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Development of a Laser Based Process Chain for Manufacturing Freeform Optics

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Abstract

The current state of the development of a laser based process chain for manufacturing fused silica optics is presented. In a first step fused silica is ablated with laser radiation to produce the geometry of the optics. A subsequent polishing step reduces the surface roughness and a third step uses micro ablation to remove the last remaining redundant material. Although the process chain is still under development, the ablation of fused silica already reaches ablation rates above 20 mm³/s with a resulting surface roughness of Ra < 5 µm and the polishing process is able to significantly reduce this roughness.

Keywords: fused silica; ablation; ablating; polishing; CO_2; laser; glass; optics; lens; freeform; asphere; aspherical; process chain;

1. Motivation / State of the Art

Increasing demands of modern optical components regarding quality and functionality affect products of the mass market like spectacle glasses as well as specialized optics like lenses for laser components. Aspherical or freeform optics are more expensive to produce but can substitute two or more spherical lenses and thus lowering the size and the weight of products.

One conventional method for manufacturing optical components is grinding and polishing. Starting from a preform, several grinding steps create the surface shape of the resulting optics. Thereby, each step uses smaller abrasive grain in order to reduce the surface damage induced by the previous grinding steps. The same procedure is used for the following polishing steps. Because of the many grinding and polishing steps, this method has disadvantages regarding the production time especially when the optics have a nonspherical shape due to a reduced processing area on the glass.

Another method for manufacturing optical components is glass precision molding which is used especially for large numbers of identical optics. In this process, glass is pressed into a casting mold which forms the resulting optics without any further treatment. According to the surface form of the casting mold, this method is capable to produce spherical as well as aspherical or freeform optics, but the fabrication of the casting mold is costly in terms

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of money and time due to its precise shape which directly forms the surface of the optics. Moreover, glasses with a high softening temperature like fused silica can't be processed due to the limited thermal stability of the casting mold [1].

So, the production of single pieces or small series of aspherical or freeform optics with conventional manufacturing methods is generally very expensive. The aim of the presented process chain is to increase the flexibility and individualization in the manufacturing of optical components by using laser radiation. This includes the processing of the geometry as well as the polishing step. Without the use of form-giving tools, especially aspheres and freeform optics can be manufactured with high flexibility and short lead time. The process chain, its process steps and first results are described in the next chapters.

2. Experimental

In this chapter, the desired process chain for building freeform optics and its single steps are described. Furthermore, the influencing process parameters as well as the analysis procedure to determine the outcome are shown and explained.

2.1. Description of the process chain

Figure 1 shows the process chain which is currently under development. Based on a spherical or cylindrical glass preform, a first processing step removes redundant material with high speed laser ablation. This step is executed with high laser power in order to achieve a high ablation rate and thus a short processing time. A second step polishes the resulting surface and reduces the surface roughness which is generated from the high speed laser ablation step. An optional third step locally removes remaining redundant material and leads to the desired freeform optics using high precision laser ablation with low laser power and a high spatial resolution. During and/or between these steps, a measuring of the geometry and shape accuracy is needed.

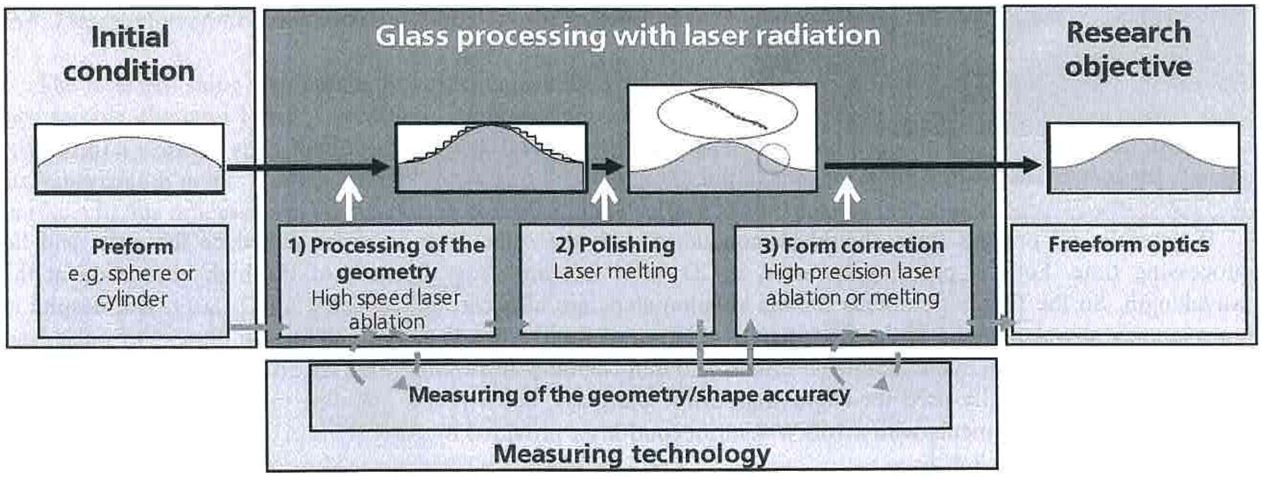


Figure 1. Process chain

2.2. Approach

To determine suitable process parameters, each process step is developed separately. The measurement to detect the surface geometry and roughness is taken offline at the moment using white light interferometry. For the ablation experiments, polished fused silica samples with a roughness of Ra = 2 nm are used. Because of its small thermal expansion coefficient, fused silica is well suited for laser processing [2]. Due to its transparency at the wavelengths of the visible light, UV and the near infrared, CO_2 laser radiation with a wavelength of 10,6 µm is mainly used for processing the glass. At this wavelength, the rate of absorption amounts to 80%, which yields to a high efficiency rate. The experiments are carried out with a cw 1.5 kW CO_2-laser and a laser scanner to position the laser beam on the glass surface which features a maximum scan speed of 10 m/s. The glass itself is heated up to 230°C with a heating plate for lowering the temperature difference and thus the residual stress when being exposed to the laser radiation. Figure 2 shows the experimental setup. In addition to the described system parts an extraction system can be seen which is used to remove the vaporized glass which from the processing area.

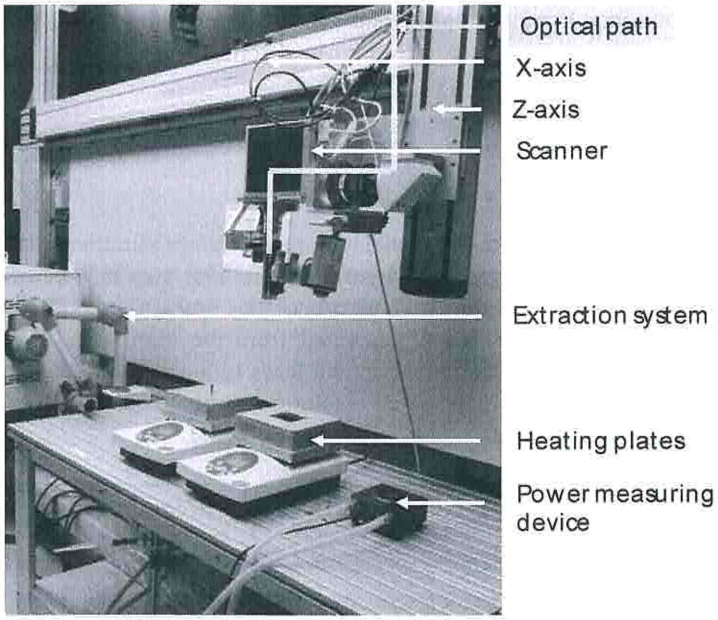
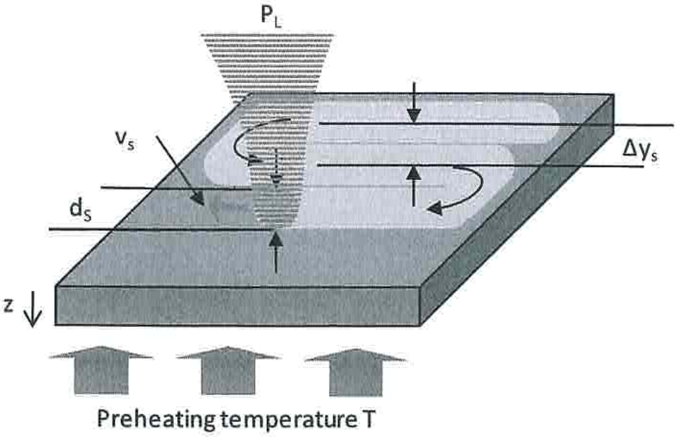


Figure 2. Experimental setup

If possible, all process steps should be conducted with the same laser in order to reduce the costs and the processing time. For the polishing process, a CO_2-laser is compulsory because of the high absorption at this wavelength. So the first experiments for the ablation steps are also carried out using a CO_2-laser. But despite its transparency at wavelengths of the far infrared, ablation of fused silica is also possible with ultra short pulse laser radiation at $\lambda = 1030$ nm due to nonlinear effects and multi-photon-absorption [3]. This effect only occurs within the focus point and is usually used for engravings inside the glass, but it is also possible to ablate material from the surface [4]. First experiments with a 160 W-femtosecond-laser provided by AMPHOS [5] have been conducted and are presented in chapter 3.4.

2.3. Description of the high speed laser ablation step

Figure 3 shows the process parameters and the scan strategy for the high speed laser ablation step as well as the formulas for the ablation rate $\dot{V}$ and the surface energy E_A. The test sample is heated up to the temperature T with a heating plate. The laser beam with the laser power P_L and the focus diameter d_s is moved over the ablated area in a meander with the track pitch Δy_s and the scan speed v_s. Together with the number of exposure layers n and the measurements of the ablation depth z, these parameters can be used to determine the ablation rate $\dot{V}$ which describes the amount of ablated glass material in a certain time. In addition with the surface energy E_A and the surface roughness Ra, the ablated area can be characterized precisely.



$$\dot{V} = \frac{z \cdot \Delta y_s \cdot v_s}{n} [mm^3/s]$$

$$E_A = \frac{P_L}{\Delta y_s \cdot v_s} [J/mm^2]$$

Figure 3. (a) Process parameters and scan strategy; (b) ablation rate V and surface energy EA

The aim of the high speed laser ablation is the fast removal of redundant glass material from the preform and the creation of the shape of the desired optics. For this purpose, high laser power is used with high scan speeds above 1000 mm/s and a track pitch which is smaller than the focus diameter in order to create an overlap of the single tracks and thus a smaller surface roughness. The resulting glass vapor is removed from the working area with the extraction system so that it neither can affect the ablation process by absorption of the laser energy nor damage the surrounding components by condensation.

2.4. Description of the laser polishing step

The laser polishing step uses a different scan strategy which is displayed in Figure 4. With an equally preheated test sample, the laser beam is used defocused and moved in one direction with high speed to create a working line instead of a working spot. This line is moved forward with the speed v_{feed} and heats up the glass material just below its vaporization point. Thereby, the viscosity is reduced and the initial roughness smoothens because of the flowing surface. In this process step, no material is ablated and the surface shape remains unchanged.

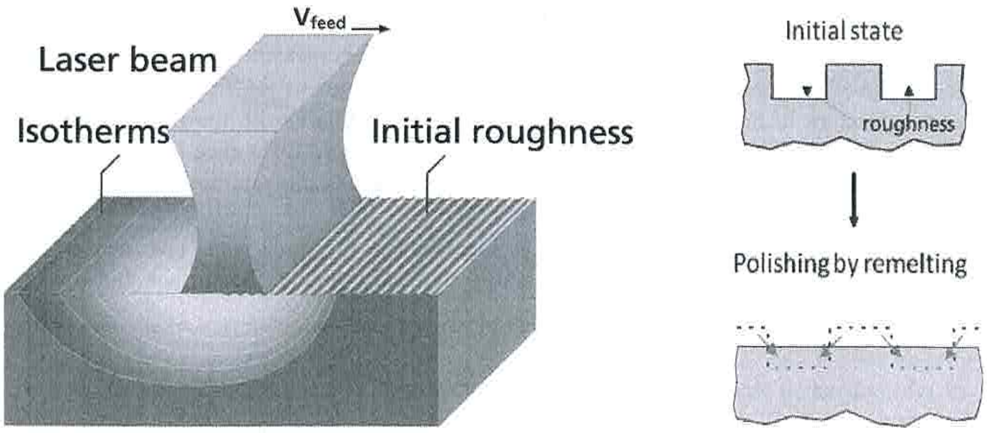


Figure 4. Principle of the laser polishing process [6]

The temperature of the glass has to be controlled very precisely to avoid material ablation at temperatures above the vaporization point of the material as well as an increasing viscosity and thus a higher remaining surface roughness at lower temperatures. This is realized with a pyrometer which controls the surface temperature of the processed glass and adjusts the laser power accordingly.

It is important for the polishing step that the glass surface is free of particles before processing. Because of the high temperatures of the laser process, any remaining particle is burnt into the surface and leads to a higher resulting roughness. To ensure a clean surface, the glass samples are cleaned before polishing and the used laser machine is encased with a flowbox which reduces the amount of air particles through a filtration. The glass polishing step is already in an advanced stadium and has been published in detail before [6, 7].

2.5. Description of the high precision laser ablation step

In contrast to the high speed laser ablation, the high precision laser ablation step aims for small ablation depths and a locally controlled ablation. This can be used to remove the roughness at high wavelengths which occurs during the polishing process (see chapter 3.2). The step uses the same scan strategy like the high speed laser ablation step which is already shown in Figure 3. The resulting ablation depth depends on the deployed surface energy and can thereby be controlled either by the variation of the laser power, the scan speed or the track pitch. Because of the importance of the track pitch to the resulting surface roughness, this parameter remains unchanged. Due to the fact that the reaction of the scan unit towards a change of its input signal is much faster, different scan speeds are used to adjust the surface energy. Thereby, a higher scan speed leads to a lower surface energy and a lower ablation depth. If the surface energy underruns a certain level, no ablation occurs. This effect in combination with a small focus diameter can be used to precisely control the ablated area.

2.6. Analysis Procedure

To determine the influence of the process parameters on the surface roughness and the ablation depth of the process chain's ablation steps, rectangular test fields with a dimension of 10x10 mm² with different parameter settings are ablated. Multiple exposures of the same area with identical parameters enlarge the ablation depth for getting more precise results. Furthermore, this procedure enables an analysis of the temperature behavior of the processed glass when ablated in several steps. The ablation depth z and the resulting surface roughness of the ablated test fields are identified using white light interferometry. This method offers the advantage of a two-dimensional data recording with a high spatial resolution in one measurement against a conventional tactile roughness measurement system.

The analysis procedure is shown in Figure 5. First, the surface roughness is measured in the middle of the ablated field. As it can be seen, a much higher ablation depth is reached at the edges of the field because of the reversal points and the higher temperature in this area. The ablation depth is determined with the measurement of another field in a not ablated area on the glass sample and the comparison of the height difference between the ablated and non ablated field. In Figure 5, the whole area around the ablated field is used as this reference surface.

When analyzing a polished area, the surface roughness is identified in the same way. The measurement of the ablation depth is not necessary due to the fact that the polishing step only remelts the surface and does not ablate material.

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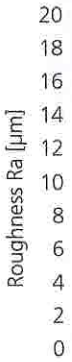

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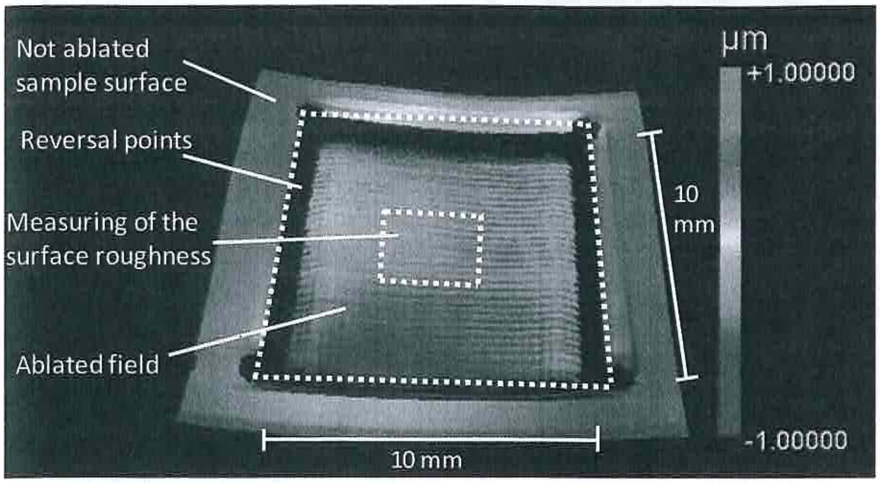

Figure 5. Identification of the surface roughness and the ablation depth

3. Results and discussion

In this chapter, the results of the development of each process step are described. Furthermore, first results of the ultra short pulse laser ablation are presented.

3.1. High speed laser ablation (CO_2-laser)

Using high laser power and suited scan speeds, ablation rates $\dot{V} > 20$ mm³/s with a resulting surface roughness of Ra < 5 µm can be achieved. An exemplary comparison of the resulting surface roughness and the ablation rate with 8 exposure layers (n) and 1.5 kW laser power (P_L) by different scan speeds (v_s) and track pitches (Δy_s) is displayed in Figure 6.

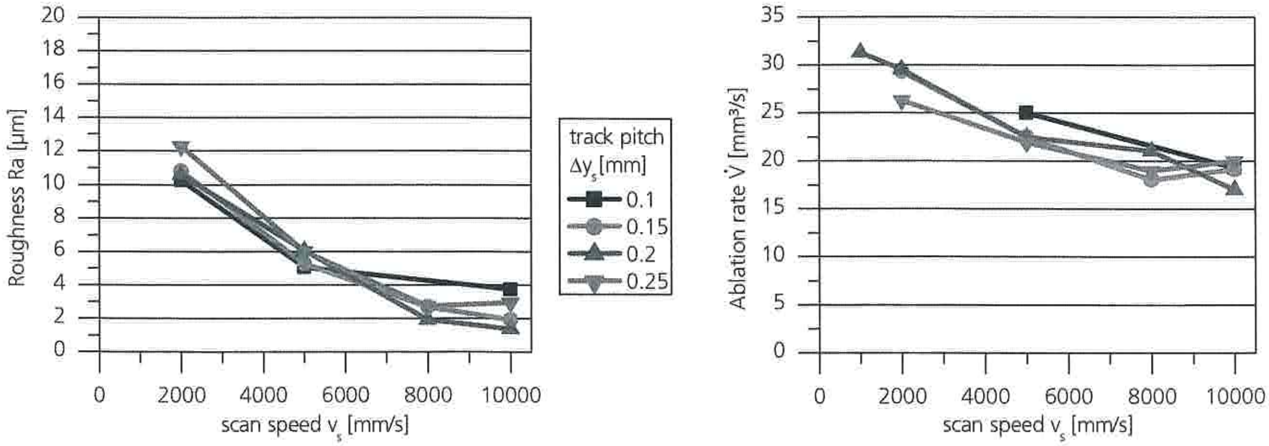

Figure 6. (a) Surface roughness and (b) ablation rate of test samples treated with high speed laser ablation

This example is representative for all experiments conducted with high laser power in order to achieve high speed laser ablation. The surface roughness is reduced with increasing scan speeds. At a scan speed of $v_s = 2000$ mm/s, a roughness of Ra ≈ 11 µm is achieved, at $v_s = 10.000$ mm/s, the roughness only accounts to Ra ≈ 3 µm due to a lower surface energy E_A. Furthermore, a track pitch of $\Delta y_s = 0.2$ mm reaches the lowest roughness. Working with a spot diameter of $d_s = 0.45$ mm, this means an overlap of about 45%. The ablation rate decreases towards higher scan speeds but still reaches about $\dot{V} = 20$ mm³/s at $v_s = 10.000$ mm/s.

It is obvious that the ablation depth decreases towards higher scan speeds with unchanged other process parameters. So, this offers a possibility to locally alter the amount of ablated material and thus forming a surface shape. In opposite to the high precision laser ablation step, the highest scan speed still ablates material, so the laser power also has to be reduced in order to receive an even smaller ablation depth. Experiments conducted with lower laser powers show the same results like the ones shown in Figure 6 with both a lower surface roughness and a lower ablation rate.

3.2. Laser polishing (CO_2-laser)

The polishing process with laser radiation is able to significantly reduce the surface roughness from not polished glass material. A comparison between conventional and laser polishing when processing a grinded surface is given in Figure 7. There, the initial and the resulting surface roughness is displayed above the spatial wavelengths λ of the roughness.

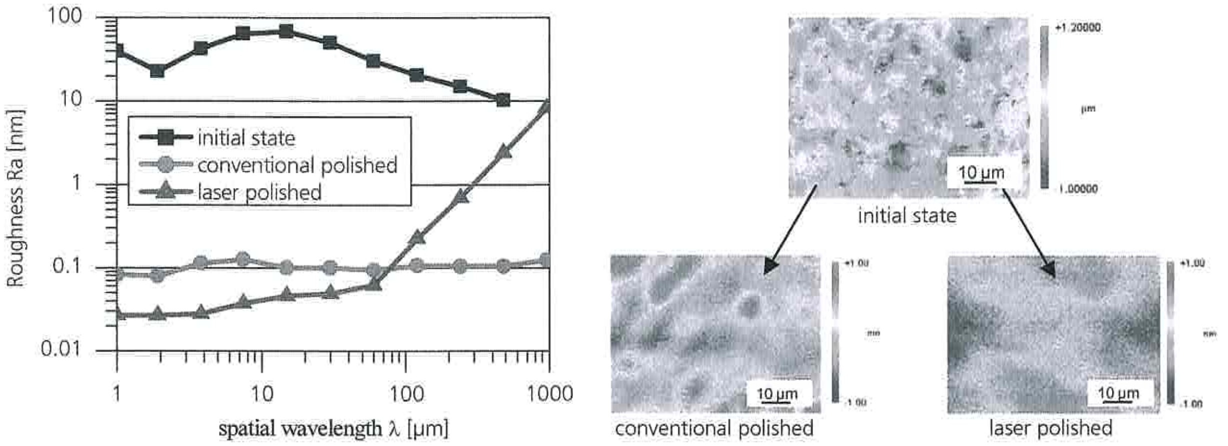

Figure 7. (a) Surface roughness in dependence of the spatial wavelengths of the roughness for the polishing process [6]; (b) surface images of the initial state, a conventional and a laser polished sample with white light interferometry

The laser polishing process already reaches a better surface roughness than conventional methods for spatial wavelengths < 100 µm. A problem remains in the longer wavelengths λ > 100 µm, where the roughness of the polishing process strongly increases. The lower roughness in short wavelengths of a laser polished sample is visible in the surface images taken with white light interferometry in Figure 7. Compared to the conventional polished sample, the laser polished sample shows a smoother surface in this high magnification.

To achieve best results, the laser beam is used defocused which leads to a bigger working area and a more homogeneous energy distribution. With an intensity of 400 W/cm, an area rate of about 1 cm²/s can be achieved. The working area exceeds the sample dimensions so that the reversal points can be placed outside the sample because of the higher temperatures and the risk of an unwanted material ablation in this area. More results of the polishing process can be found in [6, 7].

3.3. High Precision laser ablation (CO_2-laser)

The high precision laser ablation aims for ablation depths << 100 nm with a small resulting surface roughness. Therefore, the laser power is decreased in comparison to the high speed laser ablation step in order to reduce the ablation depth. The results are shown in Figure 8 for a fixed laser power $P_L = 150W$, a track pitch of $\Delta y_s = 0.2$ mm and 12 exposure layers.

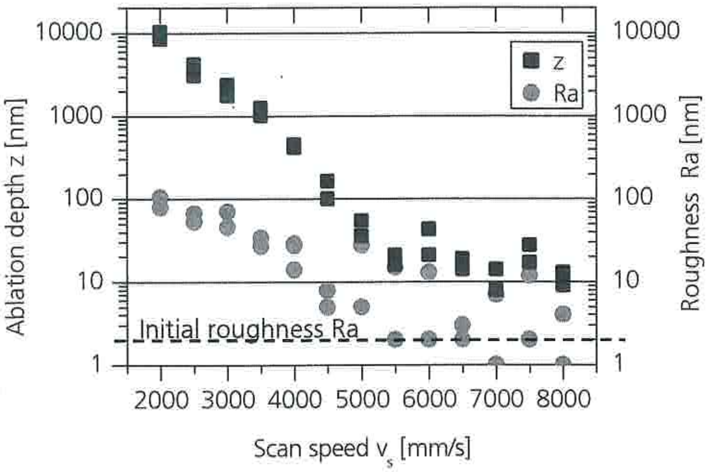

Figure 8. Ablation depth and surface roughness of test samples treated with high precision laser ablation

Both ablation depth z and roughness Ra decrease towards higher scan speeds until $v_s = 5500$ mm/s. At this point, the ablation depth is about 25 nm for 12 exposure layers and the roughness remains in an area between the initial level of Ra = 2 nm and Ra = 10 nm. If the scan speed is increased above 5500 mm/s, the ablation depth remains constantly at the same or even lower values so that an ablation about 1 nm per layer occurs. In this area, the ablation process is nearly stopped and the glass is just remelted. This can be used to exclude areas from the ablation process by increasing the scan speed while ablating others by reducing the scan speed. Figure 9 shows the high precision laser ablation step and the influence of different scan speeds towards the amount of ablation.

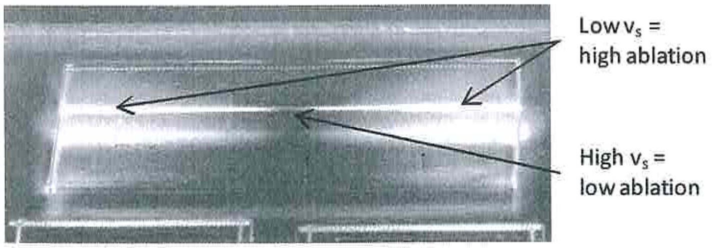

Figure 9. Illustration of the high precision laser ablation step

3.4. Ultra short pulse laser ablation

In addition to the treatment with CO_2 laser radiation, it is also possible to ablate glass with ultra short laser pulses due to nonlinear effects and multi-photon-absorption in the focus point. First results with an ultra short pulse laser with a pulse duration of $t_p = 500$ fs, a laser power of $P_L = 160$ W, a focus diameter of $d_s = 22$ µm and 20 layers are shown in Figure 10.

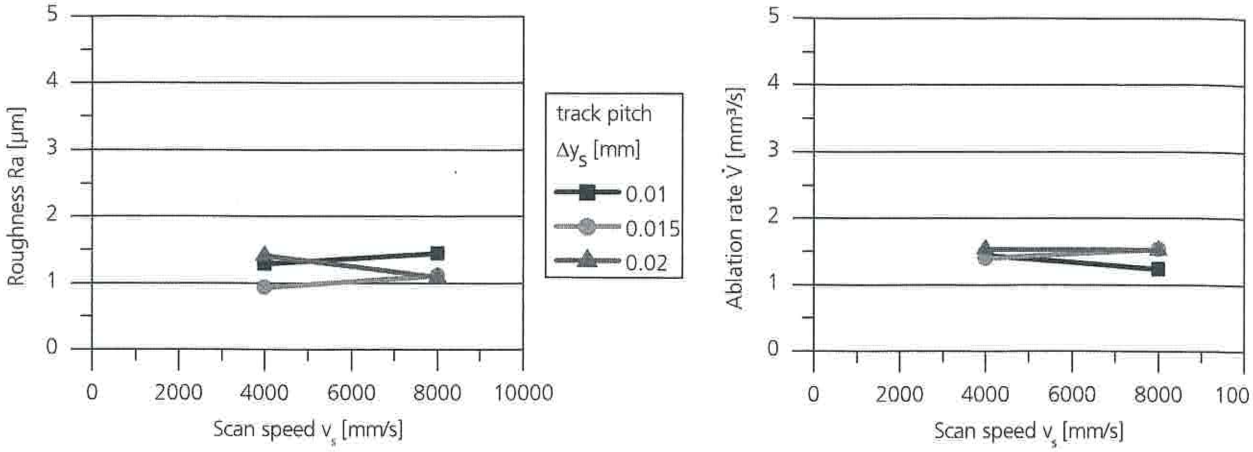

Figure 10. (a) Surface roughness and (b) ablation depth of test samples treated with ultra short pulse laser ablation

The surface roughness increases to values between Ra = 0.9 µm and Ra = 1.5 µm whereas the ablation rate reaches about $\dot{V}$ = 1.5 mm³/s regardless of the parameter setting. Compared to the results of the ablation experiments carried out with the CO_2-laser, the ultra short pulse laser ablation neither reaches the high ablation rate of the high speed laser ablation step nor the low surface roughness of the high precision laser ablation step. Nevertheless the ultra short pulse laser ablation can be used in the high speed laser ablation step when only small amounts of material have to be ablated or in the high precision laser ablation step because of its small focus diameter of just 22 µm. In Figure 11, the resulting surface roughness of the ultra short pulse laser ablation and of the high speed laser ablation is compared above the spatial wavelengths λ of the roughness. In addition, the roughness of the initial condition as well as a conventional grinded glass surface with a grain size of 9 µm is displayed. For wavelengths shorter than 100 µm, the CO_2 laser ablation reaches a lower roughness than the ultra short pulse laser ablation. This is caused by the thermal heating during the CO_2 laser ablation process which locally remelts the surrounding glass material and smoothens the surface. When considering the ability of the polishing process to remove spatial wavelengths below 100 µm which is shown in Figure 7, the ultra short pulse laser ablation is well suited for the ablation requirements. But to finally answer the qualification of the ultra short pulse laser ablation within the presented process chain, more experiments have to be conducted.

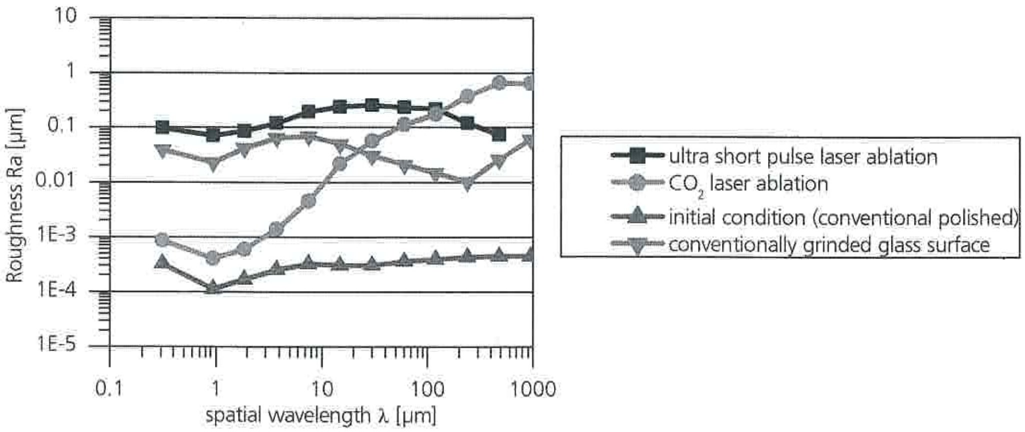

Figure 11. Comparison of CO2 laser ablation and ultra short pulse laser ablation above the spatial wavelengths of the roughness

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4. Summary

The current development of a laser based process chain for manufacturing freeform optics is presented. The process chain starts with a preform and is based on the three individual process steps high speed laser ablation, laser polishing and high precision laser ablation which are used to build the desired optics. By replacing conventional lens manufacturing methods through laser ablation and polishing, the current development shows a perspective to possibly increase the flexibility as well as the individualization of single optics especially regarding the surface shape because no form giving tool would be needed. In this paper, the main procedure with the relevant process parameters and first exemplary results of each process step regarding surface roughness and ablation rate are presented for fused silica.

5. Conclusion and Outlook

The experimental results show that it is possible to both ablate and polish fused silica with CO_2-laser radiation in a time which is interesting for industrial application. The next steps will be to reduce the resulting surface roughness which occurs during the high speed laser ablation by testing different scan strategies and process parameters. The high precision laser ablation will be used to locally ablate single areas by leaving others unaltered. For this, both the spatial resolution as well as the repeatability will be increased. Together with the polishing step, these improvements will be used to combine all three steps and to build a first freeform lens with the presented process chain.

Acknowledgements

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