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Investigation of edge-chipping reduction on silicon micro-milling

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Silicon is a crystalline material commonly used for semiconductor device manufacturing and MEMS applications. Due to its brittle nature, excessive generation of undesirable surface and subsurface damages such as edge chipping, occurs when attempted to machine at depths of several hundreds of microns. In this study, the micro-machinability experiment of silicon using single crystal diamond tool was conducted. The aim was to investigate the effects of machining conditions during silicon micro-milling and thus optimising the cutting strategy to reduce edge chipping generation. Full slot milling were performed along <100> and <110> directions on a (001) surface silicon wafer under various machining conditions. Results show that smaller scale of edge chipping was generated with proper machining conditions control at low cutting speed, low feed per tooth, small depth of cut and machining along <100>. In addition, ductile mode machining, generating good machined surface quality, was seen to predominate the cutting process at low feed per tooth of 0.2 µm/tooth and below in the size effect studies for silicon micro-milling.

Edge-chipping Reduction, Monocrystalline Silicon, Ultra-precision Diamond Machining, Silicon Micro-milling

1. Introduction

Silicon is a hard and brittle material that is widely used in the semiconductor and Micro-Electro-Mechanical Systems (MEMS) industrial sectors. Currently, subtractive techniques such as deep reactive ion etching (DRIE) and wet etching are typically used in the MEMS/semiconductor industries. These techniques can achieve patterned subtraction by patterning etch stops via photolithography. Although these approaches are economical in large scale production, they are largely limited to planar structures, due to lithography [1].

Alternatively, silicon is also manufactured mechanically by grinding, lapping and polishing. Mechanical micro-milling is a potential maskless alternative that could achieve new types of non-planar and three-dimensional structures. Despite showing promising potential in micromachining of ductile materials, excessive generation of surface and subsurface damages such as edge chipping remains a challenge for brittle materials [2, 3].

This paper aims to investigate the micro-machinability of silicon using single crystal diamond end-mills in micro-milling. These includes the investigations on the scale of edge chipping generated during silicon micro-milling under various machining conditions and the influence of the size effect on specific cutting energy respectively.

2. Experimental Method

Experiments were conducted using the Nanowave MTS5R micro-milling system as shown in Figure 1. A 0.5 mm diameter single crystal diamond end mill with single flute was used for machining. Full slot milling was performed onto a (001) surface silicon workpiece for the micro-machinability studies. Compressed air was constantly supplied onto the silicon workpiece to remove any residual chips generated during machining. Figure 2 shows the schematic of the machining plan. Feed direction of the cutting tool was represented by the arrowheads.

Four controllable factors, namely the cutting speed, feed per tooth, axial depth of cut and crystallographic orientation were included in the full factorial experimental design. This allows the effect of the machining conditions (Slots 1 to 48) against the length of edge chipping to be investigated. For the investigation on the size effect on specific cutting energy in silicon micro-milling (Slots S1 to S8), an optimized set of parameters identified from the former study was employed.

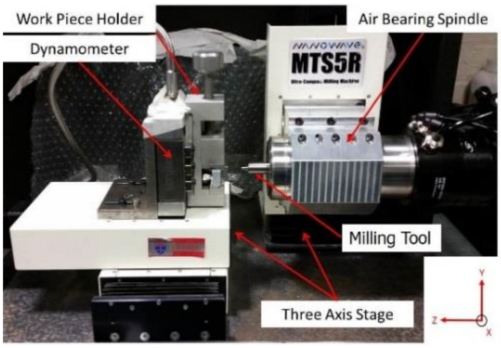

Figure 1. Nanowave MTS5R Micro-milling system with Φ 0.5 mm single crystal diamond tool and air bearing spindle.

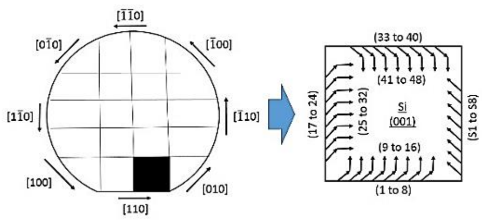

Figure 2. Schematic of the Machining Plan: Slots 1 to 48 were used for edge chipping investigation under various machining conditions. Parameters for slots S1 to S8 were chosen based on the optimal results from the former investigation for size effect studies.

3. Results and Discussion

3.1. Main Effect Analysis of Machining Conditions on Length of Edge Chipping

Choong et al. [3] quantitatively characterized the length of edge chipping generated during silicon micro-milling. Using similar technique, an average length measurement was taken across fifty equally spaced data points along the vertical SEM image view of the machined slot. Measurement was performed on the up milling side. Figure 3 shows the main effect plot of the machining conditions on the length of edge chipping. Depth of cut has significant influence on the generation of edge chipping. A tremendous increment of edge chipping was observed when the depth of cut was increased from 20 to 30 µm. This might be due to the presence of tool run out, thus causing more vibrations when the cutting tool was further lowered into the workpiece.

In contrary, the feed per tooth, cutting speed and crystallographic orientation had insignificant influences on the length of edge chipping. Large negative rake angle is believed to create highly compressive hydrostatic pressure in the cutting zone, and thus in turn being able to suppress crack propagation. As the single crystal diamond tool has a zero rake angle, propagation of cracks in silicon was unable to be suppressed without proper machining conditions. Thus, the variation of edge chipping appears to be insignificant under various feed per tooth, cutting speed and crystallographic orientation at each level of depth of cut.

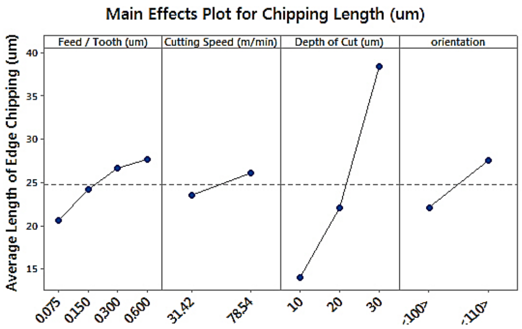

Figure 3. Main effects plot of edge chipping study under various parameters: Small edge chipping were observed at small depth of cut, low feed per tooth, low cutting speed and at <100> orientation.

3.2. Size Effect on the Specific Cutting Energy

Specific cutting energy (SCE) in machining is defined as the energy taken to remove a unit volume of the material. Wang et al. shows that material removal by plastic deformation requires a higher SCE than brittle fracture [4]. Hence, it can be used to observe the brittle-ductile transition and brittle mode machining can be observed when the SCE falls towards a low steady state value. Cutting forces, Fx and Fy, were directly obtained from the dynamometer during the machining process. Specific cutting energy at each feed per tooth can be computed using Equation (1):

$$U = \frac{v_c}{Vrem} \times \int_0^{Tc} \sqrt{{F_x}^2 + {F_y}^2}\, dt \qquad (1)$$

Figure 4 shows the fit of curve, representing the behaviour of the specific cutting energy at different feed per tooth. Higher specific cutting energy symbolizing the dominance of ductile mode machining were observed below 0.2 µm/tooth. This also suggests that edge chipping can be reduced at smaller feed per tooth. Results were also conclusive when compared to the SEM images as shown in Figure 5.

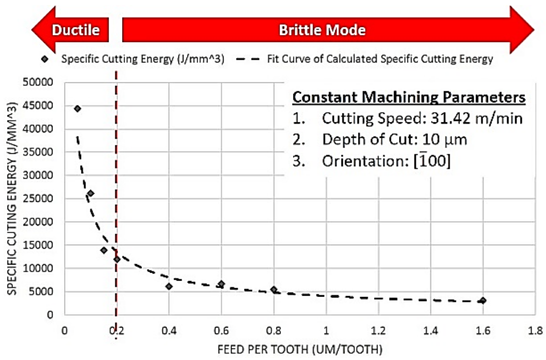

Figure 4. Fit of curve for size effect studies: Brittle mode machining was observed at ≥ 0.2 µm/tooth, due to the specific cutting energy approaching steady state with increased feed per tooth.

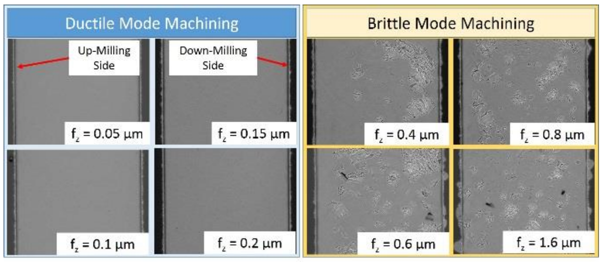

Figure 5. Machined slots at specific feed per tooth: Ductile mode machining and small edge chipping can be achieved at low feed rate.

4. Conclusion

The present studies show that edge chipping can be successfully reduced with the use of single crystal diamond end mills and proper machining conditions. Smaller scale of edge chipping was observed when machining along <100> with low cutting speed, feed per tooth and small depth of cut. In addition, ductile mode machining, which yields good surface quality, was seen to predominate the cutting process in the size effect studies at low feed per tooth of 0.2 µm/tooth and below. Further work to explore the possibility of suppressing the generation of edge chipping and optimization on the cutting quality will be conducted.

References

[1] Madou M 2002 Fundamentals of microfabrication: The science of miniaturization 2nd ed. (Boca Raton, FL: CRC Press).

[2] Huo D, Lin C, Choong Z, Pancholi K and Degenaar P 2015 Surface and subsurface characterisation in micro-milling of monocrystalline silicon. Int. J. Adv. Manuf. Tech. 81(5-8) pp 1319-1331.

[3] Choong Z, Huo D, Degenaar P and O'Neil A 2015 Effect of crystallographic orientation and employment of different cutting tools on micro-end-milling of monocrystalline silicon. Proc. IMeche, Part B: J. Eng. Manuf. In Press.

[4] Wang J and Liao Y 2007 Critical depth of cut and specific cutting energy of a micro-scribing process for hard and brittle materials J. Eng. MATER-T. ASME. 130(1) pp 011002-011002.