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MONITORING OF CUTTING PROCESS IN END MILLING OF HARD AND BRITTLE MATERIALS

Glass materials have been widely used in optical components in recent years. The purpose of this study was to develop an effective method for real-time detection of the state of cutting tools used in end milling of hard brittle materials. Cutting tests were performed to identify parameters that are useful in monitoring micro tool wear in glass milling. A specific component of the cutting force was found to be related to the progression of tool wear. Furthermore, using fast Fourier transform (FFT) analysis, the peak amplitudes of the cutting forces were found to occur at a specific frequency.

1. INTRODUCTION

The demand for miniaturization is increasing in many areas, such as the medical and electronics fields. Microfabrication techniques are indispensable to the manufacture of small parts for use in tablet-type devices, cellular phones, and similar small electronics. In recent years, microfabrication using small-diameter end mills has been used widely in the manufacture of optical components and semiconductors as high-speed machining using small-diameter end mills has increasingly been put to practical use. Because of the large effect of the cutting edge on the machining accuracy, it is important to be able to detect the state of a small-diameter end mill in real time. However, because the extent of the tool wear of a small-diameter end mill is typically very small, it is difficult to detect the state of the tool. Many researchers have tried to clarify the mechanism of micro-milling [1],[2],[3],[4].

Glass materials have been widely used in optical components in recent years because they are chemically stable and are well suited for use in optical devices. Examples of glass optical components are the lab-on-chips and micro total analysis systems (μ TAS). A flow path that is configured in the grooves and holes is formed on the glass substrate by sandblasting and chemical etching. However, the methods currently used for forming the flow path are limited in accuracy and in the cross-sectional shape that can be machined because the control of the machining in the depth direction is difficult using these methods.

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On the other hand, machining is considered an effective method of forming the flow path because the degree of freedom associated with this method is greater than with other methods used in the processing of three-dimensional shapes. However, glass materials are difficult to machine because they are hard and brittle materials. In addition, final fracture can easily occur once-cracking occur. Therefore, glass materials must be machined using ductile-mode cutting to prevent brittle cracks [5],[6]. In ductile-mode cutting of glass, the cutting thickness per cutter must be very small. Therefore, the feed rate must be very low. As a result, heavy wear of cutting tools is typical in glass milling. The actual cutting distance increases as the feed rate decreases, which accelerates the progression of tool wear. Consequently, it is important to monitor the state of the cutting tool and the tool wear during glass milling.

The purpose of this study was to develop an effective method for real-time detection of the state of cutting tools used in end milling of hard brittle materials. To this end, cutting tests were performed to identify parameters that are useful in monitoring micro tool wear in glass milling.

2. EXPERIMENTAL PROCEDURE

The experimental apparatus used in this study is shown in Fig. 1. Cutting tests were performed using a vertical machining centre. The milling tool was mounted on a brushless motor spindle to control the spindle speed electrically. The spindle unit was mounted on the head of a machining centre. The milling tools were 0.3mm diameter square-end mills made of cemented carbide.

Each end mill was mounted in such a way that the deflection of the end mill would be $1\mu\text{m}$ or less, as measured using a dial gauge. The cutting conditions are listed in Table 1. In the cutting tests, the groove on the workpiece was formed by a milling cutter moving horizontally. The cutting conditions were determined in preliminary cutting tests. The workpiece to be machined had a microgroove $20\mu\text{m}$ in depth from the surface. The workpiece was made of crown glass plate 1mm in thickness. The workpieces were attached in such a way that the inclination of the workpiece was $1\mu\text{m}$ or less, as measured using a dial gauge.

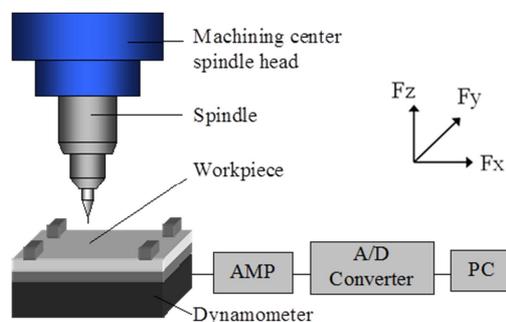


Fig. 1. Experimental apparatus

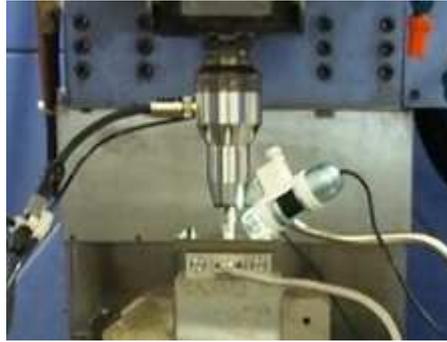
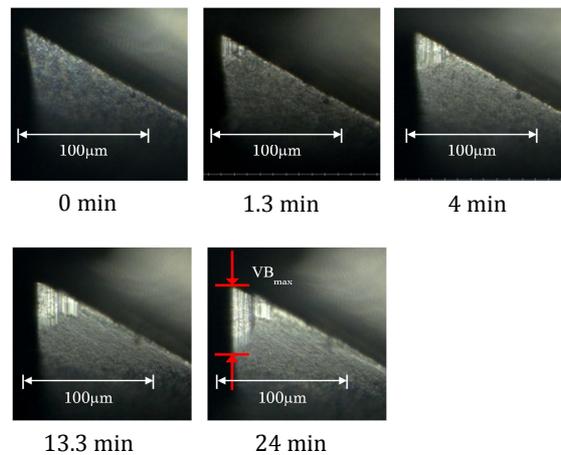


Fig. 2. State of milling

Fig. 3. State of flank wear ($f=150\mu\text{m}/\text{min}$)

The cutting tests were performed with water on the clamping device, which has a water pool as shown in Fig. 2. The cutting forces F_x , F_y , and F_z were measured with a dynamometer, as shown in Fig. 1. The dynamometer was a piezoelectric quartz force transducer affixed to a table. The machined surface of the glass material and the tool wear of the milling tool were observed using a digital micro-scope. The cross-sectional shape of the groove was observed using a laser-type microscope with a resolution of $0.05\mu\text{m}$.

The cutting forces measurements were transmitted to a personal computer via an A/D converter board every $50\mu\text{s}$.

3. EXPERIMENTAL RESULTS

3.1. FLANK WEAR OF END MILL

Figure 3 shows the tool wear observed. The flank wear increased with the cutting time. The maximum flank wear VB_{max} was measured as shown in this figure. Scratches caused by abrasive wear were formed on the flank wear surface. The scratch appeared to increase in depth with the cutting time.

Figure 4 shows the relationship between the cutting time and the maximum width of the flank wear. The tool life was defined as the time when the maximum width of the flank wear reached $50\mu\text{m}$. The maximum width of the flank wear VB_{max} increased with the cutting time at all feed rates considered.

Table. 1. Cutting conditions

Workpiece	Glass	Crown glass
Tool	Type	Cemented Carbide tool Square-end mill
	Diameter mm	0.3
	Number of cutters	2
	Overhang mm	13
Spindle speed	$N \text{ min}^{-1}$	20000
Feed rate	$f \text{ } \mu\text{m}/\text{min}$	100,150,200
Axial Depth of cut	μm	20
Cutting fluid		Water

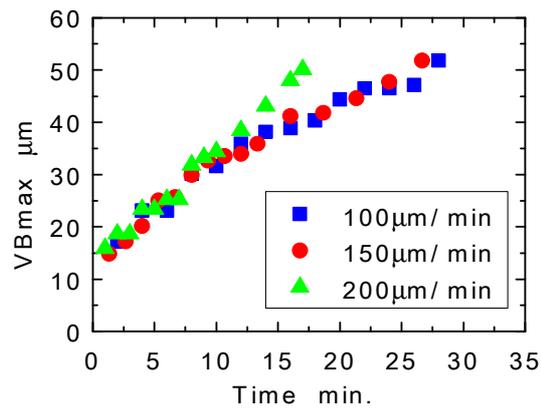


Fig. 4. Maximum width of flank wear

The influence of the feed rate on the flank wear was small for cutting times up to 10 minutes. However, the maximum width of the flank wear at a feed rate of $200\mu\text{m}/\text{min}$ increased after 10 minutes.

3.2. CUTTING FORCE

Figure 5 shows the illustration in end milling of glass material using a square-end mill. Figure 6 shows the measured values of the cutting force components. The cutting force components were sampled rates considered. The influence of the feed rate on the flank wear was small for cutting times up to 10 minutes. However, the maximum width of the flank wear at a feed rate of $200\mu\text{m}/\text{min}$ increased after 10 minutes. for 2.5 s at $50\mu\text{s}$ intervals. The amplitude of the F_y cutting force component hardly changed over time, whereas the

amplitudes of the F_x and F_z cutting force component increased over time. This tendency was particularly remarkable for the F_x component. Consequently, the F_x component of the cutting force is considered to be more closely correlated with the tool wear than the other components because it is expected that the cutting force will increase as the tool wear progresses.

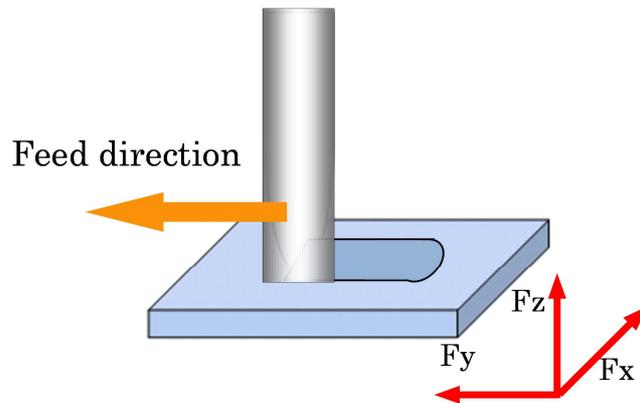


Fig. 5. Direction of cutting force

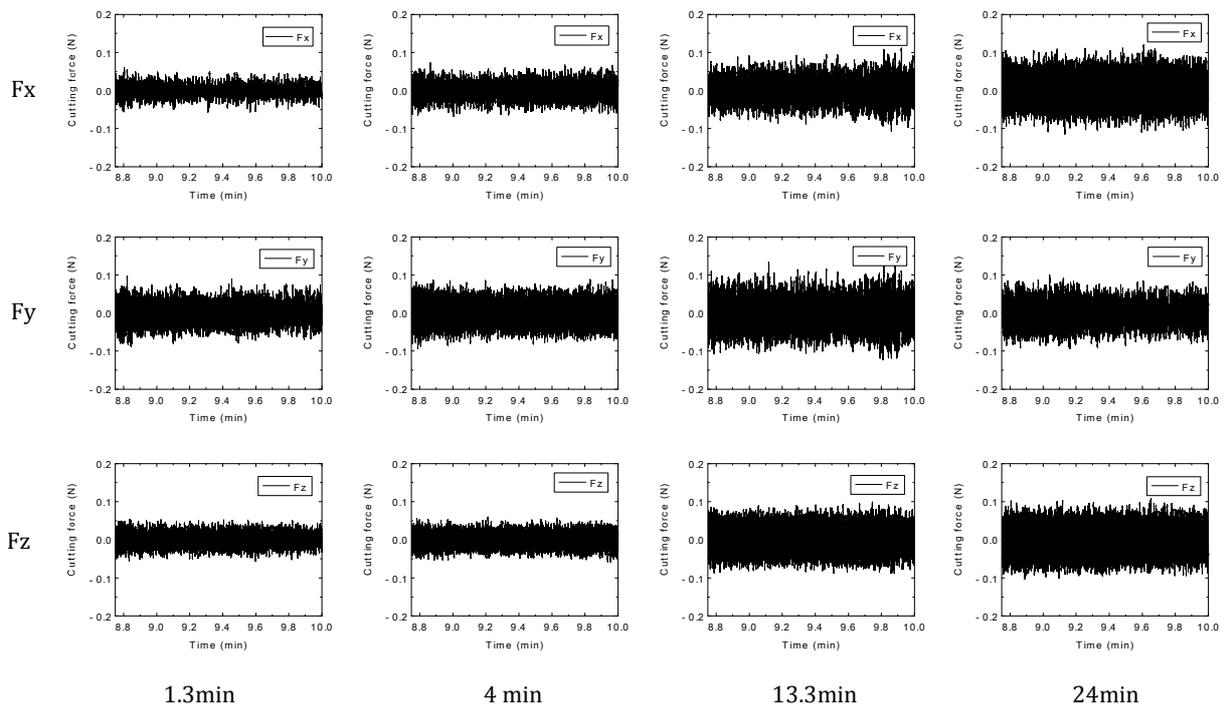


Fig. 6. Cutting force ($f=150\mu\text{m}/\text{min}$)

Figure 7 shows the measured cutting force components for one rotation of the end mill. The phases of the cutting force components F_x and F_y are almost the same, whereas

the phase of the cutting force component F_z shifts by a quarter rotations with respect to the other two components' phases.

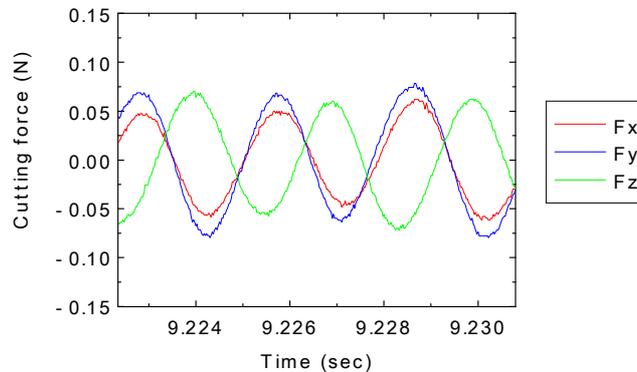


Fig. 7. Cutting force components for one rotation ($f=150\mu\text{m}/\text{min}$)

Figure 8 shows the relationship between the cutting time and the maximum value of the cutting force. The maximum value is the average value determined from the sampled data. The maximum value of the cutting force in each direction increases gradually with the cutting time. However, the maximum value of the cutting force component F_z varies particularly widely. It is thought that the cutting force increases with the progression of tool wear. Therefore, it is thought that the cutting force component F_x is most closely correlated with the tool wear. However, the amplitude of the cutting force is very small, and small vibrations of the machine tools are considered to have a significant influence.

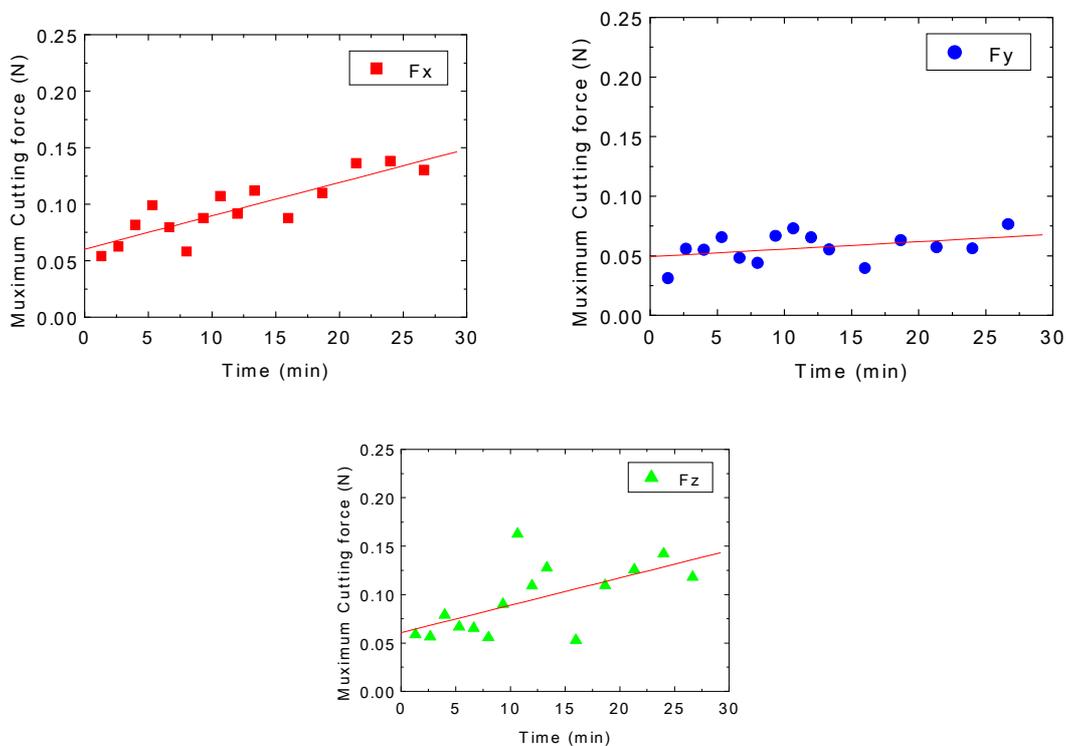


Fig. 8. Maximum value of cutting force ($f=150\mu\text{m}/\text{min}$)

3.3. FFT ANALYSIS

Figure 9 shows the spectra of the cutting force components in each direction. The spectra of the cutting forces were calculated by fast Fourier transform (FFT) analysis after the cutting tests. The peak of each spectrum is located at a frequency of approximately 670Hz. The frequency is considered to be approximately equal to twice the rotational speed of the spindle because the end mill has two cutters.

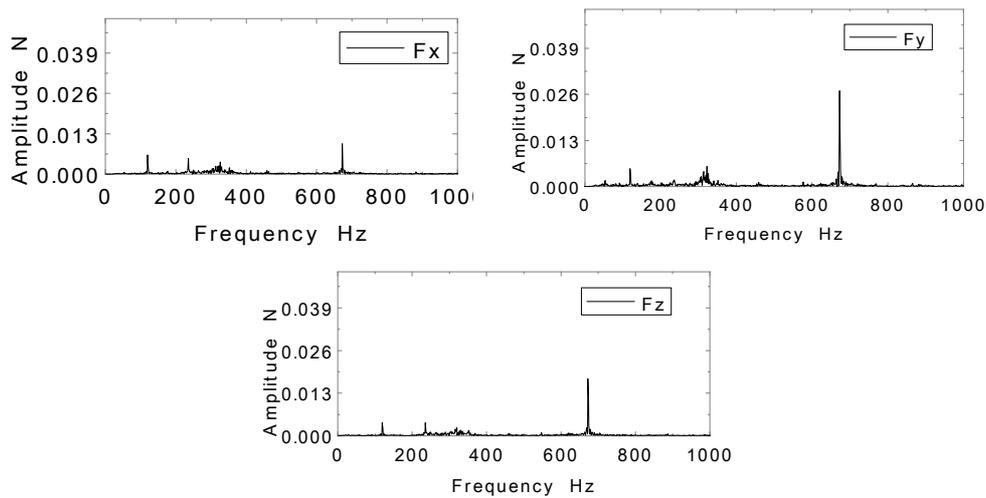


Fig. 9. Spectra of cutting force components in each direction ($f=150\mu\text{m}/\text{min}$, 1.3min)

Figure 10 shows the spectrum of the cutting force component Fx. As Fig. 8 shows, the cutting force component Fx is correlated with the tool wear. The amplitude of the spectrum at a frequency of approximately 670Hz increases with the cutting time.

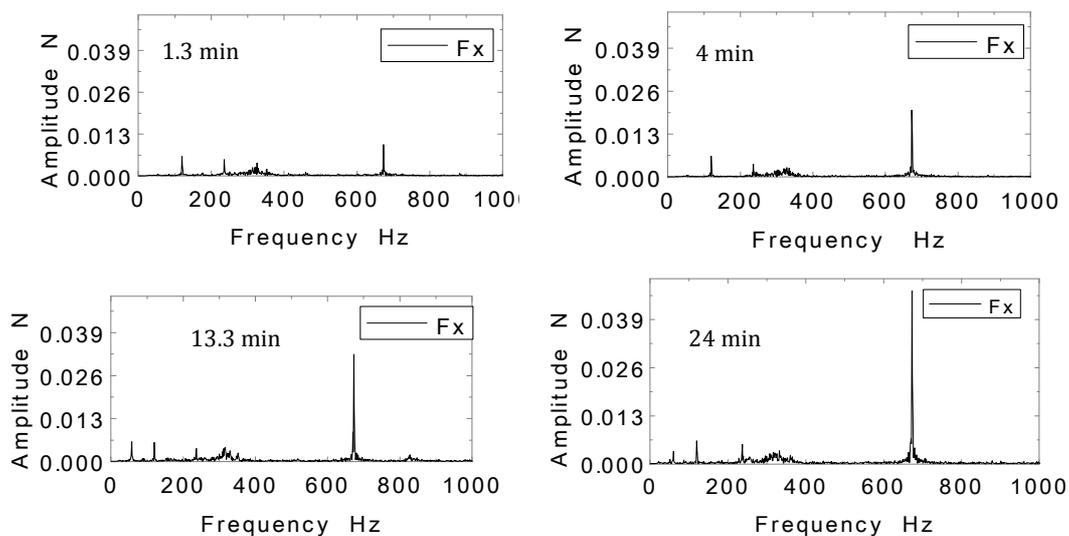


Fig. 10. Spectrum of cutting force components Fx ($f=150\mu\text{m}/\text{min}$)

3.4. STATE OF MACHINED SURFACE

Figure 11 shows the state of the machined surface. The bottom of the groove is machined in ductile-mode cutting without brittle cracks, whereas the edge of the groove is machined with brittle cracks. However, the edge of the groove becomes machined without brittle cracks as the cutting time increases. The critical cutting thickness in the milling of glass material using a worn tool is known to be thicker than that in milling using an unworn tool. The rake angle becomes negative with increasing tool wear. Therefore, it is thought that as the cutting time increases, the edge of the groove can be machined without brittle cracks because of the compressive force on the machined surface.

A slope was observed at both ends of the bottom of the groove as the cutting time increased. This slope is considered to be due to the outer peripheral side of the end mill being worn. Therefore, as Fig. 10 shows, the peak value of the spectrum at a frequency of 670Hz increases with the cutting time.

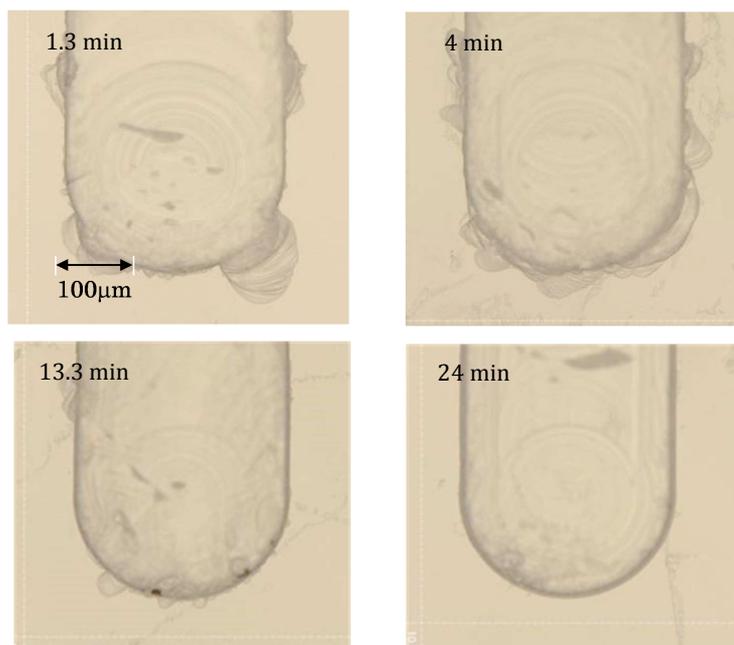
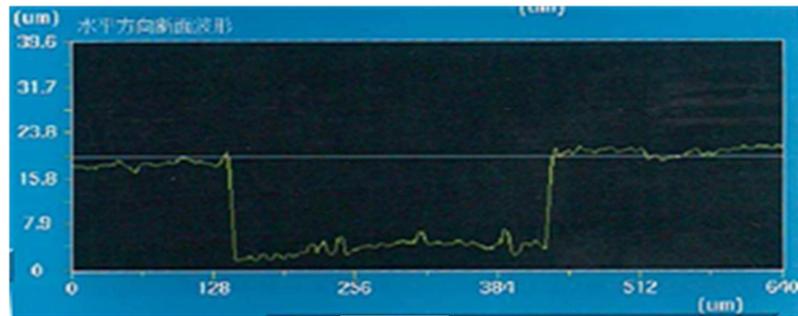


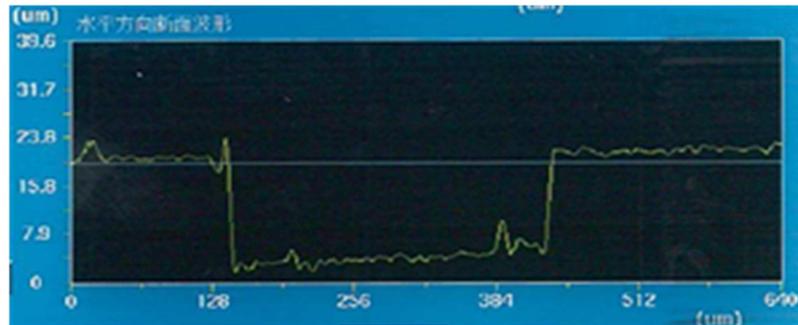
Fig. 11. State of machined surface ($f=150\mu\text{m}/\text{min}$)

Figure 12 shows the cross-sectional shape of the groove. The depth at both ends of the groove was found to decrease as the cutting time increased. A small slope was observed at both ends of the bottom of the groove as the cutting time increased, as shown in Fig. 11. The outer peripheral side of the end mill was found to be worn.

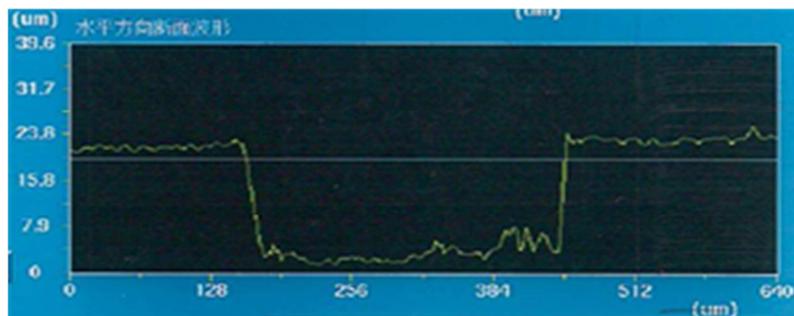
The results showed that the cutting force component F_x was more closely correlated with the tool wear than the F_y and F_z components. Furthermore, the peaks of the cutting force spectra were found by FFT analysis to occur at a frequency of approximately 670Hz. This frequency is approximately equal to twice the rotational speed of the spindle because the end mill has two cutters.



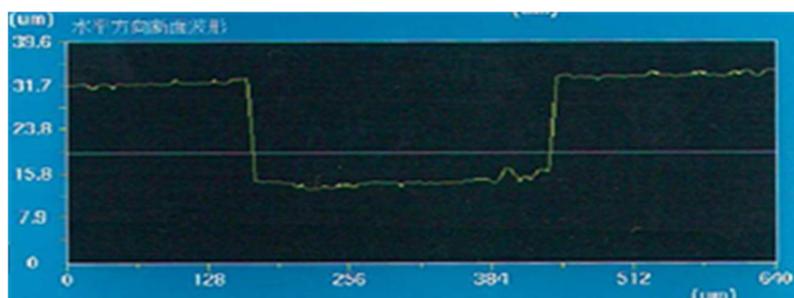
1,3 min



4 min



13.3 min



24 min

Fig. 12. Cross-sectional shape of groove ($f=150\mu\text{m}/\text{min}$)

Consequently, in the initial stage of machining, the peak value of the cutting force spectrum at a frequency of approximately 670Hz is small owing to the eccentricity of the end mill. However, in the end stage of machining, the peak value of the spectrum at a frequency of approximately 670Hz is larger because the eccentricity of the end mill is removed owing to the tool wear.

4. CONCLUSIONS

1. The cutting force was found to increase with increasing tool wear. The cutting force component F_x is more closely correlated with tool wear.
2. The edge of the groove is initially machined with brittle cracks, but as the cutting time increases, the edge of the groove is machined without brittle cracks.
3. The amplitude of the cutting force is very small and because small vibrations of the machine tools have a significant influence.

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