An Approach to Tool Wear Monitoring in Small Diameter End Milling Using CCD Image

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***Abstract*— Because tool wear, tool deflection and cutting heat are the significant factors influencing machining accuracy, monitoring, and measurement and evaluation techniques, they are exceedingly important in a machining process. To monitor tool wear, methods based on changes in the measurement of cutting force and on indirect estimation of acoustic emission signals have been used, but direct measurement is considered relatively easy for the quantitative evaluation of wear and the analysis of measurement data. This study describes a system that uses images obtained using a charge-coupled device (CCD) camera in a machining process to recognize the state of the tools on a machining center and enable the measurement of tool wear. The proposed system consists of two CCD cameras, an image processing device, and a machining center with an open computer numerical control. The monitoring technique of tool deflection was based on the analysis of the tool projection image obtained using the CCD camera, as shown in our previous study. In this experiment, tool wear in end-milling was measured based on the projection image and actual image obtained using two CCD cameras without removal of the tool from a machine tool spindle. As a result, the measurement of the cutting edge based on CCD image in a machining process enabled this system to monitor the tool wear. Moreover, a correlation was demonstrated between the measured tool wear and tool deflection.**

***Index Terms*— in-process, monitoring, tool wear, end-milling, CCD image, tool deflection**

I. Introduction

Owing to the miniaturization and high performance of products, the scope of precision processing technology has expanded, and the development of high-performance machine tools and cutting tools has been progressing in the field of machining. Therefore, in-process monitoring and measuring techniques are needed to detect the condition of the tools during the cutting process. Phenomena such as tool wear, vibration, and tool temperature are observed in machining, and several types of monitoring techniques based on these phenomena have been proposed [1-3]. Regarding cutting tools, the deflection, wear, and chipping of tools during machining are factors that affect the machining accuracy. For monitoring of the tool conditions, studies have been conducted on in-process monitoring and control based on the detection of the cutting force; the on-machine measurement of tool wear using laser sensors [4-6]. A technique utilizing thermo sensor and AE sensor has also been proposed [7]. On-machine measurement is the measurement of tools and work pieces on the machine tool. We can expect to reduce the wastage of time and measurement errors by conducting on-machine measurements during the process. The tool wear and chipping of tool cutting edge influence the lead time in the processing quality and the production process, and a rapid determination of the tool state is desired. In this study, we investigated the method of measuring tool wear without the removal of tools in the cutting process for small diameter end milling. The tool state was recognized via on-machine measurement, based on the image photographed using a CCD camera.

II. Experimental Setup

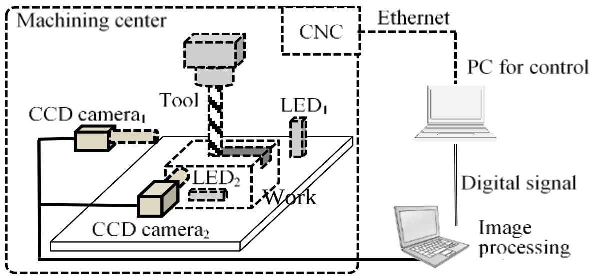

Figure 1. Experimental setup.

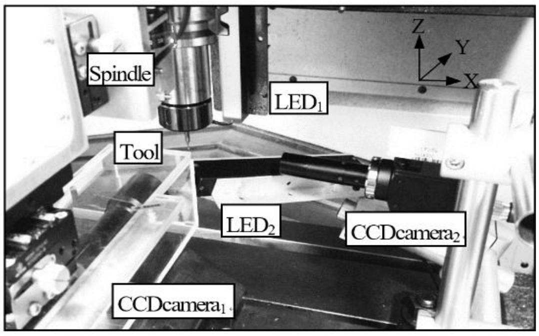

Figure 2. Photograph of measurement system.

A machining experiment was performed for end milling using a machining center. Based on image photography using a CCD camera, we constructed a system that recognizes the state of the tool on the machine tool and measures the tool wear without removal

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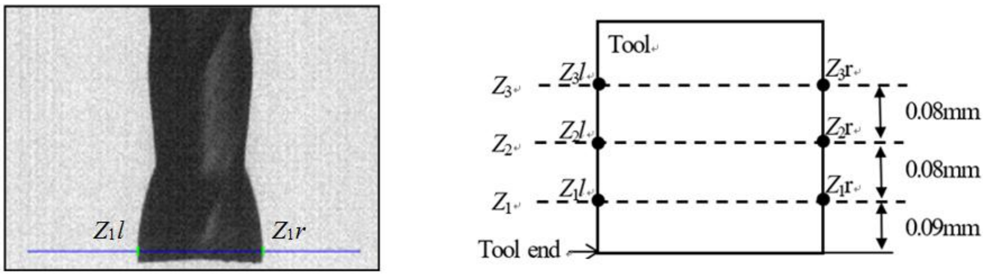
of the tool. The system configuration is shown in Fig. 1, and a photograph of the measurement is shown in Fig. 2. For end milling, two cameras and LED light units are installed around the spindle of the machining center to measure the state of the tool in the machining process. $Camera_1$ is the CCD camera installed in the tool feed direction to measure the tool width, and $camera_2$ is the CCD camera installed in the direction perpendicular to the tool feed direction to measure the cutting edge. The CCD camera is fixed to the spindle head using a bracket, and its position can be easily adjusted manually in the 3-axis direction. The measurement data is processed using a PC externally connected via a digital signal board. The resolution of the CCD camera used in the experiment is $1{,}600 \times 1{,}200$ pixels, and 1 pixel is equivalent to 4.54 µm in $camera_1$, but 2.25 µm in $camera_2$ due to the use of a 2x lens. Shutter speeds are 1/20,000 s and 1/500 s in $camera_1$ and $camera_2$, respectively. In order to shoot tools with two CCD cameras, LED units were used as a backlight for shooting projected images and as a front light for shooting real images, respectively. The shutter timing of the CCD camera is controlled by the trigger signal, which is outputted by using the laser sensor to detect a reflective tape pasted on the side of the tool holder. Trigger signal control makes it possible to take a projection image at the optional rotation angle of the tool in accordance with the main spindle rotating speed.

III. Experimental Procedure

In this study, we examined methods to monitor tool conditions in the following three ways with respect to end milling: 1) By focusing on the decrease of the tool diameter owing to wear, we determine the wear change by measuring the tool width, 2) by measuring the change in end mill cutting edge, we determine the change in wear and cutting edge condition, and 3) by measuring the decrease in axial length of end mill, we determine the change in wear of tool end.



(a) Projection image of tool (b) Measurement position from tool end

Figure 3. Measurement of tool width by $camera_1$.

In method 1), the tool width is measured based on the projection image acquired using $camera_1$ of the experimental system; an example of the photographed image is shown in Fig. 3(a). The tool width is calculated from the difference between the boundary positions $Z_n r$ and $Z_n l$ detected using CCD $camera_1$. Fig. 3(b) shows the measurement positions Z_1 to Z_3 from the tool end.

Fig. 4 shows changes in the tool width with the tool rotation angle. Since helix end mills are used in the experiment, the tool width changes as the tool rotates.

Therefore, in order to measure the change in the tool width due to tool wear, the angle at which the tool width is maximized was obtained at each measurement position, and the tool width was measured at an appropriate shutter timing by controlling the trigger delay.

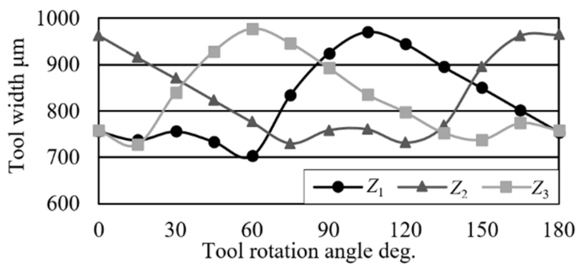
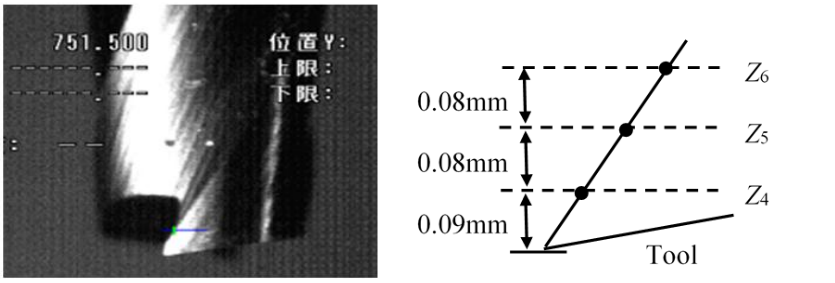


Figure 4. Change in tool width with tool rotation angle.

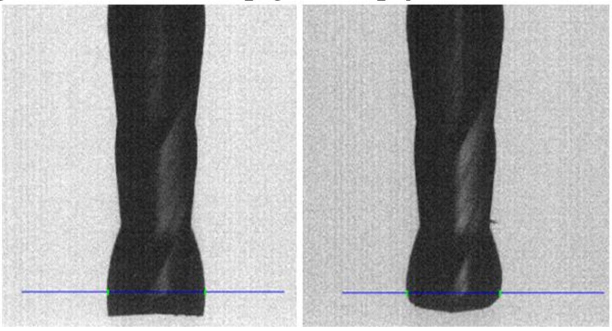
In method 2), the change in the cutting edge is measured using an image photographed using CCD $camera_2$; Fig. 5(a) shows an example of the photographed image of the cutting edge. Fig. 5(b) shows the measurement positions Z_4 to Z_6 from the tool end.



(a) Real image of tool. (b) Measurement positions from cutting edge.

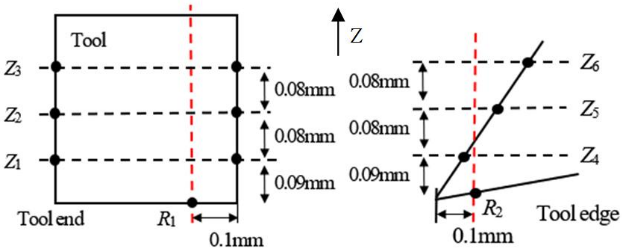
Figure 5. Measurement of cutting edge by $camera_2$.

In method 3), the decrease in axial length of tool is measured based on the projection image acquired using $camera_1$ and $camera_2$ of the experimental system; an example of the photographed image is shown in Fig. 6. Fig. 7 shows the measurement positions of the tool end. The decrease in axial length of tool at the dashed red line R_1 of the tool is measured based on the projection image obtained using $camera_1$ of the experimental system; the position 0.1 mm away from the boundary position is defined as R_1, as shown in Fig. 7(a). Furthermore, the decrease in axial length of tool at the dashed red line R_2 of the tool is measured based on the real image obtained using $camera_2$ of the experimental system; the position 0.1 mm away from the cutting edge of the tool is defined as R_2, as shown in Fig. 7(b). A measurement program was developed for each measurement, to obtain the amount of changes from the difference between the data before and after cutting at each of the three measurement positions set in the image processing system.



(a) Before cutting (b) After cutting

Figure 6. Projection image of tool.



(a) $Camera_1$ (b) $Camera_2$

Figure 7. Measurement positions (Z-axis).

In this system, when taking measurements, it is possible to obtain the measurement without removing the end mill from the spindle. In this experiment, the change in tool wear in the cutting process was measured in slotting with a small diameter end mill. The experimental conditions are listed in Table I.

TABLE I. EXPERIMENTAL CONDITIONS.

Tool	Squared end mill: 2 flutes
Work piece	Steel (S45C)
Tool diameter d (mm)	1.0
Helix angle φ (deg.)	30
Length of cut l (mm)	3.0
Cutting speed V_c (m/min)	30
Feed rate V_f (mm/min)	10.0
Axial depth of cut a_a (mm)	0.3

IV. MEASUREMENT OF TOOL WEAR

The decrease in tool width and cutting edge of the end mill for each constant cutting length L_C were measured using the constructed system in slotting. Examples of the tool images obtained by this measurement are shown in Figs. 8(a) and (b).

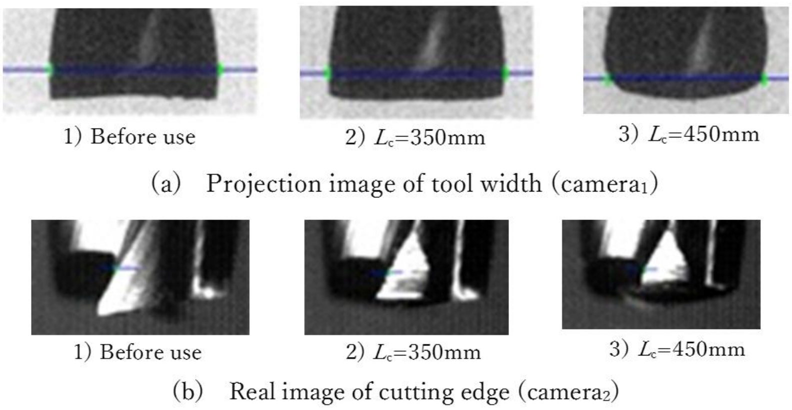
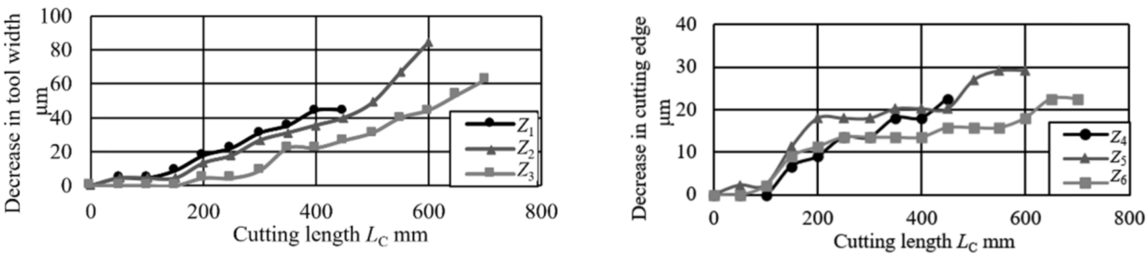


Figure 8. Monitoring image of tool wear.



(a) Decrease in tool width (b) Decrease in cutting edge

Figure 9. Relationship between cutting length and tool wear.

Fig. 9(a) shows the change in the decrease in tool width, measured using camera$_1$. Fig. 9(b) shows the change in the decrease in the cutting edge, measured using camera$_2$. The cutting length L_C = 100 mm does not correspond to significant wear; however, the wear gradually increases subsequently. In this cutting condition, abrasion also proceeded in the Z axis direction, and measurement was impossible after L_C = 450 mm and 600 mm at positions Z_1 and Z_2, respectively. Tool breakage occurred at L_C = 700 mm and the measurement was terminated.

On the other hand, wear on the bottom of the tool affects the machining accuracy of the groove depth in slotting. Therefore, the amount of axial wear of the tool is measured using the camera$_1$ and the camera$_2$. Fig. 10 shows the machined surface immediately after the start of machining and immediately before the tool breakage. Immediately before the tool breakage, it can be seen that the machined groove is considerably rough due to tool wear.

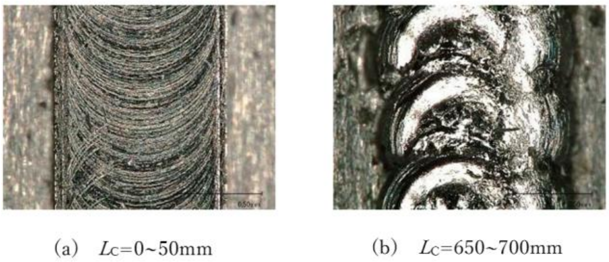


Figure 10. Photograph of machined surface.

The decrease in axial length of tool at R_1 and R_2 is shown in Fig. 11. The decrease in axial length of tool at R_1 and R_2 increases with increasing cutting length, indicating the progress of wear on the bottom surface of the tool from the initial stage of machining. Immediately before the tool breakage, the decrease in axial length of tool reaches about 0.1 mm, indicating that the machining error of the groove depth set to 0.3 mm is about 33%.

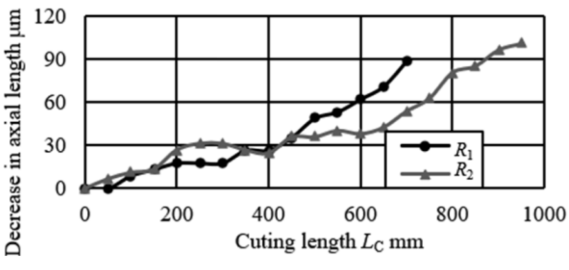


Figure 11. Relationship between cutting length and decrease in axial length.

V. Relationship between Tool Deflection and Tool Wear

In the experiment, we also investigated the relationship between tool deflection and tool wear during machining. Camera$_1$ was diverted for tool deflection measurement. The tool deflection is measured using the tool projection image taken by the camera$_1$ based on the method constructed in the previous study [8]. It is possible to measure the deflection in the direction perpendicular to the tool feed direction. Since the camera$_1$ is attached to the spindle head of the machining center via a bracket, it is possible to measure the tool deflection during machining while following the tool. As shown in Fig. 12, the tool deflection calculated the value C_n of the tool center position based on the measurement of Z_nl and Z_nr in the three measurement positions, and the deference between the tool center position C_n before cutting and during cutting. The measurement position was set to the three positions of Z_7, Z_8, and Z_9 at distances of 2, 3, and 4 mm, respectively, in the Z-axis direction from the tool end. The tool deflection as shown in Fig. 13 was increased with the accumulation of cutting length. Fig. 14 shows the relationship between tool deflection and tool wear. The measured tool deflection correlates better with tool width wear than cutting edge wear. Therefore, by using this system, it is also possible to estimate the state of tool wear based on the monitoring of the tool deflection.

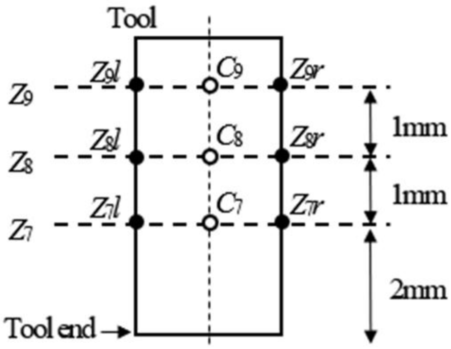


Figure 12. Measurement positions (tool deflection).

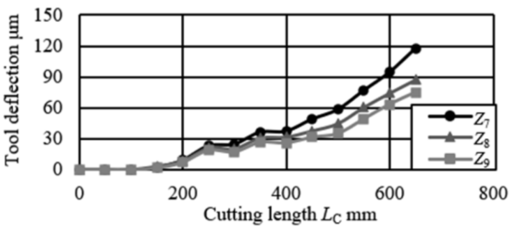


Figure 13. Tool deflection.

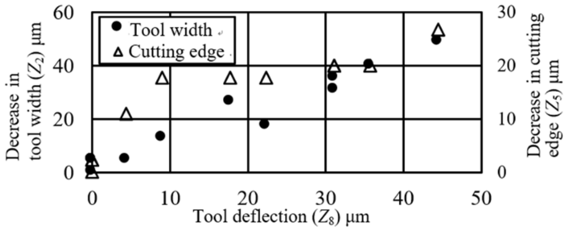


Figure 14. Relationship between tool deflection and tool wear.

VI. Conclusions

In this study, based on the tool image photographed using two CCD cameras, we studied the method of recognizing the tool state on the machine tool in the cutting process and measuring the tool wear without the removal of the tool. The constructed system enabled us to measure the decrease of tool width, that of cutting edge retraction, and that of axial length of tool with regard to tool wear during cutting using small-diameter end mill. Furthermore, it was shown that there is a correlation between tool deflection and tool wear. By improving the accuracy of the system, it can be expected to contribute to the monitoring of the tool state.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Shinichi Yoshimitsu conducted the research, analyzed the data and wrote the paper. All authors had approved the final version.

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