Monitoring for Ultra-Precision Turning of Single Crystal Silicon using Diamond Tool with Large Nose Radius and Small Chamfer at Cutting Edge

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Abstract:
It is known that brittle materials can be machined like ductile materials when uncut chip thickness is less than critical one. Face turning by using a tool having round edge with small chamfer was carried out to find out effective parameter for distinction between ductile and brittle mode cuttings using by AE signal, cutting forces and vibration acceleration. As a result, the following results were reached. (1) RMS value of AE signal was larger in brittle mode cutting than in ductile mode cutting. (2) Static thrust force per unit area of cutting cross section was larger than in brittle mode cutting.

Keywords: Monitoring, Cutting forces, AE-signal, Single Crystal Silicon, Ultra-Precision Cutting

1. Introduction

Hard and brittle materials such as glass and silicon are used for various optical components, semiconductor, and so on. Consequently most optical components are finished by abrasive machining, i.e. grinding, polishing, buffing, etc. since the finished surface of the machined part requires a mirror-like surface. However, accuracy of form of the part finished by the abrasive machining is relatively low because resistant forces are large in abrasive machining. On the other hand, it is known that hard and brittle materials could be cut like ductile materials with a single crystal diamond tool when depth of cut is less than a critical uncut chip thickness, which is called ductile mode cutting[(1)~(3)]. However, it is very difficult to always forecast the critical uncut chip thickness that hard and brittle materials can be cut in ductile mode[(4) ~ (7)]. Furthermore, it's difficult for human being to distinguish ductile and brittle mode cutting in ultra-precision cutting process. Consequently if automatic monitoring system for distinction between ductile and brittle mode cuttings could be realized, productivity of machining parts and efficiency of operator's task would be fairly improved.

The purpose of this study is to find out effective parameter for distinction between ductile and brittle mode cuttings using cutting forces, AE signals and acceleration signals during cutting.

2. Nomenclature, Materials and Methods

The ultra-precision lathe (Toyoda Machine Works AHN60-3D) shown in Figure 1 was used for experiments. End face of a single crystal silicon disc (thickness=6mm) was machined with a single crystal diamond tool. This tool has a round edge with small chamfer. Table 1 shows details of experimental conditions. The work material shown in Figure 1 was fixed on a vacuum chuck installed on the spindle and surface was beforehand machined in pre-processing with other tools due to make it small enough for cutting test. Clockwise rotation angle from the flat orientation is shown for the sign φ in figure, and the cutting direction thereafter is shown by the sign φ.

Cutting forces, AE signals and acceleration signals were measured with dynamometer (Kistler 9256A), AE-sensor (NF circuit design block AE900S-WB) and acceleration pick-up installed on the lathe, respectively. The interferometer (ZYGO New View 5032) was used for three dimensional observation and measurement of the machined surface after cutting test.

3. Results

3.1 Surface roughness in ductile/brittle mode cutting

Figure 2 shows machined surface when depth of cut is *d* is 1.5μm at feed rates *f* of 0.5 and 1.0μm/rev. The machined surface reflects lattice pattern plainly in case of 0.5μm/rev. But the machined surface is partial pear finish when feed rate *f*=1.0μm/rev. When feed rate *f* is 1.75μm/rev, the machined surface is whole pear finish.

Then, to examine the machined surfaces more in detail, the profile and roughness of machined surface of a work are measured with the ZYGO. Figure 3 shows 3-D profile of the machined surface. Clear cutter marks of which the pitch is almost the amount of feed rate cab be seen on finished surface when feed rate *f* =0.5μm/rev. When feed rate *f*=1.0μm/rev, the cutter mark of which the pitch is almost the amount of the feed rate can not be seen while brittle damage such as the cracks and pits can be seen in several small regions. When feed rate *f*=1.75μm/rev, brittle damage can be seen in the whole machined surface. Therefore, it was judged that cutting mode is ductile at *f*=0.5μm/rev, cutting mode is brittle at *f*=1.75μm/rev, and cutting mode is mixed mode at *f*=1.0μm/rev.

Figure 4 shows crystalline direction of single crystal silicon disc used to experiment. The crystalline direction changes 8 times in one rotation of workpiece. Figure 5 shows the relationship between cutting speed and surface roughness when feed rate *f*=0.5, 1.0μm/rev. In any case, surface roughness *Ra* was larger to the cutting direction [010].

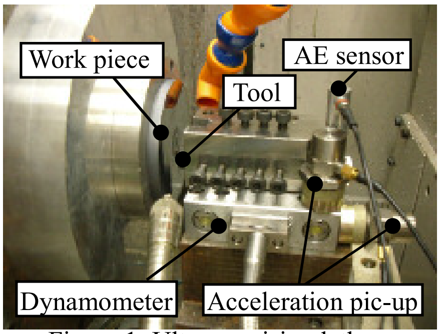
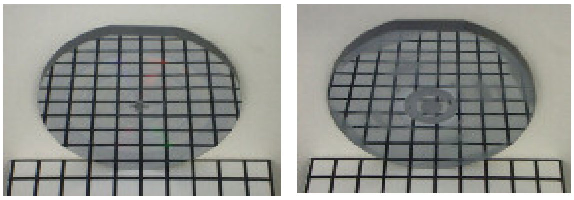


Figure 1: Ultra-precision lathe

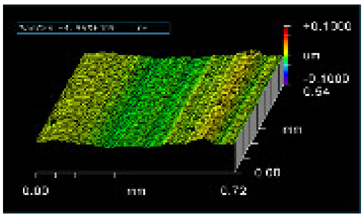
Table 1: Experimental conditions

Workpiece	Material	Silicon wafer (100)
	Diameter mm	76.2
Tool	Material	Single crystal diamond
	Nose radius mm	2
	Rake angle deg.	0
	Clearance angle deg.	4
	Chamfer μm	2
Depth of cut d μm		1.5
Feed rate f μm/rev		0.5 , 1 , 1.75
Spindle speed rpm		1000
Cutting fluid		Non

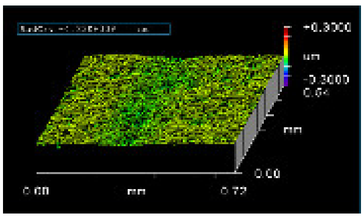


(a) f=0.5μm/rev (b) f=1.0μm/rev

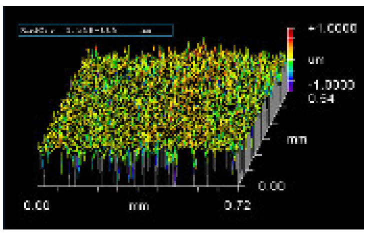
Figure 2: Photograph of machined surface



(a) f=0.5μm/rev



(b) f=1.0μm/rev



(c) f=1.75μm/rev

Figure 3: 3-D profile on the machined surface

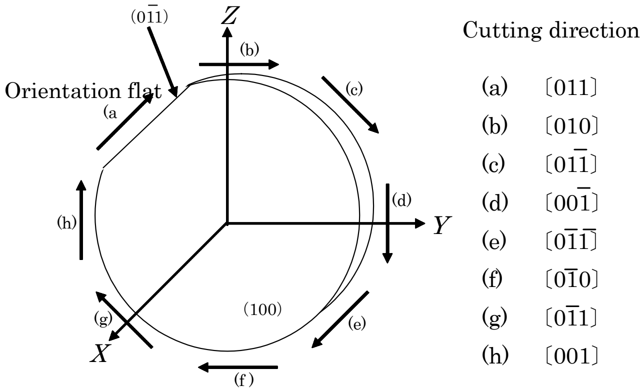
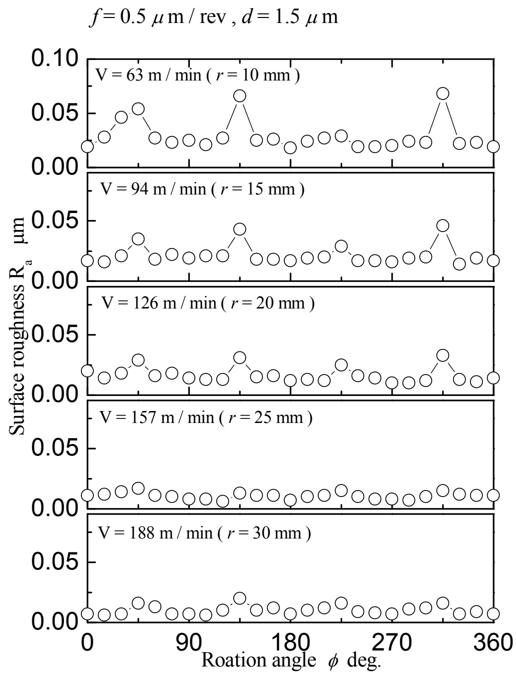


Figure 4: Crystal structure and direction



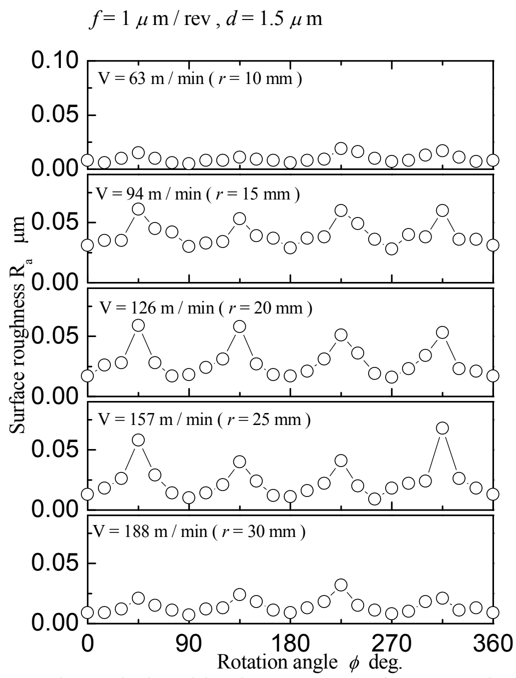


Figure 5: The relationship between cutting speed and surface roughness

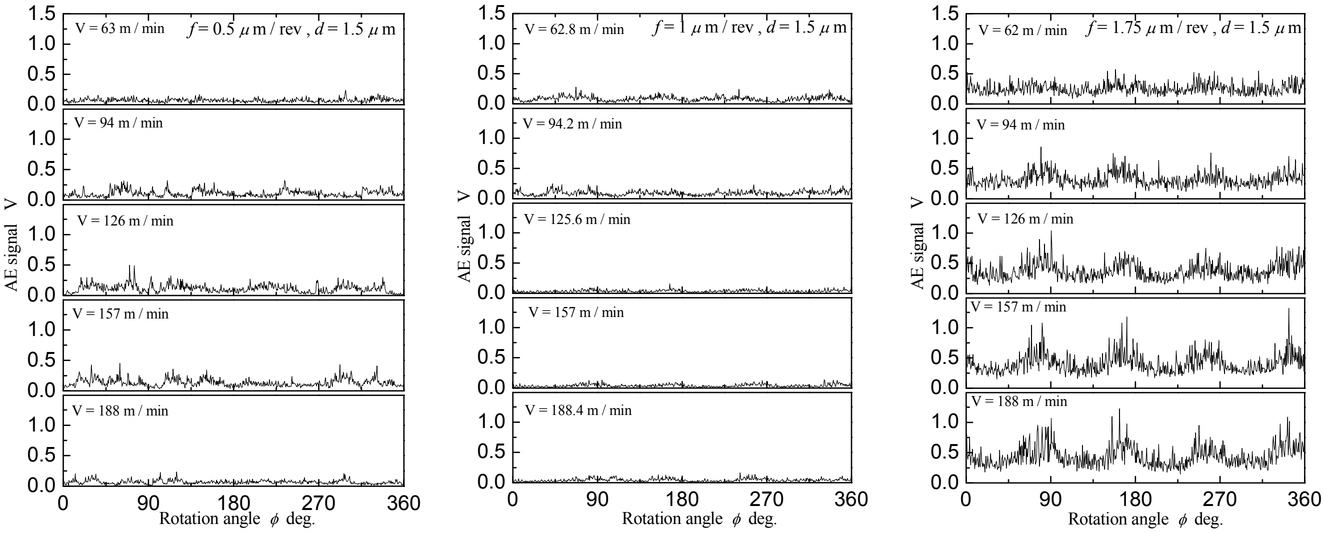
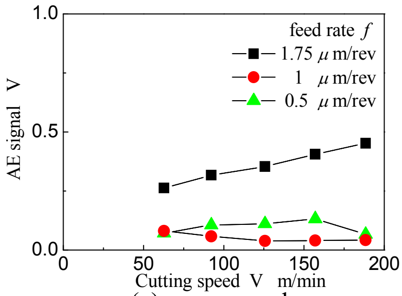


Figure 6: The envelope signal of AE

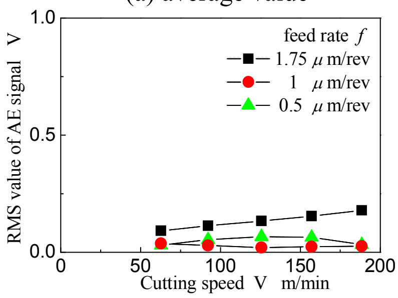
3.2 AE signals in ductile/brittle mode cutting

AE(Acoustic Emission) means the elastic wave generated by elastic energy's being liberated when the solid transforms or be destroyed [8]. It was thought that AE was effective to detect the occurrence of the crack and the pit in cutting process of the brittle material. Figure 6 shows the envelope signal of AE when feed rate f=1.75 µm/rev. The amplitude of envelope signals of AE fluctuated most greatly at feed rate f of 1.75µm/rev. And the fluctuation of amplitude was smallest at feed rate f of 1.0µm/rev. In addition, the amplitude of envelope signals of AE tended to grow at rotation angle of 30 degrees from crystalline direction [010] when feed rate f=1.75µm/rev. When feed rate f=0.5 or 1.0µm/rev, the rotation angle from crystalline direction [010] was about 10 degrees.

Figure 7 shows the relationship between cutting speed and average value or RMS(Root Mean Square) value of envelope signals of AE. Both of average and RMS values, were largest in case of brittle mode cutting than in case of ductile or mixed mode cutting.



(a) average value

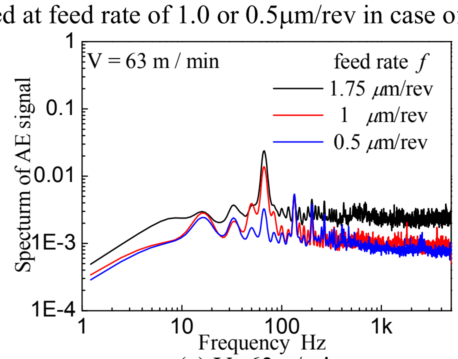


(b) RMS value

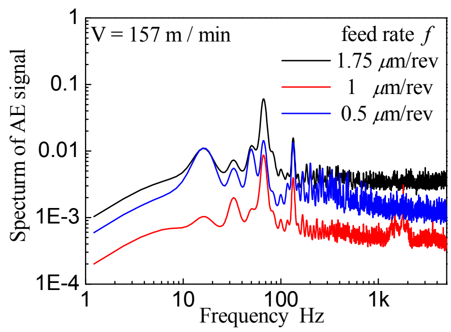
Figure 7: The relationship between cutting speed and AE

Figure 8 shows spectrum of AE envelope signals. The spectrum of AE signal has peaks at about 17Hz, 70Hz and 140Hz. The frequency of 17Hz corresponds to spindle speed (1000rpm). The frequencies of 70Hz and 140Hz equal to 4 and 8 times a rotational speed of spindle, respectively and they were caused by change of crystalline direction.

Then Figure 9 shows peak values of spectrum of AE envelope signal normalized by mean value of AE envelope signal at the frequencies with the peaks against cutting speed, respectively. It seems that the normalized peak value of spectrum that obtained at small feed rate is not substantially different from the values obtained at large feed rate in case of 14Hz and 70Hz. However, the normalized peak values obtained at small feed rate ratio of 1.75µm/rev is smaller than the normalized peak values obtained at feed rate of 1.0 or 0.5µm/rev in case of 140Hz.

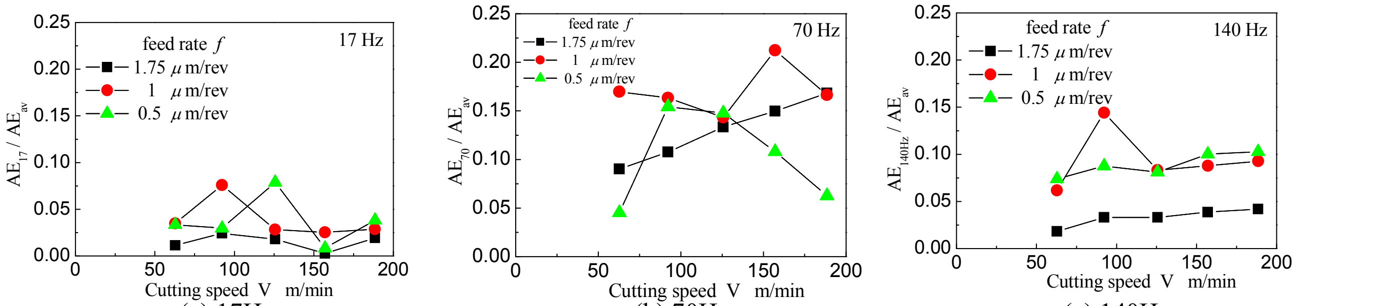


(a) V=63m/min



(b) V=157m/min

Figure 8: Spectrum analysis on envelope signals of AE



(a) 17Hz (b) 70Hz (c) 140Hz

Figure 9: The ratio of AE signals (strength of the peak/AE average) to the cutting speed

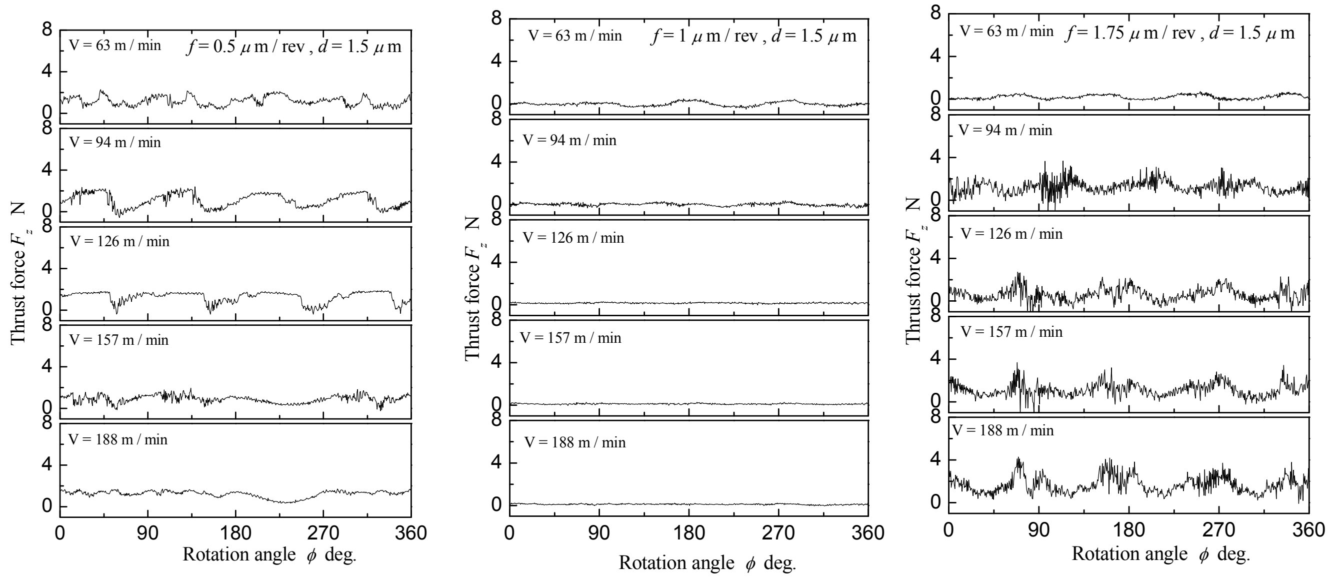
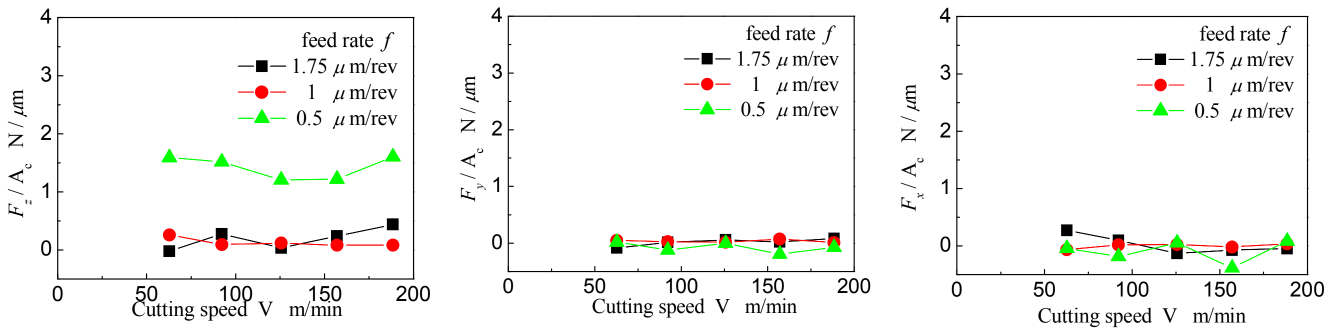


Figure 10: The relationship between thrust force and cutting speed



(a) Thrust force (b) Primary force (c) Feed force

Figure 11: The relationship between cutting speed and the thrust force for each cutting sectional area

3.3 Cutting forces in ductile/brittle mode cutting

Figure 10 shows thrust force at some cutting speeds when depth of cut d is 1.5μm and feed rate f are 0.5, 1.0, and 1.75μm/rev. The thrust forces also change at rotation angle where AE envelope signal changed shown in Fig. 6. The amplitude of the thrust force fluctuates most greatly when f=1.75μm/rev. And the fluctuation of amplitude is smallest when f=1.0μm/rev. In addition, the amplitude of the thrust force tends to grow at rotation angle of 30 degrees from crystalline direction [010] when feed rate f=1.75μm/rev. When feed rates f=0.5,1.0μm/rev, the rotation angle from crystalline direction [010] is about 10 degrees. Primary force and feed force hardly changes in one rotation of a workpiece.

Figure 11 shows the relationship between cutting speed and thrust force per unit area of cutting cross section. The thrust force per unit area of cutting cross section increases in ductile mode cutting.

On the other hand, primary and feed forces per unit area of cutting cross section obtained at small feed rate do not different from the primary and feed forces obtained at large feed rate. In addition, peaks of spectrum of dynamic thrust force are at about 17Hz, 70Hz in all cutting speeds and feed rates just like AE envelope signals.

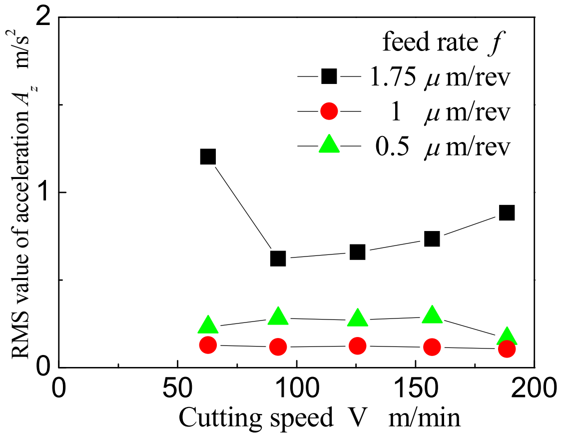
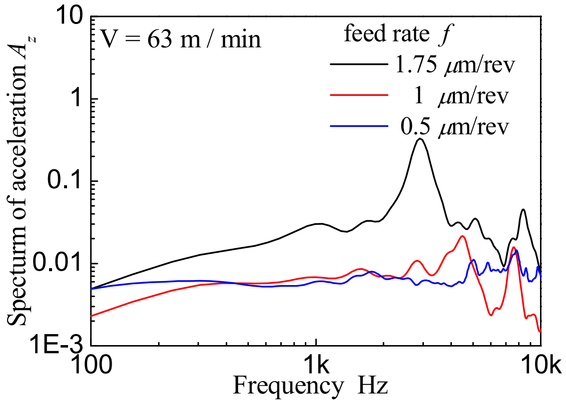
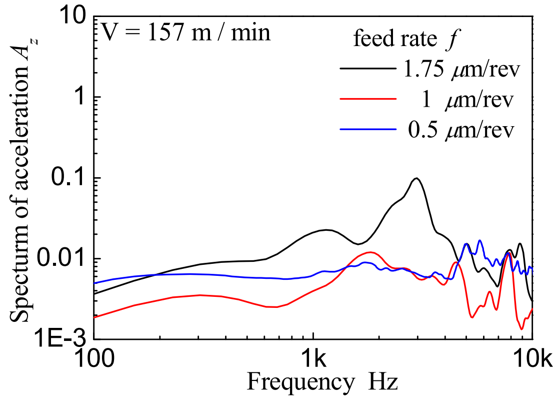


Figure 12: The relationship between cutting speed and RMS value of acceleration signals



(a) V=63m/min



(b) V=157m/min

Figure 13: Spectrum analysis on acceleration signals

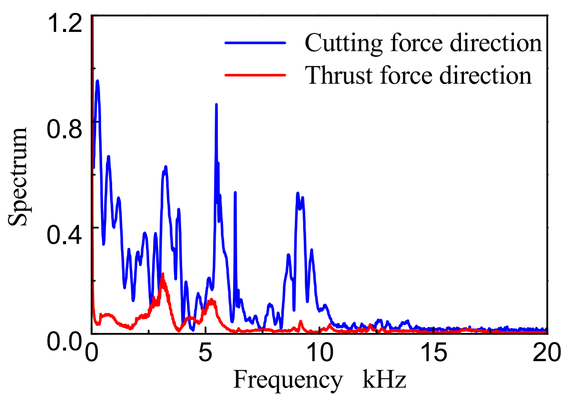


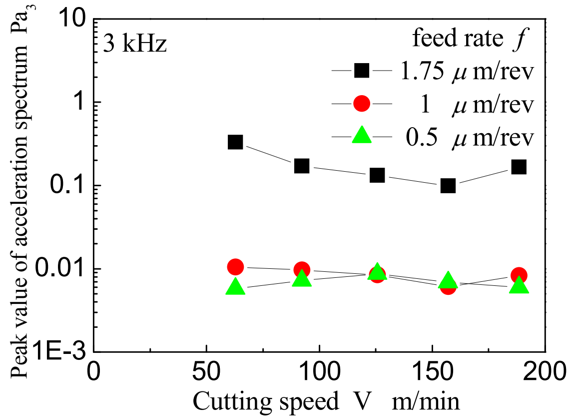
Figure 14: Dynamic response of the cutting tool system

3.4 Acceleration in ductile/brittle mode cutting

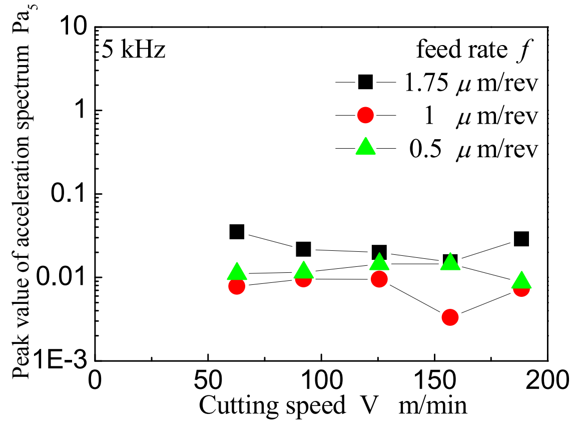
The vibration acceleration was examined just in the same way as the AE envelope signal. Figure 12 shows the relationship between cutting speed and RMS value of vibration acceleration. RMS value of vibration acceleration is larger in brittle mode cutting than in ductile and mixed mode cuttings. Figure 13 shows spectrum vibration acceleration.

Perk of the spectrum of vibration acceleration is at about 3kHz. The frequency of about 3kHz corresponds to one of natural frequencies of the cutting tool system. Figure 14 shows dynamic response of the cutting tool system obtained by a vibration test. It is clear that the frequency of about 3kHz corresponds to the natural frequency in direction of thrust force of the cutting tool system.

Figure 15 shows the relationship between cutting speed and peak value of vibration acceleration spectrum. Peak value of vibration acceleration spectrum in brittle mode cutting is larger than ductile or mixed mode cuttings at frequency of about 3kHz. However, peak value of vibration acceleration spectrum obtained at small feed rate does not roughly different from peak value obtained at large feed rate at frequency of about 5kHz.



(a) 3kHz



(b) 5kHz

Figure 15: The relationship between cutting speed and peak value of vibration acceleration spectrum.

4. Conclusion

As a result of the experiments and considerations, the following results were reached.

(1) Machined surface with mirror was obtained when feed rate *f*=0.5μm/rev, machined surface with pear skin when feed rate *f*=1.75μm/rev, and machined surface with mixture of mirror and pear skin when feed rate *f*=1.0μm/rev. Therefore, it was judged that it is ductile mode cutting when feed rate *f*=0.5μm/rev, brittle mode cutting when feed rate *f*=1.75μm/rev, and mixed mode cutting when feed rate *f*=1.0μm/rev

(2) RMS value of AE envelope signal was larger in brittle mode cutting than in ductile mode cutting.

(3) Thrust force per unit area of cutting cross section was larger in ductile mode cutting than in brittle mode cutting.

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