# Single point diamond turning of silicon for flat X-rays mirrors

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## Abstract

Silicon Mirrors are essential components for guiding the X-Ray beam and focusing it to a particular location. Due to lower X-ray wavelength, these mirrors require super smooth surface finish to avoid the strong scattering from surface. Single Point Diamond Turning is used to examine the fabrication possibility of X-Ray mirror. A number of machining cuts are performed with parameters like tool feed rate, Spindle Speed and depth of cut. The surface is characterized by mechanical profiler, optical profiler, Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM). The optimized surface roughness achieved is 0.873 nm. Copyright © 2017 VBRI Press.

**Keywords:** Silicon, single point diamond turning, surface roughness, x-ray mirror.

## Introduction

Materials that are hard and brittle such as Silicon, Germanium and ceramics are most difficult to machine. Critical components often depend on the ability to achieve good form and finish values to meet the required levels of performance and reliability. Single crystal silicon is one of the best optical materials for infrared applications and other high added value products such as X-ray optics and interferometers. Silicon Mirrors are essential components for guiding the X-Ray beam and focusing it to a particular location [**1**]. To avoid the scattering of low wavelength X-rays, smooth surface finish is required on mirrors [**2**]. Different shapes of mirrors such as flat, cylindrical, aspheric and ellipsoidal are generally used for focusing of X-rays. The advantages of mirrors include high beam throughput and no chromatic aberration compared to other focusing optics such as zone plates [**3**].

The precision machining of brittle materials like Silicon, Germanium and ceramics is very challenging. Grinding and polishing are the traditional processes used to achieve tight tolerances in terms of surface quality of Silicon. Random and uncontrolled material removal by grinding leads to the brittle fracture and Sub-Surface Damage (SSD). The nano-scale material removal by Diamond Turning is one of the popular method with which it is possible to achieve deterministic surface finish on brittle materials for such applications. With SPDT it is possible to produce good form and surface finish simultaneously. Brittle materials need to be machined at ductile regime to achieve optical level quality [**4**]. **Fig. 1** shows the schematic of ductile regime machining.

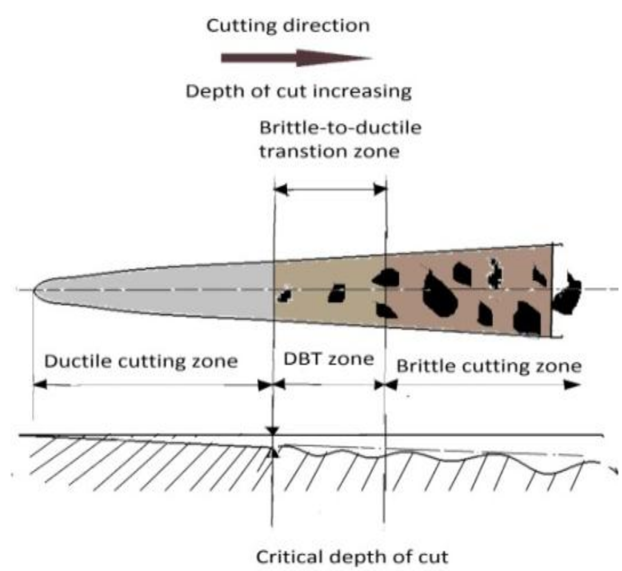


**Fig. 1**. Ductile Regime Machining [**5**].

Ductile Regime machining has been investigated by number of researchers. Some reported a critical depth while indenting brittle materials [**6**]. Some studied the ductile regime machining of germanium and silicon. The low surface roughness on germanium and high surface roughness on silicon was observed due to tool wear rate difference [**7**]. Some researchers experimentally demonstrated the possibility of ductile regime machining of single crystal silicon, the surface roughness in the order of 2.86nm was achieved by varying the machining conditions and cutting fluid [**8**]. Some researchers studied the effects of extreme negative rake angle for nano-cutting of silicon. The cutting was performed by varying the rake and the clearance face resulting in ductile machining [**9**]. Some explored the effect of large tool feed rate for ductile regime machining of silicon. They found tool feed could be as high as 5-20 µm/rev [**10**].

The influence of the machining variables such as depth of cut, feed rate and spindle speed affecting the machining process is not yet clear in the literature. In Ductile Regime Machining, brittle materials can be processed in a ductile mode with the nanometric surface finish and without sub surface damage. In this study, experiments are planned to achieve the ductile regime machining, wherein optical quality surface finish can be achieved on Silicon by SPDT, which can be further used for X-rays applications. The optimization of cutting parameters is an essential step to raise the yield of SPDT which is the major motivation of this work.

## Experimental

In this study diamond tool of nose radius 1.5mm, rake angle -20°, clearance angle 10° and non-controlled waviness mono-crystalline diamond tool is used. For these explorations, Single point diamond turning (Nanoform-250) is utilized. Optical grade silicon disc of diameter 100 mm and thickness 10 mm is used for experiments. The machining parameters used are: Tool Feed Rate (TFR) 1-5 µm/rev, Spindle Speed (SS) 500-1500 rpm, Depth of Cut (DOC) 0.5- 10 µm. To characterize the machined surface, Mechanical profiler (PGI 120) and Optical profilometer (Coherence Correlation Interferometer) is used. Further Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM) is used to characterize the best and the worst samples.

## Results and discussion

All machined surfaces are characterized under uniform metrology conditions and results are collected in terms of Surface roughness. At large depth of cut of 10 µm, higher feed rate of 5µm/rev, and lower spindle speed of 500 rpm, the machining takes place in the brittle mode leading to micro cracks on the surface and resulting in higher roughness values of 104.7nm. The surface roughness is very high and the rainbow or star pattern is observed on the machined surface during this combination. It is due to the white light diffracting from the rough surface. The star pattern is generally due to the trapping of chips between the tool and workpiece and rubbing of these trapped chips on the machined surface. The surface roughness graph and the surface morphology of silicon disc at such combination are shown in **Fig. 2** (**a**) and (**b**).

At low depth of cut of 1.5 µm, lower feed rate of 2.5 µm/rev, and high spindle speed of 1500 rpm, it is observed that the surface quality improves drastically. The surface roughness achieved is 0.873 nm as shown in **Fig. 3 (a) and (b).** The low feed rate and low depth of cut results in chip thickness lower than the critical chip thickness, which causes machining in the ductile mode leading to good surface quality.

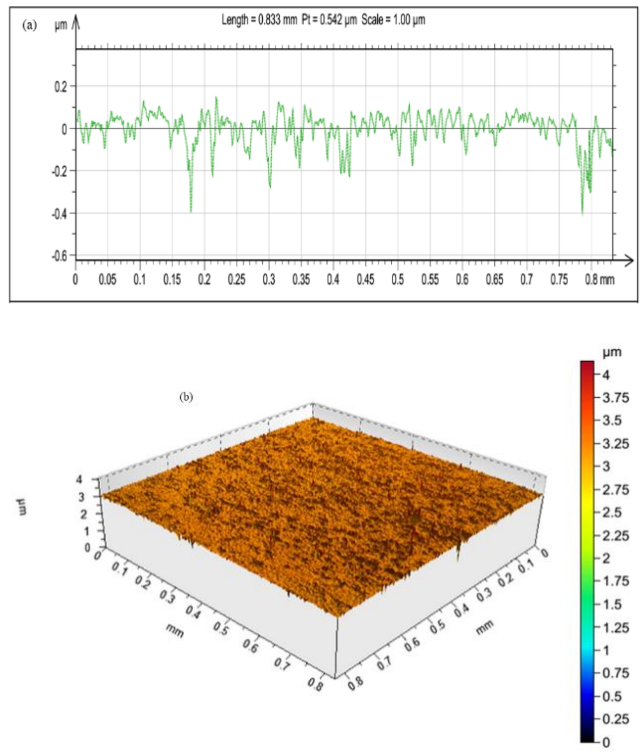


**Fig. 2**: (a) Roughness graph (b) Surface Morphology for the worst combinations.

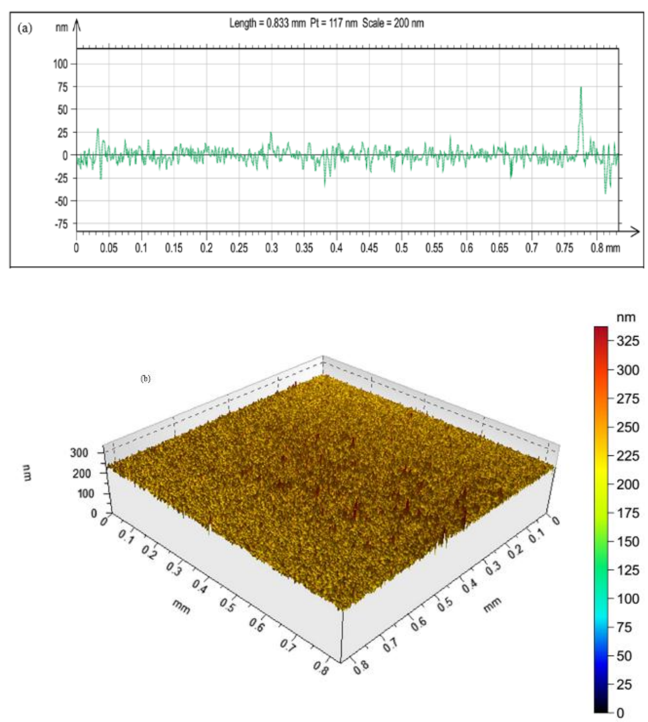


**Fig. 3**: (a) Roughness graph (b) Surface Morphology for the best combinations.

Further, the surface was analyzed by using Atomic Force Microscopy (AFM). **Fig. 4(a) and (b)** shows the AFM images for the unmachined substract with 400 nm surface roughness and for the best combinations. **Fig. 5** shows the SEM image of the diamond turned silicon for the best combination at 8,000X. SEM and AFM results also support the results taken by Mechanical and optical profilometer.

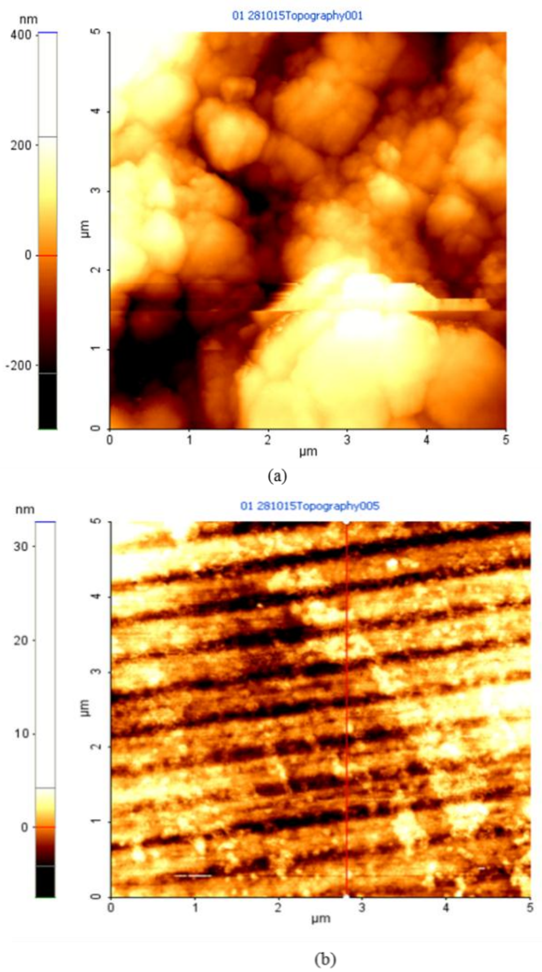


**Fig. 4**: AFM images for the (a) Unmachined Si Substrate (b) Best combination.

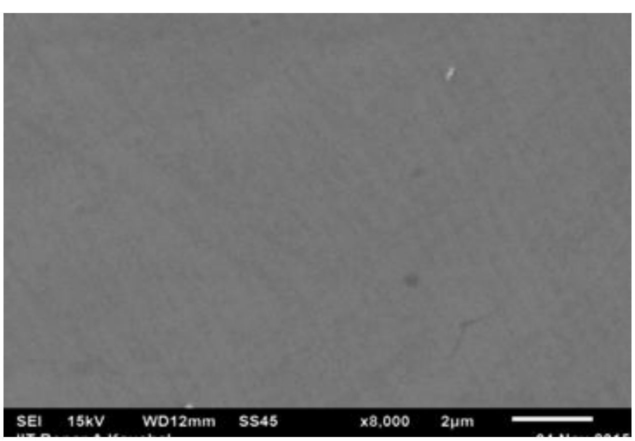


**Fig. 5.** SEM Image of Silicon Mirror at 8,000 X.

## Conclusion

The exploration using Single Point Diamond Turning over the past decades has led to the generation of optical finished surfaces on brittle materials. In the current work, an experimental study is conducted for the ductile regime machining of silicon for the fabrication of X-ray mirrors. Based on these experiments, the following conclusions are made:

- The Tool Feed Rate, Depth of Cut and Spindle Speed play a significant role in obtaining a good surface finish on Silicon.
- The best surface finish Ra value obtained on Silicon is 0.873 nm at Tool Feed Rate value of 2.5 µm/rev, Depth of Cut value of 1.5 µm and Spindle Speed value of 1500 rpm in large silicon substrate.

The Silicon mirror fabricated with this process with desired surface quality can be used for X-rays applications.

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## Author's contributions

Conceived the plan: NK, RS, VM; Performed the experiments: NK, RS; Data analysis: VM,HG; Wrote the paper: NK,RS,VK.Authors have no competing financial interests.

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