camera to observe the machining conditions. However, the research performed previously was limited to only observations and measurements of the tool deflection, and therefore does not clarify the mechanism that causes this deflection (including factors such as cutting force and processing conditions). Therefore, in this research, we measured the cutting force and used a high-speed camera to perform observations to investigate what kind of deflection behavior manifests during each rotation of the tool.

2. Experiment Devices and Method

In this research, a machining center with a mounted air bearing spindle was used. a cutting dynamometer (Kistler; kistler9272) was used to measure the cutting force. In the experiment, shoulder cutting was performed with changing the radial direction cutting depth Rd and the axial direction cutting depth Zd while keeping both the cutting speed and feed rate constant. Table 1 shows the cutting conditions and the tools used. A non-coated carbide square end mill with 1 mm diameter (flute length: 6 mm, number of flute: 2) was used as the tool, and the cutting was performed while up-cutting. A high-speed camera (Nobby-tech; PHANTOM MIRO4) was used to observe the appearance of the tool from two directions (X and Y) during the cutting. Here, the deflection width and the direction of the force are defined as shown in Fig. 1, and each of the axial directions is defined as shown in Fig. 2. Both the negative direction for both the X-axis and the Y-axis show that the force is working in the direction that the tool is pulling away from the workpiece. C50 (ISO/ DIN, 1050: AISI) was used as the workpiece.

3. Test Results and Consideration

Fig. 3 shows a picture of the appearance of the tool while cutting taken by the high-speed camera. From this figure, the line that shows the tool ridge line is tilted towards the vertical

Table 1. Cutting coonditions

Cutting speed (m/min)	50	
Feed per tooth (μm/tooth)	10	
Axial depth of cut Zd (μm)	100	200, 300, 400, 500
Radial depth of cut (μm)	100, 200, 300, 400, 500	100

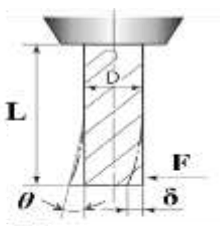

Figure 1. Definition of deflection width

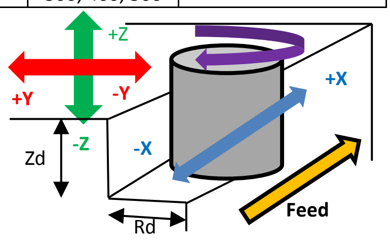

Figure 2. Direction of cutting and deflection

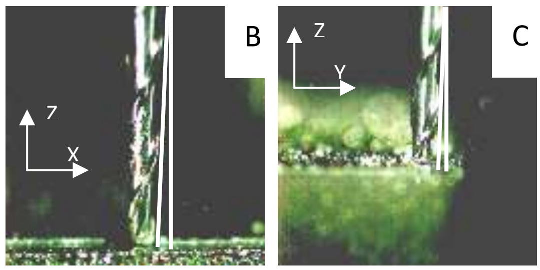

Figure 3. Observation result of tool deflection

line. Therefore, it is clear that the tool is incurring deflection during cutting. Fig. 4 and Fig. 5 show the results of measuring the maximum deflection amount δ while changing the radial direction cutting depth Rd and the axial direction cutting depth Zd. Although Fig. 4 does not show large changes in the deflection in the X-direction (feed direction) in cases where the Rd is increased while the Zd remains under constant conditions, it does show increasing deflection in the Y-direction (pick direction). In contrast, Fig. 5 shows trends of increasing deflection in X-direction when the Zd is increased, whereas almost no such changes can be seen in the Y-direction. Consideration will be provided for the reasons for this hereinafter. Upon confirming these results, evaluation was performed to clarify what factors cause tool deflection in a single rotation by measuring the cutting force and using a high-speed camera observations. Fig. 6 shows the analysis results for the cutting force in cases where no tool deflection occurred when using a tool with a rigid body. Normal cutting conditions were used, and the tool diameter was set to 8 mm. Also, Fig. 7 show the measurement results example of the cutting force incurred while performing micro end mill processing. As seen in Fig. 6, after the cutting started (A) while performing normal end milling, the values increased and then decreased in the negative direction in the X-direction while the values gradually increased in the Y-direction. The fluctuation in the cutting force was the same as that found in the micro end milling shown in Fig. 7. However, the effects from this cutting force incurring during the micro end milling led to deflection occurring in the tool in both the X-direction and the Y-direction as shown in Fig. 3. Fig. 8 shows a schematic diagram of the temporal deflection fluctuation based on the results of the high-speed camera observation and cutting force measurement. As shown in this figure, due to the underform chip thickness being substantially thin at the time the cutting begins (from A to B); consequently, the tooth rubs against and smear the surface. Deflection occurs in the -X-direction (where there are no restraints) at this time due to insufficient rigidity in the tool itself (Fig. 3 left). Following, although the cutting edge bites into the workpiece being cut as shown in (C), however the insufficient rigidity here causes the cutting edge to get caught, where after it becomes the fulcrum and creates a bending moment, and the tool continues to cutting while deflecting in the +Y direction (material side) (Fig. 3 right). Next, the cutting force will be released when the cutting finishes as shown in (D) which will cause the deflection to be released all at once, where after the tool will return to a predetermined position. The tool will deflect in the –X direction (feed and reverse direction) and the +Y direction (pick direction) while the tool spins one full rotation. Also, as shown in Fig. 6, there is almost no cutting force in the Z-axis direction during normal end milling. However, from Fig. 7 that the same degree of cutting force and other component force is being generated in the Z-axis direction during micro end milling. This is caused by cutting force being generated in the Z-axis direction when the tool incurs deflection during micro end mill processing. In the same manner, there is almost no cutting force generated when the tool is idling (non-cutting time) during normal end mill processing as shown in Fig. 6. However, during micro end milling, the dotted line in Fig. 7 shows cutting force being generated during idling. As previously mentioned, this is due to the release of the cutting force occurring after the disengagement of the tool from the workpiece that is being cut, leading to an instantaneous disappearance of deflection resulting in the recovery of elasticity and indicates that work is caused in the reverse direction relative to the X-direction and the Y-direction. As shown in Fig. 4, when the Zd conditions are kept constant, the tool deflection will increase in the Y-direction when the Rd is increased. This is caused by the increase in deflection in the Y-direction at a large bending moment (like that shown by the conditions in (C)) manifests due to increases in the acting cutting force. In contrast, when Rd is kept constant and Zd is increased, the thickness increases in the side face direction causing conditions with a larger bending moment than that shown in (C) resulting in the inability of the tools to pass over in the Y+ direction, forming deflection in the -X direction, the sole direction where there is no binding.

4. Conclusion

A study was performed on the behavior of the deflection incurred when these tools are rotated with respect to the deflection incurred by the tools used in the micro end milling here. The results clarified that the tooth rubs against and smear the surface at the cutting start time during micro end milling, and clarified that the tool incurs deflection in the feed and reverse direction. Once tooth bites the workpiece and cutting begins, bending moments are incurred by the tool tip becoming the fulcrum, whereby the tool incurs deflection in the pick direction. It was clarified that the tool deflection completely disappears instantaneously when the cutting ends. Thus, we have clarified that the lack of tool rigidity causes different phenomena in micro end mill processing compared that that incurred during normal end mill processing.

Reference

[1] H. Shizuka et al. Proc. of the 15th euspen pp.331-332 (2016)

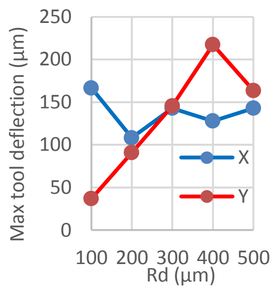

Figure 4. Tool deflection width (Zd const.: 100μm)

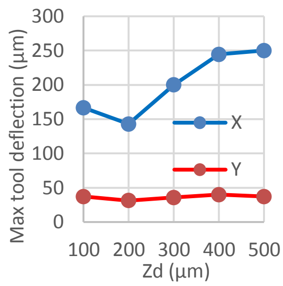

Figure 5. Tool deflection (Rd const.: 100μm)

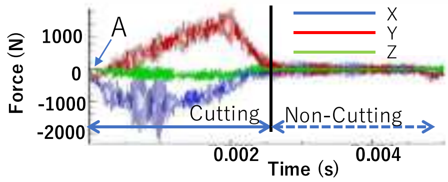

Figure 6. Analysis results for the cutting force (v150m/min, fz0.2mm, Rd4mm, Zd2mm, tool diameter 8mm)

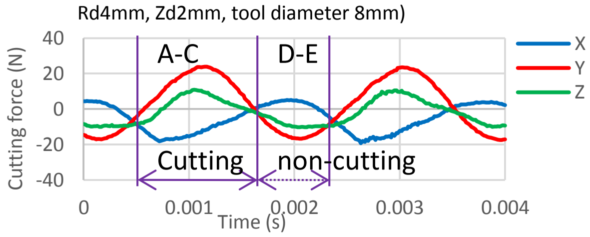

Figure 7. Relationship between cutting force and cutting time

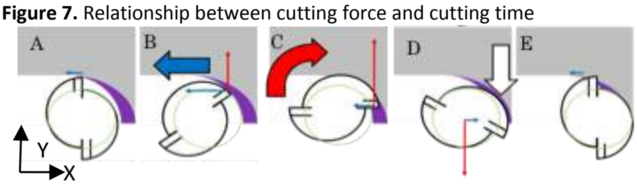

Figure 8. Model of the temporal deflection fluctuation