Surface integrity characteristics in micro end milling of monocrystalline silicon

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Abstract

Experimental investigation on micro milling of single crystal silicon was performed on an ultra-precision micro machine using cBN and diamond coated tools. Raman spectroscopy studies of micro machined surfaces provided evidence of processing induced phase transformations and residual stress under a variety of machining conditions. Surface and subsurface characterisation studies show that ductile machining mode can be achieved at certain machining conditions. Silicon brain implants used in neurosurgery application were fabricated with good dimensional accuracy and surface finishes, which demonstrated that micro milling is a promising process for fabrication of micro silicon components.

1. Introduction

It is well recognised that micro manufacturing has been a key enabling technology in industrially producing useful micro components and products. Among various engineering materials for micro products, semiconductor materials, e.g. silicon, are playing a significant role in some applications such as MEMS, microfluidics, opto-electronics, etc. Traditionally lithography-based processes dominate the fabrication of semiconductor components. However, lithography-based processes possess a number of constraints which limit their applications to certain applications. These constraints include planar 2 or 2½ process, low relative accuracy and poor surface finish, high investment cost for prototype, etc. To overcome these constraints alternative micro manufacturing processes are being investigated. Micro milling has been successfully applied in fabrication of 3D complex shape micro components over various engineering materials with excellent dimensional accuracy and surface finish, and it should have the potentials to fabricate complex shape silicon micro components if the ductile cutting regime for micro milling can be found. Success of micro milling of silicon will open new opportunities to fabricate 3D precision silicon based micro products at a cost-effective manner.

Although ultra-precision single point diamond turning of single crystal silicon at ductile cutting mode for high precision optical systems has been carried out, research on micro milling of single crystal silicon is at its very nascent stage.

2. Experimental set-up

As illustrated in Figure 1, experiments were carried out on an ultra-precision micro machining centre (Nanowave MTS5R) using 0.5mm cBN and diamond coated tungsten carbide micro end mills. 0.5mm thick polished single crystal silicon wafers with (100) crystal orientation were used. The experiments in this work include full immersion slot milling. For each test, a 5mm long and 0.5mm wide micro slot was milled along Y direction. A Horiba Jobin Yvon HR800 Raman microscope equipped with a 514 nm Ar+ ion laser probe was used for residual stress measurement.

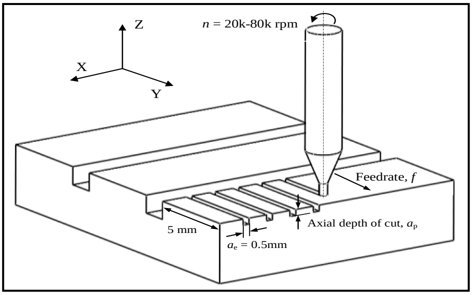


Figure 1. Experimental set-up for micro milling of silicon

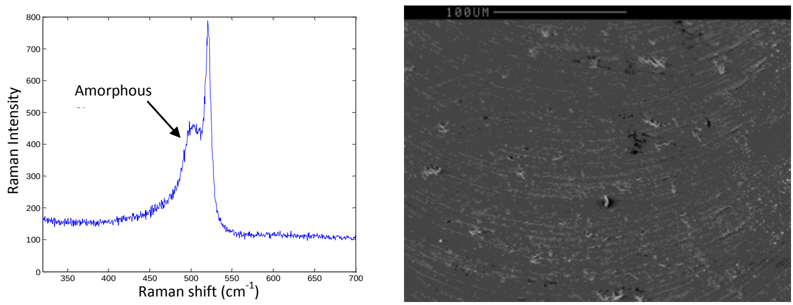
Two levels of cutting speed (31.4 m/min, 78.5 m/min) and depth of cut (20 μm, 50 μm) were selected, albeit four levels of feedrate (0.0375 μm/tooth, 0.075 μm/tooth, 0.15 μm/tooth, and 0.3 μm/tooth) were selected. Each set of cutting parameter in the 4 x 2 x 2 mixed level full factorial design was repeated once to reduce machining errors and separate effect due to interactions from measurement noise.

3. Results and discussions

An absolute value of residual stress is determined by correlating the Raman shift in the peak wavenumber with the stress present. A stress sensitivity factor of 3.2 cm^{-1} GPa^{-1} is used in this study [1].

When cBN tools were used, Raman spectra shift shows that the residual stresses are compressive, which agrees with those reported in single point diamond turning of silicon [2] and micro scratching of silicon [3]. ANOVA performed on surface residual stress data shows that within the experimental machining conditions, feedrate has the most significant influence on residual stress, and higher feedrate results in higher compressive stress values, whereas cutting speed has little influence on residual stress, and depth of cut has negative influence on surface residual stress, i.e. an increase in axial depth of cut will increase surface residual stress. The highest residual stress is observed at 0.3 μm/rev, and has the approximate value of 670 MPa.

When diamond coated tools were used, feedrate, cutting speed and axial depth of cut have similar influences on residual stress as that found from cBN tools. However, tensile stresses were found from Raman microspectrosopy measurement at very small feedrate (0.0375 μm/rev). This is because that the surface of the deposited diamond thin films has a 'rough' faceted cutting edges. When feedrate is very small, this faceted cutting edges can be considered as a grinding tool, therefore abrasive cutting process will take place. As reported in [4] tensile residual stresses are likely present in ground and lapped silicon wafer surface.



(a) (b)

Figure 2: (a) typical Raman spectra and (b) SEM micrograph on micro milled silicon surface. (cutting condition: v_c = 31.4m/min, f_z = 0.075μm/tooth, a_p = 20 μm)

Crystalline to amorphous phase transformation has been frequently observed in Raman spectra in this research. Since very small chip loads were used in the experiment, the cause of the phase transformation is believed to be high local pressure rather than temperature rise. The presence of processing induced amorphous phase would facilitate ductile material flow and suppress the micro cracks initiation and propagation, and make ductile cutting of silicon possible. SEM examinations on micro milled surfaces also provide evidences of ductile cutting. Those surfaces with clear tool marks and less surface defects are also the surfaces on which the metastable phase transformations taken place. Figure 2 shows surface morphology of a typical micro milled surface with tool marks and its Raman spectra.

Silicon micro brain implants used in neurosurgery application as shown in Figure 3 with high aspect ratio were fabricated using the optimal cutting conditions obtained through this research. Surfaces with minimal damages and good dimensional accuracy demontrated that micro milling is a promising process for fabration of 3D micro silicon products.

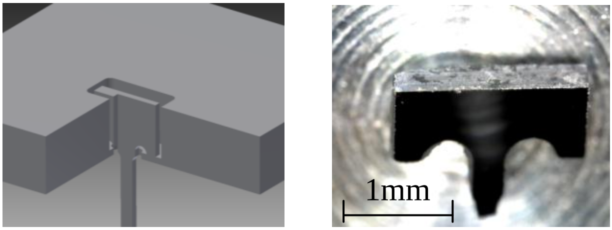


Figure 3: Silicon brain implants fabricated by micro milling

4. Conclusions

Raman microspctroscopy studies of micro machined surfaces provided evidence of processing induced phase transformations and residual stress under a variety of machining conditions. Surface and subsurface characterisation studies show that ductile cutting mode can be achieved in micro milling. Raman spectra analysis can be used to optimise the ductile cutting of silicon.

References:

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