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Study of the temperature behaviour in the polishing gap for different combinations of polishing pads and slurries

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Abstract
Polishing is one of the oldest manufacturing processes and represents a common use case in the optical industry to finish high-quality glass work pieces, such as lithography lenses or astronomy mirrors. It is used to obtain a better surface quality (e.g., in terms of the shape accuracy and roughness) and to treat possible depth damages (sub surface damages and micro cracks) caused by previous processes like grinding. Due to the ever-increasing demands of sub-nanometre level surface finishes for optical components, it is highly desired to study the polishing process more in detail. It becomes especially important to understand the processes between the polishing tool and the glass work piece, the so-called polishing gap. The aim of this work is to improve the knowledge of the polishing gap with respect to its temperature behaviour that can be influenced by mechanical and chemical effects. For this purpose, several sensors in vicinity to the polishing gap are used to measure the temperature during polishing. Due to the minimal height of the polishing gap of only a few nanometres, it is not possible to mount sensors directly inside of the polishing gap. Instead, sensors are mounted below the surface of the glass work piece (2 mm) as well as inside the polishing tool as near as possible to the polishing gap. For the experiments, an eccentric polishing tool with specific setups for each task is used, which differ in the combination of the used polishing pad and the slurry. The polishing pads vary in the surface properties, while the slurries differ in the mean particle size. The various combinations result in changing parameters like the frictional power and heat dissipation within the polishing gap. In theory, these changes result into a different temperature behaviour in the polishing gap during the process, which can be seen by the measured temperature values.

Keywords: Polishing, Glass, Polishing gap, Temperature, In-situ measuring

1. Introduction

Similar to wafer polishing, the performance requirements for modern lithography optics have reached a level that can only be achieved through more profound understanding of the polishing process and the increasingly important in-process control. Conventional process control in lithography optic fabrication relies mostly on repeated measurements of the optical components in terms of surface figure and roughness after each process step. This becomes less economically viable, when the sizes of the optical surfaces increase to the square metre range given the associated, necessary cycle times.

Therefore, process development aims not only for a more precise control of the operating resources (e.g., slurry monitoring, qualifying polishing media and batch controls) but also for in-situ approaches to assess the polishing conditions in the effective gap between the polishing pad, optical surface and slurry, for example, by the use of sensors. With such an access to the porperties of the polishing gap, the polishing process could be investigated in more detail, enabling further process improvements based on correlations with the polishing quality or process in the ideal case. However, with todays sensor technology the integration of sensors within the polishing gap without influencing the process itself still represents a major challenge. Furthermore, the interpretation of the measured data is not straightforward, given the fact that the processes within the polishing gap are still far from understood [1,2]. There is a variety of parameters (e.g., the viscosity of the slurry and the presence and size of agglomerations in the polishing pad) which have an impact on these processes and thus on the polishing result. Focusing on specific parameters, such as the temperature in the polishing gap, that is affected by the frictional forces between the polishing pad, the slurry and the work piece during material removal, could reduce the complexity of such an approach. The dependency of the temperature on the friction was previously investigated by Cornely *et al*. [3], who observed an increasing temperature for increasing polishing forces due to a higher friction. In this work, different polishing pads and slurries are utilized in order to increase or decrease the friction during polishing, resulting in a temperature change within the polishing gap. Horng *et al*. [4] corroborated with a mathematical model, that the pad and slurry properties influence the resulting friction in the polishing gap.

The slurry contains abrasives, floating in a carrier medium, typically water (see figure 1). The abrasives lead to a material removal in the polishing gap, where they are pressed with a certain force and speed on the work piece by the polishing tool. These abrasives can move freely between the tool and the work piece or penetrate into the pad, loosing their freedom of roll. This leads to minimal surface roughness of the tool and small removal rates. The amount and size of abrasives penetrating into the pad is depending, among other things, on the properties of the pad and the composition of the slurry. Consequently, using different polishing pads and slurries lead to a change in friction, which should be detectable by a change of the temperature in the polishing gap.

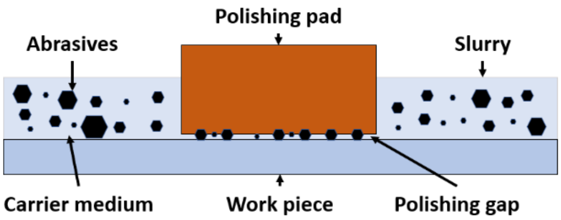

Figure 1. Schematic illustration of the polishing gap during the polishing process. The abrasives in the slurry can move freely between the polishing pad and the work piece or penetrate into the pad.

2. Proceeding

This section provides an overview of the experimental setup, which is used for the experiments in this work. Furthermore it includes the used metrology and the parameters of the programmed toolpath. Lastly, information about the experimental design is given.

2.1. Experimental setup

The setup consists a polishing head which is driven by an six-axis industrial robot (see figure 2). The polishing head is equipped with a rotational motor and pressure cylinder which guides the polishing tool. For this work, the polishing weight on the polishing tool is set to 3 kg and the rotational speed to 700 rpm. These parameters were kept constant throughout all experiments. The polishing tool is mounted to the bottom of the polishing head. An eccentric mode with an eccentric distance of 7 mm is used. The tool is used for polishing a planar glass work piece, which is mounted onto a zero point clamping system. The latter is mounted on a polishing work space. The slurry is contained by a polishing bath, which encases the work piece and enables reproducible fill level height for the trials.

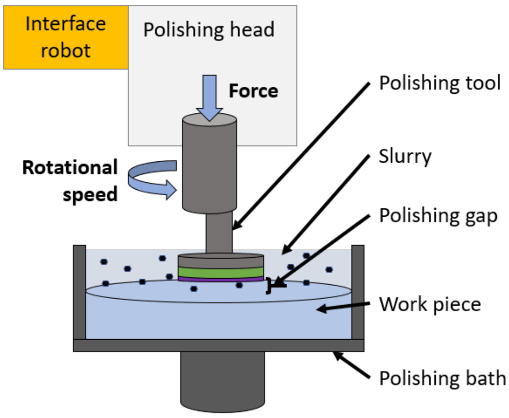

Figure 2. Schematic representation of the experimental setup. The polishing tool, guided by a robot, is pressed onto the glass work piece with a defined force and speed. The work piece is surrounded by the polishing bath, containing the slurry.

In the next sub-chapters, more details about the set up are provided, including the positions of the temperature sensors.

2.1.1. Polishing tool

The polishing tool consists of three different main parts, which are shown in figure 3. The upper part is a metallic body, which is directly mounted to the polishing head. To measure the temperature in close vicinity to the polishing gap, two temperature sensors (TT1 and TT2) are fixed into the metallic body with a distance of 0.2 mm to the bottom of the body. The smaller the distance between the sensors and the polishing gap is, the less thermal loss and other measurement uncertainties are expected.

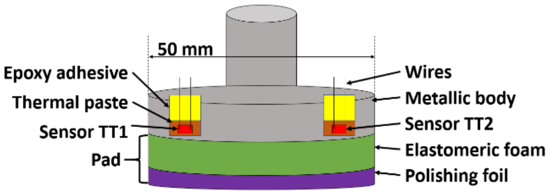

Figure 3. Schematic illustration of the polishing tool. The temperature sensors TT1 and TT2 are mounted into the metallic body. The pad is glued to the bottom of the metallic body and consists of a polishing foil and an elastomeric foam.

The sensors are glued with a thermal paste into the body for an optimized heat transfer. To avoid damages to the sensors connection due to stress (e.g., due to the eccentric movement of the polishing tool), additionally an epoxy based glue is used. On the bottom side, a polishing pad with a diameter of 50 mm is glued. The polishing pad comprises an elastomeric foam and a polishing foil, with the latter being in direct contact with the polishing gap. For the experiments, three different polishing pad combinations are used, which differ in the used polishing foil. An overview about the used polishing pads is given in table 2.

2.1.2. Slurry

Two different SiO_2-based dispersions are used in this work, which are mixed with deionized water in a ratio of 1:3. The two slurries differ with respect to their mean particle size (see table 2). For all trials, a slurry volume of 400 ml is filled into the polishing bath.

Table 1. Properties of employed polishing pads and slurries.

Polishing pad	Pad material type
P1	Synthetic felt pad 1
P2	Synthetic felt pad 2
P3	Poromeric urethane foam pad
Slurry	**Mean particle size [nm]**
L1	<50
L2	>50

2.1.3. Work piece

The work piece used for the experiments is a glass piece (ULE) with a diameter of 150 mm and a thickness of 20 mm. In order to be able to attach temperature sensors as close as possible to the polishing gap (distance of 2 mm), five recesses were grinded into rear of the glass (see figure 4). Due to the fact, that the same work piece is used for all experiments, the distance to the polishing gap is decreasing as material is removed during the trials. Because the removal rate is less than 5 µm per trial, (maximum decrease in distance of 0.25%), the error due to this effect can be neglected for this work. To isolate the sensors against incoming heat from the bottom side of the glass and to avoid damages due to mechanical stress, the sensors are glued into the glass in the same way as the temperature sensors in the polishing tool (see section 2.1.1).

As shown in figure 4, six temperature sensors are mounted in radial arrangement inside of the glass work piece. The sensors TW3-TW6 are placed individually into recesses, whereas sensor TW1 and TW2 are mounted into the same recess. This is made to check if the temperature measurement within a hole can be reproduced by the used sensors.

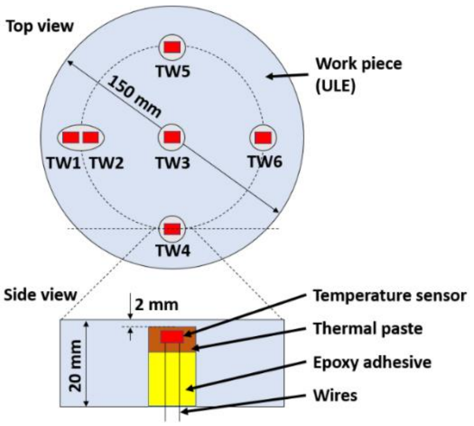

Figure 4. Schematic illustration of the glass work piece with the position of the five recesses and the six temperature sensors. The distance of the sensors to the surface of the work piece is about 2 mm.

2.2. Metrology

All temperature sensors used in this work are PT1000 sensors with a specified tolerance class B, leading to an accuracy of ±0.4°C at room temperature. Each is connected by two wires to an analog-to-digital converter (ADC) with an accuracy of ±0.25°C and a resolution of 0.01°C. This leads to a theoretical system accuracy of ±0.65°C. This setup is expected to have better accuracy, as a qualification process at room temperature showed a maximum error of 0.05°C between the used sensors. The sampling frequency is set to 32 Hz.

2.3. Toolpath

The robot toolpath, is identical for each trial and is designed as a meander path over the whole glass surface (see figure 5). The forward speed is set to 12 mm/s with a path distance of 0.4 mm. One trial contains thirty-four cycles, where seventeen cycles are from the left to right and the other cycles vice versa. This leads to a total polishing time of about ten hours per trial and a polished area of ca. 176.7 cm².

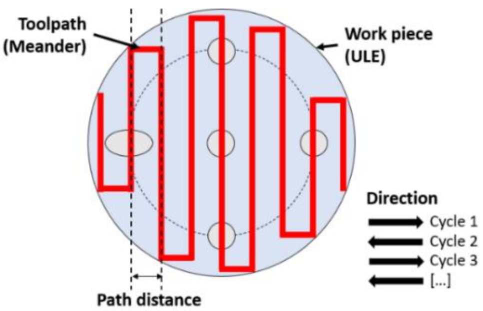

Figure 5. Schematic illustration of the toolpath (red line). Designed as meander path with a speed of 12 mm/s and a path distance of 0.4 mm.

2.4. Design of experiments

The experiment is designed to cover five scenarios which vary in the combination of the pad and the slurry (see table 2).

Table 2. The experimental is designed with five different scenarios, which differ in the combination of the used pad and slurry.

Scenario	Trial	Pad	Slurry
S1	T1-T3, T15	P2	L1
S2	T4-T6	P1	L1
S3	T7-T9	P2	L2
S4	T10-T12	P3	L2
S5	T13-T14	P1	L2

The employed trial sequence enables an assessment of the reproducibility of the data for scenario S1 over time. In the beginning of every trial, a new polishing pad is attached to the tool and a fresh dispersion of the polishing slurry is used.

3. Results

In the following sub-chapters, the results of the measured temperature data from the experiments are presented and discussed, starting with the temperature sensors in the polishing tool followed by the sensors in the work piece.

3.1. Temperature sensors in the polishing tool

The sensors mounted into the tool are expected to measure mainly the slurry temperature near the polishing gap. In figure 6 the averaged data measured by the sensors TT1 and TT2 is shown for each trial. The temperature signals for the same scenario were not perfectly reproducible, because the ambient temperature was slightly inconstant during the course of the experiments, although the laboratory is air-conditioned. Nevertheless, the temperature curves for all scenarios show a consistent trend over time. That is, a rapid increase in temperature within the first minutes of each experiment followed by a cooling phase, which lasts about two hours. This behaviour could be explained by evaporative cooling that is intensified by the movement of the polishing tool mixing the slurry in the bath. Subsequently, a monotonous increase in temperature can be observed, implying a stronger impact of the temperature increase due to the friction within the polishing gap than of the evaporative cooling at this point of the experiment.

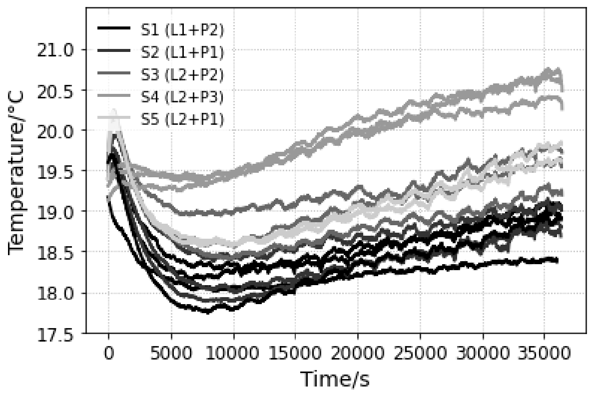

Figure 6. Comparison of the averaged temperature data measured by the sensors TT1 and TT2 mounted in the polishing tool for different scenarios which differ in the combination of polishing pad and slurry.

When comparing the temperature curves for the different scenarios in more detail, it becomes evident that the temperature signals for scenario S4 do not show such a big cooling effect compared to the other scenarios. This suggests that the combination of the used pad and slurry for scenario S4 is causing the highest frictional heat. Interestingly, the higher slurry temperature for scenario S3 and S5 in comparison with S1 and S2 could be rationalized by the higher particle sizes of slurry L2.

3.2. Temperature sensors in the work piece

Because the results in the previous section 3.1. strongly suggest that the ambient temperature has a significant influence on the temperature data for each trial, the temperature signals for the work piece sensors are corrected in a way to eliminate this effect. This should be achieved by substracting the averaged temperature signals recorded with the tool sensors from the data measured with the work piece sensors. In this way, a relative increase or decrease of the glass surface temperature in relation to the temperature in the slury bath (measured by the TT1 and TT2 sensors) can be achieved. When performing this correction, the temperature data of the different trials within a scenario show a very good reproducibility allowing a more meaningful evaluation.

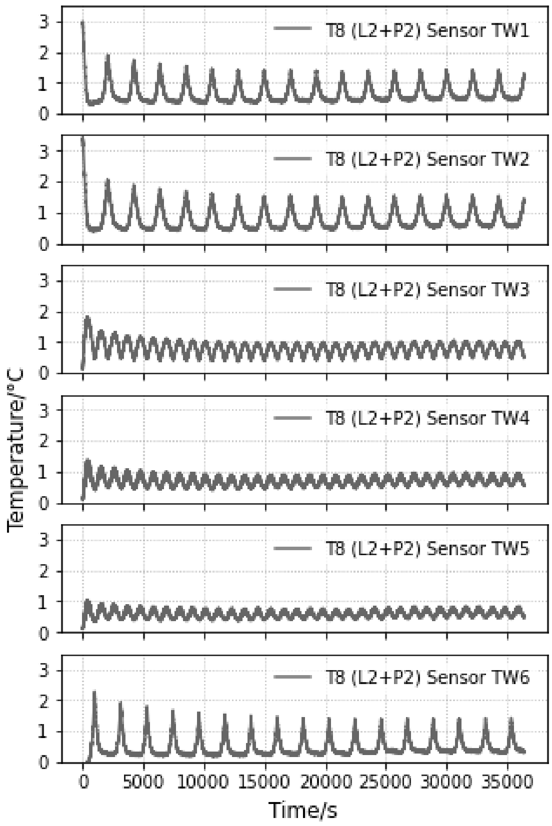

Figure 7. Comparison of the resulting corrected data from trial T8 for the sensors TW1-TW6. The graphs show the temperature behaviour of the glass surface relative to the slurry temperature.

Figure 7 shows the corrected temperature data of trial T8 for all work piece sensors, demonstrating the typical temperature behaviour during the polishing process. The corrected temperature characteristics for all trials of the same scenario closely resemble each other. The temperature signals recorded with the sensors TW1 and TW2, which are located in the same recess, reproduce each other, further corroborating the plausibility of the temperature measurement. To further assess the correlation of the corrected temperature curves with the movement of the polishing tool, the time dependence of the temperature signals is evaluated in more detail. In principle, an increase in temperature is expected, when the polishing tool is overlapping with the work piece sensors. Indeed, sensor TW1, TW2 and TW6 show seventeen local maxima and minima with a constant time distance of two cycles, which is about 2120 seconds, whereas sensors TW3-TW5 have thirty-four local maxima and minima with a distance of one cycle or 1060 seconds. When comparing these results with the polishing toolpath (see section 2.3.), it becomes evident, that the number of temperature maxima is in good agreement with the path of the polishing tool. In addition, the smaller temperature amplitudes recorded with the sensors TW3-TW5 can be rationalized by the shorter overlapping time of the tool and the sensor due to the toolpath properties. The decreasing peak temperature of the maxima over time could be explained by deterioration of the polishing pad leading to a smaller friction and thus to an increase of the temperature.

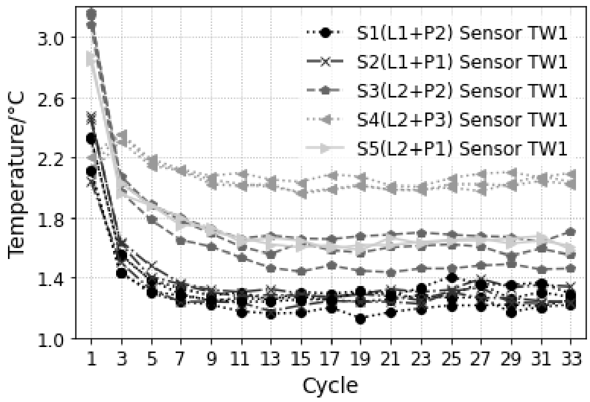

Figure 8. Comparison of scenarios' local maxima measured by sensor TW1, which is located 2mm under the glass surface. In the beginning, the maxima decrease rapidly until they reach an almost constant level.

To compare the temperature behaviour of the different scenarios, the local maximas of sensor TW1 are plotted in figure 8. When comparing scenarios S3-S5, the influence of the polishing pad on the temperature behaviour can be evaluated, because the same slurry is used in these scenarios. The highest increase in temperature is observed for pad P3, whereas no significant difference between pad P1 and P2 can be seen. The same applies, when comparing the temperature signals of scenario S1 and S2. To evaluate the impact of the slurry, the scenarios S1-S2 are compared with scenarios S3-S5. It is evident, that the experiments with slurry L2 result in a significantly higher increase in temperature, most likely because of the higher mean particle size in comparison with slurry L1. With respect to the above discussed deterioration of the polishing pad possibly leading to the decrease of the peak temperature over time, it can be hypothesized that polishing pad P3 shows a less pronounced deterioration than the pads P1 and P2.

4. Summary and discussion

This work showed that it is possible to achieve an in-situ measurement of the temperature in or close to the polishing gap. In addition, various combinations of polishing pads and slurries could be discriminated by the differences in their temperature characteristics. This observation implies that the properties of the pad and the slurry have an direct impact on the friction between the tool and the glass surface (see figure 8).

These results represent an important step towards an improved process control. In future, further design experiments and additional sensor types might further enable access to and clarify the conditions within the polishing gap.

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