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ORIGINAL ARTICLE

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A study of the effect of tool cutting edge radius on ductile cutting of silicon wafers

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Abstract Ductile mode cutting of silicon wafers can be achieved under certain cutting conditions and tool geometry. An experimental investigation of the critical undeformed chip thickness in relation to the tool cutting edge radius for the brittle-ductile transition of chip formation in cutting of silicon wafers is presented in this paper. Experimental tests for cutting of silicon wafers using diamond tools of different cutting edge radii for a range of undeformed chip thickness are conducted on an ultra-precision lathe. Both ductile and brittle mode of chip formation processes are observed in the cutting tests. The results indicate that ductile cutting of silicon can be achieved at certain values of the undeformed chip thickness, which depends on the tool cutting edge radius. It is found that in cutting of silicon wafers with a certain tool cutting edge radius there is a critical value of undeformed chip thickness beyond which the chip formation changes from ductile mode to brittle mode. The ductile-brittle transition of chip formation varies with the tool cutting edge radius. Within the range of cutting conditions in the present study, it has also been found that the larger the cutting edge radius, the larger the critical undeformed chip thickness for the ductile-brittle transition in the chip formation.

Keywords Edge radius · Diamond tool · Silicon wafer · Ductile cutting

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1 Introduction

Silicon reigns supreme as a semiconductor material mainly because of its ease of manufacturing. Single-crystal silicon is not only a dominant substrate material for the fabrication of micro-electro and micro-mechanical components but also an important infrared optical material. It is also the favored element for MEMS (micro electro-mechanical system) because of its structural strength and its ability to be miniaturized easily. Silicon and its processing are emerging technologies of the 21st century. Currently, silicon wafers are finished by grinding, lapping, and polishing. The polished wafer must be flat, clean and damage free. In the slicing and grinding stages, much damage is caused to the surface of the material. The subsequent polishing stage has to remove the damage and produce the final surface in which devices are made. An alternative approach would be to machine silicon wafers through a ductile chip formation process. In this way, damages due to fracture can be minimized and reliability of parts in service can be largely improved.

Some works have been done on the brittle-to-ductile transition and ductile cutting of silicon to overcome those problems [1–8]. A series of fracture experiments were carried out at various strain-rates on pre-cleaved silicon single crystals between –196° and 1,000°C. The brittle-to-ductile transition was rate-dependent and obeyed the activation energy close to that for thermally activated dislocation glide. A mechanism based on crack-tip blunting through dislocation nucleation and glide was developed to explain the abruptness of the brittle-to-ductile transition [1]. Experimental work showed that brittle-to-ductile transition in silicon was controlled by the processes with the same activation energy as for dislocation motion. The observations suggested that ductile behavior was due to the shielding of the crack by dislocations emitted from a few dislocation sources at favorable sites along the crack front [2]. Although the interaction forces between dislocations in different slip systems were small, their influence of multiple slip systems on the brittle-to-ductile transition behavior in silicon was significant. Multiple slip systems increase the crack tip shielding by increasing the near tip dislocation density. The sharpness of the brittle-to-ductile transition in silicon was strongly dependent on the number of active slip systems [3]. Koshimizu and Otsuka studied micro-indentation performance of single-crystal silicon. The critical values in these micro-indentation tests were 0.55 to 0.65 μm in depth loading from 40 to 50 nm [4].

Yan et al. documented that in the cutting of silicon using an ultra-precision machine tool with a single-crystal diamond tool of large negative rake angle (−40°) and an extremely small cutting edge radius (50 nm), smooth surface and ductile cutting of silicon yielding continuous chips could be obtained when the undeformed chip thickness was less than 58 nm. They also reported that the ductile cutting performance of silicon was greatly improved by having an external hydrostatic pressure (400 MPa) acting on the workpiece surface [5]. The effect of crystal orientation in ductile regime machining of (100) silicon wafers had been investigated by Hung and Fu. A ductile regime was achieved when machining along the<110> directions when the maximum chip thickness of less than 0.5 μm [6]. Single-crystal germanium wafers of 80-mm diameter were machined using a single-point cutter in facing operation on a Rank-Pneumo ASG 2500 diamond turning machine. The chip topography showed a brittle-to-ductile transition point, which was manifested by the frayed topology along the thicker portion of the chip [7]. Using different diamond tools with rake angles of 0° and –25° at different cutting speeds, taper cutting experiments were carried out with increasing depth of cut on silicon. The cutting groove formation changes from ductile mode to brittle mode as the depth of cut exceeded a critical value [8]. These results suggest that silicon wafer could be machined in ductile mode under a sufficiently small scale of machining.

Although there has been previous research work done on the transition from ductile mode to brittle mode and for the chip formation in cutting of silicon, there has been no report on the effect of tool cutting edge radius on the ductile-brittle transition in the chip formation. In the present study, the effect of tool cutting edge radius on the critical value of the maximum undeformed chip thickness for the ductile-brittle transition of chip formation in cutting of silicon wafers has been investigated through experimental tests.

2 Experimental setup and procedures

2.1 Experimental setup

Face-turning experiments of silicon wafer were carried out on an ultra-precision lathe (Toshiba ULG-100C) with 10-nm positioning resolution using diamond tools. Figure 1 displays the setup for ultra-precision face turning experiments. Silicon (111) wafers of 76.2 mm in diameter, 0.5 mm thick and having a lapped finish were used as specimens. The wafers were bonded on aluminum blanks using a heat-softened glue and then vacuum chucked on the machine spindle. As the layer of glue may not be evenly spread out, facing cuts (pre-trimming) were performed before the start of the experiments to ensure that the silicon surface was extremely flat.

Cutting was performed using three different single-crystal diamond tools and their tool geometry parameters are listed in Table 1. The cutting conditions of the ultra-precision face turning experiments are listed in Table 2. Dry cutting was carried out for the purpose of collecting the cutting chips. The chips were collected using a double-sided tape, which was set onto the rake face of the diamond tool. After cutting, the tape was fixed to a special holder for scanning electron microscope (SEM) observation.

2.2 Maximum undeformed chip thickness

Figure 2 shows the schematic diagram of chip formation in ductile cutting of silicon wafer. Here, r is the cutting edge radius, γ is the tool rake angle, a_o is the depth of cut.

Figure 3 shows the schematic diagram of the maximum undeformed chip thickness in the ultra-precision face turning experiments. Here, O_1 and O_2 are the centers of two adjacent arc cutting edges, and the distance between O_1 and O_2 is the feed rate used in the experiments. The nanometer scale values for undeformed chip thickness were achieved by arranging combinations of the radius of tool corner R, depth of cut a_o and feed rate f, as shown in Fig. 3 [9]. The maximum undeformed chip thickness $d_{\max}$ can be simplified using the equation when $\sqrt{2Ra_o - a_o^2} \le f$ as shown in Fig. 3a:

$$d_{\max} = a_o \tag{1}$$

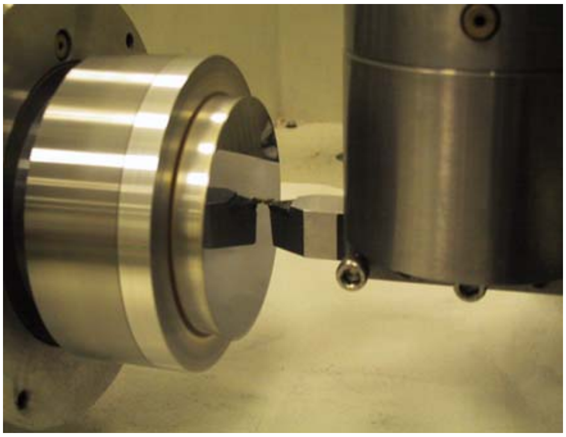


Fig. 1 Ultraprecision face-turning experimental setup

Table 1 Diamond cutting tool geometry parameters used in the experiments

Diamond tool geometry	Tool A	Tool B	Tool C
Rake angle (°)	0	0	0
Cutting edge radius (nm)	45	335	647
Tool nose radius (mm)	0.3	1.0	0.8

The maximum undeformed chip thickness $d_{\max}$ can be determined using the equation when $\sqrt{2Ra_o - a_o^2} > f$ as shown in Fig. 3b:

$$d_{\max} = R - \sqrt{R^2 + f^2 - 2f\sqrt{2Ra_o - a_o^2}} \tag{2}$$

The maximum undeformed chip thickness, $d_{\max}$, can be calculated from Eqs. (1) and (2) for the ultra-precision face turning experiments according to the cutting tool geometry and cutting conditions used in the experiments. The values of undeformed chip thickness obtained in the experiments are listed in Table 2, which vary in the range of 10 to 66 nm for the diamond tool A, in the range of 118 to 337 nm for the diamond tool B, and in the range of 50 to 690 nm for the diamond tool C.

Table 2 Cutting conditions and maximum undeformed chip thickness for the ultraprecision face turning experiments

Cutting tools	Cutting conditions			
	Spindle speed (rpm)	Feed rate (μm/rev)	Depth of cut (nm)	Undeformed chip thickness (nm)
Tool A (cutting edge radius, 45 nm)	1,000	5	10	10
			20	20
			30	30
			40	40
			50	50
			70	66
Tool B (cutting edge radius, 335 *nm*)	1,000	5	900	118
			2,000	178
			5,500	298
			5,800	307
			6,000	320
			6,500	325
			7,000	337
Tool C (cutting edge radius, 647 *nm*)	1,000	5	70	50
			210	100
			740	200
			2,770	400
			5,000	543
			6,000	596
			7,200	655
			8,000	690

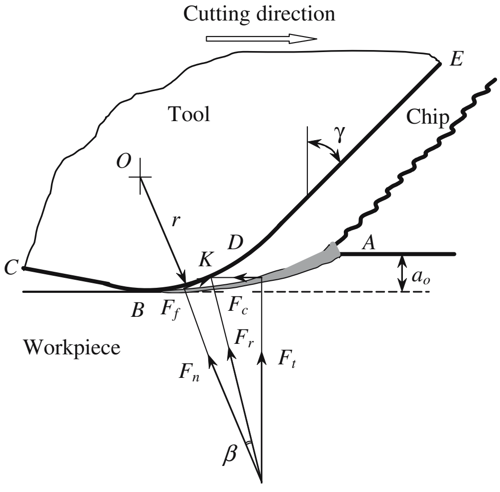
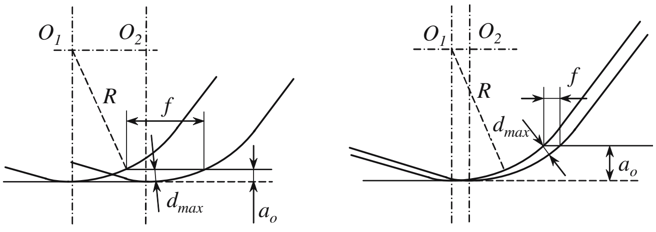


Fig. 2 Schematic diagram of chip formation in ductile cutting of a brittle material

3 Experimental results

Figure 4 shows SEM micrographs of chips obtained in cutting of silicon wafers using the diamond tool A with the cutting edge radius of 45 nm under cutting speed of 4 m/s (1,000 rpm) and feed rate of 5 μm/rev (5 mm/min), where the maximum undeformed chip thickness were (a) 10 nm, (b) 20 nm, (c) 30 nm, (d) 40 nm, (e) 50 nm and (f) 66 nm, respectively. It can be seen that when the undeformed chip thickness was smaller than 40 nm (Fig. 4a–d), the chips obtained were in the form of ribbons and layers, i.e., the chips formed were continuous. The appearance of such chips was similar to the chip generated when machining ductile metals. Hence, such continuous chips obtained from the cutting of silicon at these undeformed chip thickness indicated that the cutting was carried out in a ductile mode and plastic deformation had taken place. On the other hand, as the undeformed chip thickness increased



a $\sqrt{2Ra_o - a_o^2} \le f$ b $\sqrt{2Ra_o - a_o^2} > f$

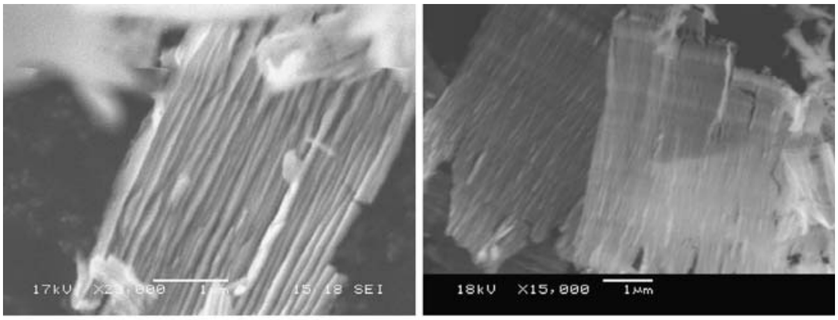
Fig. 3 Schematic diagrams of maximum undeformed chip thickness. **a** is for large feed rate ($\sqrt{2Ra_o - a^2} \le f$); **b** is for small feed rate ($\sqrt{2Ra_o - a^2} > f$)

beyond 40 nm, discontinuous and fractured chips were obtained. It can be seen that the chips generated were blocky and irregular in shape (Fig. 4e,f). They also had sharp ends and such fragments were a result of crack propagation in fracture process. Hence, the cutting at the undeformed chip thickness larger than 40 nm indicated that the chip formation was in a brittle mode.

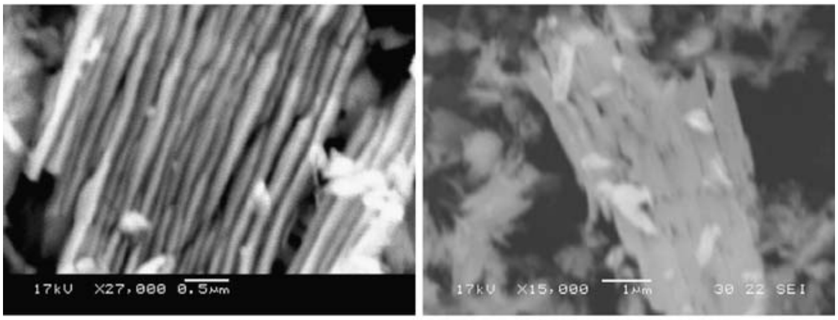
SEM micrographs of chips obtained in cutting of silicon wafers using the diamond tool B with the cutting edge radius of 335 nm at a cutting speed of 4 m/s (1,000 rpm) and feed rate of 5 μm/rev (5 mm/min) are shown in Fig. 5, where the undeformed chip thickness were (a) 118 nm, (b) 178 nm, (c) 298 nm, (d) 307 nm, (e) 320 nm, (f) 325 nm and (g) 337 nm, respectively. It was found that when the undeformed chip thickness was smaller than 320 nm, the chips obtained were in smooth layers (Fig. 5a–e). As mentioned earlier, such continuous chips obtained were similar to the chip formation during the cutting of ductile materials, where chip formation is dominated by dislocation. Therefore, these chips show that the cutting was carried out in a ductile mode under the cutting conditions. As the undeformed chip thickness was increased further, irregular and blocky chips were once again obtained (Fig. 5f,g). These chips were formed in a disorderly manner. Under the above conditions, brittle fracture dominated the chip formation such that the cutting was performed in a brittle mode.

Cutting of silicon wafers was finally made using the diamond tool C with the cutting edge radius of 647 nm under a cutting speed of 4 m/s (1,000 rpm) and feed rate of 5 μm/rev (5 mm/min). SEM micrographs of chips obtained are shown in Fig. 6, where the undeformed chip thickness were (a) 50 nm, (b) 100 nm, (c) 200 nm, (d) 400 nm, (e) 543 nm, (f) 596 nm, (g) 655 nm and (h) 690 nm, respectively. The micrographs show that the chips formed in cutting with values of the undeformed chip thickness in between 50 nm to 596 nm were in the form of long ribbon, which is similar to the chip generated in machining of ductile metals as shown in Fig. 6a–f. The chips are continuous with fine ripples on the surfaces, indicating that the chip formation was in a ductile mode dominated by dislocation. On the other hand, the chips in cutting with values of the undeformed chip thickness larger than 655 nm were fragmented and discontinuous with non-

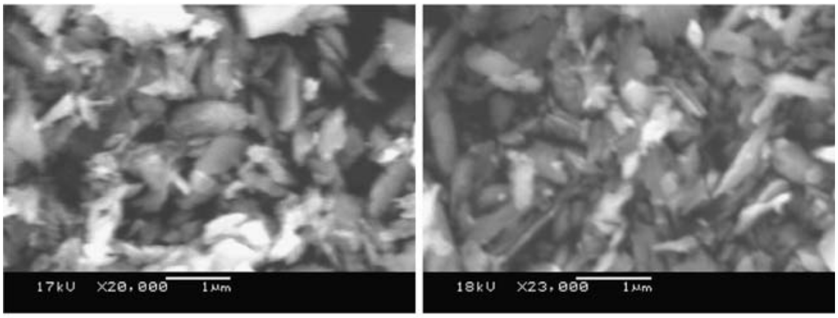
Fig. 4 Chips formed at different undeformed chip thickness in cutting of Si wafer using diamond tool A (cutting edge radius, 45 nm)



a Undeformed chip thickness: 10 *nm*   b Undeformed chip thickness: 20 *nm*

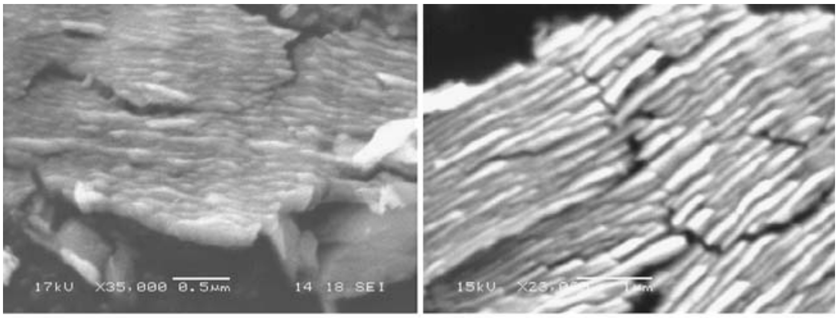


c Undeformed chip thickness: 30 *nm*   d Undeformed chip thickness: 40 *nm*

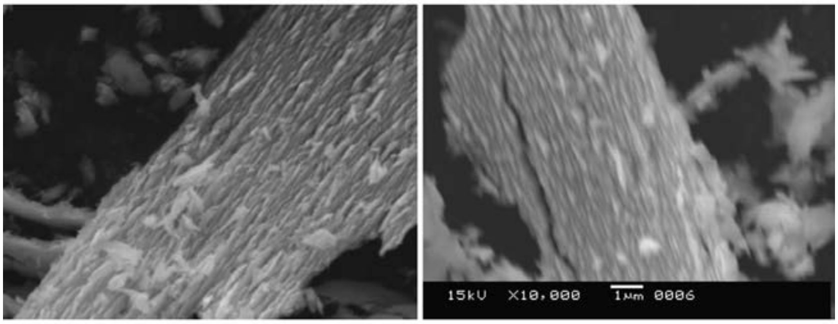


e Undeformed chip thickness: 50 *nm*   f Undeformed chip thickness: 66 *nm*

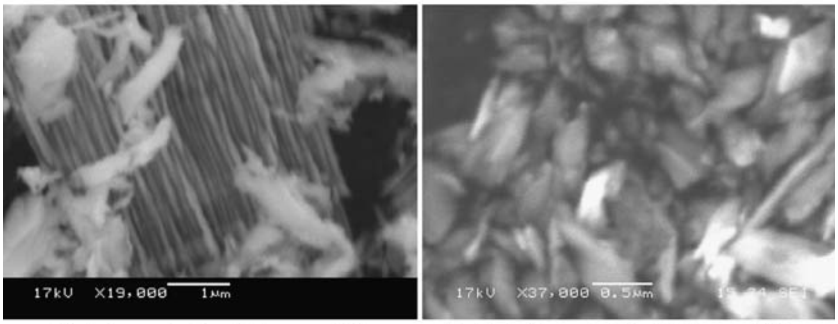
Fig. 5 Chips formed at different undeformed chip thickness in cutting of Si wafer using diamond tool B (cutting edge radius, 335 nm)



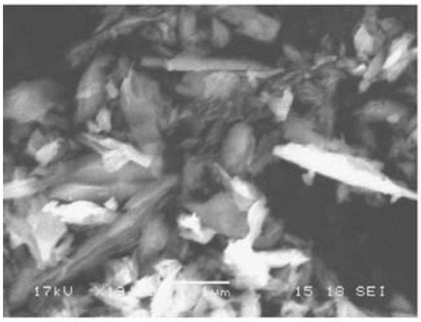
a Undeformed chip thickness: 118 *nm* b Undeformed chip thickness: 178 *nm*



c Undeformed chip thickness: 298 *nm* d Undeformed chip thickness: 307 *nm*



e Undeformed chip thickness: 320 *nm* f Undeformed chip thickness: 325 *nm*

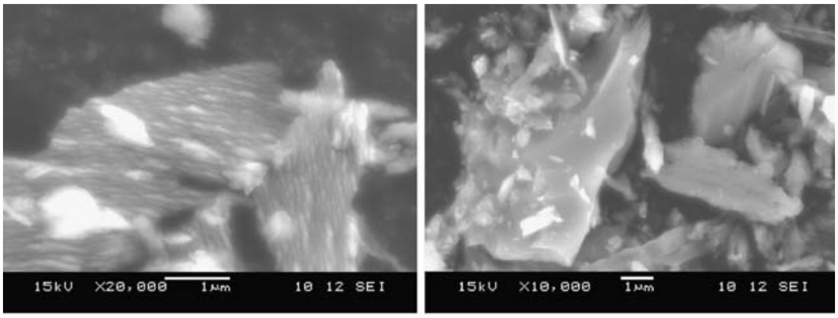


g Undeformed chip thickness: 337 *nm*

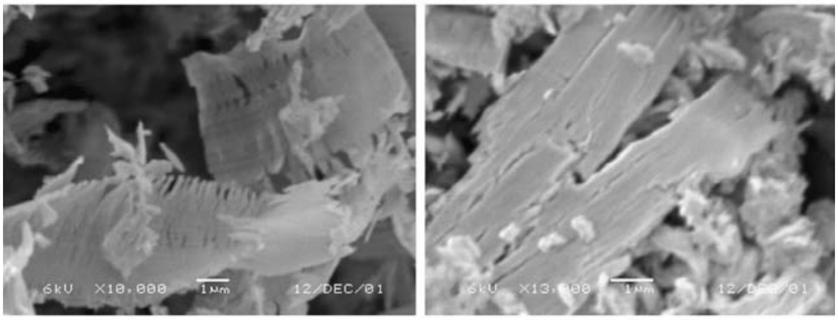
uniform length as shown in Fig. 6g,h. These chips are fractured particles and blocks with sharp ends. Such appearance indicates that in the cutting process, the chip formation was dominated by crack propagation and brittle fracture.

In summary, all the experimental results show that in cutting of silicon wafers using diamond tools of different cutting edge radii, there is a transition from ductile mode to brittle mode in the chip formation as the undeformed chip thickness is increased to a certain level. However, comparing the results from cutting with the three different tool edge radii, as shown in Figs. 4, 5, 6, it can be seen that the critical undeformed chip thickness corresponding to the ductile-brittle transition of the chip formation varies with the tool cutting edge radius. The larger the tool edge radius, the larger critical value of undeformed chip thickness. Also, it should be noted that the values of the critical undeformed chip thickness are close to the values

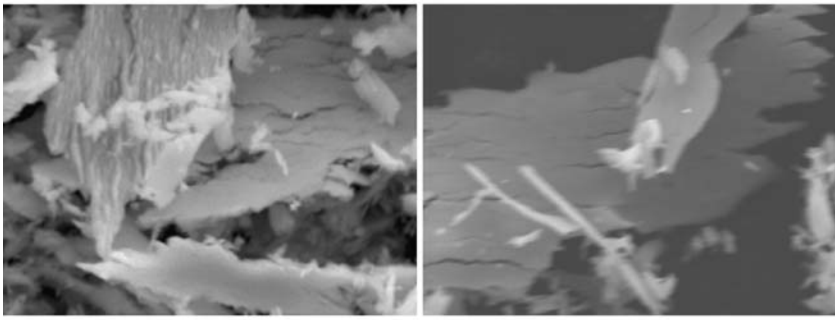
Fig. 6 Chips formed at different undeformed chip thickness in cutting of Si wafer using the diamond tool C (cutting edge radius, 647 nm)



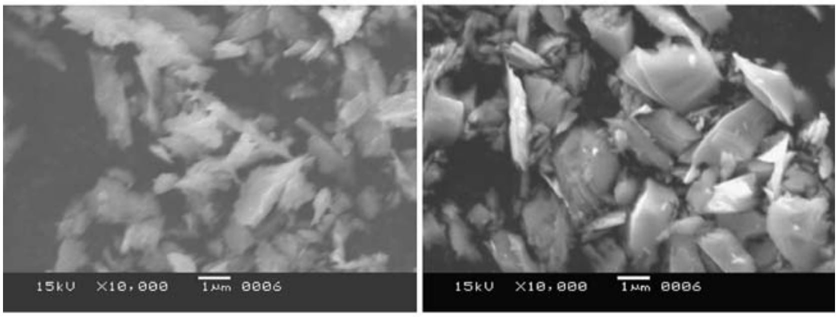
a Undeformed chip thickness: 50 *nm* b Undeformed chip thickness: 100 *nm*



c Undeformed chip thickness: 200 *nm* d Undeformed chip thickness: 400 *nm*



e Undeformed chip thickness: 543 *nm* f Undeformed chip thickness: 596 *nm*



g Undeformed chip thickness: 655 *nm* h Undeformed chip thickness: 690 *nm*

of the cutting edge radius. In the range of the present study, the critical undeformed chip thicknesses were 40, 320 and 596 nm when the tool cutting edge radiuses were 45, 335, and 647 nm, respectively.

4 Discussions

The results from the cutting tests indicate that in cutting of silicon wafers under certain cutting conditions, there is a critical value for the undeformed chip thickness, at or below which the chip formation is in ductile mode which generates continuous chips. This observation is similar for all three cases of the tools with different radii. Although there is a critical undeformed chip thickness for all the three tools, this critical value differs. From the above Figs. 4, 5 and 6, it can be seen that the critical value of the maximum undeformed chip thickness at the ductile-brittle transition increases with the cutting edge radius of the diamond cutter. Meanwhile, the critical value of maximum

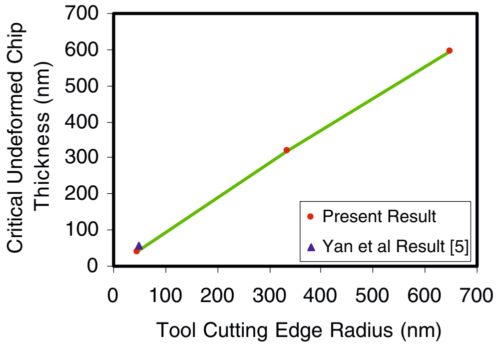


Fig. 7 Linear relationship between the tool cutting edge radius and the critical undeformed chip thickness

undeformed chip thickness at the ductile-brittle transition in cutting of silicon wafer coincides with the cutting tool edge radius: the critical value of the maximum undeformed chip thickness was 40 nm when the cutting edge radius of the diamond tool A was 45 nm in cutting of silicon wafers, while the critical value was 320 nm when the cutting edge radius of the diamond tool B is 335 nm, and the critical value was 596 nm when the cutting edge radius of the diamond tool C is 647 nm. Figure 7 shows the relationship as the critical undeformed chip thickness increases linearly with the tool cutting edge radius.

It is implied that ductile chip formation is a result of large compressive stresses in the chip formation zone, which acts to stop the growth of pre-existing flaws in the material by suppressing the stress intensity factor, K_I. This large compressive stress can be generated by having an extremely small undeformed chip thickness and the undeformed chip thickness being smaller than the tool cutting edge radius. In addition, ductile chip formation in cutting of brittle materials can be a result of the enhancement of material yield strength in the chip formation zone, such that the brittle materials can undertake a much large cutting stress in chip formation zone without fracture. This can be achieved by dislocation hardening and strain gradient by having a nanometric scale of undeformed chip thickness during the cutting process [9].

5 Conclusions

An experimental investigation on the effect of tool cutting edge radius on the ductile-brittle transition of chip formation in cutting of silicon wafers has been conducted. The results show that

- The chip formation in cutting of silicon wafers using diamond tools of different cutting edge radii changes from ductile mode to brittle mode as the undeformed chip thickness is increased to a certain level.
- The critical undeformed chip thickness for the ductile-brittle transition of chip formation in cutting of silicon wafers varies with the cutting tool edge radius.
- The larger the cutting edge radius, the larger the critical undeformed chip thickness. There is a linear relationship between the critical undeformed chip thickness and the tool cutting edge radius.
- The values of the critical undeformed chip thickness are close to the values of the cutting edge radius.

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