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Pre-heating by defocusation of the CO_2-Laser polishing beam: an experimental report from the lab-floor -INVITED

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Abstract. The laser beam polishing for glass and plastics is a purely thermal process and melts the ground or lapped structures to a depth of limited extent. This results in a smoothing of the surface, whereby the 1st - 4th order shape deviations can be corrected very well and transparent surfaces are created. The process is excellently suited for quartz glasses and other optical glasses with a low coefficient of expansion α. Furthermore, thermoplastics or metallic molds for injection molding and precision molding applications can also be polished with the laser beam. On the other hand, special measures are required for glasses with a high α, e.g. preheating of the component. For the investigations, a defocused laser beam was used for the defined preheating of glasses with high linear expansion coefficients. After reaching the material-specific preheating temperature, the laser beam was focused and the polishing process started. A defined cooling process follows again with a defocused beam. In this way, a ground biconvex lens made of boron crown glass was successfully polished. The laser-polished surfaces have an RMS value of 1- 3 nm. The polishing process can be used very flexibly. Likewise, very differently shaped optical components can be polished.

The newly developed polishing regime is transferable to other optical glasses with high linear expansion coefficients.

1 Introduction

Thermal polishing processes represent a special form of interaction on optical surfaces. Two processes, laser polishing and plasma polishing, are suitable for this form of energy input to smooth optical functional surfaces. A microwave-excited Ar/He plasma jet can be used to smooth finely ground and lapped surfaces in relatively short process times. Average plasma powers of 100 W-150 W are required to achieve a temperature of approx. 1600 °C on the glass surfaces as a result of thermal heating. This temperature range is required for smoothing the high-melting quartz glasses. [1]
Laser polishing of glasses is also a purely thermal process and melts the surface structure to a limited depth. Due to the reduction of the viscosity in the near-surface zone to approx. $\eta = 2$ - 3 dPa-s, flow occurs in the depressed zone. This flowing and rearrangement of material fractions leads to a smoothing of the surface. [2] In [3] and [4] the polishing process could be developed very successfully for fused silica. Micro-roughnesses comparable to those of mechanical polishing were produced. An important process parameter is the temperature as well as the temperature distribution. In [5] simulation results for the temperature distribution during laser polishing were presented, which allow to derive important process models. The shape correction and polishing of optical functional surfaces with laser radiation could also be successfully demonstrated in the works [6] and [7]. However, a process disadvantage is the formation of mid spatial frequencies, which are somewhat more pronounced compared to conventional polishing processes. [8]
Mostly, laser polishing investigations are carried out for glasses with a low coefficient of thermal expansion. These glasses, such as fused silica and borosilicate glasses, are very suitable due to their high thermal shock resistance. Glasses with a high coefficient of thermal expansion, on the other hand, require special measures to be able to polish them with the laser beam. This polishing process and the results obtained are presented below.

2 Material properties and experimental setup

For the laser polishing process, the knowledge of the material parameters softening point, thermal shock resistance is a prerequisite to determine the required polishing temperature. Table 1 shows these parameters for three different types of glass. These are very different for the three glasses to be processed. The low thermal shock resistance of borosilica and boroncrowns glass makes it necessary to take special precautions for the polishing process.

Table 1. Relevant material parameters for laser polishing.

Parameter	Fused silica	Borosilica (BF33)	Boron crowns glass (BK7)
Softening point	1660°C	820°C	719°C
thermal shock resistance	2292 K	338 K	133 K
Process temperature	1950 – 2000 °C	1150 – 1350 °C	1150 – 1350 °C

Figure 1 shows the basic temperature-time curves for thermal forming processes, e.g. precision molding. The typical curves show three areas, preheating, forming and postheating. In particular, the postheating region determines the residual stresses remaining in the glass

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volume.

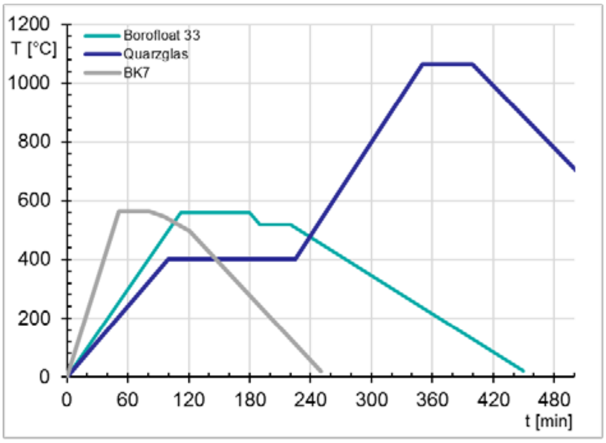

Fig. 1. Temperature-time curves for different glasses.

Due to the low thermal shock resistance of most optical glasses, the glasses must be heated to the softening point by a controlled temperature-time curve. This is necessary so that the glass does not exceed the critical range of internal stresses during the polishing process. In the investigations carried out, a defocused laser beam is used for the preheating phase in order to distribute the line energy over a larger volume of material. This prevents the glass sample from heating up too quickly and the risk of breakage. Figure 2 shows the range of beam defocusing required.

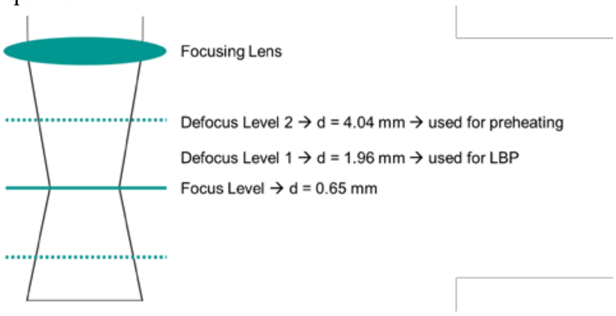

Fig. 2. Defocusing setup of the CO_2 laser beam for preheating

To achieve fast switching between the focused and defocused beam, a 3D scanner with dynamic z-position control can be used.

During the laser-based processes, the influence of the following parameters is investigated:

- preheating temperature [°C]
- values of laser power [W]
- values of scanning speed [$m \cdot s^{-1}$]
- laser scanning strategies.

Finally, the influence on the following output parameters is examined:

- process temperature [°C]
- contour width and length
- surface and edge quality
- state of thermal stress.

3 Experiments and Results

In the experiments conducted, the focus was on processing the glasses that have a low thermal shock resistance value. These must be specifically processed through the 3 phases of (1) preheating, (2) laser beam polishing and (3) postheating. Figure3 shows a typical temperature-time curve used for laser beam polishing of boroncrown glass. This functional curve was recorded with a special pyrometer suitable for the material glass.

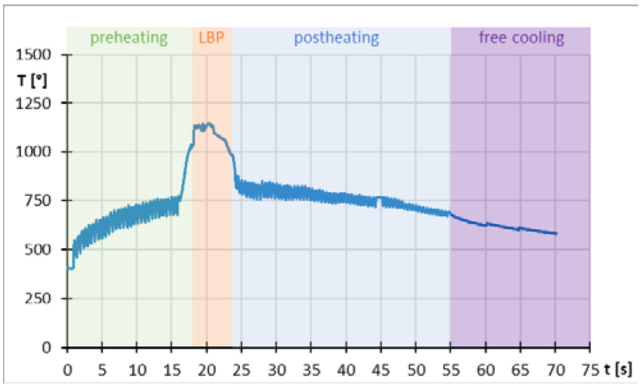

Fig. 3. Temperature-time curves for boroncrown glass (BK7)

The comparison of the T-t-function of boroncrown glass to the temperature-time curve of fused silica is illustrated in Figure 4. The comparison shows very clearly the considerably longer process times for pre- and postheating in the case of boroncrown glass.

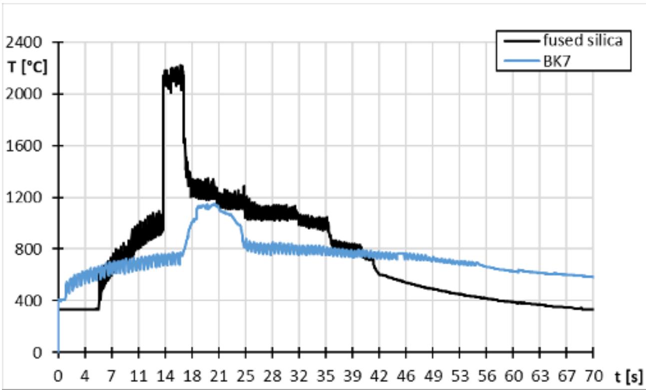

Fig. 4. Temperature-time curves for glasses with with high and low thermal shock resistance

Depending on the optical component to be processed, suitable scanning strategies and temperature-time function must be selected. Figure 5 compares thermographic images during the three phases using the example of a convex-concave lens with a diameter of 30 mm.

The scan direction and scan strategy for this example were chosen to allow the lens to be heated as homogeneously as possible by scanning in a meandering. The lens support was provided from a plate of fused silica.

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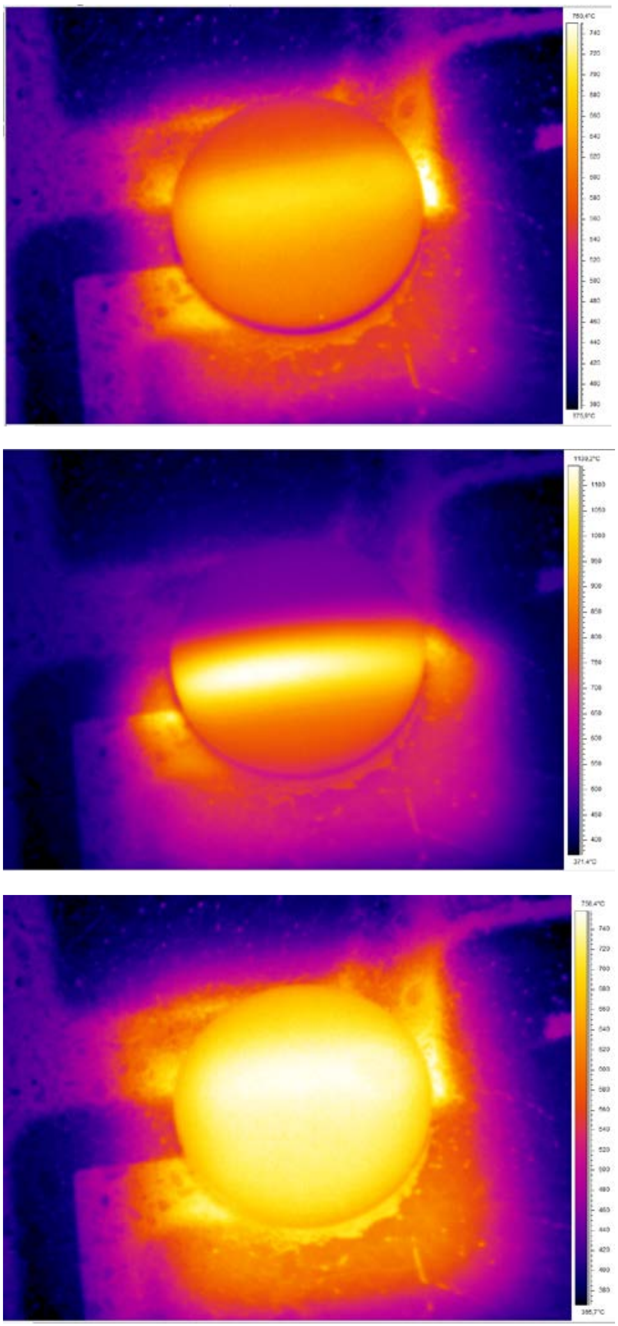

Fig. 5. Thermographic images during the three phases.
a) preheating, b) laser beam polishing and c) postheating.

Compared to mechanical-chemical polishing processes, laser polishing does not produce any disturbing edge effects.

Figure 6 shows the achievable micro-roughnesses for boroncrown glass BK7. The values were recorded according to DIN standard 4287 using two different measuring methods. Polishing with different line energies of the laser radiation was investigated. For the optimum parameter set (value 11), RMS values of less than 1 nm are obtained.

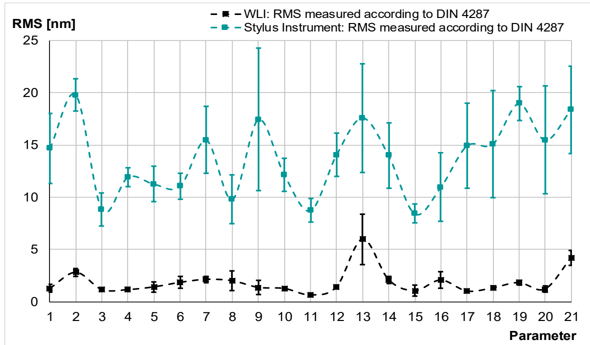

Fig. 6. Representation of the measured roughness values as a function of the parameter sets for the change in line energy.

Further information on the shape deviation, waviness and roughness parameters is provided by the PSD functions in Fig. 7. The measurement results were recorded for two phases. Firstly, after preheating and secondly, after postheating. As expected, significantly higher values are illustrated by the curve after the preheating phase. The increased mid spatial frequencies values after postheating, which are typical for the laser polishing process, can also be seen.

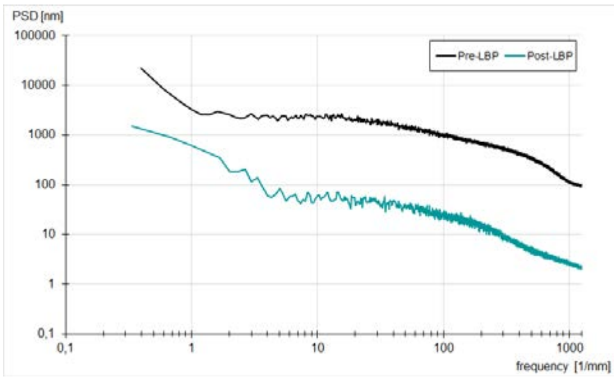

Fig. 7. Power spectral density functions for BK7 after preheating and postheating.

Fig. 8. Functional proof of the laser-polished convex-concave lens.

During the experimental investigations, the laser polishing results were applied to different optical geometries. Figures 8 and 9 illustrate two selected optical components made of broncrown glass.

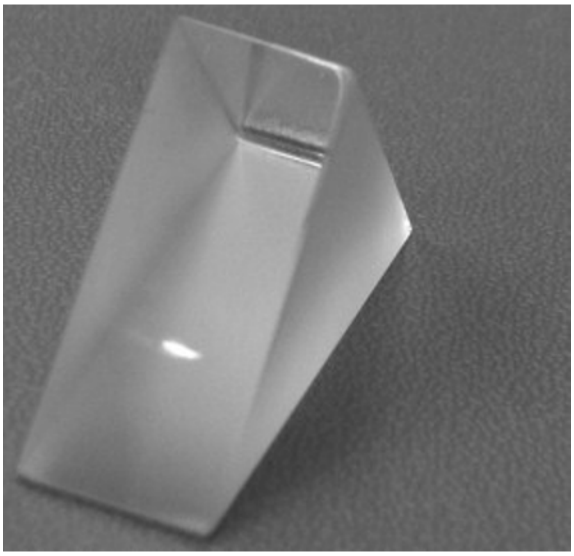

Fig. 9. Functional verification on a laser-polished prism.

The laser polishing process presented can also be used in principle for structured or almost arbitrarily shaped surfaces. However, the angle of inclination between the laser beam and the glass surface should not exceed 45°. Figure 10 illustrates an array structure with rectangular domes that could be polished with shape retention.

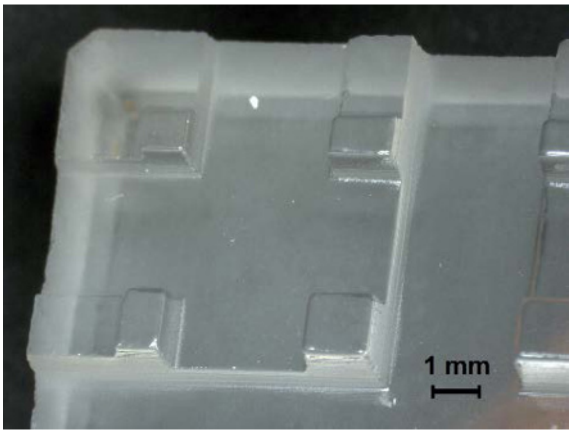

Fig. 10. Functional verification on a laser-polished array structure.

4 Conclusion and Outlook

The presented investigations allow the use of the laser polishing process also for glasses which have only a low thermal shock resistance. A prerequisite is the determination and optimization of the phases preheating, laser polishing and postheating. This can be done advantageously with the rapid variation of the laser beam diameter.

Fig. 11. Laser polishing of a biconvex lens made of Boroncrown glass (BK7).

In further investigations, the aim is to extend the process to other optical glasses, such as flint glasses.

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