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Ultra-precision Cutting Process Monitoring of Single Crystal Silicon by Radius Nosed Cutting Tool

Yuya Kobaru[1], Eiji Kondo[2], Ryuichi Iwamoto[3]

[1]*National Institute of Technology, Kagoshima College,* [2]*Kagoshima University,* [3]*Kagoshima Prefecture Institute of Industrial Technology* [1]

Kobaru@kagoshima-ct.ac.jp

Abstract

It is known in ultra-precision cutting of single crystal silicon using a single crystal diamond tool that ductile mode cutting will be attained in general, when the amount of depth of cut is smaller than a certain critical value. The ultra-precision cutting of single crystal silicon was conducted diamond cutting tools, and the cutting force and AE-signals were investigated to clarify the effective parameter for distinguishing brittle and ductile mode cutting in an in-process. As a result, RMS value of thrust force and AE signal were larger in brittle mode cutting than in ductile mode cutting. AE signal increased monotonically with increasing of the surface roughness in ductile and mixed mode cutting.

ultra-precision cutting, single crystal silicon, brittle material, diamond, chamfer

1. Introduction

Single crystal silicon is used to create infrared lenses because silicon has a high transmissivity and refractive index in the infrared domain. The fabrication of single crystal silicon lenses by cutting are desired because it is difficult to create aspherical lenses and ensure the accuracy of the lens shape using the conventional grinding and polishing processes[1,2]. Numerous studies have reported the cutting of single crystal silicon, and the cutting tools used in the cutting tests had a sharp cutting edge. Therefore, chipping is easy to occur at the cutting edge. In machining shops, cutting tools with a small chamfer which chipping is hard to occur are usually used, but few studies have investigated this cutting tool. On the other hand, it is known in ultra-precision cutting of single crystal silicon using a single crystal diamond tool that ductile mode cutting will be attained in general, when the amount of depth of cut is smaller than a certain critical value[3]. However, it is very difficult to keep ductile mode cutting, this amount of critical depth of cut are very small.

The purpose of this study is to establish the practical cutting technology of single crystal silicon and to obtain monitoring parameters of the cutting process effective for stabilizing ductile mode cutting. The ultra-precision cutting of single crystal silicon was conducted diamond cutting tools with a chamfered cutting edge and a large nose radius, and the cutting force and AE-signals were investigated to clarify the effective parameter for distinguishing brittle and ductile mode cutting in an in-process.

2. Experimental apparatus

The cutting tests were conducted on an ultraprecision lathe (Toyoda Machine Works: AHN60-3D) shown in Fig.1. The experimental conditions are given in Table 1. Before the cutting tests, the workpiece was machined to remove the surface of the workpiece outside a radius of 32 mm and inside a radius of 8 mm, leaving a raised disc, as shown in Fig. 2, to prevent the unpredictable chipping of the cutting edge. In Fig. 2, ϕ represents the rotation angle from the orientation flat. In the cutting tests, the tool was fed from the outside of the workpiece to its center to machine the workpiece surface. The cutting forces and AE signals were measured at radii between 10 and 30 mm from the center of the workpiece at intervals of 5 mm. The roughness of the machined surface was measured using an interferometer (ZYGO: New View 5032).

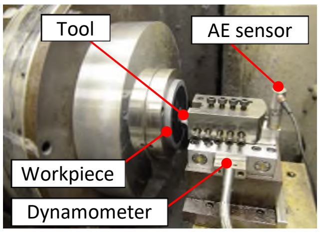


Figure 1. Ultra-precision lathe

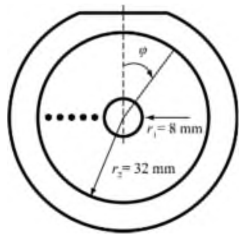


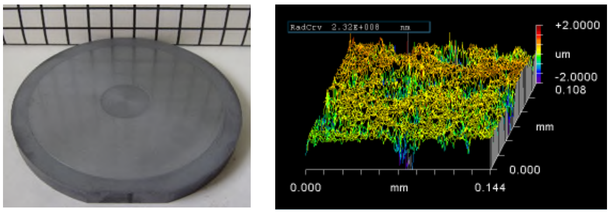
Figure 2. Shape and size of workpiece

Table 1. Experimental conditions

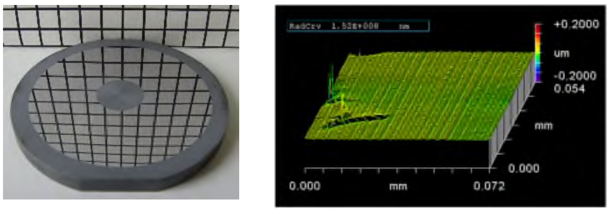
Workpiece	Material	Single crystal silicon (100)
	Diameter mm	76.2
Tool	Material	Single crystal diamond
	Nose radius mm	2
	Rake angle deg.	0
	Clearance angle deg.	4
	Chamfer μm	2 (-45 deg.)
Spindle speed rpm		1000
Depth of cut d μm		1.0
Feed rate f μm/rev		0.5 ~ 8.0
Cutting fluid		Kerosene

3. Experimental results

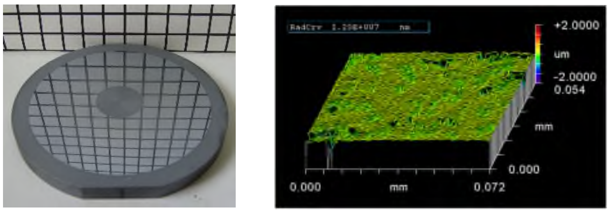
Fig.3 shows the photograph of machined surface and 3-D profile observed by interferometer. The machined surface is glossy at a feed rate of 2.0 μm/rev and the cutter mark corresponding to the feed rate is observed. However, The machined surface at a feed rate of 0.5 μm/rev is pear skin and the cutting mode is brittle. When a feed rate is 8.0 μm/rev, the machined surface is a little glossy. In addition, both the cutter mark and the brittle damage mark are observed. This state is defined as the mixed mode cutting[4]. Fig.4 shows the influence of the cutting speed and the feed rate on the surface roughness. At all feed rates, the surface roughness increased with decreasing cutting speed. When the feed rates are 0.5 and 1.0 µm/rev, the cutting mode is brittle. It is considered that the pear skin of the machined surface at the feed rate of less than 2.0 µm/rev was caused by the decrease of the effective rake angle where the uncut chip thickness was less than the radius of the cutting edge roundness[5]. When the feed rate are 4.0 and 8.0 µm/rev, the cutting mode is the mixed mode.



(a) f = 0.5 µm/rev



(b) f = 2.0 µm/rev



(c) f = 8.0 µm/rev

Figure 3. Machined surface and 3-D profile

Figure 4. Effect of cutting speed and feed rate on average surface roughness

Fig. 5 shows thrust force against the cutting speed. At a brittle mode cutting, The thrust force is larger than the other cutting modes. Fig. 6 shows the RMS value of thrust force. RMS value of thrust force is larger in brittle cutting mode than in ductile and mixed mode cuttings. On the other hand, when the cutting mode is ductile, RMS value is the minimum. Fig. 7 shows the average value of AE signal. The dependence of the AE signal on the feed rate is qualitatively similar to that of the surface roughness shown in Fig. 4. Fig. 8 shows the relationship between AE signal and surface roughness. AE signal increases monotonically with increasing of the surface roughness in ductile and mixed mode cutting. However, when the cutting mode is brittle, the surface roughness increases rapidly in comparison with other modes. In addition, AE signal increases monotonically as well as other modes.

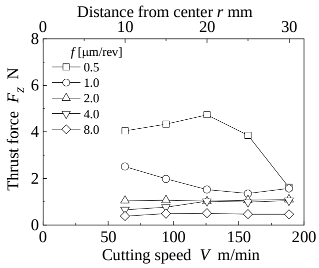


Figure 3. Thrust force against cutting speed

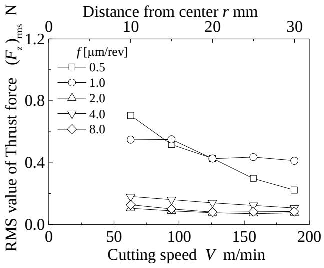


Figure 4. RMS value of thrust force

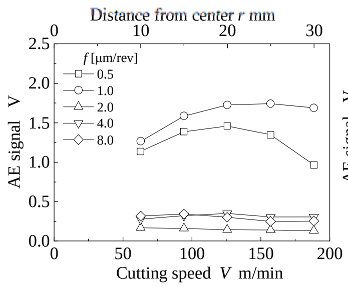


Figure 5. AE signal against cutting speed

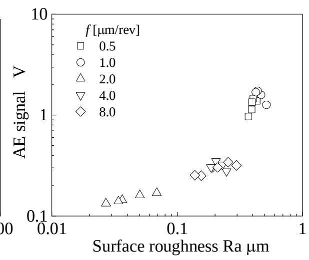


Figure 6. Relationship between AE signal and surface roughness

4. Conclusions

The ultra-precision cutting of a single crystal silicon workpiece was conducted using a diamond tool with a chamfered cutting edge, and the cutting force and AE-signals were investigated to clarify the effective parameter for distinguishing brittle and ductile mode cutting in an in-process. When the ductile mode cutting was conducted, the RMS value of thrust force and AE signal were smaller than the brittle cutting mode. AE signal increased monotonically with increasing of the surface roughness in ductile and mixed mode cutting.

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