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Scratch healing with CO2 Laser on fused silica for surface repair

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Abstract. To prevent the disposal of minimally damaged lenses that fall outside the acceptable scratch and dig tolerance levels, an experimental study was conducted to repair mechanical scratches on a fused silica surface. The scratches were created using a diamond tip and then repaired using a CO_2 laser. Various loads on the diamond tip and laser output power were tested. The transmission changes and subsurface damages were analysed. The surface quality analysis was performed using a white light interferometer, while the subsurface damage analysis was performed using optical coherence tomography. Local absorption differences can be quantified using photothermal deflection. To significantly enhance local transmittance, brittle and ductile scratches of various depths have been successfully healed.

1 Introduction

Surface imperfections such as mechanical scratches on optical lenses have a severe impact on the lens' performance. If a lens cannot meet the quality standard after the polishing process, the lens must undergo a successive polishing process, which can be time and cost intensive. Finished lenses with small subsurface damages (SSD) and mechanical surface imperfections (below the quality standard) could undergo a local laser beam polishing process to remove the scratches. The topic has been the subject of numerous scientific studies dealing with various materials for several years. The application of laser polishing in industrial production was made easier by the development of specialized machinery [1]. There is an extensive literature on surface treatment, with a focus on glass polishing with laser radiation, shown in publications such as [2], [3], [4] and [5].

In this experimental study we investigate the removal of mechanical scratches made with a diamond tip on fused silica with laser radiation. The laser heats up the material locally, enabling the material to flow und level out the imperfection. In this particular case, the sharp edges of the scratches get melted forming a smoother surface finish with enhanced transmission. For the detection of SSD photothermal deflection (PTD) and optical coherence tomography (OCT) measurements were performed to verify existence and depth of the occurred SSD. The PTD measurements are conducted as described in [6] to detect mechanically formed SSD on fused silica.

2 Experimental setup

The experimental setup for the laser polishing consisted of a CO_2 laser (10.6 μm) with a max cw output power of 120W. The laser output was stabilized, and the output power can be varied by with an acousto-optic modulator. The collimated laser beam was adjusted to a diameter of 8.4 mm ($1/e^2$) and guided into a galvo scanner. With an F-Theta lens the beam is focused to a fixed distance. The substrate is clamped onto a rotation stage, which is mounted onto a movable platform. The working distance between the substrate and the galvo scanner can be adjusted with a vertical motorized linear stage. The diamond scriber was mounted on to the platform to hold the position of the diamond tip constant relative to the substrate. Different weights could be attached to mounting setup to vary the force on the diamond tip. The working distance between the focused laser beam and the substrate was set to obtain a diameter of 4 mm ($1/e^2$) on the substrate surface. The laser output power was determined experimentally and set to approx. 45 W to prevent ablation and to reduce thermal load on the material which could lead to more damage e.g. lateral cracks in the vicinity of the scratch path. The rotation speed of the rotation stage is set to have a constant relative speed of approx. 5.25 mm/s between the tip and the substrate. The diamond scriber was mounted with a rake angle of approx. -20° to the substrate and the laser spot was positioned on the scratch path behind the diamond tip, to heal the created scratch as shown in Fig. 1.

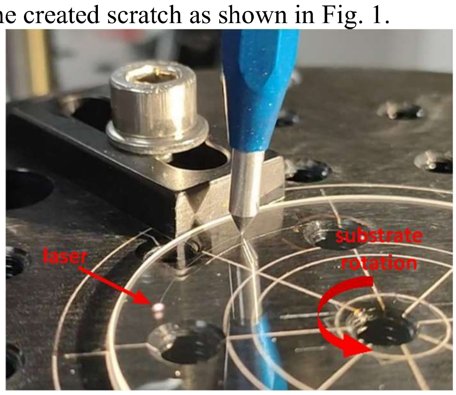

Fig. 1: In situ image of scratch and heal process on fused silica substrate.

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3 Proceeding

The experiments were conducted as follows: The weights were loaded onto the diamond scriber setup to obtain the desired force. Then the parameters for the laser system such as laser power, beam position and rotation speed in respect to the scratch radius were set. After that, the diamond tip was lowered onto the substrate. The rotation stage was turned continuously while the laser was switched on and off. This enabled to verify how efficient the laser healing process with the specific parameters was. The experiments were repeated with different forces on the diamond tip.

The scratches were examined first with a microscope for an overview and to check for unwanted irregularities. The surface roughness and the scratch depth were then measured with a white light interferometer (WLI) and with OCT to detect and quantify SSDs. These OCT measurements are used to correlate with the SSD results obtained with PTD. PTD measurements provided data over the local transmission changes around the scratches.

4 Surface roughness results

The microscope investigations revealed, that inclusions could be observed particularly in scratches that were produced with larger force on the diamond tip. Those samples contained major surface damage as seen in Figure 2. Scratches produced with less force only left minor inclusions on the scratch path behind as shown in Figure 3.

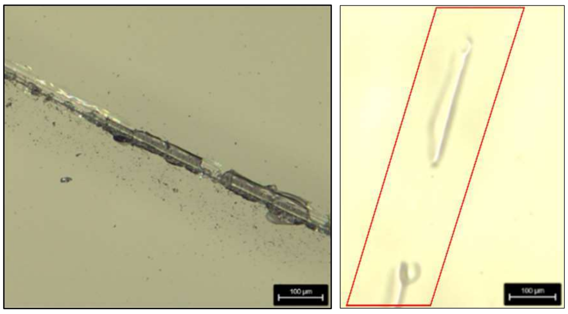

Fig. 2: Microscopy images of scratches created with a force of 1.8 N (left) and laser healed scratch path (right) containing visible inclusions (red box).

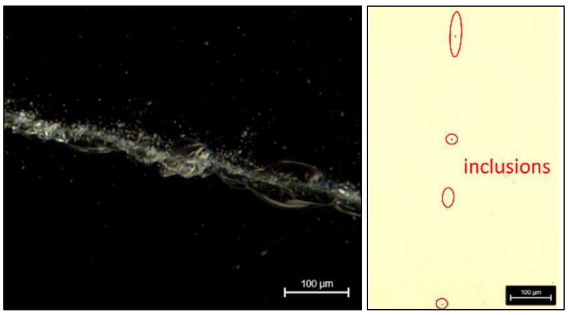

Fig. 3: Microscopy image of scratch formed with 1.1 N of force on diamond tip (left) and laser healed scratch with small inclusions barely visible along the scratch path (right).

WLI measurements were taken of areas approx. 700 µm by 700 µm to obtain S_q and S_z values listed in Table 1. The substrate's initial surface roughness was specified with R_a <1 nm by the substrate manufacturer.

Table 1: WLI measurements results of the scratches

Force on diamond tip [N]	Laser On/Off	Sq [µm]	Sz [µm]
1.8	Off	0.68	13.03
	On	0.19	2.22
1.4	Off	0.46	11.33
	On	0.08	0.82
1.3	Off	0.41	27.23
	On	0.03	1.13
1.1	Off	0.45	16.05
	On	0.03	0.39

5 Conclusion and future work

The preliminary results from the microscope and the WLI measurements showed that even scratches in an extreme form can be healed to some extent. The OCT results, however, show that SSD still exist below the laser-processed surface. Only the Top few microns were fused and sealed the surface. This might be due to the fact that the CO_2 laser beam does not penetrate the material deep enough for complete SSD removal. The results from the transmission and PTD measurement also revealed the existence of residual SSD. In the absence of SSD, transmission could be improved. Further tests with less scratch damage demonstrate better healing performance, though the process window for laser healing is very narrow and requires exact process control.

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