

EFFECTS OF CRYSTALLOGRAPHIC ORIENTATION ON TOOL WEAR AND MACHINING FORCES IN SILICON

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Introduction

As the electronics industry pushes to meet tight geometric form and surface finish tolerances on larger silicon wafers, rapid and cost effective advancements of the silicon machining processes are needed. Recent progress by researchers such as Tricard have shown promise in reducing the finishing time for a silicon wafer using fixed abrasives on high throughput grinding machines [1]. Grinding silicon is an excellent alternative to the slow material removal of the conventional lapping process; however, silicon has the advantage of being a diamond turnable material based upon its chemical composition [2]. Tool wear is not negligible resulting in an increase in machining forces, loss of control over part geometry, and an increase in sub-surface damage. Previous work on the crystallographically similar diamond suggests that machining silicon along preferred crystallographic orientations may lower machining forces and mitigate tool wear [3]. This study focuses on the effect, if any, of crystallographic orientation on extending the track length (tool life) for diamond machining of silicon.

Experimental Setup

The flycutting machine tool is shown in Figure 1. The machine base is a Moore plain way No. 3 with DC gearmotors providing XZ travel. The air bearing spindle is a Professional Instruments 4R with integral AC motor. A HP 35670A dynamic signal analyzer is used to capture the cutting forces measured by the Kistler MiniDyn 3-Component Dynamometer - Type 9256. A sampling rate of 800 Hz was typically used to take full advantage of the high bandwidth capabilities of the Kistler while allowing sufficient sample time to capture the entire pass of the diamond tool over the entire workpiece (many minutes long for most feed rates). Some tests were sampled at higher rates and then digitally filtered afterwards to match the bandwidth of the dynamometer. In both cases, proper use of analog anti-alias filtering was observed.

Five tools with different geometries were tested until the surface finishes were of visibly poor quality (as characterized by a significant diffraction grating appearance in the surface). The test parameters are outlined in Table 1.

Table 1: Silicon cutting test parameters.

Test	DOC μm	Rad mm	Feed μm	Spindle RPM	Speed m/min	Rake degrees	Sample #	Chip thick μm	Track/pass km
0	5	4.88	25	240	115	-30	2/3	1.15	0.03
1	5	4.88	3	477	228	-30	2/4	0.13	0.27
2	5	5.08	25	477	228	0	1/4	1.13	0.03
3	5	1.52	6	477	228	0	1/3	0.50	0.13
5	5	1.60	6	477	228	-30	1/3	0.50	0.13



Figure 1: Close up view of air bearing spindle with flycutter head, dynamometer, and silicon workpiece. A hose for coolant is shown above the workpiece/tool contact point.

Results

Each tool was tested until the forces became high and the surface finish was visibly poor. Additional pre-tests were performed to verify that good surfaces could be made with fresh diamond tools. Figure 2 shows a typical good surface made with a new (0.4 kilometer track length) tool.



Figure 2: Typical silicon surface.

The intermittent contact of flycutting provides a convenient reference for removing any low frequency artifacts that may occur because of thermal gradients from changing coolant flow (the location at which the coolant impinges upon the dynamometer changes during the test). A typical force trace with many revolutions of cutting is shown in Figure 3.

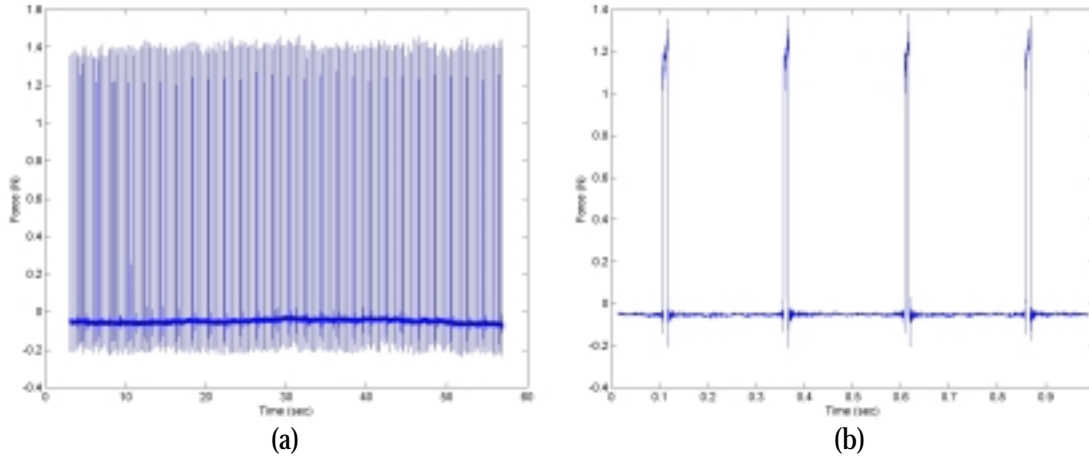


Figure 3: (a) Long cutting force time capture with several hundred passes over the workpiece and (b) Four consecutive flycutting passes over the silicon workpiece.

Close up inspection of a typical cutting force trace reveals the fine detail as the tool cuts the 19 mm length workpiece, as shown in Figure 4.

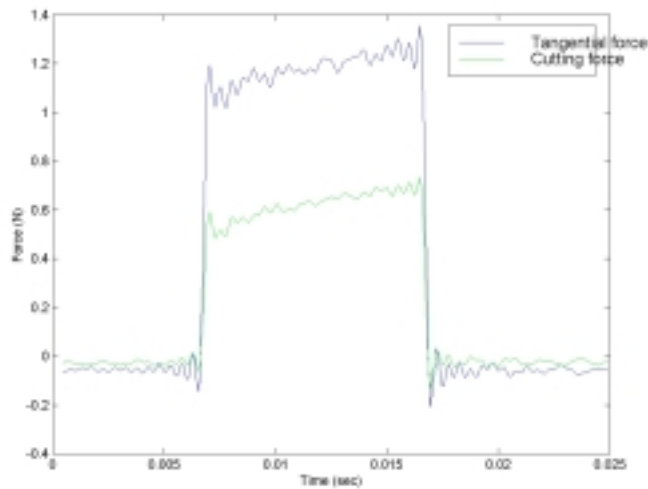


Figure 4: Close up of cutting and tangential forces from one cut over the workpiece.

Data from pre-tests performed at varying depths of cut show that the specific cutting energy does not remain constant, as shown in Figures 5 and 6. However, the cutting forces do remain constant when normalized by the effective chip thickness given by Equation 1.

$$t_c = f \sqrt{\frac{2h}{R}} \quad (1)$$

where t_c is the effective chip thickness, f is the feed per revolution of the cutting tool, h is the depth of cut, and R is the tool nose radius.

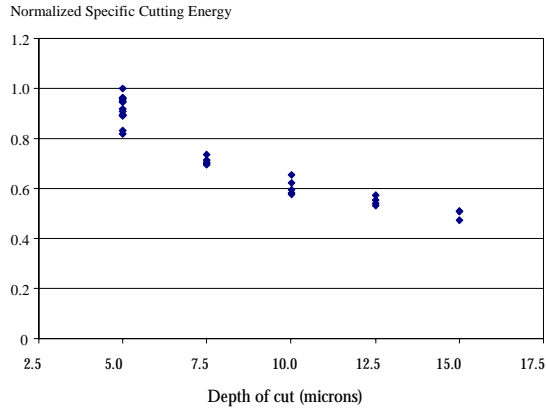


Figure 5: Normalized specific cutting energy.

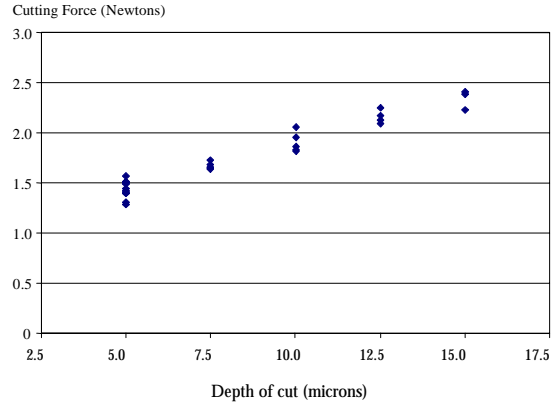


Figure 6: Cutting force vs. depth of cut.

Conclusions

A series of tests were undertaken to explore diamond tool wear in the intermittent cutting of brittle materials, specifically silicon. The test results show that workpieces requiring on the order of three kilometers of track length can be made with low tool wear and excellent surface finish. With longer track lengths, the tool forces (and presumably tool wear) begin a roughly linear increase as surface finish steadily worsens. No catastrophic tool failures were observed, only slow changes as the track length increases. Interestingly, the specific cutting energy did not remain constant with depth of cut, suggesting that there are significant friction forces in the cutting of silicon. These findings support published results emphasizing the importance of a large clearance angle on the tool and hints that aggressive cuts may be the most efficient way to remove material. That is, tool life may turn out to scale with track length, not volume indicating that machining parameters for silicon should be chosen to minimize track length by taking heavier cuts.

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silicon, crystallographic orientation, diamond turning