The study of ductile-brittle transition on micro-cutting of single crystal silicon

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INTRODUCTION

The studies of ultra precision machining of brittle materials, such as silicon, ceramics and so on, have been widely noticed recently. It has been made clear that material removal with plastic deformation was accomplished by a very small depth of cut. The presence or the absence of surface cracks occurred in cutting are generally applied as the criteria to decide machining mode brittle mode or ductile mode. On the other hand, it has been reported that various types of cracks are developed from the border between a plastic and an elastic deformation zone in indention tests for the brittle materials. These include internal cracks that progress inside the materials. These are invisible with the observation of material surface. The internal cracks influence the quality of semi-conductor. The observation of internal cracks plays important roles in the evaluation for the machining of brittle materials. On these backgrounds, the authors have investigated the ductile-brittle transition on micro-cutting of single crystal silicon.

EXPERIMENTAL METHODS

The workpiece material used in the experiment was polished single crystal silicon with (100) and (110) surface. A single crystal Vickers diamond penetrator with 148° apex angle was used as the cutting tool. Face-turning of the workpiece was done from the center to the outside with the fixed feed rate 30μm/rev. Cutting speed was 170 and 700m/min. The workpiece, single crystal silicon wafer, was mounted on a vacuum chuck. A partial inclination was given to the mounted workpiece by a partly inserted spacer between the workpiece and the chuck surface. Machining the inclined workpiece could generate various depth of grooves. Table 1 shows some machining conditions.

Table 1. Machining conditions

Cutting method	Face-turning
Workpiece	Single crystal silicon Crystallographic plane : (100), (110) Dimensions : ϕ100×0.7mm
Cutting tool	Vickers diamond penetrator Apex angle : 148°
Cutting speed	170, 700m/min
Feed rate	30μm /rev
Coolant	Dry

The investigation has been performed by observing not only the surface cracks but also the internal cracks grown inside the workpiece. An atomic force microscope (AFM) was used for observing the surface of the workpiece. This microscope was also used to measure the depth of grooves and surface crack ratio of each groove. It is the ratio between the total length of surface cracks generated along a groove and the length of the groove in the observing area on the AFM. Moreover a part of the workpiece was lapped obliquely to measure the depth of internal cracks on a laser scanning microscope. Furthermore the lapped workpiece was etched to manifest the internal cracks. The depth of internal cracks was evaluated as the depth form the deepest point of the groove to a pointed end of the internal crack progressed inside.

RESULT AND DISCUSSION

An AFM image of a cutting groove is shown in Fig.1 for example. The groove was generated on the (110) surface of single crystal silicon with cutting speed 170m/min. Surface cracks are observed in the right side of the groove.

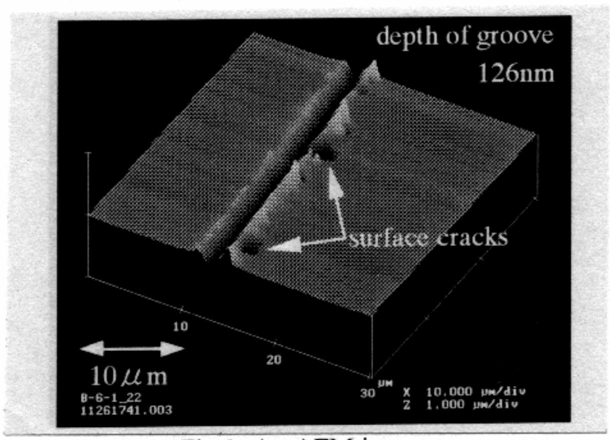


Fig.1 An AFM image

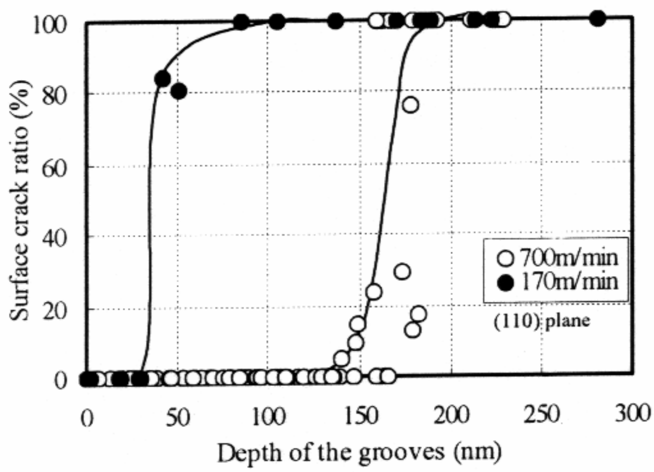


Fig.2 The relation between the depth of the grooves and the surface crack ratio

The relation between the depth of grooves and the surface crack ratio on the (110) surface is shown in Fig.2. The surface cracks are invisible around the depth less than approximately 30nm and 120nm at the cutting speed 170m/min and 700m/min, respectively. When the depth of grooves become more than 30nm and 120nm, respectively, the surface crack ratio increases rapidly. The ratio reaches 100% at the depth approximately 100nm and 170nm, respectively. The transition points evaluated by the surface cracks would be approximately 30nm at the cutting speed 170m/min and approximately 120nm at 700m/min on the (110) surface.

The surface crack ratio and the depth of internal cracks as a function of the depth of grooves on the (100) surface are shown in Fig.3. The surface cracks were not observed around the grooves which depth are less than approximately 50nm and 100nm at the cutting speed 170m/min and 700m/min, respectively. The transition points based on the surface cracks would be approximately 50nm and 100nm at each cutting speed on the (100) surface. Compared the (100) surface and the (110) surface, the transition points at each cutting speed would be nearly equal on both surface. The transition points would be dependent upon the cutting speed on the (100) and (110) surface.

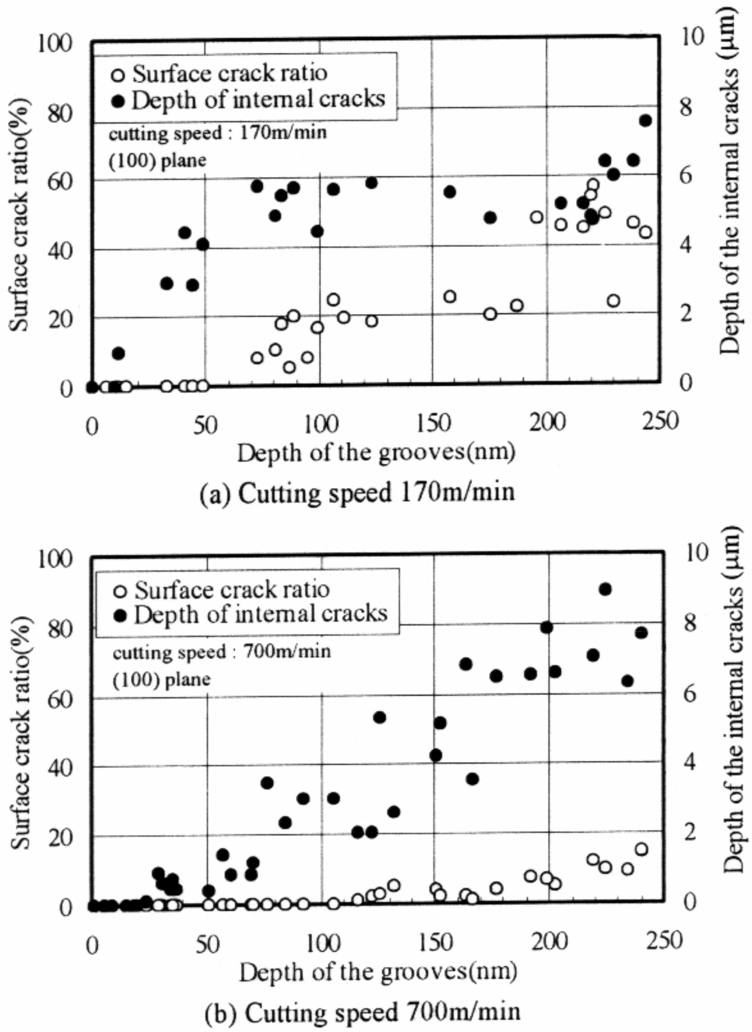
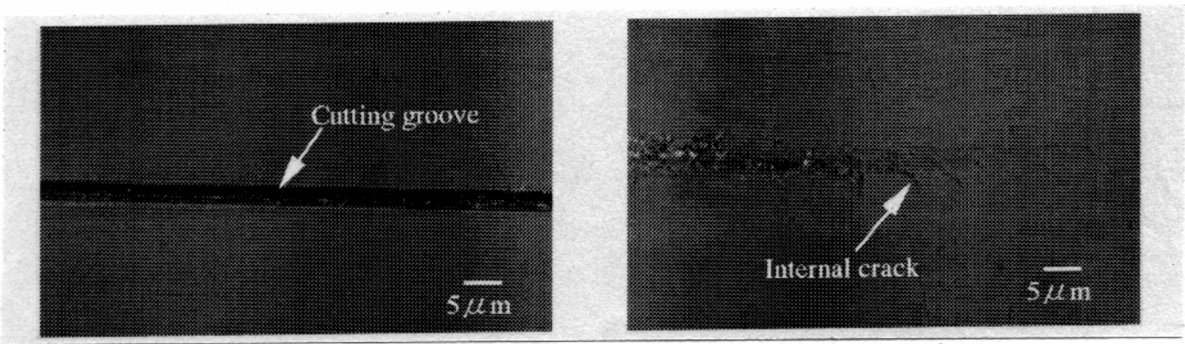


Fig.3 The surface crack ratio and the depth of the internal cracks as a function of the depth of grooves

On the other hand, the internal cracks begin to be generated earlier than the surface cracks in the Fig.3. The internal cracks generated under the grooves which seem to be crack-free with the surface observation. The images of the (100) surface cut at the cutting speed 700m/min was observed by the laser scanning microscope, as shown in Fig.4. Fig.4(a) is the cut surface with a groove and Fig.4(b) is a obliquely lapped and etched surface with the internal cracks. Although crack-free cutting seems to be accomplished in Fig.4(a), the internal cracks progress under the grooves in Fig.4(b).



(a) Surface

(b)Cross section
(Obliquely lapped and etched)

Fig.4 The laser microscope images

CONCLUSION

The micro-cutting experiment using the Vickers penetrator was carried out on (110) and (100) surface of single crystal silicon with cutting speed 170m/min and 700m/min. The conclusions are as follows.

(1) The internal cracks are generated under the cutting grooves in some case, even if the depth is less than transition point. It is detected that the ductile-brittle transition point determined by the internal cracks is shallower than that determined by the surface cracks. Therefore to estimate these internal cracks would be important especially in finishing.

(2) Compared two different cutting speed, the relatively high speed cutting expands crack-free surface range and is unlikely to create the internal cracks.