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# Study of sub surface damage in preparation of freeform glass optics using laser assisted single point diamond turning

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**Abstract**

Freeform optics are a lucrative choice for optical designers looking to further enhance high end optical systems and reducing commonly known optical aberrations. A rotationally non-symmetric surface poses manufacturing challenges where a multi-axis CNC machine is required to produce such a surface. The real challenge, however, lies in polishing the surface from this state. An ultra-fine generation tool may still induce 20 – 60 µm of sub-surface damage. The process of removing the full extent of sub-surface damage using a sub-aperture tool is time consuming and induces undesirable mid spatial frequencies. Laser assisted single point diamond turning of amorphous glass is shown to exhibit merely 3 – 5 µm of sub-surface damage while maintaining accurate form. A custom Optical Coherence Tomography (OCT) instrument developed by ZEISS will be used to quantify sub surface damage in diamond turned and CNC generated freeform glass optics. This study will illustrate the differences in sub surface damage and resultant form produced using different manufacturing processes, including laser assisted diamond turning.

Laser assisted machining, diamond turning, OPTIMUS, sub surface damage, glass freeform, freeform optics, precision polishing, Optical Coherence Tomography (OCT)

## 1. Introduction

Freeforms optics are defined by rotationally non-symmetric surface shapes with little to no axis of symmetry. This makes the fabrication of such surfaces challenging because of the additional complexity required in manufacturing techniques/axis, as well as the specialized metrology equipment required to analyze such surfaces. The advent of ultra-precision machines (diamond turning machines) has allowed manufacturing of freeforms for several years in materials like Aluminum, Brass, Plastics, and even Infrared materials like Silicon or Germanium. The primary techniques used in ultra-precision machining are turning, grinding, and milling. Each fabrication technique has its advantages and disadvantages; however abrasive subtractive processes such as milling and grinding suffer from significant sub-surface damage (SSD) these processes impart beneath the surface. It is important to carefully control the amount of SSD, and use successive polishing strategies to smoothen/polish the freeform within the desired optical specification [1]. This paper will focus on examples of directly turning optical glass using micro laser assisted machining in being able to significantly reduce sub surface damage in freeforms. The two examples covered in this paper are round mild freeforms described as an Alvarez lens and phase plate.

## 2. Micro laser assisted machining process

Micro laser assisted machining was popularized by Ravindra *et al*. for the machining of hard and brittle materials such as Silicon [2]. The success seen in machining Silicon was later realized in several other diamond turnable materials such as Zinc Sulfide, Zinc Selenide and Calcium Fluoride. The laser had varying degrees of improvement dependent on material. There is an improvement in speed and yield on materials like Silicon and Germanium, whereas Zinc Sulfide and Zinc Selenide may see improved quality and yield with similar cutting speeds.

Tungsten carbide is conventionally not diamond turnable, however with the invention of micro laser assisted machining, it is possible to use an ultra-precision lathe to machine smooth optical surfaces for use in precision glass molding.

A 1064 nm continuous wave laser is delivered through the rear face of a diamond cutting tool and aligned such that the zone of contact between the workpiece material and diamond cutting edge is preferentially heated. This promotes increased ductility. In the case of conventional machining, most of the energy required in machining comes from a mechanical process. Using laser energy offsets mechanical energy required and augments this with photon absorption. A schematic of the laser assisted process is shown below in Figure 1 with the region of enhanced ductility highlighted in red. Lastly, the energy imparted by the laser into the workpiece material is immediately removed in the forms of chips. Therefore, the bulk material property remains unaffected.

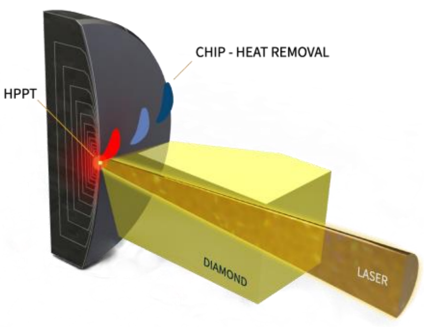


**Figure 1.** Micro laser assisted machining process cut away section view

Optical glasses such as fused silica and Schott N-BK7 are also not conventionally diamond turnable. However with micro laser assisted machining, it is possible to shape lenses to desired surfaces namely: spherical, aspherical, or even freeform using an ultra-precision lathe. The resultant SSD is 3 – 5 µm versus upto 60 µm with precision grinding. The total SSD induced prior to polishing is necessary to be removed by the polishing process. For aspherical and freeform polishing, sub aperture polishing techniques must be used which induce mid-spatial frequencies. A visual representation of the sub surface damage generated using grinding versus diamond turning with laser assisted machining is shown below in Figures 2 and 3. Figure 3 illustrates difference in appearance of 'gray' using different grits of grinding versus diamond turned.

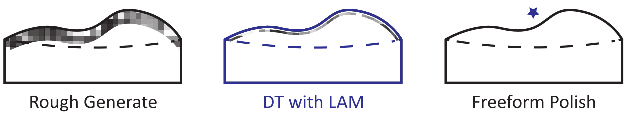


**Figure 2.** Process chain including laser assisted machining for the manufacture of freeform optics.


**Figure 3.** Visual comparison of 'grayness' of generated (D64 & D20) versus laser assisted diamond turned sample (right).

### 3. Freeform design and metrology

The design characteristics for the two freeforms presented in this paper are outlined in Table 1 below. These designs are examples of mild freeforms capable of being machined using slow tool servo on an ultra-precision machine. A slow tool servo process is where the Z-Axis is traversed in an out of the lens in conjunction with the rotary position of the C-Axis while also traversing along the lateral axis (X-Axis) [3].

**Table 1.** Freeform design and description.

| | Units | Design 1 | Design 2 |
|---|---|---|---|
| Material | - | Schott N-BK7 | Fused Silica |
| Sag range | mm | 0.161 | 0.544 |
| Diameter | mm | 28 | 28 |
| Edge Slope | deg | 1.9 | 7 |
| Slope Range | deg | 2 | 11 |

#### *3.1 Surface Roughness*

The average surface roughness (Sa) obtained for the precision freeforms range from 20 – 80 nm. A comparable surface directly from a generator using a D20 wheel would be near 300 nm. Figure 4 shows the measured average surface roughness for the different regions on the lens.

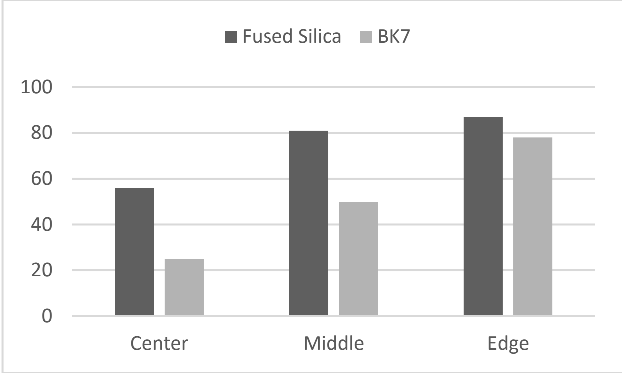


**Figure 4.** Average surface roughness of fused silica Alvarez lens and BK7 phase plate directly after diamond turning. (20X Objective, 10th order form removed)

#### *3.2 Surface figure*

The Schott N-BK7 phase plate is depicted in Figure 5 with the total sag range of 161 µm.

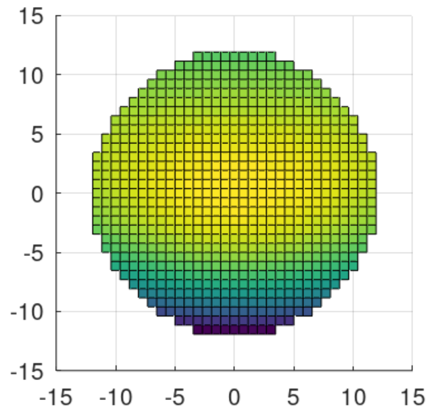


**Figure 5.** Schott N-BK7 phase plate freeform 3D sag map

As shown in Figures 6 and 7, there is still some deviation of the machined form. This is explainable due programming differences between the designed and machined part. Future efforts will negate this effect, by correcting the tool path adjusted to the measurement after the first run.

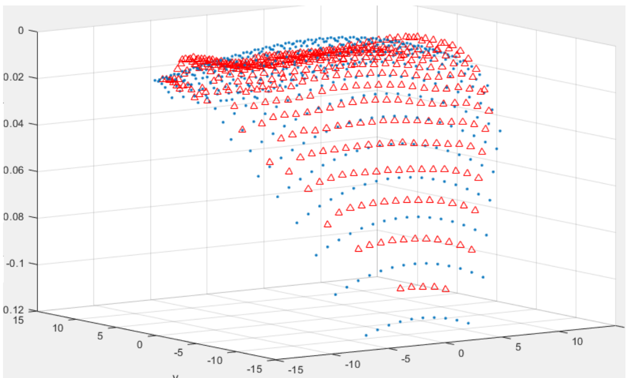

**Figure 6.** N-BK7 CMM measurement. Theoretical surface (blue), measured surface (red).

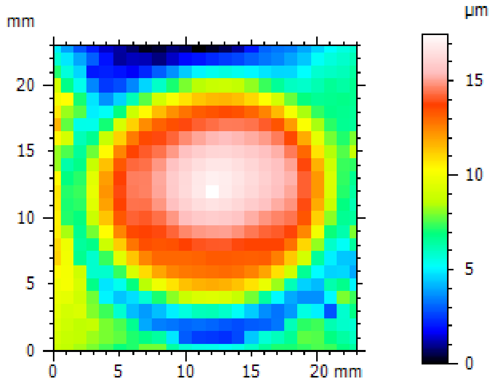


**Figure 7.** N-BK7 form deviation map. PV Irregularity: 17.48 µm.

The Fused Silica Alvarez design is depicted in the map of Figure 8 with the total sag range of 544 µm.

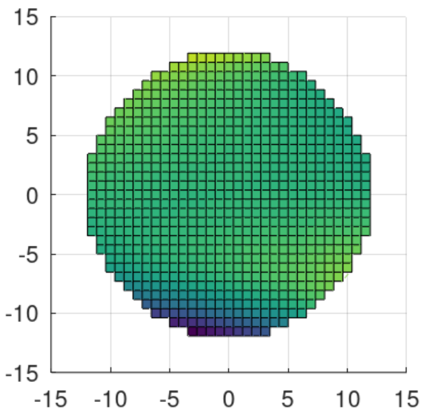


**Figure 8.** Fused silica alvarez freeform 3D sag map

Similar to the BK7 phase plate, there is also some form deviation of the fused silica Alvarez plate due to programming limitations. The measuerement of this optic is depicted in Figures 9 and 10. The first figure shows a comparison measurement versus model data and in the second figure the deviation map shows just the amount of deviation.

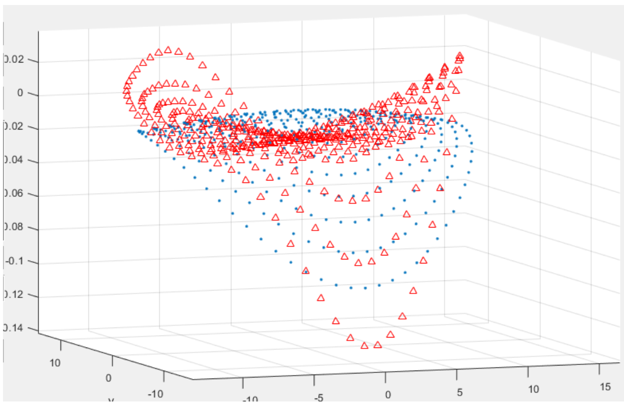

**Figure 9.** Fused silica alvarez CMM Measurement. Theoretical surface (blue), measured surface (red).

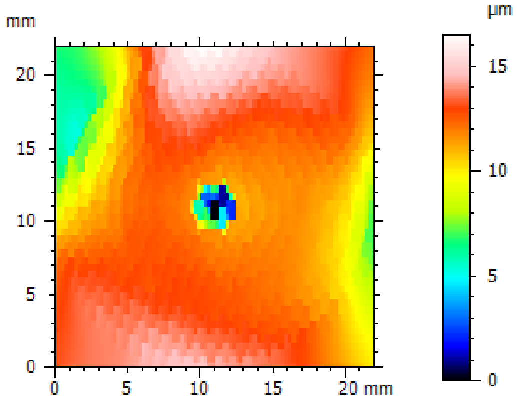


**Figure 10.** Fused silica form deviation map. PV Irregularity: 16.490 µm.

***3.3 Sub-surface damage***

One of the defining characteristics of glass machining processes is the amount and depth of sub-surface damages (SSD) the process induces into the machined surface. These are unavoidable because of the brittle behaviour of these materials. But since these SSDs absorb and scatter light, they reduce the quality of the optical element. If these optics are used for high energy laser applications, SSDs are able to absorb high amounts of energy, which can lead to the destruction of the optical element.

The classic approach for measuring SSDs is to polish a ramp of several micrometers into the surface, etch the surface with hydrofluoric acid, to open even tiny invisible cracks and then evaluate the visible cracks. An example of past plano samples that were measured in this way are depicted in Figures 11 and 12. Figure 11 shows the measurement of the whole surface for referencing the depth analysis of the polished ramps. Figure 12 shows the microscopic image of one of the ramps. This method is time consuming and destructive. Nonetheless all initial evaluation processes in the past were performed in this way.

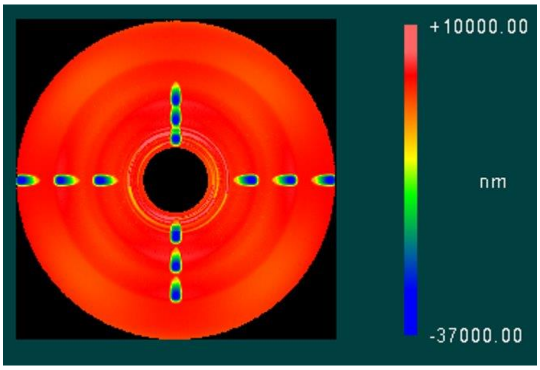


**Figure 11.** Surface measurement of a plano test sample with several polished ramps for SSD analysis.

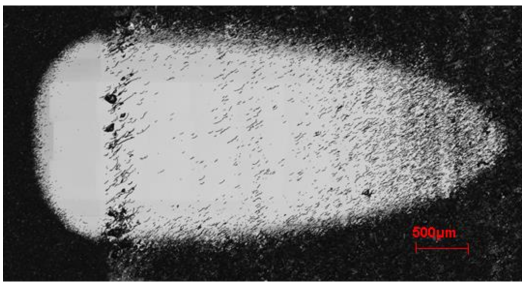


**Figure 12.** Microscopic image of a polished ramp with visible cracks (SSD).

To improve the measurement speed and process, a non-destructive SSD analysis method was developed, which was used for later SSD measurements of the optics introduced in this paper. The OCT measurement system was introduced by Schwoerer *et al*. [4].

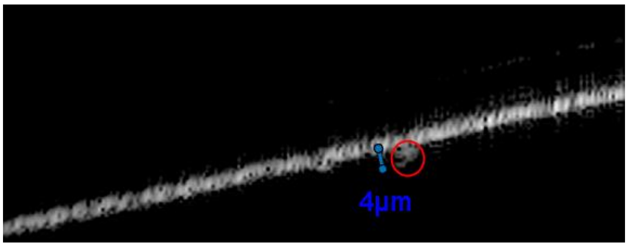


**Figure 13.** OCT Measurement, one scanning line of the BK7 optic. All SSDs are <4 µm, SSDs are depicted as grey dots below the white surface.

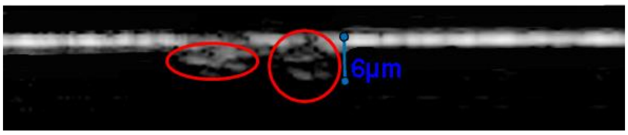


**Figure 14.** OCT Measurement, one scanning line of the fused silica optic. All SSDs are <6 µm, SSDs are depicted as grey dots below the white surface.

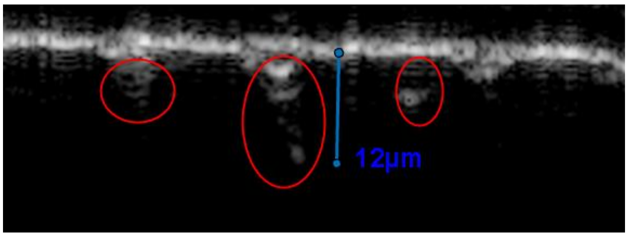


**Figure 15.** OCT Measurement, one scanning line of the fused silica optic that was fine ground. All SSDs are <12 µm, SSDs are depicted as grey dots below the white surface.

Even though the setup is still in an experimental state, comparative measurements show the great potential of this system. The intensity plots show a greyscale picture. Two examples of measurements of the discussed freeform optics are shown in Figures 13 and 14. Most of the intensity comes from the surface of the measured optic, so it is represented as a white line. Some grey lines or blobs, that go over into the material represent the measured SSDs. Via greyscale analysis the amount and depth of the SSDs is evaluated. The process presented in this paper leaves only SSDs of less than 4 µm in BK7 material and less than 6 µm in fused silica material respectively. These are very good results compared to grinding and even fine grinding of optics of these materials. Figure 16 shows a OCT Measurement of a fine ground freeform optic. The amount of SSDs are higher and the SSDs are up to 12µm deep.

### *3.4 Visual aesthetics*

Both freeform designs appear to be transparent/clear to the naked eye when machined using laser assisted machining. The visual appearance of the freeform surfaces are shown in Figure 16.

**Figure 16.** Schott N-BK7 (left), Fused Silica (right)

In Figure 17 there is a comparison of microscopic images of a glass surface "cut" by diamond tunrning without laser assistance on the one hand and the glass surface of the fused silica freeform on the other hand. Without the laser there is no defined cutting process visible. At the surface level there are just glass chunks torn out of the surface. The laser assisted diamond turned surface is a lot smoother. There are still surface damages visible, but they are a lot smaller in size. These are the defects that are measured by the OCT. In the OCT measurement in Figures 13 and 14 there are both little dents in the surface as well as some cracks that lead from those dents.

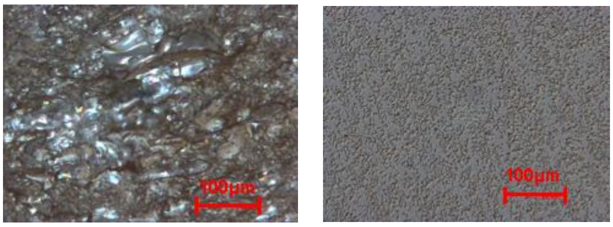


**Figure 17.** Microscopic images of glass surfaces. To the left diamond turned surface without laser assistance, to the right laser assisted diamond turned surface.

## 5. Conclusion and discussion

Laser assisted machining of optical glass could be an important avenue in the fabrication of precision freeforms with the aid of an ultra-precision CNC machine. Previous examples in the use of laser assisted machining technology for infrared materials as well as fabrication of precision glass aspheres have shown tremendous promise. This paper has demonstrated the capability and need to extend the capability further to freeforms. An optimized form irregularity of 16 µm was readily obtained without the ability to further correct because of the lack of on site 3D freeform form metrology. A future study shall be conducted with the ability to measure and correct form during diamond turning. We hypothesize the ability to correct measured form will result in being able to generate a total form deviation <1 µm. This paper also demonstrates the quality of the optical surface after laser assisted machining. Surface roughness values below 90 nm and SSDs below 6 µm were readily produced on two different glass types, which only need limited polishing to be finished. Since polishing usually is a process step that enhances surface quality but loses form accuracy, reducing polishing time produces optical surfaces with higher form accuracies.

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