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OCT system for the detection of Subsurface Damage in glass-substrates

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Abstract

The manufacturing process of high-tech optics for semiconductor manufacturing, space or military applications poses many challenges. One of them is a class of hard to detect defects called Subsurface Damage (SSD). This refers to microscopic defects beneath brittle material surfaces, often occurring because of mechanical stresses during manufacturing. Conventional methods, such as microscopy, are inadequate for SSD detection. The prevailing quantification technique [1,2], hydrofluoric acid etching and subsequent microscopy, is destructive and cannot be applied on the original high-value optic.

We propose a non-destructive solution - Optical Coherence Tomography (OCT).[1] OCT is a cross-sectional imaging technique offering high resolution and high sensitivity, presenting an opportunity to replace destructive SSD assessment methods. Our research focuses on enhancing the sensitivity of a high-speed OCT system while preserving rapid imaging capabilities. We conducted multiple experiments to evaluate the sensitivity within the OCT system under different configurations, such as the influence of optical power output and imaging rate. The results of these experiments are promising. Operating at its maximum imaging rate, the system demonstrated a sensitivity of up to 120 dB. This outcome shows the potential of this system as an effective tool for non-destructive SSD detection and quantification in high-value optics. Additionally, it may have the capability to detect other defects such as bubbles or impurities in similar materials.

In summary, our research highlights the necessity for non-destructive SSD detection methods in high-tech optics manufacturing. The development and optimization of our high-speed OCT system showed promising results. Achieving this notable level of sensitivity at a high imaging rate opens new possibilities for elevating the quality and reliability of high-value optics in critical applications such as semiconductor manufacturing and space exploration.

Subsurface Damage (SSD), Optical Coherence Tomography (OCT), Imaging rate, High-sensitivity

1. Introduction

Manufacturing high-technology optics for critical applications, ranging from semiconductor manufacturing to space and military applications, presents many challenges. Among these challenges lies the detection of a particular class of defects known as Subsurface Damage (SSD). SSD refers to tiny faults directly underneath the surface of a material, a consequence of stresses introduced during the mechanical processing of brittle materials such as glass or ceramics. SSD is introduced during most conventional manufacturing methods of modern optics. [2,3]

Understanding and measuring the extent of Subsurface Damage in modern optics is important for several reasons. SSD can exert a significant impact on the performance and longevity of optics. This impact stems from the unique characteristic of SSD to scatter and absorb light, leading to compromised image quality and reduced light throughput. In applications involving high-energy lasers, the presence of SSD can even lead to catastrophic failures of optical components. [4] Accurate measurement of SSD within optics is indispensable for ensuring compliance with industry standards related to reliability and lifespan, ultimately contributing to enhancing of the manufacturing process.

The quest to speed up manufacturing processes forms the core motivation for the high-tech optics industry. The existing challenge lies in the inherently destructive nature of current measurement methods, rendering it impossible to measure optics intended for use in end products. The lack of precise information about the remaining SSD in optics post-grinding necessitates the incorporation of large safety margins during the final polishing phase. The absence of a reliable, non-destructive method for SSD measurement has resulted in prolonged final polishing processes, sometimes extending days or even months.

This gap in knowledge and methodology underscores the critical need for a reliable technique to measure SSD in optics production. Such a method has the potential to accelerate final polishing processes, leading to reduced machining time and costs while simultaneously augmenting throughput.

In this paper, the primary objective is to present a comparison between Optical Coherence Tomography (OCT) and the well-established destructive method of Magnetorheological Finishing (MRF) spot polishing to detect Subsurface Damage (SSD) in optics. The goal is to showcase the development of an OCT system that produces measurements correlating with the outcomes of the established MRF spot polishing method. This comparison aims to highlight the potential of OCT as a reliable and non-destructive tool for SSD characterization, while highlighting the correlation between its measurements and those obtained through the widely used MRF spot polishing method.

2. Materials & Methods

Glass discs composed of the optical material NPK51 (SCHOTT) were chosen as samples for this study. NPK51 was selected based on the fact, that destructively tested glass samples could be supplied by the company Carl Zeiss. The chosen glass discs had a standard diameter of 80 mm and a thickness of 8 mm. To ensure uniformity, the samples underwent a precision grinding process at Zeiss, reducing surface irregularities to ± 1.5 µm. This step was crucial to establish a consistent baseline for subsequent procedures. The NPK51 sample is shown in Figure 1.

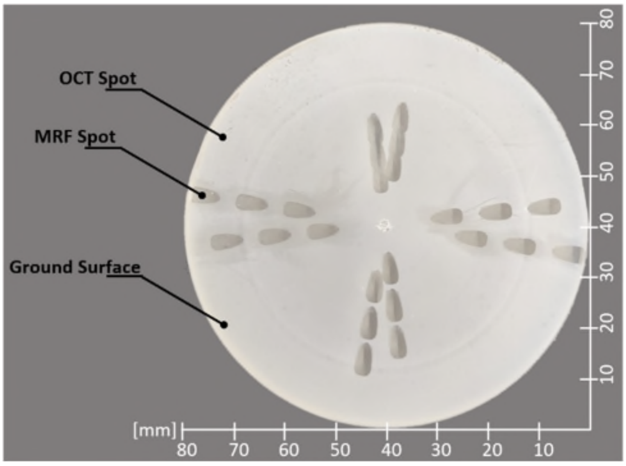

Figure 1. Image of the NPK51 glass sample with polished and etched MRF spots for the SSD analysis.

The reference SSD measurement was conducted using a well-established combination of Magnetorheological Finishing (MRF) polishing and hydrofluoric acid etching. MRF was chosen as the primary polishing technique due to its ability to achieve nanoscale precision and to not introduce additional Subsurface Damage into the sample. With the MRF polishing process, 24 spots were polished into the glass surface, as depicted in Figure 1. The hydrofluoric acid was then applied locally to each spot to preserve portions of the original surface for reference purposes and subsequent Optical Coherence Tomography (OCT) measurements.

For the OCT measurements a custom build system, engineered for the measurement of Subsurface Damage was chosen. Developed in-house, based on previous research, this system offers a lateral resolution of 800 nm, an axial resolution of 1 µm, and a sensitivity of 115 dB.[5] In contrary to the MRF method, this system also offers high-resolution 3D tomographic measurements. The used OCT system, a resolution test as well as an example of a 3D tomographic OCT image are shown in Figure 2.

Post-OCT data acquisition, the obtained raw data was processed to enhance the image quality of the OCT scans. Initially, the OCT data was processed in MATLAB to correct for dispersion and compensate the material refractive index.[6] Correction of the systems dispersion was crucial for minimizing distortions in the acquired data and compensation of the material refractive index was essential for accurate depth profiling.

Subsequently, the processed OCT data was rendered into a high-resolution 3D volume, providing a detailed representation of the internal structures of the modified glass samples. The rendering process allowed for a comprehensive visualization of subsurface features and damage.

The location and depth of subsurface damages was then established using the open source image processing tool ImageJ.[7] This involved an iterative process where cross-sections of the 3D volume were analysed.

These analytical steps were essential to extract meaningful information about the distribution and characteristics of subsurface damage, contributing to a thorough understanding of the effects of the surface modification techniques applied in this study.

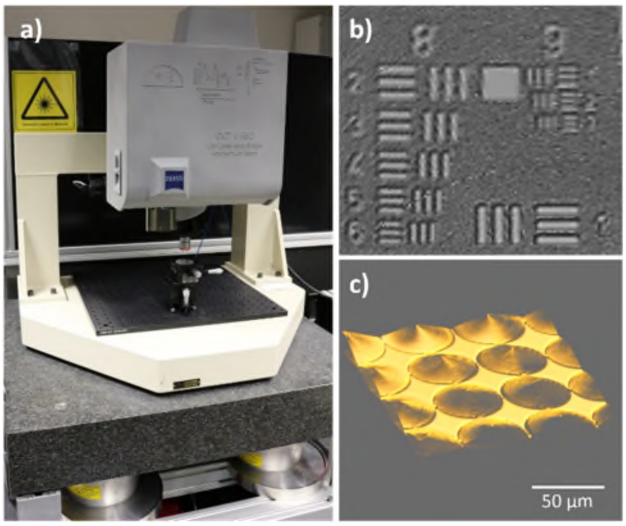

Figure 2. (a) image of the custom build OCT system. (b) OCT measurement of a USAF target showing G9E3 (linewidth 800 nm). (c) 3D OCT image of a microlens array created with a Nano scribe 3D printer (lens height 8 µm, lens diameter 50 µm).

3. Results

The depth profile of Magnetorheological Finishing (MRF) spots was initially measured using an optical profilometer (Taylor Hobsen, Luphoscan 420 HD), providing a baseline for the following SSD analysis. The measured profile is shown in Figure 3

To analyse the Subsurface Damage within the MRF spots, high-resolution images were captured and stitched together using a microscope (ZEISS Axio Imager 2). Figure 3 shows the resulting image of the MRF spot. The SSDs as revealed by etching can be seen as black dots within the MRF spot.

Quantitative assessment of the SSD was achieved by counting the amount of SSDs and mapping them to a depth based on the previous profilometer measurement. The compiled data was organized into a chart (see Figure 4) depicting the amount of SSD per depth.

The analysis of the compiled data revealed a predominant concentration of Subsurface Damage within the initial 10 µm beneath the surface. A subset of damages extended to greater depths, with some reaching as far as 14 µm. The measurement process using the MRF method typically requires approximately 2 hours for both the polishing and etching stages. However, due to limited machine availability, waiting periods of up to 12 weeks are not uncommon.

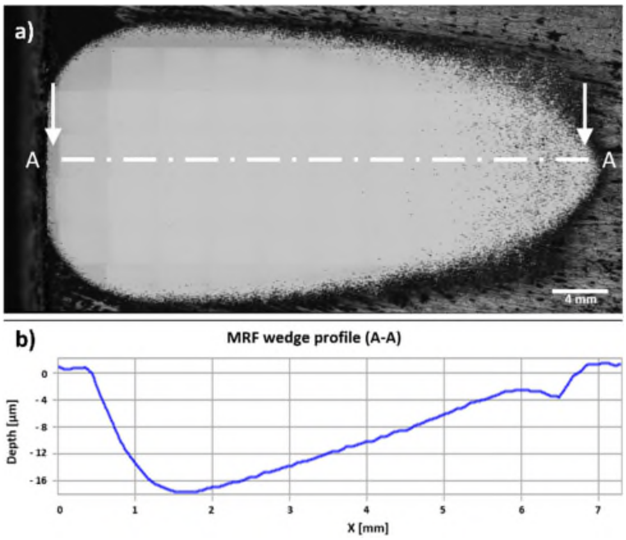

Figure 3. (a) microscopy image of the hydrofluoric acid etched MRF spot. (b) graph showing the depth profile of the MRF spot.

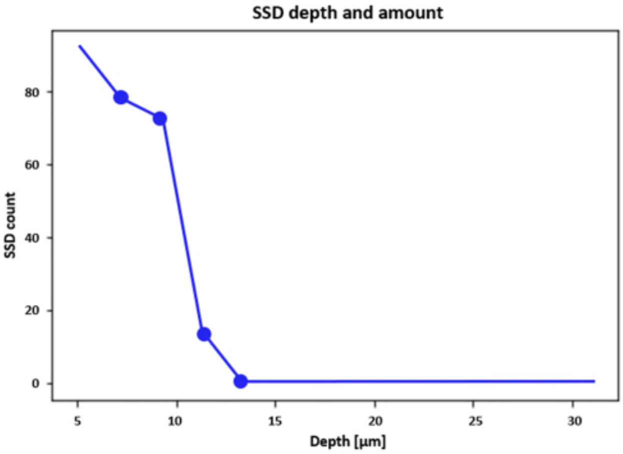

Figure 4. Graph showing the result of the MRF method as SSD amount over the measured depth.

The OCT measurement was performed next to the MRF spot on the untreated surface of the NPK51 sample. The acquired data was first analysed in a cross-sectional manner as shown in Figure 5. With this process a maximum SSD depth of 16 µm was measured. Similar to the MRF analysis, the OCT data also showed that the majority of the damages lie within the first 10 µm underneath the surface of the sample. Both the deepest crack with 16 µm as well as the mainly damaged zone from 0 to 10 µm can be seen in Figure 5. The full scan, rendered as 3D volume of the OCT data is shown in Figure 6. This image shows the bottom view of the sample with the SSD protruding in the positive y-direction. This image also shows the deepest damages at a depth of 16 µm. The SSD measurement using OCT including data processing and analysis took only a few minutes.

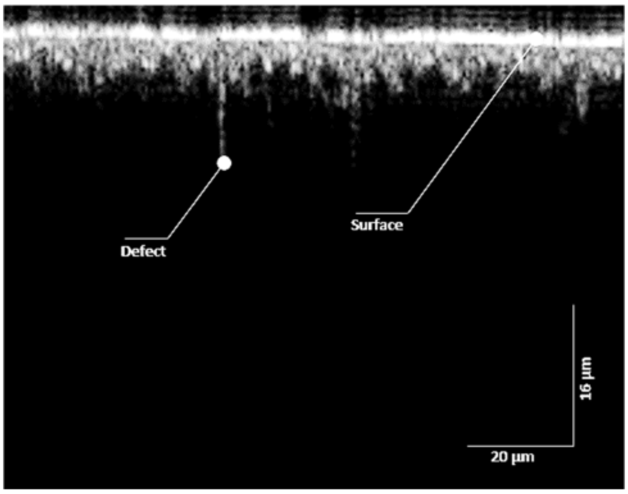

Figure 5. Cross-sectional OCT scan of the NPK51 sample, showing the sample surface and SSD defects up to a depth of 16 µm.

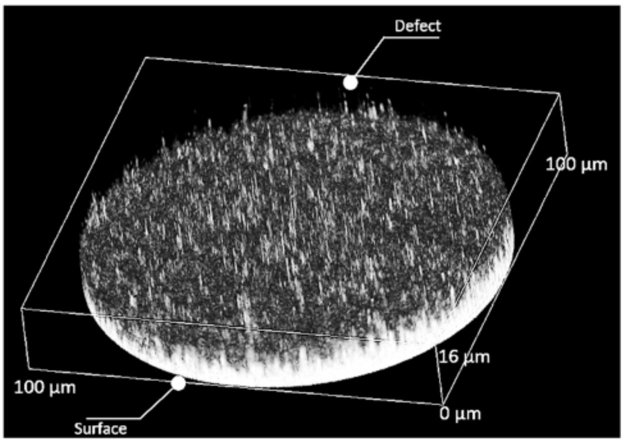

Figure 6. Bottom view of the NPK51 sample rendered OCT data.

4. Discussion

The identification of Subsurface Damage (SSD) in glass materials remains a challenging task, with only a limited set of methods available, none of which are non-destructive. In this context, Optical Coherence Tomography (OCT) has emerged as a highly promising technique, offering a non-destructive and contactless way to precisely image SSD in transparent materials.

The conducted research specifically aimed at assessing the capabilities of OCT in detecting SSD within a defined size range, showcases its effectiveness for a size range of up to 20 micrometres. The results highlight OCT's potential as a valuable tool for identifying and characterizing Subsurface Damage in glass materials with a high degree of precision.

One crucial observation from this study is the consistency in results between OCT and the currently established measurement method, such as Magnetorheological finishing (MRF). This agreement between these two distinct techniques strengthens the reliability of OCT in detecting and characterizing SSD.

The small difference in the measured maximum depth may be attributed to the inherent nature of the different measurement methods. OCT, with its non-destructive characteristics, provides detailed volumetric measurements without causing harm to the investigated material. On the other hand, MRF, while effective, only analyses a very small portion of the sample, potentially leading to variations in results. The ability of OCT to capture a full volume of the sample might explain the observed discrepancy in measurements.

5. Conclusion

In conclusion, the research demonstrates the potential of Optical Coherence Tomography (OCT) in detecting Subsurface Damage (SSD) within a specific size range in glass materials. The non-destructive nature of OCT sets it apart from existing methods, providing detailed volumetric measurements without compromising the integrity of the material under investigation.

The agreement in results between OCT and established SSD metrology methods, such as Magnetorheological finishing (MRF), underscores the potential of OCT in SSD detection. While a difference for the maximum SSD depth between the measurements obtained from MRF and OCT is noted, it is hypothesized that OCT's ability to analyse a full volume of the sample contributes to this variance. This distinction highlights the importance of considering the measurement method's characteristics and limitations when interpreting results.

Overall, the findings suggest that OCT could become a cornerstone in the measurement of SSD, potentially establishing itself as the future standard in this domain. Its non-destructive nature, applicability to high-value optics, and independence from reliance on manufacturing samples contribute to its potential as a versatile and reliable method for SSD detection in various glass materials.

Looking ahead, the system will undergo continuous development aimed at further improving image quality, resolution, and imaging speed. Additional experiments will be conducted to generate more data regarding the correlation between OCT measurements and already established SSD measurement methods. Furthermore, it is planned to expand the class of materials the system is capable of measuring, including, for example, polymer optics. These future endeavours aim to enhance the system's capabilities, broaden its applicability, and contribute to the advancements in non-destructive SSD detection.

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