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Laser Beam Polishing of Quartz Glass Surfaces

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Abstract

The laser beam is a small, flexible and fast polishing tool. With laser radiation it is possible to finish many outlines or geometries on quartz glass surfaces in the shortest possible time. It's a fact that the temperature developing while polishing determines the reachable surface smoothing and, as a negative result, causes material tensions.
To find out which parameters are important for the laser polishing process and the surface roughness respectively and to estimate material tensions, temperature simulations and extensive polishing experiments took place. During these experiments starting and machining parameters were changed and temperatures were measured contact-free.

Keywords: laser; quartz glass; polishing; temperature; residual stress, simulation; contactless measurement

1. State of the Art and Motivation

From state of the art methods of polishing surfaces with laser radiation are already known [1]. It's possible e.g. to reduce the polishing time of metallic injection moulding tools. The manual polishing takes between 10 and 30 min/cm² [2]. Also in polishing cast materials good surface quality is reached [3]. The laser material processing of glass has made good progress whereas the high-precision finish (for optical parts) causes still problems [4]. Furthermore it's barely possible to reach good surface quality without creating critical thermal tensions.

Compared to traditional glass polishing methods the laser beam is small, flexible and fast. With laser radiation it is possible to finish many outlines or geometries on quartz glass surfaces in the shortest possible time. Starting with RMS = 600 nm for example just one machining step is necessary to achieve a surface quality below 10 nm. Furthermore it is possible to negotiate restrictions given by the conventional mechanical polishing methods and their tools.

To finish the quartz glass parts in this present report a CO_2-laser is used. The analysis should show how the starting roughness, the changeable laser or process parameters and the resulting temperature influence the final surface quality. It's interesting too, how the parameters have to be changed to reach requested roughness values.

The Optimisation of these parameters should be carried out by measuring temperature and surface quality. This quality is detected by the help of different surface analysing methods (e.g. stylus instrument, AFM, REM).

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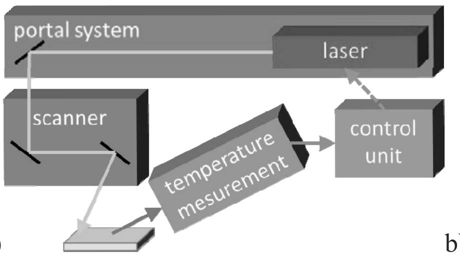
It is possible to analyze complex processes and effects on the material with the numerical simulation. The examples in the literature show that can be realistically studied the temperature field and residual stress state of welding and cutting processes using numerical models and methods [7-12]. The numerical simulation allows to study the thermal and mechanical changes during the polishing process in quartz glass and to vary the parameters for the polishing. A sensitivity analysis permitted the qualitative and quantitative assessment of the influence of changes in different input data to the results. The numerically calculated results should enable a better understanding of the thermal and mechanical processes during the polishing processes and a problem-specific limitation of the process parameters.

2. Experiments

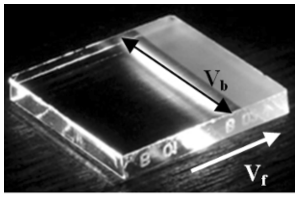
To investigate the technical feasibility of the reported laser polishing method the research starts with planar surfaces. The polishing is carried out by a regional short softening of a thin surface layer with a defocused beam. Using adjusted laser power stock removal is prevented and the smoothing happens because the surface tension of the softened layer. This tension is responsible that the profile peaks were levelled and the valleys were filled.



a)

V_f[mm/s]	12…50
V_b [mm/min]	900…1500
P [W]	490…830
RMS [µm]	0,2…0,8
influenced values: intensity, line spacing, polishing time	

b)



c)

Figure 1. (a) Scheme of experimental setup; (b) Range of polishing parameters; (c) quartz glass sample during the polishing process

Figure 1 a) shows the experimental setup. It's a portal system where the laser beam is coupled in and leaded over different mirrors to a scanner system. The galvanometric scanner mirrors move the beam with a maximum speed of 3 m/s. In combination with a special beam guiding concept this beam velocity (v_b) causes a so called "polishing line" (Figure 1 c) on the glass part (part size: 25 x 25 x 3 mm³). To reach a homogeneous surface an additional motion – the feed rate v_f – is realized with the axis of the portal system. Because of this motion the "polishing line" is carried along the surface.

It is expected that the temperature is the essential determining factor for the hole smoothing process. Viscosity, stock removal and material tensions are influenced by this value. Therefore the measurement and control of this important value is crucial. During the whole series of experiments the temperature is measured continuously on every surface polished. To do so a special glass pyrometer (wavelength 5.14 µm) is used. The maximum temperature and a temperature curve for each polished sample are recorded. They can be used to check the influence of the machining parameters (shown in Figure 1 b) on temperature and furthermore the influence of the temperature on the reachable surface quality. The pyrometer measuring spot for the temperature recording is located within the "polishing line".

To handle the range of parameters and to check their influence on temperature, surface quality, stock removal and on each other too, the DoE (Design of Experiments) is used.

3. Simulation

To understand and predict the temperature values developing during the laser polishing process a numerical simulation is beneficial. If it is possible to prove the results of this simulation with the current experiments it is imaginable to reduce the amount of necessary experiments for new geometries, too. Furthermore this simulation should show the material stress state developing during the thermal heating.

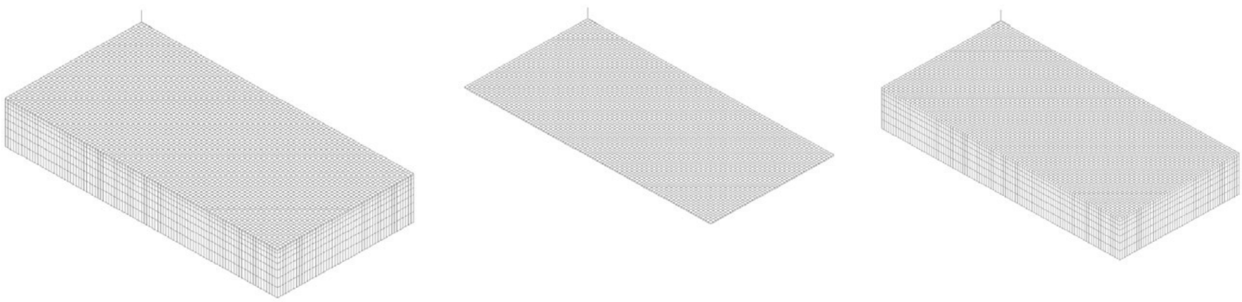
The simulation bases on parameters given by the first experiments. The beam velocity v_b is replaced by the simplification of the motion to the described “polishing line”. The line width is given by the diameter of the defocussed laser beam and all the rest of the starting and environmental conditions find their way into the simulation.

This numeric simulation uses a three-dimensional model, which also includes physical non-linearity in the decoupled thermal and mechanical simulation for the calculation of the stress state dependent on the time and the position. The equation for the temperature state is:

$$(\partial q_x/\partial x + \partial q_y/\partial y + \partial q_z/\partial z)dxdydzdt + (c_p * \rho * (\partial T)/(\partial t))dxdydzdt - Q\, dxdydzdt = 0 \qquad (1)$$

T	temperature
$q_{x,y,z}$	heat fluxes in principal axes x, y, z
ρ	density
c	specific heat capacity
Q	heat flow per volume

It is necessary to define boundary conditions and an initial value for the temperature for the complete and unique description of time-varying process of thermal conduction in the element. In the first step, it is important to describe the energy input. The wavelength of a CO_2-laser beam is $\lambda = 10.6$ µm. In the infrared range above the wavelength of five µm silicate glasses are nearly opaque. For an absorption coefficient of $\beta = 10^3$ cm^{-1} the optical penetration is less than 10 µm. In the simulation a small layer with the thickness d = 10 µm is used for the input of the heat (Figure 2 b).



a) mesh part 1 and mesh part 2 b) mesh part 1 c) mech part 2

Figure 2. Mesh of the model

The radiation intensity of the laser without optical correction is assumed idealised mathematical GAUSSian distributed in the simulation. The required energy input q(x, y, z) is obtained in the simulation by a time-dependent function h (t) taking into account the mesh of the model and the position of the heat source.

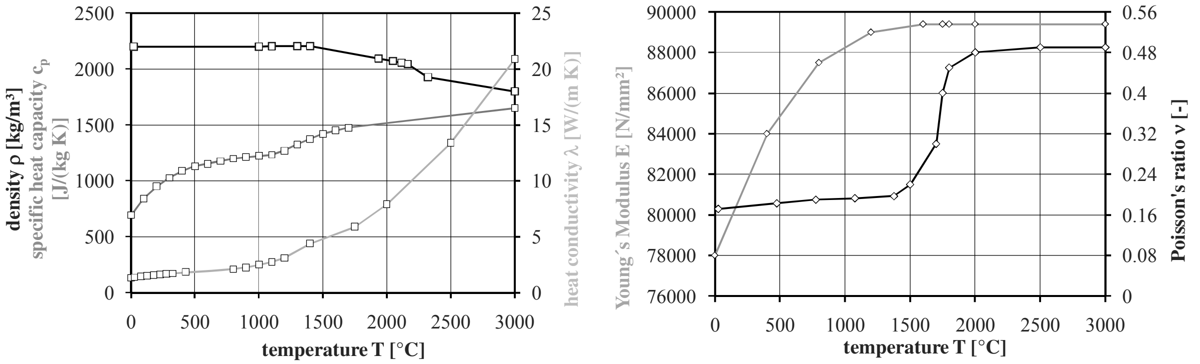
Equation 2 describes the functional of local energy input for the polishing line.

$$q(x,y,z) = h(t) * P * exp-((y - y_0 - v_f * t)^2/A^2) \qquad (2)$$

h(t)	
P	heat input or power [W]
y	y-position of a node [mm]
y0	start-position in y-axes of the heat source [mm]
v_f	feed rate of polishing line
t	time
A	geometry parameter of GAUSSian distribution equal half diameter of beam

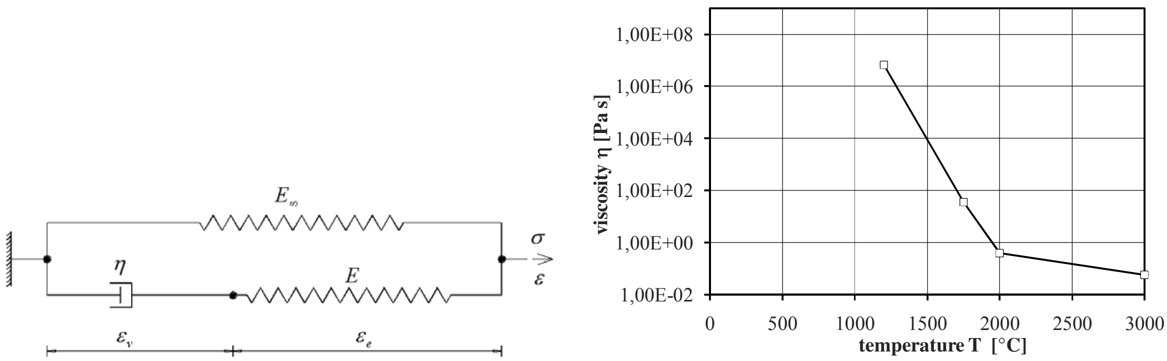
The radiation can be described with the Stefan-Boltzmann law and directional-, material- and surface-dependent emission coefficients for a "gray" body. Temperature-independent emission coefficients are accepted for the material of quartz glass and the polishing process. In the literature, no detailed data on temperature or process dependence are present. The emission coefficient of the quartz glass is stated with $\varepsilon = 0.91$ in [13] at T = 20 ° C. An adjustment of the emission coefficient must be made on the basis of measurements for each case.

During the polishing process, the quartz passes a temperature span from room temperature (T = 20 °C) to a defined softening temperature of about T = 2000 °C and above. At this stage, it is necessary to use temperature dependent material properties in the simulation. Therefore, the numeric simulation has carried out physical non-linear. The temperature-dependent material properties are from the literature and present the results of experimental investigations. Figure 3 a) shows the values for the selected thermal properties for quartz glass. The values of density are from [14]. The values of specific heat capacity are from [15]. The values of thermal conductivity may vary considerably, so a mean of two representative curves is determined [16], [17]. The values for temperatures above T = 1100 °C are estimated. A selection of the most important material properties in dependence of temperature is illustrated in Figure 3.



a) Thermal properties b) Mechanical properties

Figure 3. Selected properties of quartz glass dependent on temperature



a) Model for the representation of the viscoelastic solid behavior b) Viscosity of quartz glass dependent on temperature

Figure 4. Viscous model approach

A special mechanical feature of the quartz glass is its viscous flow behavior. At room temperature, the quartz glass shows an ideal elastic behavior. When reaching the stress limit, a brittle fracture occurs. In the region of the vitreous transition temperature at T = 1250 °C, the reduced viscosity of the material leads to a viscous flow behavior by which stresses are reduced.

In the mechanical analysis is used a viscous model approach. The standard solid model is an extension of the model according to MAXWELL [18]. It describes the relationship between the end-modulus E_∞, the time-dependent modulus E(t) and the viscosity η a solid. The extension to the model according to Maxwell is in the availability of an independent end-modulus, so the deformations are stored within the material during the mechanical process. This model represents the mechanical properties of glass below the transformation temperature at small deformations. Figure 4a) shows schematically the mechanical material behavior of a viscoelastic solid.

The values for the Young´s Modulus and Poisson's ratio for quartz glass are illustrated in Figure 3b. The values of Young´s Modulus up to a temperature T = 1500 °C are from [19] and a constant Young´s Modulus is assumed above a temperature of T = 1500 °C. The values of Poisson's ratio are based on the data from [20] to the temperature T = 1375 °C determined. The values up to the temperature T = 3000 °C are assumed to the specific behavior of a liquid (Figure 3b).

The values in Figure 4b) show a description of the viscosity of quartz glass. The end-shear modulus is $E_{s,\infty}$ = 37200 N/mm² [21]. A constant value is assumed for the thermal expansion for the total temperature range α = 5.5*10-7 1/K [22].

4. Experimental Results

For the exemplarily described DoE a 2³ experimental design (with one center point and one repetition) was used to investigate the influence of laser power P, feed rate v_f and beam velocity v_b. The developing temperature T, roughness (e.g. RMS) and stock removal (SR) stand for the investigated role variables.

To show the significance of the effects (given by the parameters P, v_f, v_b and their combination) parameter estimates based on student's distribution (t) were plotted. Figure 5 shows these three plots where the red lines stand for confidence regions. Every effect or combination of effects that crosses the 99.9 % - line is regarded as significant. Effects under the 95 % - line are not significant. It is possible to determine theses parameters (e.g. on an average value) and keep them constant during following experiments. So the experimental amount can be reduced.

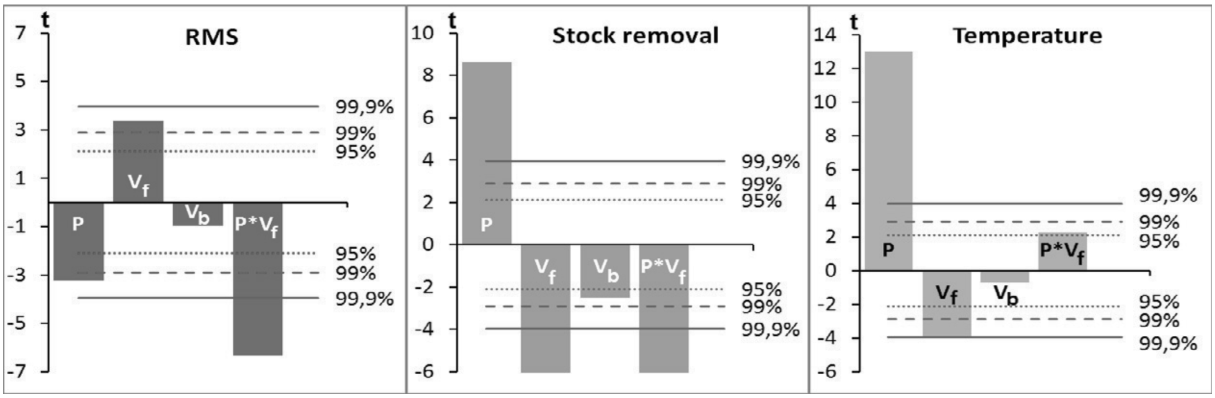
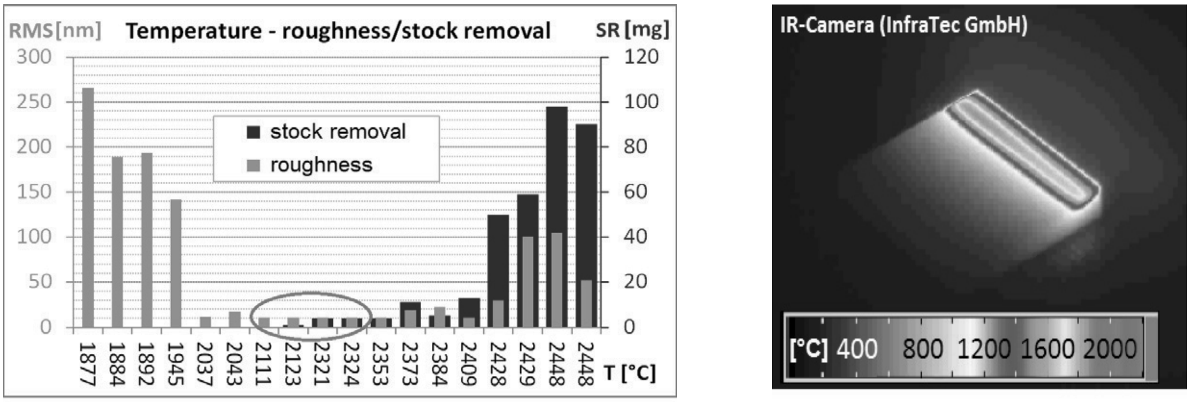


Figure 5. Parameter estimates for the selected role variables (roughness, stock removal, temperature)

Regarding Figure 5 it is obvious that P, v_f and their combination are significant to influence the role values RMS, SR and T. The beam velocity is not significant (except for SR in this special case) so the simplification of a "polishing line" is feasible. Further investigations are aimed to accelerate polishing process (raise v_f and P accordingly).

The results in Figure 6 show the enormous influence of the temperature, as well as the interaction between temperature and surface quality - demonstrated in Figure 6 a). There is indeed an ideal temperature range (marked in Figure 6 a) wherein it is possible to finish rough-machined quartz glass surfaces in just one laser-polishing step – without significant stock removal. The heat image in Figure 6 b) emphasizes the heat distribution on the quartz glass surface and – regarding the front side – in the surface. It can be seen, that the assumed laser line (caused by the rapid beam moving) is actually developing during the polishing process. This relatively broad area assures the evenly surface softening that is required to reach the high surface quality of 10 nm (RMS) and less.



a) b)

Figure 6. (a) Interaction between temperature and surface quality/stock removal; (b) Heat image of a polished quartz glass sample

To get the information about surface quality the surfaces were analysed with a stylus instrument as long as the roughness was big enough. But as in further experiments RMS reaches 5 nm and less is was necessary to check the measured values with a proper measuring method – the AFM.

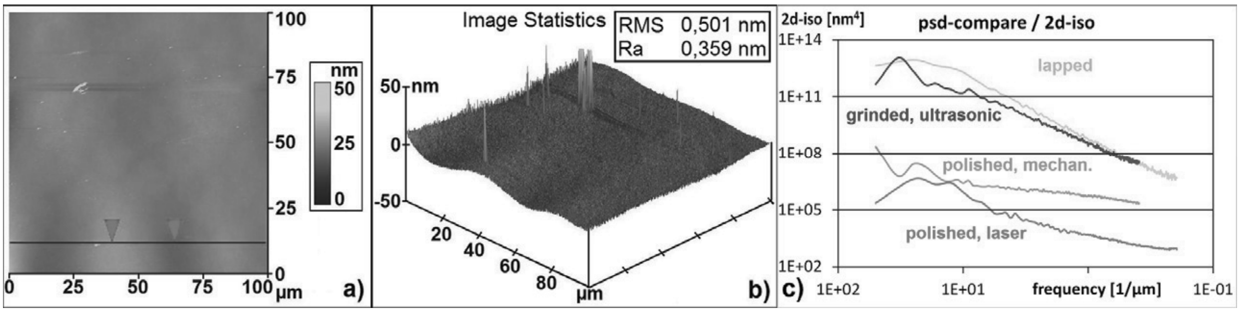


Figure 7. AFM-result of a laser polished quartz glass surface – a) 2D-image; b) 3D-image of structure; c) PSD-functions

In Figure 7 a) and b) you can see the AMF-pictures and the associated roughness of one of the best polished surfaces. Consider this picture in particular it gets obvious that there is a kind of surface structure on the quartz glass part. It seems that there are smooth hills and valleys. This structure was visible from the beginning of the investigation. It is considered as a result of the surface softening. The depth of this softening is apparently not big enough to eliminate the structure of waviness (a result of the mechanical pre-machining). But in theses later experiments it was possible to reduce this wave-structure. Now it is so slight that we are able to reach almost optical surface quality with this method of laser beam polishing. This gets even more obvious considering Figure 7 c), too. There is a plot that includes the PSD-function of a laser and a mechanically polished quartz glass part as well as a lapped one. (The grinded part was manufactured on an ultrasonic supported milling machine.) A PSD-function includes the spectrum of the spatial frequencies of the surface roughness measured in reciprocal units of length. It allows a complete description of the surface quality and it is qualified for description of high polished surfaces. [5]

Equation 3 describes the functional relation of spectral power density and spatial frequency.

$$2D\text{-}isotropic\text{-}PSD = P/(2\pi f(\Delta f)) \quad (3)$$

P Power under a part of surface (in nm²)

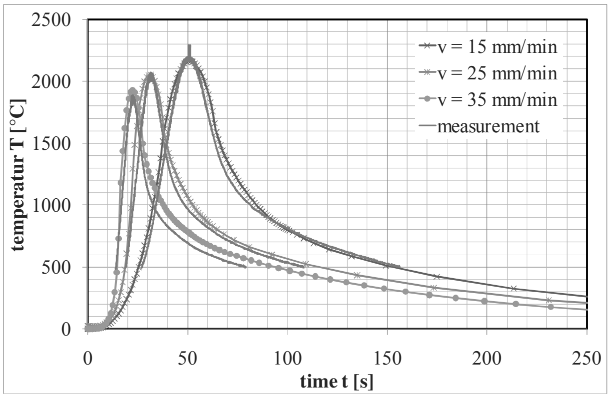
Δf change of frequency

f frequency which equates to a defined surface size (in nm-1) [6]

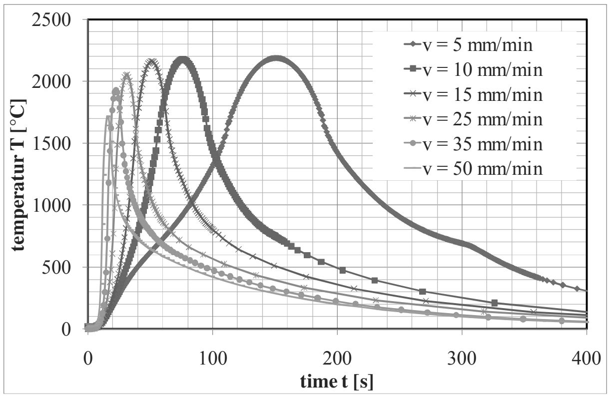
With Figure 7 c) it can be demonstrated that – in this case – the laser beam polishing method permits better surface qualities as the classical and time-consuming mechanical polishing method does. Until now it was possible to reduce the current laser polishing process time to 6 cm²/s.

5. Simulation Results

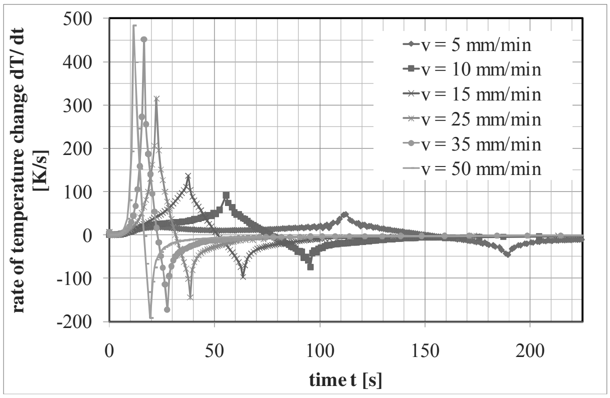
The numerical simulations are carried out with a heat input of P = 460 W and a diameter of beam A = 6.4 mm for the polishing line. It can be observed that the results of the simulation and the results of the experiment coincide very well (Figure 8a). At high feed rate of polishing line, a greater difference in temperature values is observed as a feed rate of polishing line. The results in Figure 8b shows that the maximum temperature decreases with increasing feed rate for the measurement point. The increase of the feed rate has the result that a very high change in temperature per time is possible. It can be assumed that the material is stressed very strongly. Optimal process parameters can be determined with the results of thermal analysis.



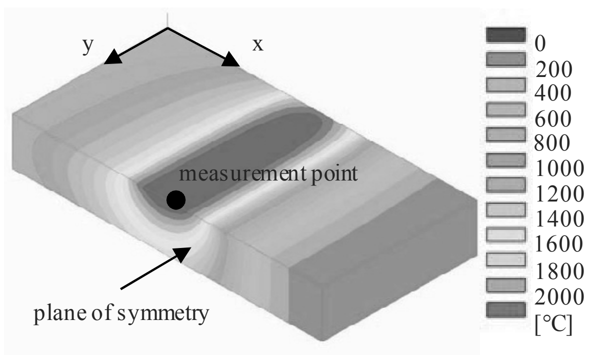
a) Comparison between experiment and simulation



b) Comparison of different feed rates v of polishing line



c) Comparison of rate of temperature change

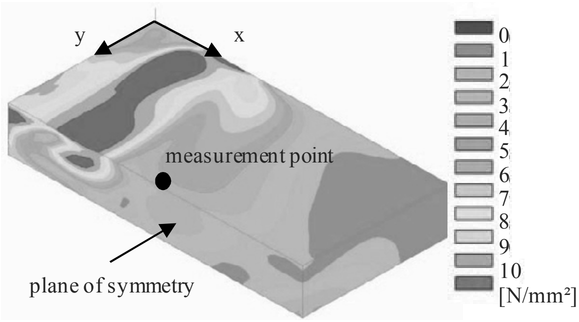


d) position of measurement point

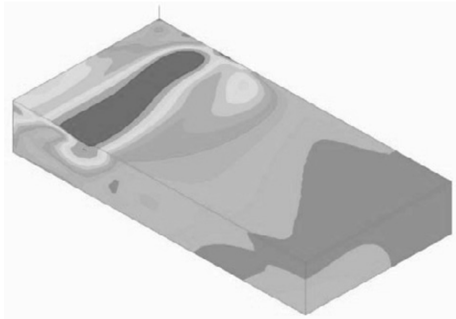
Figure 8. Results of the numerical thermal analysis

The Figure 9 shows the summary of the results of mechanical analysis. The von-Mises-stress state is illustrate for four different feed rate of polishing line after the complete cooling down process in the case of heat input of P = 460 W. The results in Figure 9 show that a relatively complex stress state is available in the initial region of the sample at feed rate of polishing line. At very high feed rates a low stress state is existent after the end of the process in the sample. Only during the polishing process, the sample is stressed with high stress variability at feed rate. A critical tensile stresses state does not occur during the process due to the low thermal expansion of quartz glass.

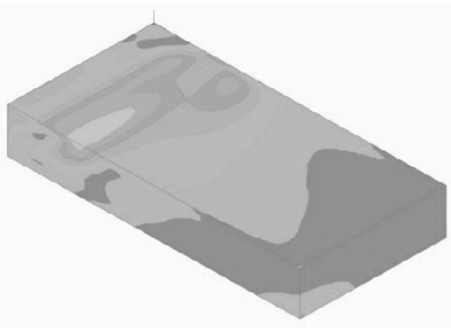
Without thermal treatment, the different stresses in the glass can lead to optical distortions. It is not possible to polish the surface and to get a stress-free sample at the end of the process for modified polishing parameters.



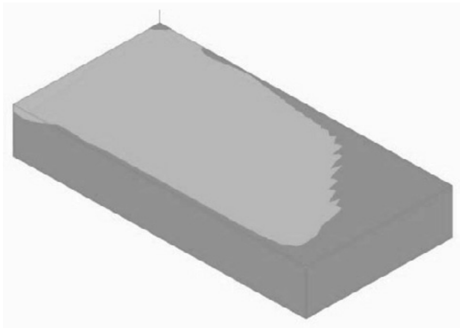
a) von-Mises-stress t = 1000 s, v = 15 mm/min, P = 460 W



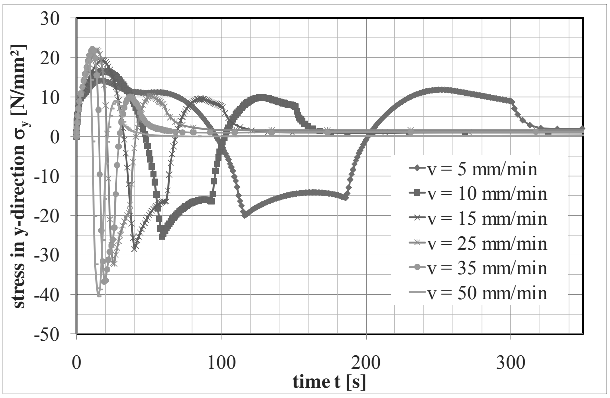
b) von-Mises-stress t = 1000 s, v = 25 mm/min, P = 460 W



c) von-Mises-stress t = 1000 s, v = 35 mm/min, P = 460 W



d) von-Mises-stress t = 1000 s, v = 50 mm/min, P = 460 W



e) Change of stress during the process for different feed rate, P = 460 W

Figure 9. Results of the numerical mechanical analysis

Furthermore, a sensitivity analysis is performed for the thermal calculation. In the investigation following parameters are considered: the preheat temperature, the emission coefficient, the feed rate, the factor of heat input, diameter of laser. The results are calculated for a small number of combinations (Figure 10). The heat input is Q = 460 W. The influence of heat capacity, density and thermal conductivity is presented in [10].

The Monte Carlo method is used to generate the stochastic input values with the mean and standard deviation. The standard deviation of 0.2 x mean is assumed because static data for the input values are missing. The evaluation is realized for the maximum temperature for the measurement point in Figure 10. The results show that, for example, no clear correlation between changes in the preheat temperature and the maximum temperature is present.

Significant changes in maximum temperatures can be seen in the case of the heat input and the emission coefficient. This demonstrates that a critical examination of the input values is necessary.

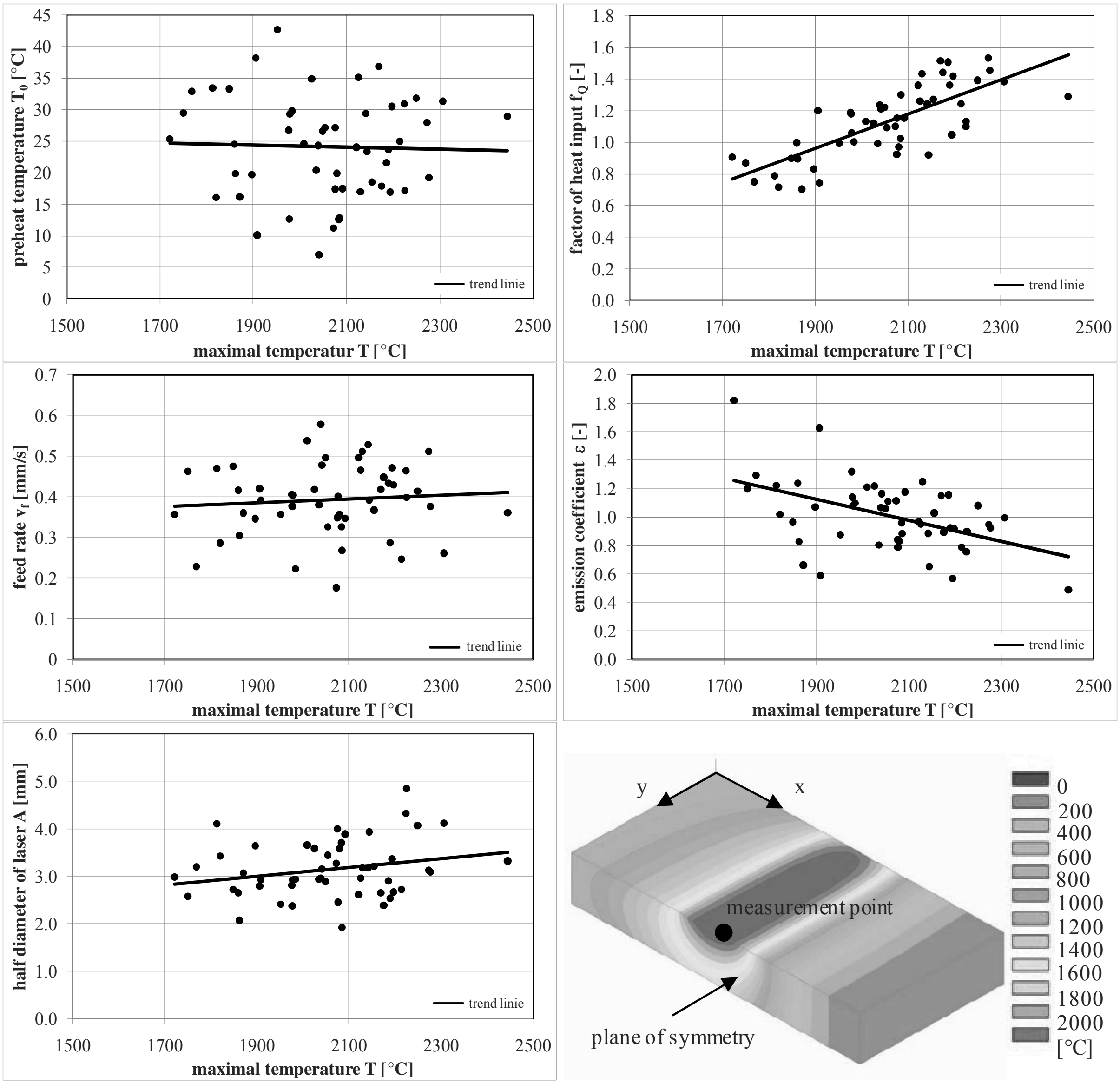


Figure 10. Results of sensitivity analysis for polishing process of quartz glass

6. Conclusion

The polishing process could be investigated by use the commercial FE-software SYSWELD for the calculation of the time- and location-dependent temperature distribution and stress distribution in the plate. The application of the laser beam polishing process requires an extensive adaptation of the used material models. The application of simulation is suitable to optimization the process parameters of targeted temperature and residual stress state.

The laser polishing experiments contain more than 200 polished parts until now. At the moment we know that the final quality depends on starting roughness and (more important) starting waviness. With the polishing method the roughness can be improved about 100 times. The remaining visible waves are no laser-polishing-structure but smoothed relicts of pre-machining (e.g. grinding, lapping) and they are much more difficult to reduce or remove. The quality also depends in the shown way on laser power, feed rate and (not demonstrated here) on beam guiding concept, defocusing, sample geometry an environmental conditions (pollutions – proved with AFM-analysis).

In further investigations the results of the planar surfaces should be adapted on surfaces and samples with a more complex geometry. In this case the numerical simulation could help to reduce the experimental amount, because it is easier to adapt the geometry in the model, to change the parameters and to check their influence with this simulation. This is feasible because the results of all experiments show the knowledge and optimisation of the temperature is half the battle to control the polishing process and its results. The time consuming measurements of surface quality (especially with AFM) could then probably be reduced.

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