Research Article 2017, **2**(7), 433-435 Advanced Materials Proceedings

Surface finish and subsurface damage distribution during diamond turning of silicon

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Received: 31 March 2016, Revised: 30 September 2016 and Accepted: 20 April 2017

DOI: 10.5185/amp.2017/706
www.vbripress.com/amp

Abstract

Subsurface Damage (SSD), which is introduced to optical materials by diamond turning processes, affects the performance in optical, laser and infrared applications. For optical applications, SSD can be the source of component instability (e.g., surface stress) and flaw. The objective of the present study is to investigate the subsurface damage in silicon. Interferometry and Raman Spectroscopy are used to detect the surface finish and SSD. The surface roughness of 0.243 nm is achieved at best combination. A sharp Raman shift at 409 cm^{-1} is obtained, which reveals that a thin layer of Silicon has transformed to amorphous state resulting in subsurface damages. Copyright © 2017 VBRI Press.

Keywords: Subsurface damage, micro-cracks, diamond turning, brittle machining, raman spectroscopy.

Introduction

The need to manufacture highly precise optical components with dimensions and accuracy in micro-nano scale is a rising research area. It is well accepted that micro-manufacturing has been a key facilitated technology in industries producing useful micro-electronic components and products [**1-2**]. Subsurface Damage, which was introduced to optical materials by fabrication processes, may bring about the decrease of output in optical, laser and infrared applications. For optical applications, SSD can be the source of component instability (e.g., surface stress) and contamination.

Brittle machining is a difficult area to work with. Depth beyond the critical depth is known as the Ductile to Brittle Transition (DBT) depth, will result in a brittle cut [**3**]. Precision machining of Ge has become immensely important both technologically and economically in Micro-electronics, micro-mechanical and optics manufacturing [**4**]. During machining processes involving tool-workpiece contacts unavoidably cause subsurface damage and formation of amorphous layer near surface layer will impinge on the mechanical, optical and electronic performance of Si products. Some research groups have used cross-sectional Transmission Electron Microscopy (TEM), Laser Raman Spectroscopy (RS) and Optical Microscopes to examine the subsurface structure and formation of amorphous layer. Shibata et al. exposed that, when the crystalline material is Diamond turned it leads to the formation amorphous layer (150 nm thick) above the crystalline layer (2-4 µm) with dislocations [**5**]. The microstructure and intensity of the subsurface damage layer is directly influenced by machining conditions, such as rake angle, machining conditions and depth of cut [**6-7**].

A few other studies on machining damage in brittle materials (viz. Silicon, Germanium, and Quartz) via: X-ray diffraction [**8**], Raman scattering [**9**], micro laser Raman [**10-11**], and a combination of laser Raman and chemical etching [**12**] have also been reported. The objective of the present study is to investigate the subsurface damage in Silicon and to predict the formation of amorphous layer in different machining conditions. Different methods are used to characterize subsurface damage and morphology of machined surface i.e. Laser µ-Raman Spectroscopy, Coherence Correlation Interferometer (CCI-OPTICS) and Phase Grating Interferometer (PGI-120). Laser µ-Raman Spectroscopy is an influential method for materials characterizations [**13**].

The subsurface damage mechanism in brittle material is related to machining pressure. The machining pressure about (>10GPa) is sufficiently high to cause phase change in silicon. Shaitaba et. al. suggested that higher negative rake angle will lead to the higher machining pressure [**5**].

Experimental

Sample preparation

Optical grade Si disc with structural orientation (100) is used for current study. Circular disk of Si with diameter 50 mm and thickness 15 mm is prepared for experiments. Substrate sample is turned by diamond tool with a tool nose radius (TNR) of 1.50 mm and a rake angle of -20˚ with a fixed overhang. Random experiments are performed within the specific parametric value of: spindle speed (SS): 1000 rpm, tool feed rate (TFR): 2.5 µm/rev and depth of cut (DOC): 0.5 µm. These parameters are chosen because this lead to minimum surface roughness [**14**]. Surface roughness is measured by Taylor Hobson's CCI-OPTICS, Raman Spectroscope.

Diamond turning equipment

Precision turning operation is performed on 2-axis Diamond Turning machine (Nanoform-250 Taylor Hobson) at National Aspheric Facility, CSIR-CSIO, Chandigarh, India. It has vacuum chuck to ensure the rigid as well as strain free holding within the centering error of 0.01 µm. The machine feedback accuracy is 0.09nm. To minimize the vibrations from the surroundings and to get the best results, machine is kept on air floating table. Schematic of diagram is as shown in **Fig. 1.**

Fig. 1. Diamond Turning equipment Nanoform-250.

Results and discussion

Surface roughness and morphology

In this section, experimental investigations are explained for various parameters used during machining. These parameters lead to the generation of SSD damage in optical component, which hampers the (under) surface quality. After the machining experiments, surface roughness is measured by the contact type profilometer having the stylus tip radius of 2 µm.

Roughness profile and surface morphology are shown in **Fig. 2** (**a**) and (**b**) respectively. In this case, the machining parametric combination used for Si substrate: TFR - 2.5 µm/ rev; SS - 1000 rpm and DOC - 0.5 µm and the optimum value of roughness achieved is 0.243nm with minimum micro-cracks (SSD.

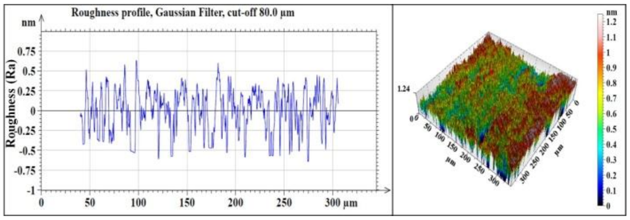

Fig. 2. (a) Surface Roughness (b) Surface morphology for the machining at TFR - 2.5 µm / rev; SS - 1000 rpm and DOC - 0.5 µm.

Raman spectroscopy and SSD

Raman Spectroscopy is used for non-destructive characterization for the phase change in material. A 633nm wavelength laser is used to study the phase change in machined sample of silicon. The main purpose of the Raman spectroscopy, this study is an attempt to detect the amorphous layer underneath the machined surface as shown in **Fig. 3**. Raman tests were conducted at different points within the ductile-cut surface.

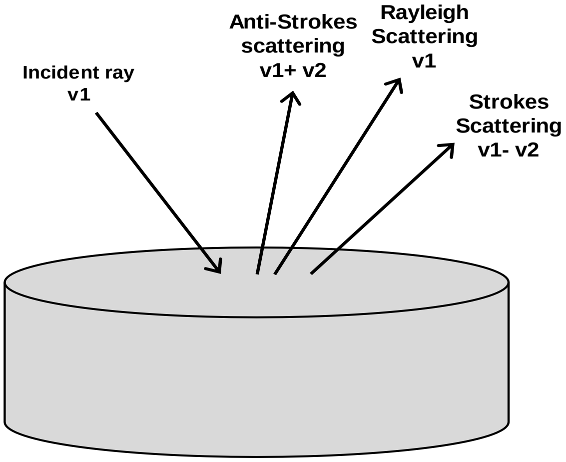

Fig. 3. Schematic model of laser scattering.

Fig. 3 shows the Raman spectrum of a sample machined. There are sharp peaks at 409 cm^{-1}; responses at other Raman shifts are weak. This indicates that the structural phase change in the single crystal silicon under these conditions. This reveals that a thin layer of silicon has been transformed into the amorphous state (a-Silicon), with the bulk material beneath that layer remaining crystalline (c-Silicon). The thickness of the a-Silicon layer in the **Fig. 3** was calculated from the Raman intensity ratio "r" by the process reported [**10-11**]. The Raman intensity ratio "r" is defined as:

$$r = \frac{Ia}{Ic} \tag{1}$$

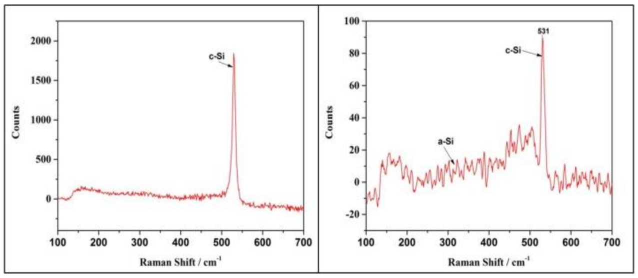

Fig. 4. Raman Spectrum of unmachined surface and machined surface at DOC of 0.5µm.

In **Fig. 4**. the spectrum shows the crystalline peaks of the machined Si sample. It is observed that a combination of the crystalline peaks and amorphous peaks are formed in the machined surface. The amorphous layer is an indication of a ductile-regime machining. As the thickness of the amorphous cover increases as the depth of cut is increased [**13**].

Conclusion

SPDT was a chosen as the material removal method in this study as it offers better accuracy, faster fabrication and higher precision. Surface roughness is a critical quality parameter for the components being used in optical, Infrared and opto-mechanical components. But, SSD is also an equally important parameter, where nonmetric surface finish is required.

1. Surface Roughness is well maintained with small DOC of 0.5 µm, TFR of 2.5 µm/ rev & SS of 1000 rpm.
2. The achieved Surface Roughness for Si-substrate is 0.243 nm.

From this study it has been observed that the amorphous Raman shift is seen at 409 cm^{-1} at absolute intensity of 59.55 counts as shown in figure 4. This indicates that, the crystalline surface is changed to amorphous after turning due to HTPT leading to SSD.

Acknowledgements

We highly acknowledge Director CSIR-CSIO, Chandigarh & 12th Five Year Plan (OMEGA) for necessary support & carrying out the research work.

Author’s contributions

Conceived the plan: VK, HG, RS; Performed the expeirments: VM, RS, NK; Data analysis: RS, NK, VM; Wrote the paper: RS, NK, VM.

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