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Laser polishing of fused silica

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Abstract

A novel process for polishing fused silica involving CO_2 laser irradiation is presented. This technique can reduce the roughness to Ra < 10 nm and provide processing rates for polishing of fused silica samples up to 1 cm²/s. The CO_2 laser irradiation is absorbed in a few tens of microns in the silica sample. Therefore, the laser irradiation is used to heat up a thin surface layer close to the evaporating temperature without causing material removal. The heating lowers the viscosity in the thin layer. The roughness flows out due to the surface tension and the sample is polished. The samples are preheated to reduce thermal stresses and to avoid cracks. The residual birefringence can be reduced to 5 nm/cm by tempering, which is usual for standard optics.

Keywords: polishing, glass, laser polishing, fused silica

1 Introduction

Polishing of optical components is a time consuming process. In this paper new results for polishing fused silica with CO_2 laser radiation are presented. This technique can reduce the roughness of a sample with initial Ra=100 nm to Ra<10nm. The experiments show that micro defects can be efficiently removed. This leads to higher thresholds of destruction [1].

Different processing times gain different polishing results. Additionally the polishing result can be influenced by different preheating temperatures. The dependence of the polishing result on the processing rates and the preheating temperature and a strategy to improve the best polishing results is presented.

The samples are tempered afterwards to avoid thermal cracking and birefringence. The birefringence and the distortion of the laser-polished samples before and after tempering is measured.

A great advantage of laser polishing is the processing time: such times of up to 1 cm²/s can be achieved. Compared to conventional techniques this is faster by a factor of >10. In comparison with conventional processes laser polishing of fused silica is very flexible. The process is adaptable to most geometries. For future work the process shows great promise especially for polishing of free-form surfaces.

2 Procedural principle

The CO_2 laser radiation is directed on the surface of the sample. The diameter of the laser beam is about a few millimeters. The laser radiation is directed on the glass surface and is absorbed in a thin layer of 10-30 µm. The viscosity of this thin layer is reduced to about 10^4Pa·s at a temperature of 2200°C which is very close to evaporating temperature. Due to the low viscosity in the thin layer the glass can flow. The roughness is reduced by the surface tension. Higher process temperatures are not desired because evaporation induces material removal has to be avoided. Holes or other surface deformations may be formed. The polishing parameters presented refer to polishing without material removal.

A sketch of the procedural principle is shown in **Fig. 1**.

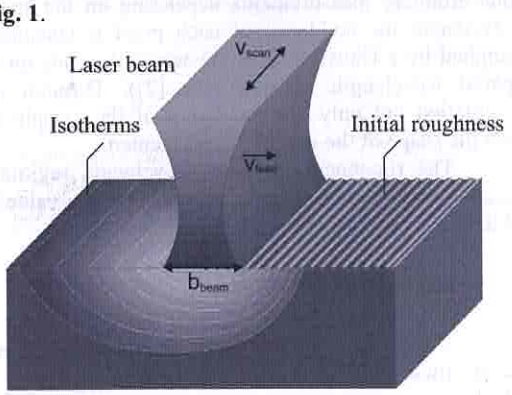

***Fig. 1:** Procedural principle of laser polishing of fused silica*

The area rate FR which is the polished area per time of a polishing process can be calculated by:

$$FR = v_{feed} \cdot b .$$

The interaction time of the material with the laser radiation can be calculated by:

$$t_W = \frac{b_{beam}}{v_{feed}} .$$

The most important process parameters are the laser power, the size of the laser beam, the size of the

scanned field, the interaction time of the laser beam and the material, the temperature to which the samples are preheated and the scanning speed. Some of those are interdependent process parameters and cannot be treated alone. Besides those process parameters the size of the samples is important for the polishing process.

CO_2 laser with a maximum output power of 600W is used for the experiments. The laser beam is guided by a laser scanner which can reach scanning speeds up to 5 m/s in the distance of the focal point. The beam is scanned as a meander over the surface. Due to fast feed speeds a quasi-line is formed on the surface. The samples are preheated with a hot plate and an aluminum setup. The aluminum setup forms a process chamber for a more homogeneous heat distribution. *Fig. 2* shows a scheme of the setup for the experiments.

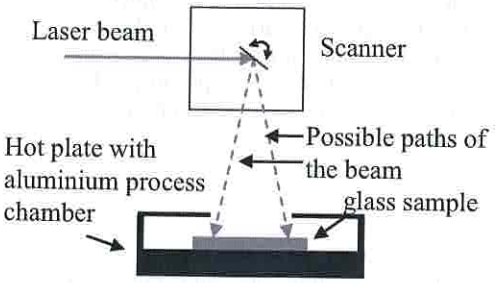

Fig. 2: *Setup of the experiments*

3 Measurements of the surface quality

The polished samples are measured by white light interferometry.

To obtain the roughness of the white light interferometry measurements depending on the spatial wavelength the ambience of each pixel is considered weighed by a Gaussian function which depends on the spatial wavelength as well (see [2]). Through this calculation not only the roughness of the sample but also the shape of the surface is represented.

The roughness for each wavelength regime is determined by calculating the arithmetic mean value Ra of the surface roughness:

$$Ra = \frac{1}{l}\int_0^l |z(x)| \cdot dx .$$

A measurement for the initial state of grained fused silica and the resulting roughness is shown in **Fig 3**.

The roughness can be segmented in three different sections: the micro defects, the middle wavelengths and the waviness. The section of the micro defects includes wavelengths below 10 µm, the section of the middle wavelengths includes wavelengths from 10 µm to 40 µm and the section of the waviness includes wavelength above 40 µm.

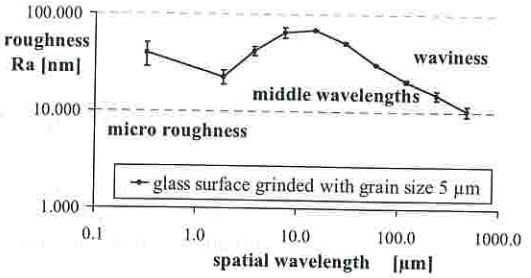

Fig. 3: *Roughness depending on the spatial wavelength*

For all laser-polished samples this tool is used to calculate the roughness depending on the spatial wavelength. The results are compared and evaluated based on those values.

4 Results

Samples of fused silica are laser polished and the roughness is measured as mentioned in chapter 3. The process parameters mentioned in Paragraph 2 have a different influence on the roughness of the polished samples. The influence of the parameters is investigated by varying of one parameter while keeping all other parameters constant. The results for different interaction times of the laser beam and the material and different preheating temperatures are shown in the following.

4.1 Interaction time

The laser parameters have a great influence on the temperature distribution and therefore the evaporation limit. In chapter 2 the dependence of the feed speed v_{feed} and therefore the area rate FR on the interaction time of the laser radiation with the material is shown. The feed speed is directly proportional to the interaction time of the laser radiation with the material.

By varying the feed speed and therefore the area rate different polishing results following from different interaction times can be achieved. The area rate is lowered as long as no evaporation takes place. The lowest area rate in **Fig. 4** refers to the lowest possible area rate without evaporation.

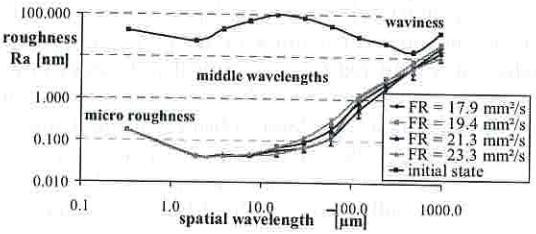

Fig. 4: *Roughness depending on the spatial wavelengths for different area rates (FR) and therefore different interaction times*

The treated area per time FR is listed in the diagram to compare the different interaction times. The micro roughness can be reduced to under 1 nm for all area rates.

In the middle wavelengths range the roughness can be reduced to below 2 nm for all area rates. The best roughness can be achieved with the area rate 17.9 mm²/s which is the closest to the evaporation limit.

The waviness of the laser-polished sample especially for the high wavelengths is almost not reduced. This results from thermal distortion due to a local treatment of the glass samples. The heat deposition into the glass induces bending of the whole sample due to the fast cooling (≈ 50°/s) in the treated area. The lower the area rate the higher the energy deposition in the material. That is why the waviness is higher for the lower area rates. The result for the waviness is not sufficient for optical components yet.

4.2 Preheating temperature

The samples are preheated by the hot plate with an aluminum setup. Temperatures of up to 280°C can be reached on the surface of the samples. The achieved roughness of the laser-polished samples depending on the spatial frequency for three different preheating temperatures is shown in **Fig. 5**.

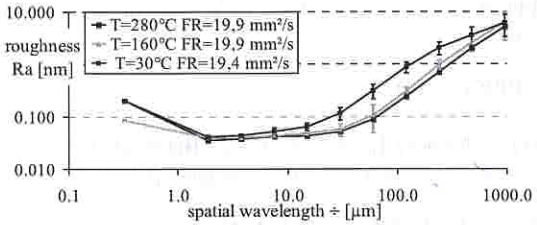

Fig. 5: Roughness depending on the spatial wavelengths for 3 different preheating temperatures

Similar area rates are reached as a best parameter for the different preheating temperatures.

The micro roughness is less than 0.1 nm for all preheating temperatures. This roughness presents optical quality.

The roughness of the middle wavelengths range can be reduced by a higher preheating temperature. It is possible that thermal distortion does not only influence the wavelengths above 40 µm but also the wavelengths below 40 µm. Therefore higher preheating temperatures generate lower roughness.

The waviness of the lower preheated samples is higher than the high preheated samples.

By preheating the sample thermal distortion and consequential the waviness of the polished regions is reduced. Therefore the experiments are carried out using the highest preheating temperature. For this setup the maximum preheating temperature is 280°C of the sample surface. Higher preheating temperatures can be reached within a new experimental setup.

4.3 Distortion and Birefringence

Due to the local treatment of the glass and too low preheating of the samples distortion and birefringence take place.

The thin melted layer is cooled down to the temperature of preheating very quickly (50°/s). The melted layer reaches up to 2200°C which is near to the evaporation temperature. The preheating temperature is 280°C. This fast cooling rate results in tensile strengths in the top of the thin melted layer. Due to this tensile strength the sample bends. The distortion is measurable in the roughness of the long wavelengths (see **Fig. 5**).

The thermal expansion coefficient of fused silica is low compared to other types of glass (≈0.5 $\cdot 10^{-6}$ K^{-1}). Glasses with higher thermal expansion coefficients may be destroyed during laser polishing. In fused silica the thermal stresses are not sufficiently high for destruction. But the induced thermal stresses in the treatment cause birefringence, which can be measured by two perpendicular polarisers. A measurement of the birefringence of a probe with a diameter of 90 mm with a 20x20 mm² laser-polished field is shown in **Fig. 6**.

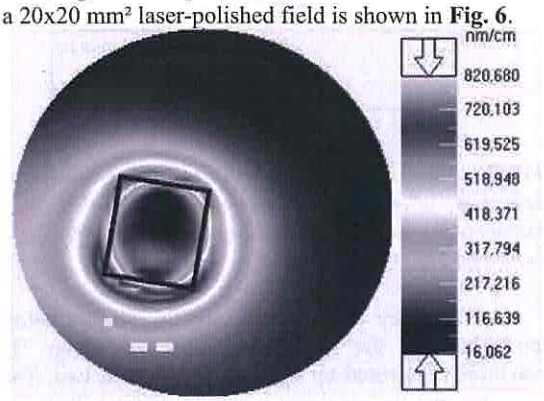

Fig. 6: Birefringence of a laser polished 20x20 mm² field on 90 mm diameter sample [3]

By tempering the sample the birefringence can be reduced (**Fig. 7**).

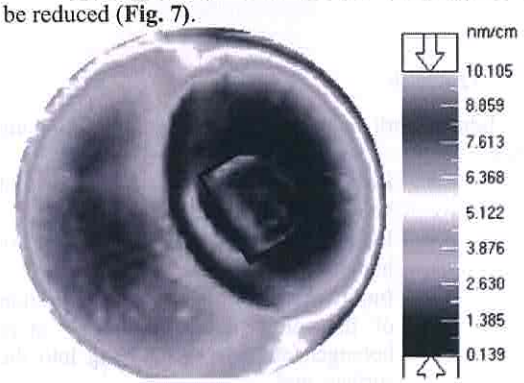

Fig. 7: Birefringence of the sample after tempering[3]

The birefringence is reversible and can be lowered to 5-10 nm/cm which is usual for standard optics. The induced thermal distortions can be reduced.

Laser polishing of fused silica requires sufficient preheating and/or tempering after the treatment. Otherwise the birefringence in the samples is too high for optics.

The thermal distortion can be measured in the spectrum of the roughness. The spectrum of the roughness, which is shown before and after the laser treatment is shown in **Fig. 8**.

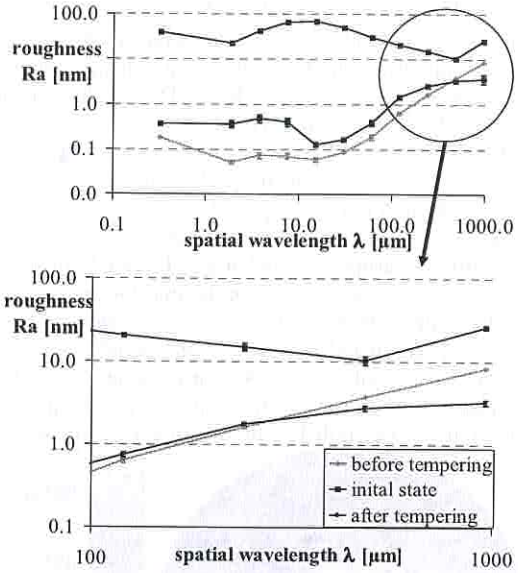

Fig. 8: Above: Full roughness spectrum of the samples before and after tempering. Below: More detailed extract of the waviness (wavelengths of 100-1000 nm) before and after tempering

The grey lines show the waviness before tempering and the black lines after tempering. The waviness is lowered up by a factor of up to two. This indicates that the waviness is due to thermal distortion and can be lowered by lowering the thermal distortion. This can be realised by higher preheating temperatures as mentioned before.

5 Outlook

The future work will concentrate on the following topics:

- Reducing the roughness for the spatial wavelengths > 10 µm.
- Reducing the thermal distortion by higher preheating temperatures
- Improving the roughness in the region of the middle wavelengths by more homogeneous energy coupling into the surface, and
- Decreasing the process times by the laser parameters (e.g. laser power, preheating temperatures).

6 Summary

Laser polishing of fused silica achieves a roughness of Ra<1nm for spatial wavelengths <10 µm and Ra<2nm for spatial wavelengths < 80 µm. Processing rates of up to 1cm²/s can be achieved. The waviness induced by the treatment can be reduced by higher preheating temperatures.

Laser polishing induces thermal stresses in fused silica which lead to severe birefringence. If the laser-polished sample is tempered, the birefringence can be reduced to 5-10 nm/cm which is suitable for optics. The tempering of the glass also reduces the waviness.

Laser polishing of fused silica represents an alternative to conventional polishing due to the faster processing rates, the low roughness for wavelengths smaller than 10µm and the potential of the process for polishing free-form surfaces of fused silica in the future (see **Fig. 9**).

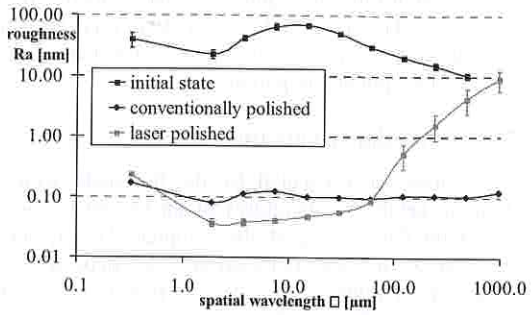

Fig. 9: *Comparison of laser polishing and mechanical polishing*

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[3] Measurements within the BMWi Project PoliLas - by Heraeus

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