Basic Study on Micro End-milling

- Cutting Phenomena of Side Cutting -

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Abstract

Ultraprecision parts are in high demand in the machinery, electronic, and medical industries. Technologies such as micro-electromechanical systems (MEMS) and ultraprecision machining are used in micromachining to manufacture these parts. The focus of this study is mechanical machining using a micro end mill. In this paper, we experimented with a variety of cutting phenomena that occur during actual machining processes to achieve high machining accuracy, high finished-surface quality, and long tool life. Through examination of these phenomena, micromachining achieved high-accuracy, high-grade machining by considering the dynamic vibrational behavior and elastic contact of the tools. In addition, we suggest criteria for determining the tool life of a micro end-mill.

Keywords: Micro end-mill, Cutting phenomena, Tool wear, Tool life, Accuracy

1 INTRODUCTION

The fields of semiconductors, mobile devices, biotechnology, and medical testing require miniaturized, highly accurate parts [1][2], and highly accurate, microscopic die and mold are necessary for the manufacture of such parts. A tool with low rigidity [3][4], which is bent by even small force, needs to be used for machining a microscopic workpiece. Therefore, to achieve the required machining accuracy and finished-surface quality [5], it is necessary to consider the slight amount of tool deformation and tool tip retraction caused by tool wear, as well as the elastic springback, that occur during machining.

In this study, a micro end-mill was used during side cutting to precisely evaluate cutting resistance, static and dynamic displacement of the tool, and tool wear so that the cutting phenomena could be clearly demonstrated, achieving high-accuracy, high-efficiency machining. This paper also suggests criteria for determining the tool life of a micro end-mill.

2 EXPERIMENTAL METHOD

Figure 1 shows the overview of the cutting experiment. The cutting resistance was measured by cutting Workpiece 1, which was connected to a dynamometer, while machining the larger Workpiece 2 to wear out the tool.

Figure 2 shows the cutting paths to obtain the amount of residual stock removal and elastic deformation. The reference surface was created by Path I, and Path II was cut repeatedly until the cutting force was stabilized to obtain residual stock removal d_r in the normal condition. d_r can be defined by the following Equation (1):

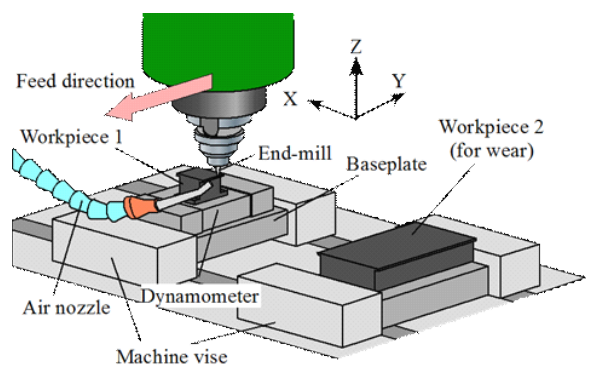

Figure 1: Schematic diagram of experimental set up

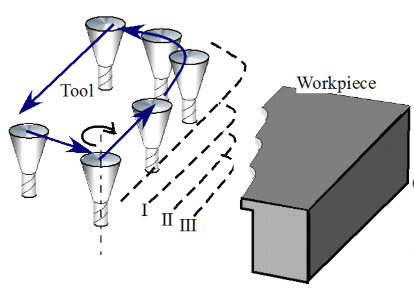

Figure 2: Machining paths to analyze cutting phenomena

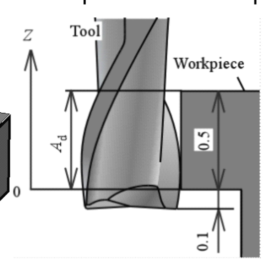

Figure 3: Interference between tool and workpiece

d_r = (Tool deflection) + (Spring back of workpiece and tool) + (Radial wear of tool) (1)

Zero cutting was performed on Path III several times to obtain critical residual stock removal d_e.

Table 1: Cutting conditions

Tool	TiSiN coated square end-mill ϕ 0.5 mm, 2 flutes
Workpiece	JIS: SKD61 (HRC53)
Spindle speed N_s	10,000 min^{-1}
Feed rate f	5 μm /tooth
Radial depth of cut R_d	10 μm
Axial depth of cut A_d	0.5 mm
Tool run out	< 3 μm
Coolant	Dry air
Cutting direction	Down cut

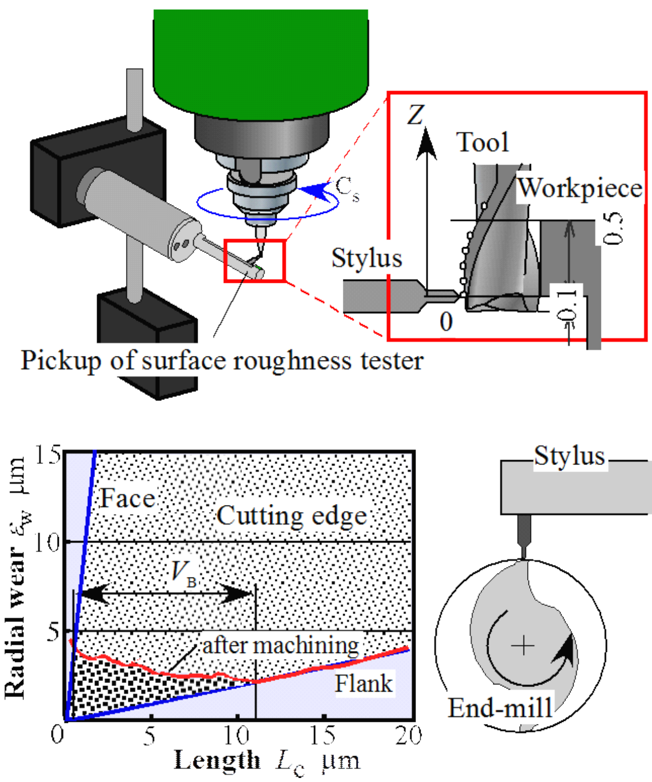

Figure 4: Measuring method of tool wear

Figure 3 shows the interference between the workpiece and the tool. Side cutting was performed by using only the peripheral cutting edges with the end cutting edge projected by 0.1 mm to simplify analysis of the cutting phenomena.

The cutting conditions are shown in Table 1.

The method for measuring tool wear is illustrated in Fig. 4 [6]. A micro end-mill tool was mounted on the spindle of a machine tool equipped with Cs axis control. With this control function, the spindle (end-mill) can be precisely rotated at extremely low speeds. Consequently, the tool's width of flank wear and radius reduction can be precisely measured by the pickup of a roughness tester.

The five positions of the cutting edges that actually machined the workpiece were measured to obtain the flank wear width V_B by comparing it with the nose shape of the cutting edges that were not used for the cutting shown in the figure. The average flank wear width $\overline{V_B}$ was determined as average of V_B at five points.

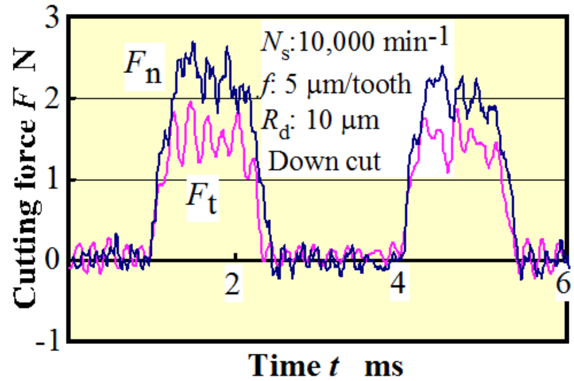

Figure 5: Changes in cutting resistance during a rotation

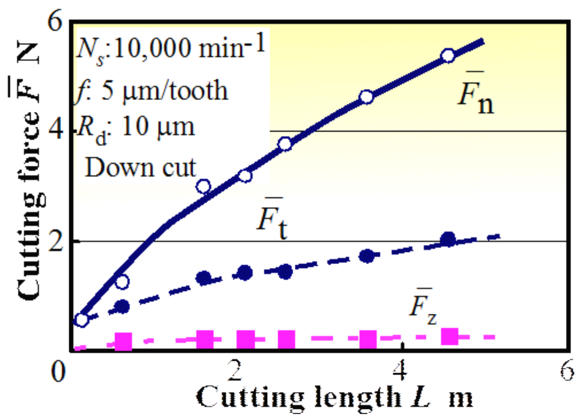

Figure 6: Changes in average cutting resistance depending on cutting length

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Changes in cutting resistance and residual stock removal caused by tool wear

Figure 5 shows the changes in cutting resistance during one rotation of the tool. The normal force F_n was larger than tangential force F_t in high-hardness material machining. Moreover, we used a tool with two teeth; therefore, the resistance of each tooth differs because the run-out during tool rotation cannot be completely eliminated. The cutting resistance was generated in the form of pulses, so complete intermittent machining was performed and the tool's deflection changed in the form of pulses. The cutting points rose in the Z-axis direction due to the helical tooth's shape. Thus, tool behavior and residual stock removal must always be discussed separately as static and dynamic issues.

The average cutting resistance depending on cutting length is depicted in Fig. 6. It was determined that, when the same workpiece was machined with a 10-mm-diameter end-mill, the normal force increased 2.5 times and the tangential force 1.2 times by the end of the tool life [6], whereas the cutting resistance increased enormously with a micro end-mill. The force necessary for the tool to cut into the workpiece increased because the tool's sharpness deteriorated with increasing tool wear. This can be explained by the increase in the normal force by several times to almost 10 times compared to the increase in the tangential force. In particular, cutting resistance in the normal direction must be considered to

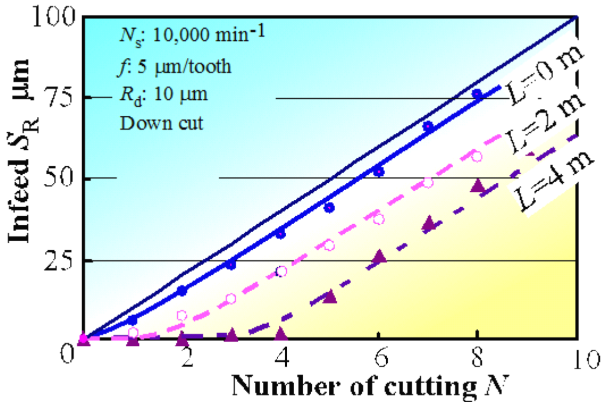

Figure 7: Infeed and changes in residual stock removal

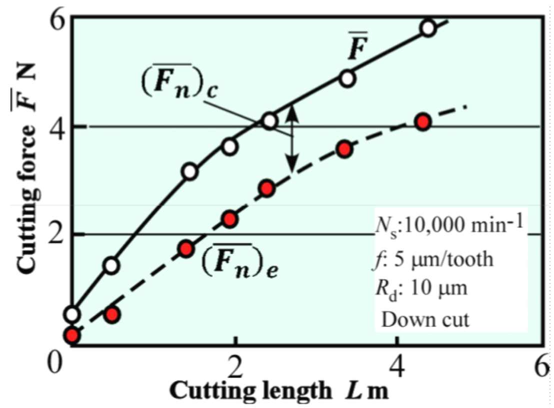

Figure 9: Separating normal force into elastic contact force and normal cutting force

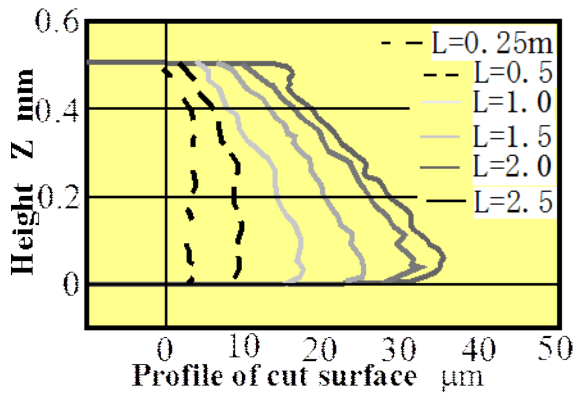

Figure 8: Changes in shape of side face caused by tool wear

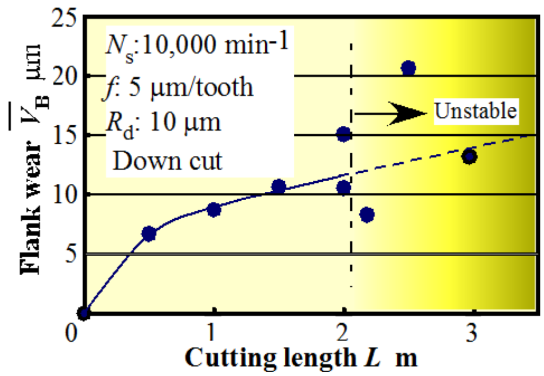

Figure 10: Average flank wear width with cutting length

improve dimensional accuracy because it is directly related to residual stock removal.

Figure 7 shows the infeed S_R with the increase in tool wear and changes in stock removal. It indicates stock removal for every 10-µm infeed by following machining of the specified cutting length L. The solid line shows the set total stock removal. The differences to this solid line represent residual stock removal. As cutting resistance increased with the progression of tool wear, residual stock removal increased from several µm to 25 µm. The cutting depth for an end-mill after 4-m cutting was shallow, so the end-mill was not able to machine the stock. When the total cutting depth reached 30 µm or more, the workpiece was cut only a little at a time. With low rigidity of the micro end-mill, when the normal force increased, residual stock removal that adversely affected the dimensional accuracy also increased; therefore, tool flank wear and cutting resistance must be correctly grasped in order to achieve high-accuracy machining.

Figure 8 shows changes to the side face shape of the workpiece with ongoing in tool wear. The side face accuracy deteriorated due to the large tapered angle and increased residual stock removal caused by greater cutting resistance. This result indicates that machining processes using a micro end-mill require high accuracy, but it is difficult to achieve the required machining accuracy in actual machining.

The elastic contact force and normal cutting force are shown in Fig. 9. In this figure, the normal force $\overline{F_n}$ is separately shown as the force that removes chips $(\overline{F_n})_c$ and the elastic contact force that does not remove chips $(\overline{F_n})_e$. This figure indicates that the elastic normal force, i.e., the rate of force required for a tool to cut into a workpiece, becomes very large. Normal force increases in both end-milling and micro end-milling. The rate of the elastic normal force in end-milling is low, whereas it is high in micro end-milling.

In micro end-milling, a sharp cutting edge is necessary for a tool to cut into a workpiece, so it is desirable to have a positive rake angle. In addition, the cutting resistance varies greatly with increased tool wear; therefore, tool wear and cutting resistance increases must be suppressed as much as possible, which requires development of new base and coating materials.

3.2 Tool wear and cutting phenomena

Figure 10 shows the average flank wear width $\overline{V_B}$ and cutting length L. The average flank wear width advances rapidly at an early stage; however, this merely corresponds to the typical initial wear of cutting tools. Also, it is found that cutting phenomena, such as cutting resistance, surface roughness, and wearing speed, become unstable at a cutting length of L = 2 m or more. When the cutting length is L = 2 m or more, it is possible to continuously use the tool for rough machining, but stable machining is not feasible. Drastic deterioration of the surface roughness indicates that the tool life limit has been reached finishing purpose. However, we believe that a tool's lifespan should be determined by the tool diameter and flank wear width that correspond with the purpose of use.

We predicted that, with advanced tool wear, the cutting edge will dull and the elastic contact amount will increase. We therefore machined a workpiece several times with a cutting depth of zero and measured the critical residual stock removal - the point at which cutting is no longer achieved.

Figure 11 shows the critical residual stock removal d_e and average flank wear width $\overline{V_B}$. This indicates that, with greater tool wear, critical residual stock removal increases. When the average flank wear width is more than 12 μm, residual stock removal is more than 5 μm, which is half of a 10-μm set cutting depth. Thus, machining accuracy is very sensitive to end-mill sharpness.

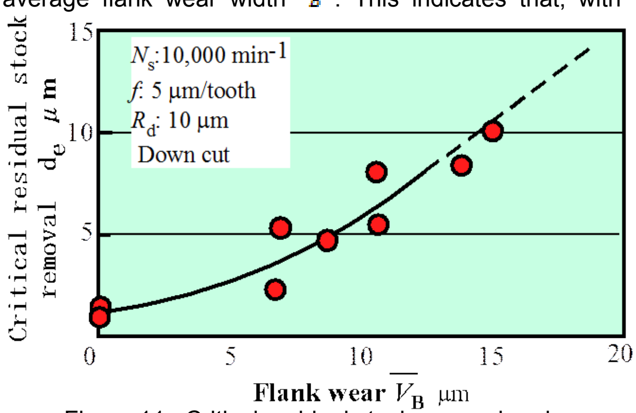

Figure 11: Critical residual stock removal and average flank wear

Figure 12 shows the changing wearing profiles to the cutting length L, which were measured at five points in the Z-axis direction. The figure represents results of just one tooth that had larger wear, although the micro end-mill we used had two teeth. As shown in this figure, the cutting edge, i.e. Z = 0 mm, was worn diagonally, but not horizontally, in the rotating direction. We can surmise that diagonal wear shown in the figure occurs once the dynamic motion path of the end mill is examined in detail [5]. For intermittent cutting, the end mill is displaced away from the workpiece as the cutting edge cuts into the workpiece. When comparing the wear amount in the Z-axis direction, initial wear occurs relatively uniformly, but the wear amount at the end cutting edge gradually increases. This is because a helical tooth performs a down-cut and the end cutting edge is the point of the first cut into a workpiece. As shown in Fig. 8, the set cutting depth is 10 μm but the actual cutting depth is several times larger due to residual stock removal. Thus, the end cutting edge receives the largest impact while cutting. Figure 8 also demonstrates that longer the cutting length is, the larger taper angle of the workpiece section becomes. This is caused not only by larger residual stock removal at the end cutting edge depending on rigidity, but also by fact that it wears out drastically more than in other positions.

The wear measurement method employed in this research can measure retract amount of a tool tip as well, which is several μm in its lifespan. This fact should be considered to achieve dimensional accuracy of ultraprecision die and mold.

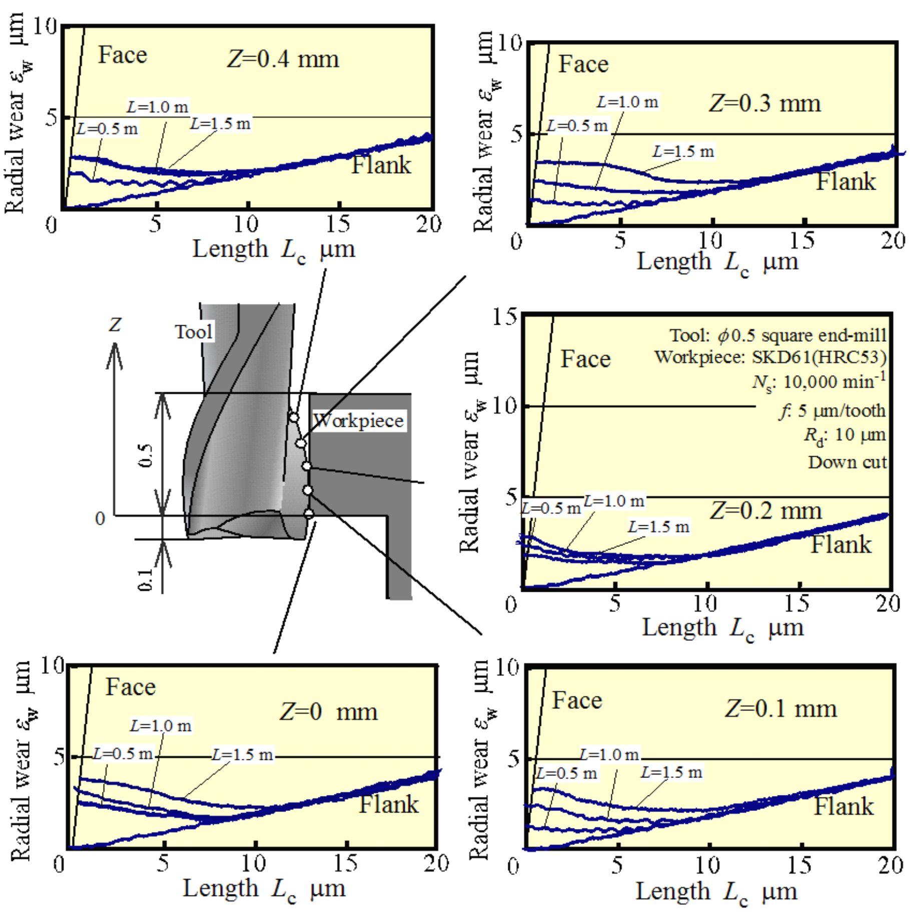

Figure 12: Cutting length and flank wear width in the Z-axis direction

3.3 Generating chips and finished surface roughness

Next, we observed the profiles of chips that changed with progressing tool wear.

Figure 13 shows the scanning electron microscope (SEM) photos of chips: the overall profile together with enlarged photos at the starting point, in-between point, and end point. With a new tool, stream shaped chips were generated stably. At cutting length L = 2.5 m, where tool wear had advanced significantly, the chips were non-uniformly sheared, indicating the onset of broken chips. As a result of the deterioration of the cutting edge due to wear, cutting resistance was increased and the chips were not generated uniformly.

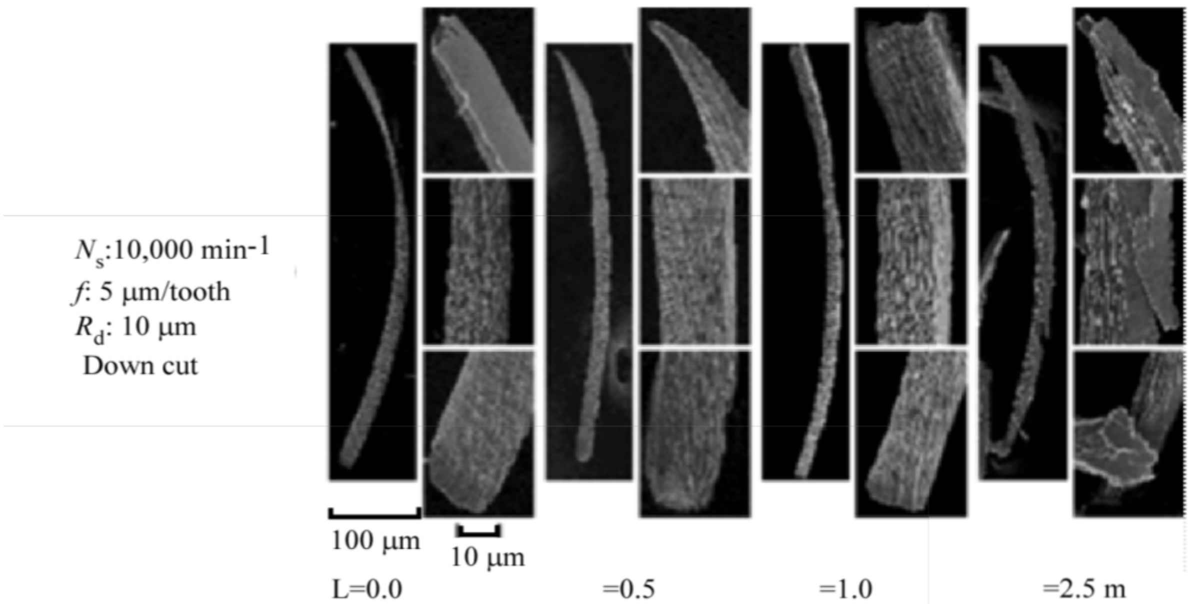

Figure 13: SEM photos of chips

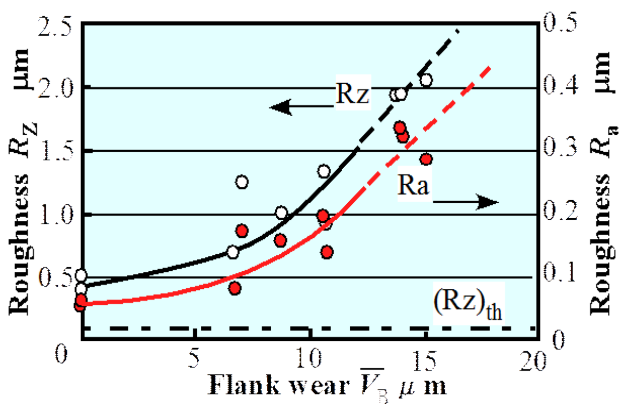

Figure 14: Relationship between surface roughness and average flank wear width

Figure 14 shows surface roughness Ra and Rz, which fluctuated according to tool wear. As the tool wear increased, the finished surface roughness gradually became larger and drastically fluctuated once the average flank wear width reached 12 µm or more. Furthermore, the cutting resistance values and profile accuracy values started to disperse, so we can infer that the maximum tool life is reached when the average flank wear width reaches 12 µm or more.

4 CONCLUSIONS

Side cutting was performed using a 0.5-mm-diameter micro end-mill. Residual stock removal and tool wear were precisely measured to observe the dynamic and static tool displacement, cutting edge, and chips. As a result, we found the following:

- When machining with a micro end-mill, which is different from an end-mill with a diameter of several millimeters or more, the state of the cutting edge hugely influences dimensional accuracy, profile accuracy, and finish roughness. Therefore, it is crucial to correctly grasp cutting edge wear.
- When the average flank wear width is 12 µm or more, cutting becomes unstable, which indicates that tool's life span for the purpose of finishing is over. Note that the tool is still usable for roughing purpose.
- When wear is advanced, critical residual stock removal with elastic contact exists even when zero cutting is performed. The values are larger than required for dimensional accuracy and profile accuracy. Therefore, countermeasures, such as in-machine measurement before finishing or changing tools, are required for high-precision machining.

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