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Monitoring for Ultra-Precision Cutting Process of Single Crystal Silicon

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Summary

It is well known that brittle materials such as glasses, silicon and so on, can be machined ductile mode cutting like soft metals when the depth of cut is less than critical depth. Face turning using R shaped tool were carried out two types of cutting method (Extreme low feed cutting and Extreme small depth cutting) to distinguish brittle mode from ductile mode by AE signal and cutting forces. Perfectly mirrored surface with roughness (PV) of several tens nanometers can be obtained when maximum undeformed chip thickness was thin in extreme low feed cutting. RMS value of AE signal was larger and cutting force ratio (Thrust / Principal force) was lower when PV of machined surface was larger.

Key words: ultra-precision cutting, monitoring, brittle mode, ductile mode, cutting forces, AE-signal

1. Introduction

It comes to obtain the material removal mechanism mainly composed of the plastic deformation that is brittle materials such as the glass and ceramics, when the depth of cut is kept below the critical amounts. It is confirmed to obtain mirrored surface without destruction damages as results[(1)~(3)]. This processing method is called ductile mode cutting of the brittle materials, and paid to attention as one of the new processing technologies to advance streamlining high and making to high accuracy in the ultra-precision processing of the brittle materials. However, the level of the influence of [(4)~(6)] and each factor is not clarified though there are a lot of factors to rule the transition behavior between the condition to ductile mode cutting and brittle mode cutting. If the difference of ductile mode cutting and brittle mode cutting can be distinguished in process, it becomes easy to process the ultra-precision cutting of the brittle materials. In this research, it aimed to distinguish brittle and ductile mode cutting in process in a practicable cutting condition, and the single-crystal silicon was examined about the relation among the cutting forces, AE signal, brittle mode cutting, and ductile mode cutting when the ultra-precision cutting was done.

2. Nomenclature, Materials and Methods

The experiment is used ultra-precision lathe (Toyoda Machine Works AHN60-3D) that shows in Figure 1. , The single-crystal silicon wafer was cut by face-cutting with a single crystal diamond tool having large top corner radius on the lathe. The work material shown in Figure 2 arranged bonding to a stainless parallel plate, adsorption by the vacuum chuck, installation on the spindle, pre-processing beforehand with other tools, and surfaces roughness *Ra* roughly of several nanometers. Rotating angle from a flat orientation is shown for the sign φ in figure, and the cutting direction thereafter is shown by the sign φ. Cutting forces and AE-signals were measured by dynamometer (Kistler co., Ltd. 9256A) and AE-sensor (NF circuit design block co., Ltd. AE900S-WB) installed on the lathe.

The factor that should be considered when the brittle materials is cut is maximum chip thickness *hmax*, and it is 0.1μm that the critical amounts of the brittle materials[(5)]. Then, the experiment was done by the following two cutting methods.

Ⅰ. Extreme low feed cutting: extreme low feed and large depth of cut
Ⅱ. Extreme small depth cutting: extreme small depth of cut and large feed rate.

Figure 3 shows the outline chart of extreme low feed cutting and extreme small depth cutting. It is decided that maximum chip thickness *hmax* as shown in Figure 3 by tool nose radius *R*, depth of cut *d*, and feed rate *f*. The chip thickness increases from the tool center to uncut shoulder in case of extreme low feed cutting ($\sqrt{2Rd-d^2} \geq f$). It can be shown that maximum at this time chip thickness *hmax* by the expression of (1).

$$h_{\max} = R - (R^2 + f^2 - 2f(2Rd - d^2)^{1/2})^{1/2} \qquad (1)$$

It can be simply shown that maximum chip thickness *hmax* in case of extreme small depth cutting ($\sqrt{2Rd-d^2} \leq f$) by the following expressions.

$$h_{\max} = d \qquad (2)$$

Table 1 shows details of experimental conditions. The interferometer (ZYGO New View 5032) was used for the surface observation and roughness measurement of the work material after cutting, and the microscope was used for the observation of the tool edge.

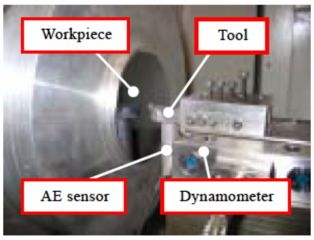


Fig.1 Ultra-precision lathe

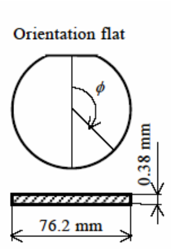


Fig.2 Workpiece

3. Results

3. 1 Extreme low feed cutting experiment

3. 1. 1 Surface roughness

It is pointed out as ductile-brittle mode cutting and surface roughness that there are implications according to a current research [7]. Two tools (new and worn tool) in the experiment to examine the influence of the tool wear on the condition of the ductile mode cutting were used. Figure 4 shows the tool edge photograph of these two tools. There was not being worn out to a new tool, and the edge was sharp. It is clearly that the tool edge retreats by wear and wear on flank face is greatly worn. The photograph on surface after cutting with these two cutting tools is shown in Figure 5 respectively. The experiment has gradually changed feed rate. Figure shows representative sample when depth of cut is d=2μm. The center part of work material is uncut area. In any case of new and worn tool, the lattice pattern reflects plainly, and it is understood that finish respect is mirrored surface in the range of cutting (from 23 to 38mm radius).The difference between new tool and worn tool is not so seen. Then, to examine what cutting performed more in detail, it was measured that profile and roughness on the work material with ZYGO. Figure 6 shows 3-D profile and surface profile in normal section on the work when cutting with worn tool. A clear cutter mark of which the pitch was the amount of feed rate was seen in finish respect when depth of cut is d=2μm and feed rate is f=1.5μm/rev. When feed rate is f=6μm/rev, the cutter mark of which the pitch is the amount of the feed rate is seen as well as the case f=1.5μm/rev, but brittle damage such as the cracks and pits is seen in several places. It is requested that it is theoretical roughness Ry from feed rate f and tool nose radius R by expression (3).

$$R_y = f^2 / 8R \tag{3}$$

When feed is f=1.5μm/rev, and 3μm/rev, the mean value of surface roughness PV(Peak to Valley) is about 42nm, it has grown more than the theoretical value 0.56 nm in case f=3μm/rev. However, when it is f=4.5μm/rev or more, the PV value of the surface roughness grew in as shown in Figure 6 because the crack and brittle damage of the pit etc. occurred in finish respect, and became the amounts of several microns. It was judged that cutting mode was brittle mode when the crack and the brittle damage of the pit etc. occurred in finish respect like this. Oppositely, when the brittle damage was not seen in finish respect, cutting mode was judged to be a ductile mode. Moreover, the surface roughness Ra was about 5nm in ductile mode which the brittle damage was not seen, and was about 6nm in brittle mode cutting which the brittle damage were seen. A similar tendency was seen even if it cut with new tool.

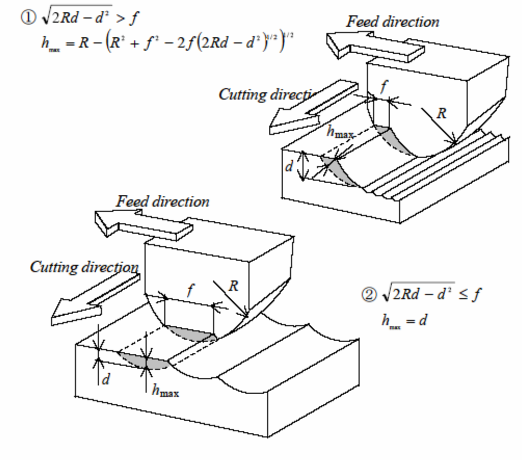
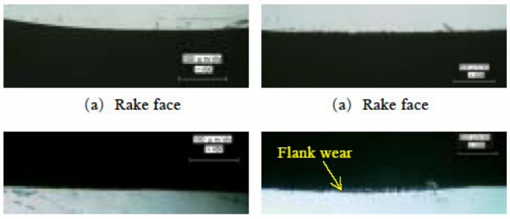


Fig.3 Schematic diagram of two types of cutting method

Table 1 Experimental conditions

Type of cut		low feed	small depth
Workpiece	Material	Silicon wafer (100)	
	Diameter mm	76.2	
Tool	Material	Single crystal diamond	
	Nose radius mm	2	
	Rake angle θ deg.	-15	0
	Clearance angle deg.	20	5
Depth of cut d μm		2 ~ 17	0.06 ~ 0.1
Feed rate f μm/rev		1.5 ~ 7.5	30
Cutting speed V m/min		145 ~ 240	4 ~ 240
Cutting fluid		Non	

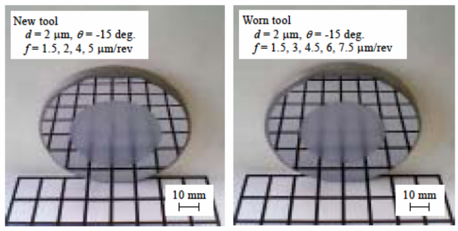


(a) Rake face (a) Rake face

(b) Flank face (b) Flank face

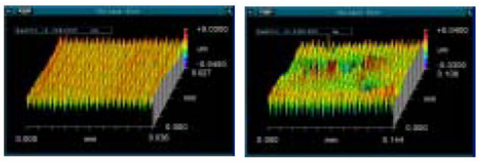
New tool Worn tool

Fig.4 Photograph of cutting tool



New tool Worn tool

Fig.5 Photograph of workpiece



(a) ZYGO image of interferometry (a) ZYGO image of interferometry

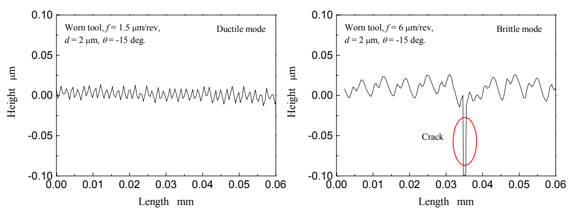


Fig.6 Surface texture after machined

3. 1. 2 The critical chip thickness.

It was examined to distinguish ductile and brittle mode cutting from the surface roughness, and obtained the conclusion of possible in the foregoing paragraph. Then, the relation between the cutting condition and ductile and brittle mode cutting was examined here. Figure 7 is a distinction result of ductile and brittle mode cutting on the surface in each condition when cutting with a new tool and the tool worn out. Ductile mode cutting are shown in ○ sign and brittle mode cutting are shown × signs in figure. Moreover, the broken line in figure shows that maximum chip thickness *hmax*. When the depth of cut is d=2μm, feed rate is f=1.5, 2μm/rev, it only became ductile mode in case of new tool, and all surface became brittle mode in other conditions. Moreover, it is 0.1μm or less that maximum chip thickness *hmax* for becoming ductile mode cutting. On the other hand, when the depth of cut is d=2μm, feed rate is f=1.5, 3μm/rev and d=2, 5, 8μm, f=1.5μm/rev, it only became ductile mode in case of worn tool, and all surface became brittle mode in other conditions. Moreover, it is 0.14μm or less that maximum chip thickness *hmax* for becoming ductile mode cutting. The ductile and brittle mode cutting decide according to it is cut neither feed rate nor the depth of cut but the maximum chip thickness, and are corresponding to the result by the research of the past from the above-mentioned [5] [7]. The maximum chip thickness has grown worn tool than new tool which cutting edge is sharp according to the result in this experiment. The new tool is sharp as this is shown in Figure 8, but the worn tool edge have caused roundness, and have grown in the more negative direction larger than the angle actually set in rake angle (θ=-15°). The rake angle is pointed out that -45° neighborhood becomes a ductile mode cutting easily most according to a current research[5] and it is considered that the critical chip thickness grew worn tool than new tool in this experiment. It can be shown that the ductile mode cutting is possible and critical chip thickness h_{cr} that uses flat byte as a function of rake angle γ(-80°~0°) like expression (4) according to research [5] . On the other hand, there is linear relationship approximately shown in expression (5) between ratio of the thrust force component and primary force component $(Fx/Fy)_2$ and rake angle γ. Therefore, the relationship consists between $(Fx/Fy)_2$ and critical chip thickness h_{cr} which ductile mode cutting is more possible than expression (4) and (5). Figure 9 shows the cutting force in this cutting experiment. The ○ sign expresses a new tool and △ sign expresses worn tool, respectively. In same cutting condition (f=1.5μm/rev, d=2μm), the difference is seen by the cutting force and the tool worn out has grown. Then, Figure 10 shows the relationship between obtained maximum chip thickness *hmax* and $(Fx/Fy)_3$ in this cutting experiment.

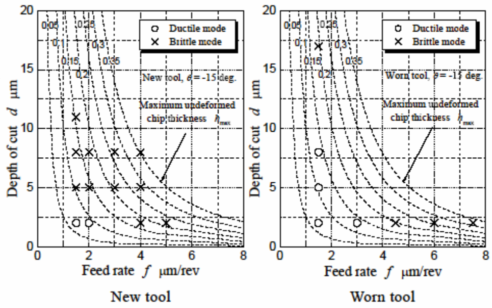


Fig.7 Distinction of ductile mode and brittle mode

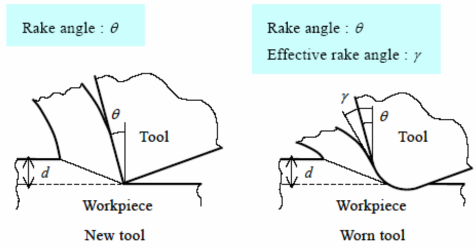


Fig.8 Effect of cutting edge radius

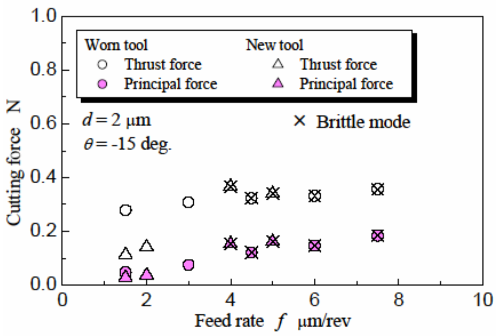


Fig.9 Comparison of cutting force using new tool and cutting force using worn tool

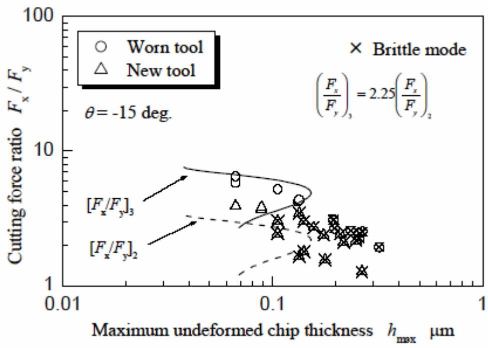


Fig.10 Relations between maximum undeformed chip thickness h_{max} and cutting force ratio F_x / F_y

A critical condition in two dimension cutting by the flat byte shown by expression (6) is shown in the curve of the broken line. A critical value obtained for a three-dimensional cutting with R byte agrees with value obtained for two-dimensional cutting with flat byte qualitatively, but not agree quantitatively. It was corrected to cutting force ratio $(Fx/Fy)_2$ in two-dimensional cutting, and showed in Figure 10 by the solid line.

$$h_{cr} = 5.0\times10^{-2}\sin[4\gamma - 92] + 3.4\times10^{-4}[\gamma] + 0.1 \tag{4}$$

$$\left(Fx/Fy\right)_2 = -2.5\times10^{-2}[\gamma] + 1.1 \tag{5}$$

$$h_{cr} \le 5.0\times10^{-2}\sin\left[-160\left(\frac{Fx}{Fy}\right)_2 + 84.6\right] - 1.4\times10^{-2}\left(\frac{Fx}{Fy}\right)_2 + 0.1 \tag{6}$$

$$\left(Fx/Fy\right)_3 = 2.25\left(Fx/Fy\right)_2 \tag{7}$$

It was almost corresponding to critical condition of correcting and critical condition that had been obtained by the experiment. Therefore, if it defined as standard maximum chip thickness $hmax/h_{cr}$ which maximum chip thickness $hmax$ obtained by this cutting experiment divided by critical chip thickness h_{cr} of a three-dimensional cutting with the obtained R byte by using expression (7), it will be cut in ductile mode in case of $hmax/h_{cr}<1$, and will be cut in brittle mode in case of $hmax/h_{cr}>1$. Figure 11 shows the relationship between standard maximum chip thickness ($hmax/h_{cr}$) and cutting force ratio $(Fx/Fy)_3$. In this cutting experiment, it became ductile mode cutting in case of $(Fx/Fy)<3.6$, and became brittle mode cutting in case of $(Fx/Fy)>3.6$.

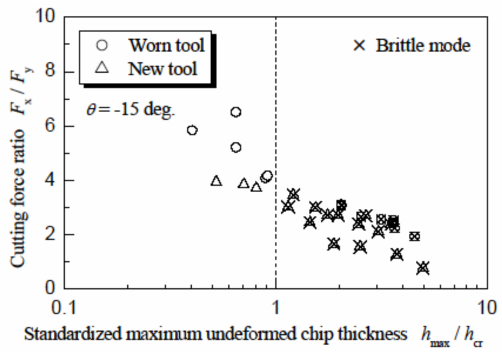


Fig.11 Relations between standardized maximum undeformed chip thickness h_{max} / h_{cr} and cutting force ratio F_x / F_y

3.1.3 Measurement result of AE signal

AE(Acoustic Emission) means the elastic wave generated by elastic energy's being liberated when the solid transforms or destroys it [8]. It was thought that AE was effective to detect the occurrence of the crack and the pit caused by cutting for the brittle material. Figure 12 shows the shape of waves of the AE signal with worn tool in ductile and brittle mode cutting. It is understood that broken AE signal is detected and the amplitude is growing in brittle mode cutting. Then, it was summarized that maximum chip thickness $hmax/h_{cr}$ to make the AE signal in each condition standard by paragraph 3.1.2 in Figure 13. When the peak amplitude of the AE signal is seen, the ductile mode cutting is a value that is comparatively smaller than the brittle mode cutting. However, it can be said that it is difficult the distinction of ductile and brittle mode cutting according to the peak amplitude indiscriminately. Then, it pays attention to the RMS(Root Mean Square) value of the AE signal (Hereafter, it is assumed AE_{RMS}). AE_{RMS} became a small value when a ductile mode was cut on the boundary of a certain constant value, and when the brittle mode was cut, reached a large value. Thus, it is thought that AE_{RMS} can become a parameter that distinguishes ductile and brittle mode cutting.

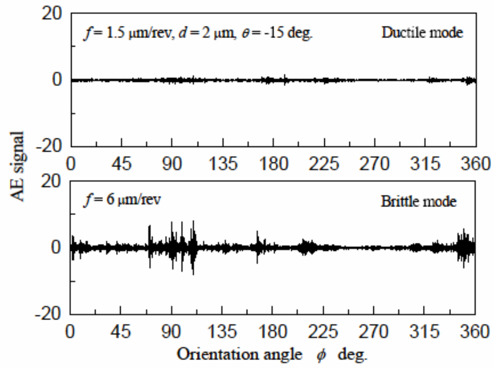


Fig.12 AE signal

3. 2 Extreme small depth cutting experiment

3. 2. 1 Ductile and brittle mode cutting

In the extreme small depth cutting, it was cut by rake angle (θ=0°) and feed rate was constant(f=30μm/rev), depth off cut d changed 0.06 0.08, and 0.1μm, respectively. The work material was cut within the range from 2 to 38mm radius. The finish respect became pear ground overall when the depth of cut is d=0.06μm. The center part became pear ground though the outside became mirrored surface comparatively when the depth of cut is d=0.08μm.

It became mirrored surface where the outside was comparatively as shown in Figure 14 when the depth of cut is d=0.1μm. Moreover, the pear ground and the mirrored surface appeared in one rotation at 1/4-rotation cycle. Next, to examine it more in detail what cutting performed, the work material measured the cutting surface with ZYGO. When depth of cut is d =0.06, 0.08, 0.1μm, brittle damage such as the cracks (brittle pit) was seen in some places though the cutter mark of which the pitch was the amount of the tool feed was seen for m in finish respect in any direction φ. When the depth of cut is d=0.1μm, the most was seen brittle damage such as the cracks but the part at the position of φ=0° was seen the cutter mark of which the pitch was the amount of the feed rate. However, the cutter mark of blade of saw was formed at the position of φ=45°.

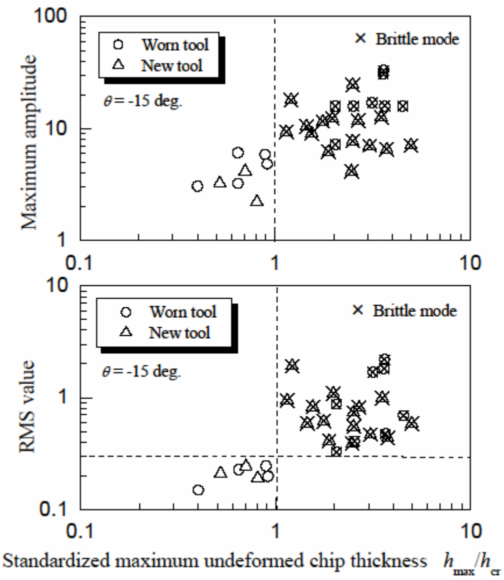


Fig.13 Relations between standardized maximum undeformed chip thickness h_{max} / h_{cr}, maximum amplitude and RMS value of AE signal

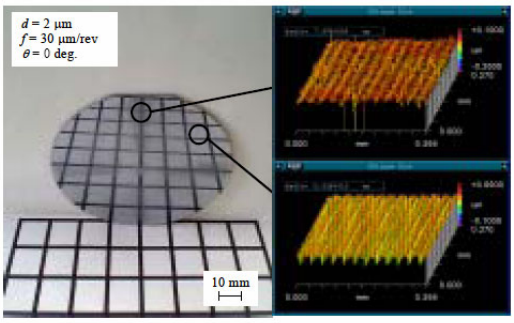


Fig.14 Sample photograph and surface texture

It is presumed that it is a cause that it was not the cutting edge was accurately transcribed in the work material, a small chipping is caused, and transcript decreased.However, it is possible to presume for a ductile mode to have been cut because the brittle damage of the crack (brittle pit) etc. that did ahead is not seen on the surface, and the cutter mark corresponding to the amount of the tool feed is seen. Next, when depth of cut is d = 0.06, 0.08μm, surface roughness PV was a growing several microns in any cutting direction. When the cut of cut is d=0.1μm, the measured value has dispersion that the surface that differed from d = 0.06, 0.08μm as shown in Figure 15. Especially, PV reached a small value in the cutting direction of φ=45,135,225,315°, and minimum value was 79 nm. The surface roughness Ra and PV value show a similar change.

In extreme small depth cutting experiment, it became ductile mode cutting when the depth of cut is large, and became the brittle mode when the depth of cut is small. This result is different from references research result[5][7]. It is presumed that this is due to the influence of the tool wear as shown in Figure 8 of paragraph 3.1.2. The experiment started from d=0.06μm, and the depth of cut was enlarged one by one. It is presumed that the ductile mode cutting was promoted by roundness of worn tool edge in Figure 8, by the effective rake angle γ becoming negative gradually, and by the stress of compression on the work material[5] because the same tools were used for all experiment. For this, it is thought that it become a ductile mode when depth of cut is small, oppositely, it become brittle mode when depth of cut is large.

In extreme small depth cutting experiment, it was not to obtain the overall mirrored surface, but very interesting surface where the cutting mode of ductile and brittle changed at the cycle of 1/4 rotations was obtained in case of d=0.1μm. Because it did not become ductile mode cutting in other depth of cuts, thereafter, it discuss only in case of d=0.1μm. Here, the technique for defining it by extreme low feed cutting tried whether extreme small depth cutting was also applicable. Figure 16 shows cutting force and cutting force ratio in one rotation of the work material. Primary force component (Fy) had little change. The value of thrust force(Fx) changed depending on cutting direction of cutting, it became a small value in φ=0,90,180,270° neighborhood, and it became a large value in other directions. Moreover, cutting force ratio became a small value when it was φ=0, 90,180,270° in cutting direction based on the change of thrust force. On the other hand, in extreme low feed cutting, the brittle mode was cut when cutting force ratio is falling below with a constant value, and the crack and the brittle damage of the pit etc. were caused on the work material. Then, whether the ductile and brittle mode cutting can be distinguished is examined by cutting force ratio in extreme small depth cutting. The value of cutting force ratio became small in the place where the cutting direction was φ=0, 90,180,270° neighborhood, the brittle mode was cut in this direction. It can be said that it is an almost corresponding qualitatively result though it differs quantitatively a little compared with surface roughness showing in Figure 15.

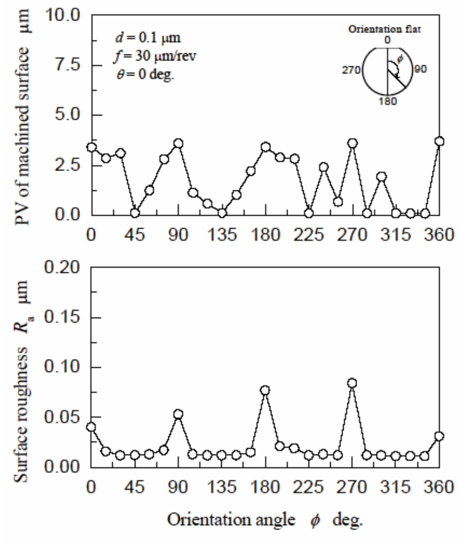


Fig.15 Surface roughness

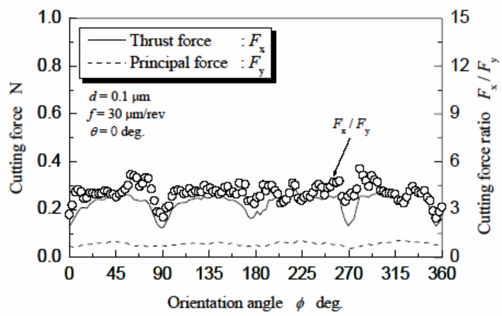


Fig.16 Cutting force and cutting force ratio

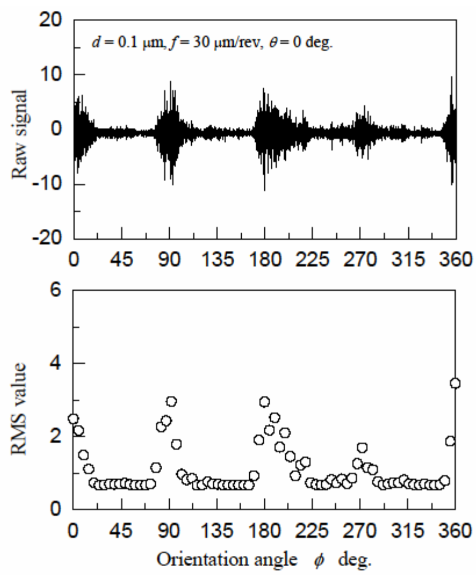


Fig.17 Raw signal and RMS value of AE signal

Therefore, the distinguish method between ductile and brittle mode cutting by cutting force ratio obtained in extreme low feed cutting was qualitatively effective in extreme small depth cutting though differed quantitatively a little. Therefore, the possibility of distinguishing the ductile and brittle mode cutting by measuring the cutting force and monitoring cutting force ratio was obtained.

3.2.2 Measurement result of AE signal

Figure 17 shows the shape of waves and the RMS value of the AE signal. AE signal was seen a large change while one rotation. Especially, the amplitude of the AE signal is growing breaking out in the cutting direction φ=0, 90,180,270° neighborhood. However, the amplitude is a very small value in other directions. It can be said that it is almost corresponding qualitatively though it differs quantitatively a little for surfaces roughness PV in Figure 15. It is almost corresponding for surface roughness Ra. Figure 16 shows the relation that cutting force ratio become small when AE_{RMS} grows, and cutting force ratio become large when AE_{RMS} decreases. Thus, it is thought that implications can be seen so that it is AE signal and the surface roughness and it become effective parameter that can distinguish the ductile and brittle mode cutting.

4. Conclusions

The following results were obtained by two kinds of ultra-precision cutting methods (Extreme low feed cutting and Extreme small depth cutting) of the single-crystal silicon.

(1) In extreme low feed cutting, it was cut by ductile mode that the cutter mark was transcribed over all aspects of the material when the feed ratio and the depth of cut is small, mirrored surface was obtained that surface roughness is PV=42nm, Ra=5nm.

(2) In extreme small depth cutting, when the depth of cut is d=0.1μm, feed rate is f=30μm/rev, the cutting mode changed at the cycle of about 1/4 rotations depending on the cutting direction, it was cut in brittle mode cutting in cutting direction φ=0, 90,180,270° , and was cut in ductile mode in other cutting directions.

(3) In extreme low feed cutting, cutting force ratio (thrust force/primary force) become small value in brittle mode cutting, and become large value in ductile mode cutting.

(4) In extreme small depth cutting, the RMS value of the AE signal become large, and cutting force ratio (thrust force/primary force) become small in the brittle mode cutting. An opposite tendency was shown at the time of the ductile mode cutting.

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