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Experimental and Numerical Investigations of Laser Beam Polishing of Quartz Glass Surfaces

J. Hildebrand*[1], B. Wittor[1], K. Hecht[2], J. Bliedtner[2], H. Müller[3]

[1]Bauhaus University of Weimar, Faculty of Civil Engineering, Marienstrasse 7A, 99423 Weimar, Germany
[2]University of Applied Sciences Jena – Department SciTec, Carl-Zeiss-Promenade 2, 07745 Jena, Germany
[3]Günter-Köhler-Institut für Fügetechnik und Werkstoffprüfung
GmbH, Otto-Schott-Str. 13, 07745 Jena, Germany

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Abstract

The aim of laser beam polishing is to achieve an even surface finish in the shortest possible time without changing the contour of the material. Laser radiation acts as a topology-independent sub-aperture tool. Analyses of influences on the process, interaction between laser radiation and the quartz glass as well as comprehensive evaluation of the results with regard to surface quality, and manipulation of tensions and mechanical properties support the development of an industrially applicable laser polishing technology.

The polishing process was investigated with the commercial FE-software SYSWELD for calculation of the time- and location-dependence of temperature and stress distribution in the plate. The application of the laser beam polishing process requires extensive adaptation of the material models used. The application of simulation is suitable to optimize the process parameters of the targeted temperature and residual stress state.

The design, execution and evaluation of the experiments for laser beam polishing are performed with the help of statistical methods. These show that power and persistence (i.e. dwell time) are the most significant factors. Temperature, as one of the main parameters, is measured accurately either punctually or linearly with a pyrometer and two-dimensionally with an infrared camera. In a defined temperature range a polishing process without stock removal is achievable.

Keywords: Laser beam polishing, stock removal, roughness, numerical simulation, sensitivity

I. State of the art and motivation

Methods for polishing surfaces with laser radiation to reduce the polishing time needed for metallic injection molding tools are already known. But laser material processing of glass is still a field of research with great potential. The most important thing is to achieve good surface quality without creating critical thermal tensions. Compared to traditional glass polishing methods, polishing with a laser beam provides a fast, flexible and small tool. Therefore laser polishing should be suitable for finishing not only even 2D surfaces but also micro-structured 2½D parts. Further fields of application for this technology are polishing mold inserts for plastics processing and also particular areas of optical components.

II. Concept of Laser Beam Polishing (LBP)

A 1.5 kW CO_2 laser (10.6 μm) with a high rate of absorption in quartz glass is used to soften the surface based on the introduction of energy into the workpiece. Because of material tensions in the softened surface layer, unevenness and roughness are smoothed. This polishing process can also cause stock removal (sublimation) too, so it is necessary to determine an appropriate temperature range for polishing while avoiding stock removal.

The experimental setup shown in Fig. 1 consists of a CO_2 laser beam coupled in a portal system, guided over several mirrors to a scanner (maximum scanning velocity 3.0 m/s). The feed rate is realized by the portal system. Thus the motion results in the formation of a "laser line" that then moves along the surface. The measurement system applied to detect the temperature distribution as an essential determining factor is realized with a pyrometer (5.14 μm), the measuring spot of which is located in the middle of the "laser line" for constant temperature recording as it moves with the line for the purpose of process optimization.

III. Experiments

Working samples are pre-machined by means of several cutting technologies (e.g. grinding, lapping) and then polished with laser radiation. The pre-machining processes, especially grinding, were investigated as well, but these are not the subject of this paper. It is important to note that several grinding methods (e.g. pendular grinding, CNC profile grinding) result in different surface qualities (different roughness). So the samples were classified in groups (A to C) depending on the roughness (range $2.0 > RMS > 0.2$ μm). The easiest way to produce a large

* Corresponding author: joerg.hildebrand@uni-weimar.de

number of planar samples is lapping. So this method was chosen to pre-machine most of the laser-polished samples. To obtain the defined starting roughness groups, different lapping agents were used.

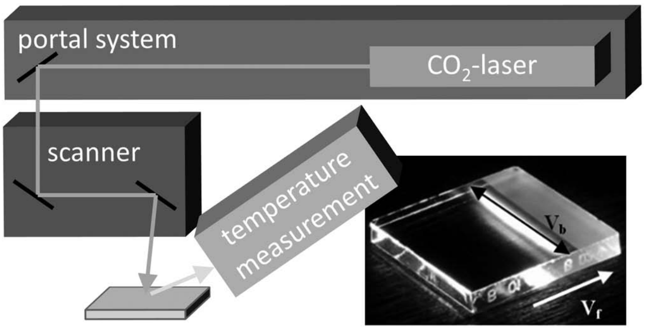

Fig. 1: Experimental setup.

An additional IR camera is used in the course of the later tests to confirm the pyrometric measurement results and the supposed temperature distribution.

The investigation into laser polishing starts with smoothing planar surfaces of quartz glass parts (size: 25 x 25 x 4 mm^3) because it is necessary to adapt a great number of parameters to achieve a flawless surface. The analyzed parameters are laser output power (P), feed rate (v_f), beam velocity (v_b) and temperature (T). During extensive pilot tests, the parameters focus diameter/defocussing, beam guiding (scanning concept) and overlap were defined. To smooth the surface by softening the quartz glass without significant stock removal, it was necessary to find the appropriate beam diameter, the minimum scanning velocity v_b and an adapted range of overlap.

The galvoscanner with an f-theta-optic that was used moves the laser beam with a high velocity (v_b) in lines over the glass surface (in a kind of zigzag motion). This movement is so fast that a "polishing line" is generated. The axis of the portal system, where the scanner is mounted, moves this "polishing line" with a defined feed rate (v_f) over the sample.

The value T is both a result of P, v_f and v_b as well as an influencing parameter. Much depends on the temperature developed by the introduced energy and it is most important to keep its value constant. Several series of tests were conducted. The evaluation of the tests is performed with statistical methods to check the parameters and their influence on each other and the surface quality. Table 1 shows the range of parameter variation in the different groups.

A DoE with a 2^3 experimental design (one center point, one repetition leading to 18 single experiments per group) examines the influence of the parameters with developing temperature, roughness (RMS) and stock removal (SR) as investigated role variables.

IV. Experimental results

The intention of the investigation with its experiments is to reduce the surface roughness RMS by means of laser beam polishing without significant stock removal. So there are no fixed thresholds for good or bad polishing results. This means for the DoE that RMS and SR were defined as the values to be minimized while a range was to be determined for T.

Parameter estimates based on student's t-distribution show the significance of the effects of P, v_f, v_b and their combination. The horizontal lines in Fig. 2 are the confidence regions. If an effect or combination of effects cross the 99.9 % line, it counts as highly significant. If it stays under the 95 % line, it is not significant. It is logical to set these parameters to an average value and reduced the experimental effort required in that way. Significant influences on the role values RMS, SR and T are P, v_f and their combinations. The simplification of a "polishing line" is feasible because v_b shows no significance in the selected range. It would make no sense to reduce v_b below the given limit because it has to be fast enough to create the polishing line. The line and its overlapping is a requirement for the investigated polishing process. The enormous influence of T and the interaction between temperature and surface quality was examined intensively so as to set an ideal temperature range to finish rough-machined quartz glass surfaces in just one laser polishing step without significant stock removal (Fig. 3). It is possible to reduce RMS below 20 nm and SR < 1 mg.

During the experiments concerning the different roughness groups it was seen that the surfaces of group A and B are too rough for polishing without significant stock removal. So the range of group C (0.5 > RMS > 0.3 μm) was set as a reasonable starting roughness.

The results of the experiments show that it is necessary to stay in this very small temperature range of 2000...2100 °C, which is difficult if conditions change. To transfer the results of the small even samples to other sizes and geometries, simulation is useful, enabling the number of tests required to be reduced.

Table 1: Field of parameter variation.

Parameter gr.	A (2>RMS>1 μm)	B (1>RMS>0.5 μm)	C (0.5>RMS>0.3 μm)
P [W]	220...450	220...450	300...450
v_b [mm/s]	5...15	5...15	15...35
v_f [mm/min]	900...1500	900...1500	900...1500
Influenced values: intensity, line spacing, polishing time			

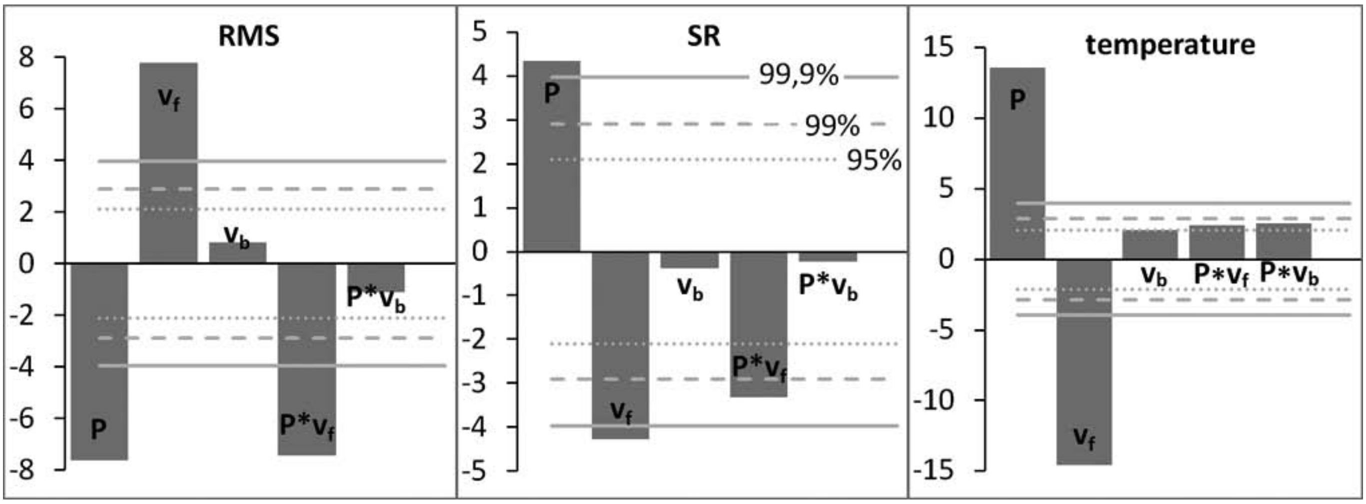

Fig. 2: Effect's significance test for RMS, SR and temperature.

With regard to surface quality, it turned out that a clean surface is required. Analyses with a scanning electron microscope (SEM) show micro-defects and enclosures on the polished surfaces. Theses impurities are caused by pre-machining (i.e. particles of lapping suspension or tool abrasion) located in/on the glass surface structure or they are fine particles (dust) from the polishing environment. If these particles stay or fall on the softened surface, they probably create a new glass blend with a different coefficient of expansion. In the worst case, tension increases during the fast cooling and the glass blend breaks away. SEM images of a quartz glass surface before and after polishing, as shown in Fig. 4, demonstrate the described effect.

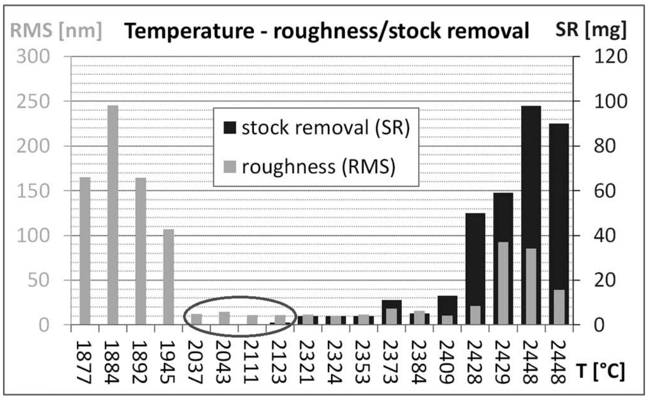

Fig. 3: Dependence of temperature from SR and RMS.

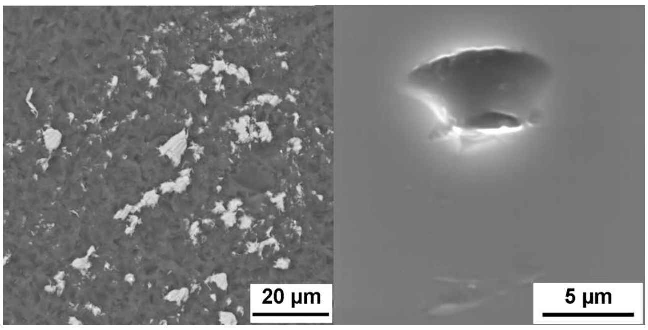

Fig. 4: SEM; left: BSE – impurities, right: SE – micro-defect.

The mechanical properties of a laser-polished surface were also examined during this research. When a juvenile surface is created, it turned out that the bending strength increases with laser polishing. The micro-hardness is comparable to a mechanically polished surface but there is no soft gel layer that normally causes hardness depending upon depth.

V. Simulation

The numerical simulation enables thermal and mechanical analysis of the polishing process to determine the temperature state and stress state during the process and to optimize the process parameters. The numerical 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:

$$\left(\frac{\delta q_x}{\delta x} + \frac{\delta q_y}{\delta y} + \frac{\delta q_z}{\delta z}\right) dxdydzdt + \left(c_p \cdot \rho \cdot \frac{\delta T}{\delta t}\right) dxdydzdt - Qdxdydzdt = 0 \quad (1)$$

where

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

It is necessary to define boundary conditions and also an initial value for the temperature for the complete and unique description of the 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 $b = 10^3$ 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 heat input (Fig. 5b).

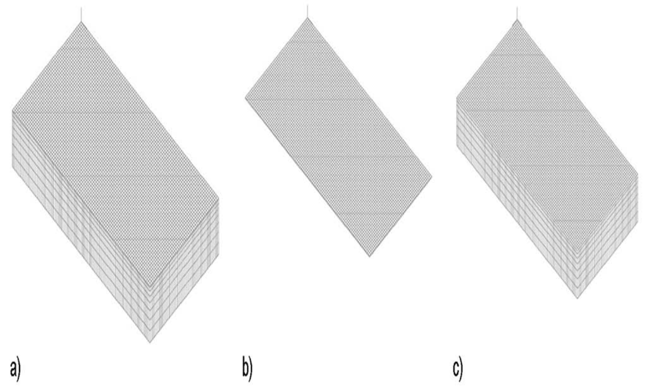

Fig. 5: Mesh of the model: a) mesh part 1 and mesh part 2; b) mesh part 1; c) mesh part 2.

The radiation intensity of the laser without optical correction is assumed to have an idealized mathematical Gaussian distribution in the simulation. Two energy distributions for the moving laser (heat input model 1) are created and implemented in the numerical model. The first equation describes the energy input depending on time and position:

$$q(x,y,z,t) = h(t) \cdot P \cdot \exp\left(\frac{(y - y_0 - v_f \cdot t)^2}{A^2}\right) \quad (2)$$

where
- $h(t)$ function for mesh of the model and the position of the heat source,
- P heat input or power,
- y y-position of a node,
- y_0 start position in y-axes of the heat source,
- v_f feed rate of polishing line,
- t time

A geometry parameter of Gaussian distribution equal to half the diameter of the laser beam.

It is assumed that the movement of the laser beam is very fast and produces a uniformly heated surface. In the experiment, the width of the heat-up area is determined by the beam diameter whereas in the simulation it is defined by the width of the Gaussian distribution. The length of the heat-up area depends on the width of the sample (Fig. 1). It is assumed that the laser beam moves over the sample surface quickly enough to ensure its homogeneous heating.

The second description of the laser beam is a moving source. In this case the movement is modeled in a kind of zigzag motion of the laser spot. The very high speed of the laser beam on the sample surface is considered in the equation for the determination of the energy input position:

$$x(t) = \frac{b}{\pi} \cdot \left(\frac{\pi}{2} - \frac{4}{\pi} \cdot \sum_{n=1}^{\infty} \frac{\cos\left((2 \cdot n - 1) \cdot \frac{t}{a}\right)}{(2 \cdot n - 1)^2}\right) - \frac{b}{2} \quad (3)$$

where
- a function for time alignment,
- b function for amplitude, corresponds to 1.05*sample width,
- t time.

The energy input is described with the following equation (heat input model 2) depending on time and position:

$$q(x,y,z,t) = h(t) \cdot P \cdot \exp\left(-\frac{(x - x(t))^2}{A^2}\right) \exp\left(-\frac{(y - y_0 - v_f \cdot t)^2}{A^2}\right) \exp\left(-\frac{(z - z_0)^2}{B^2}\right) \quad (4)$$

where
- $h(t)$ function for mesh of the model and the position of the heat source,
- P heat input or power,
- $x(t)$ function of position,
- y_0, z_0 start position in y- and z-axes of the heat source,
- x,y,z x-, y- and z-position of a node,
- v_f feed rate of polishing line,
- t time
- A geometry parameter of Gaussian distribution equal to half the diameter of the laser beam,
- B geometry parameters of Gaussian distribution equal to the depth of the laser beam.

A minimal time step of $\Delta t = 0.07$ s and a maximum time step of $\Delta t = 0.5$ s are used for the numerical solution of the thermal and mechanical problem. The time steps were selected to achieve a 50 % overlap of the laser spots between two successive points and a continuous input of energy is simulated.

The radiation can be described with the Stefan-Boltzmann law and directional-, material- and surface-dependent emission coefficients for a "gray" body. But for the polishing process the emission coefficient of the quartz glass is stated with $\varepsilon = 0.91$ in [1] at T = 20 °C. The assumption in the simulation is that the emission coefficient is temperature-independent for the temperature range between 20 °C and 3000 °C. The aim of the first numerical simulation is to reduce the calculation time and to obtain qualitative trends for temperature during the process. It is known that the emission coefficient is temperature-dependent.

The temperature-dependent material properties are from the literature and represent the results of experimental investigations. Fig. 6 shows the values for the selected thermal properties for the quartz glass. The values of density are from reference [2]. The values of specific heat capacity are from reference [3]. The values of thermal conductivity may vary considerably, so a mean of two representative curves is determined [4,5]. The thickness of the sample is constant. For heat input model 1, the energy input is P = 460 W and the diameter of the beam is A = 6.4 mm. For heat input model 2, the energy input and the feed rate depend on the width (Table 2). But the beam has a constant velocity $v_s = 800$ mm/s and the diameter of beam is 7 mm independent of the width.

Table 2: Parameter of power and feed rate.

Sample width [mm]	15	25	40	50
Power [W]	600	670	960	1000
Feed rate [mm/min]	80	50	40	30

VI. Numerical results

The numerical simulations are performed with a parameter from the experiment for samples with 15 mm, 25 mm, 40 mm and 50 mm width. The aim of the process is to generate a constant temperature of 2000 °C on the sample surface in one line. The influence of heat capacity, density and thermal conductivity is presented in [6–8]. The results for the thermal and mechanical simulation for the heat input model 1 are presented and discussed in [9]. The results in [9] show that, for example, no clear correlation exists between changes in the preheat temperature and the maximum temperature.

With Fig. 7, it can be demonstrated that the description of the laser beam in the simulation can explain the significant temperature field and the temperature change during the polishing process. The calculation time for simulation with heat input model 1 is low, but the results are conservative and descriptions can be used for small samples. In the case of an increase in the sample width (Fig 7b, c, d), it is not possible to create a constant temperature in a line of sample surface. During the polishing process, the samples are subject to a time- and location-dependent temperature field. For small samples the influence of scan velocity v_b is not important, but in the case of complex samples a new concept for the polishing process or temperature field must be developed.

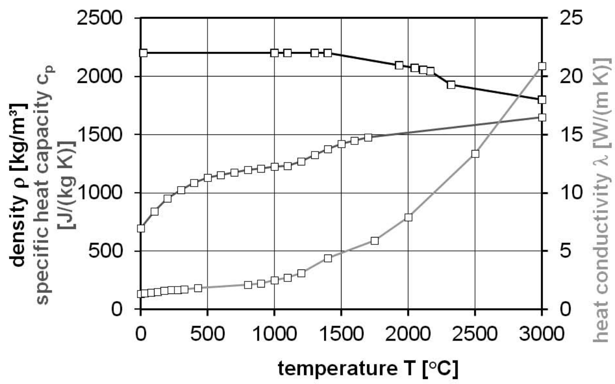

Fig. 6: Selected thermal properties of quartz glass dependent on temperature from [2,3,4,5].

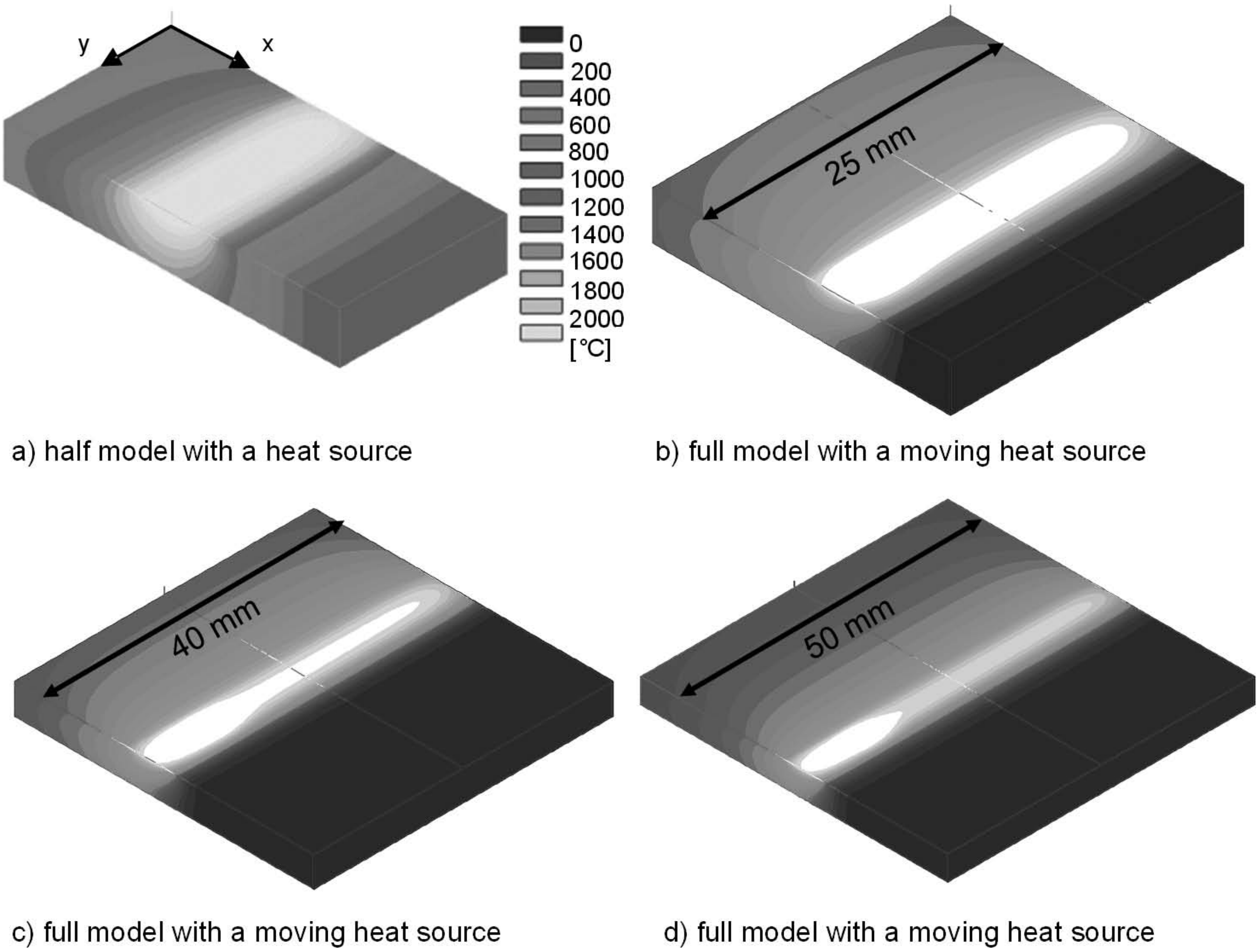

Fig. 7: Temperature fields for different situations.

A sensitivity analysis is performed for the thermal calculation for the sample with 15 mm width and the data from Table 2. In the investigation, the following parameters are considered: the feed rate, the beam velocity, the beam diameter and the beam intensity. The evaluation is realized for the maximum temperature for the measurement points in Fig. 8. The Monte Carlo method is used to generate the stochastic input values with the mean and standard deviation. The standard deviation of 0.1 x mean is assumed because static data for the input values are lacking. The results in Figs. 9 – 12 depend on the position of measurement. The polishing process starts from measurement point M1 and ends in the measurement point M4. In all cases, the temperature in measurement point M1 is lower than in measurement point M4, and the highest temperature is at measurement point M4. There are the heat loss and thermal conduction in the cold sample at the beginning and a heat-up in the warm sample at the end of process. At the beginning of the process a large amount of heat can be conducted into the cold sample, whereas at the end of the process the sample is pre-heated and the heat flow is reduced. For a uniform temperature on the surface of sample, the laser spot should be moved more slowly at the beginning and faster at the end. This change in v_b is necessary to enable a kind of pre-heating at the beginning and to reduce heat accumulation at the end of the polishing process. With the numerical simulation the time points for the change in feed rate are determined.

The results show that, for example, no clear correlation between changes in the beam velocity and the maximum temperature is present. Significant changes in maximum temperatures can be seen in the case of the beam diameter and beam intensity. This demonstrates that a critical examination of the input values is necessary.

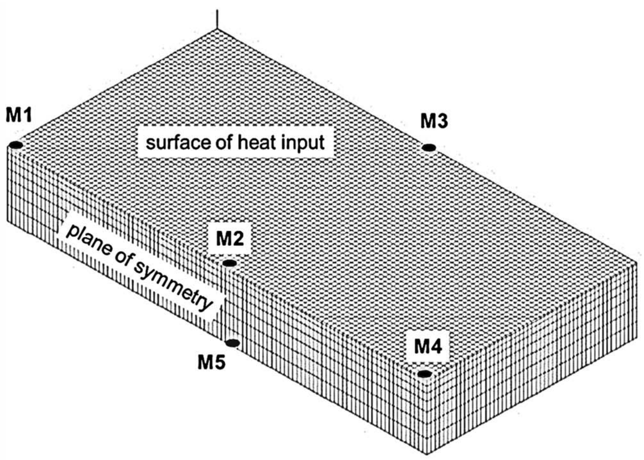

Fig. 8: Position of measurement point.

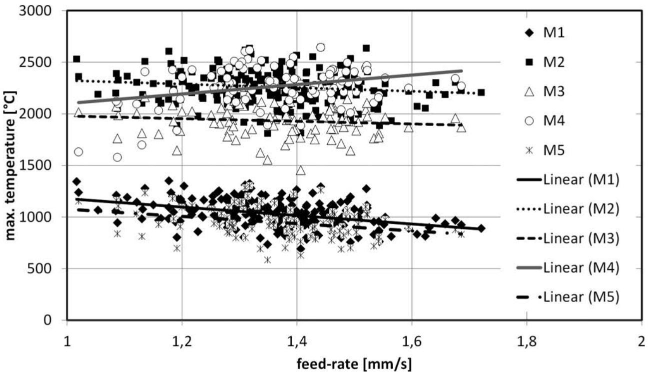

Fig. 9: Results of sensitivity analysis – influence of the feed rate.

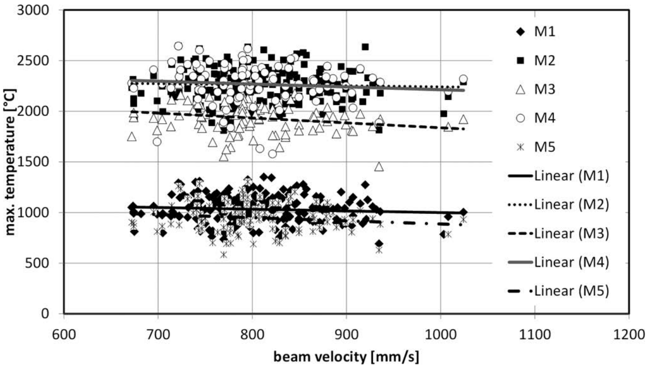

Fig. 10: Results of sensitivity analysis – influence of beam velocity.

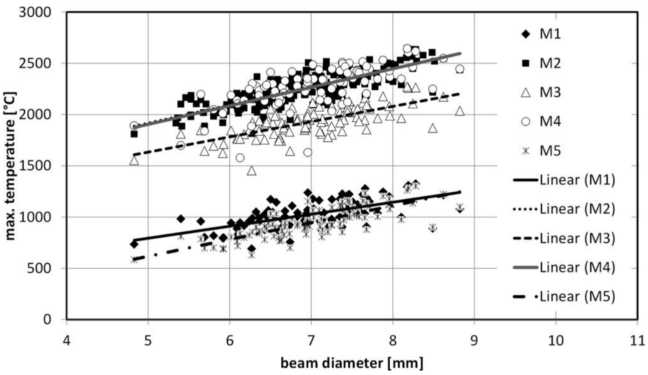

Fig. 11: Results of sensitivity analysis – influence of beam diameter.

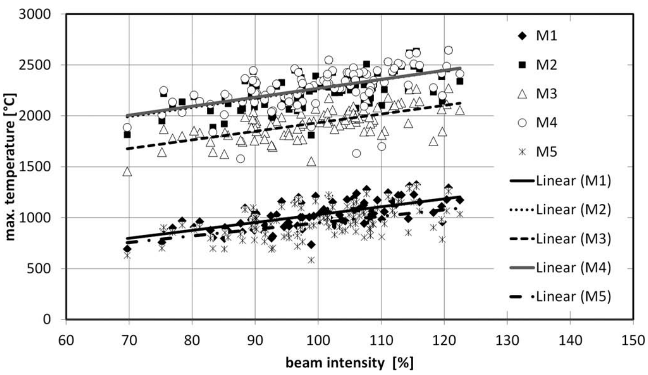

Fig. 12: Results of sensitivity analysis – influence of beam intensity.

VII. Conclusion

Measurements on a stylus instrument (2D and 3D) show that laser beam polishing can reduce the initial roughness Ra from 0.2 ... 0.8 µm down to 5 ... 15 nm. Among other things it is indicated that the laser beam polishing technology does not change the surface contour, however, a suitable cooling process to reduce tensions may be necessary. Furthermore, SEM investigations show that a very clean surface and polishing atmosphere is required to reach excellent surface quality. In contrast to the comparable mechanical finishing with a polishing rate of 228 s/cm², it is now possible to finish fused silica surfaces at 4.8 s/cm² by polishing with laser radiation (providing that optimized parameters are applied).

The polishing process could be investigated with the commercial FE-software SYSWELD for calculation of the time- and location-dependent temperature distribution in the plate. Application of the laser beam polishing process requires an extensive adaptation of the material models used. Simulation can be performed to optimize the process parameters to achieve the targeted temperature state.

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