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**Research Article**

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# Novel procedure for the identification of a starting point for the CMP

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**Abstract:** In the field of precision optics, more and more glass materials that are difficult to machine are being used because of their interesting optical properties. At the same time, the geometries are getting more demanding and the tolerances to be achieved are tighter. The establishment of an efficient process chain is therefore becoming an ever-greater challenge. Particularly in the field of CMP, knowledge of the machining properties of pads and slurries are required to design efficient processes. This knowledge has to be gained through time-consuming in-house tests, as the manufacturers of the consumables are usually only able to provide basic data. In addition, the boundary conditions under which the data were collected are often incomplete defined and thus not comparable. The novel methodical procedure presented here for the initial design of CMP processes is based on a standardized procedure for carrying out the tests. From the resulting database, a starting point for the design of own processes can be identified quickly and unerringly. This article describes the structure of the procedure as well as the necessary background. In addition, the visualization and the procedure for selecting start parameters are discussed using an example application.

**Keywords:** CMP; polishing; polishing pad; polishing slurry; process design.

## 1 Introduction

Chemical mechanical polishing (CMP) is one of the most frequently used processes for finishing optically effective surfaces. In addition, it is often used as a pre-process for highly accurate but low in material removal rate finishing technologies such as MRF or IBF. But the polishing process is also one of the most time-consuming and cost-intensive processes in optics production. It is therefore of great economic importance to make these parts of the process chain as efficient as possible. For this purpose, it is necessary to achieve the desired surface quality (roughness, shape and cleanliness) by removing the glass material in the shortest possible time (MRR material removal rate).

The variety of glass materials and their processing properties, as well as the large number of polishing agents and polishing pads available on the market, are a great challenge for the user when designing CMP processes. In addition, there is often a lack of information from the manufacturers of the consumables on how to use them correctly and efficiently. So before new polishing agents or polishing pads can be used in production, time-consuming and cost-intensive preliminary tests must be carried out to determine optimal operating points. In practice, therefore, due to lack of time and capacity in machinery and staff for detailed examinations, one slurry and one pad are often used for processing all glass materials. Inefficient processes are the result. To simplify the selection of consumables for the CMP, the user needs more precise information about the performance of the products when processing different materials. In addition, the information must be comparable and the procedure for obtaining it must be verifiable.

Against this background, the novel methodical procedure presented below was developed to identify suitable process parameters. With the help of the results obtained in this way, different products can be compared by their performance under different process conditions. So, it is also possible to search for the most efficient combination of pad and slurry for processing a specific glass material. The combination of consumables and process parameters identified in this way can be used as a starting point for designing specific CMP processes.

## 2 CMP basics and influences – a brief overview

The effective system of the CMP consists of the components shown in Figure 1, namely the polishing pad, the workpiece

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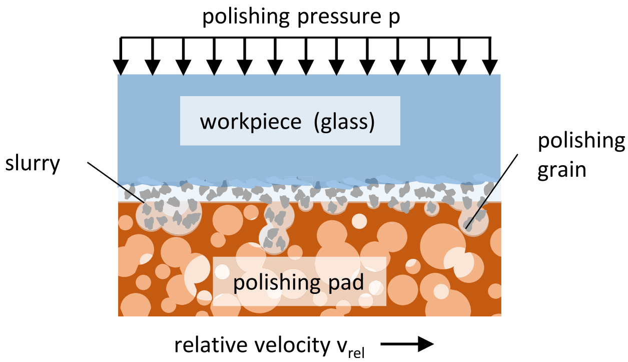


**Figure 1:** The effective system for the CMP of glass [1].

and the slurry consisting of the abrasive grain and a liquid (usually water). The workpiece is processed under the influence of polishing pressure and relative speed [1].

It is well known that each component of the effect system has influence on the process result at the CMP. Some possible influences of the polishing pad, the polishing slurry and the process parameters used are briefly discussed below.

## 2.1 Influences due to the polishing slurry

Polishing slurries consisting of cerium oxide and deionised water are most commonly used in precision optics. The influence of these slurries on the process results is determined by various factors:

With increasing concentration of polishing agent in the slurry, the material removal rate (MRR) also increases [2]. At the same concentration, smaller grains achieve a higher MRR than larger ones. This is due to the increasing number of contact points between the smaller grains and the glass surface [3]. Above a certain concentration, the MRR stagnates because the maximum number of active grains in the gap between polishing pad and glass is reached. All additional available grains therefore have no influence on the material removal [3–6].

Also, the surface roughness is influenced by the polishing agent. It increases with increasing grain size. This is due to the force transmitted to the workpiece per grain and the associated mechanical stress. Due to the smaller number of grains in the effective gap, larger grains transmit greater forces, but also cause rougher surfaces [2, 7, 8].

The CMP is also influenced by other parameters of the slurry, such as the pH value, the temperature and the chemical composition. For example, this is discussed in more detail in [9–11].

## 2.2 Influences due to the polishing pad

The polishing pad takes on a major role in the CMP. It transfers the process forces via the grain to the workpiece and transports fresh slurry into and removed material out of the effective gap.

Polyurethane foam with different hardness and structure is most commonly used for the CMP of optical glass. The surface of these pads has open pores that can vary both in size and number. Over the duration of the polishing process, the surface of the pad changes. Polishing agent is deposited in the pores and the surface wears out. With increasing wear, the pad becomes smooth. This so-called glassing has a negative effect on the MRR [12, 13]. To make the pad "grippy" again, it must be dressed.

The hardness of the pad also affects the MRR. Soft materials achieve increased MRR compared to harder materials. This is due to the embedding behaviour of the polishing grains. In soft pads, the grain can penetrate deeper. As a result, smaller grains also reach the glass surface. The MRR increases as a result [2, 14, 15].

The macrostructure of the pads also influences the polishing result, as well as the chemical change of the polyurethane when it comes into contact with water. The investigations of [16, 17] are dedicated to these parameters.

## 2.3 Influences due to the process parameters

The Preston equation describes the formal relationship between how the polishing pressure $p$ and the relative velocity $v_{\mathrm{rel}}$ affect the MRR. In the Preston coefficient K, all other influences, for example by the polishing pad or the slurry, are summarized [18]

$$\frac{dz}{dt} = K \cdot p \cdot v_{\mathrm{rel}}$$

As $p$ and $v_{\mathrm{rel}}$ increase, so does the MRR. However, this increase is not linear. At higher relative speeds, the curve flattens out. This is attributable to the changing friction conditions between the components. At high $v_{\mathrm{rel}}$, the slurry film becomes more load-bearing. This results in a kind of aquaplaning of the pad and an associated drop in MRR [2].

With increasing relative speed, a decrease in surface roughness can also be observed. This is explained by a reduction in the forces transmitted through a grain as the load-bearing capacity of the fluid film increases [1, 2].

### 2.4 Design of CMP processes in the manufacturing environment

For various reasons, the variables influencing CMP, which have been well studied in the scientific environment, are not or hardly considered in the manufacturing environment. This may be related to a lack of information about the properties of the slurries and pads, as well as a lack of equipment and time to carry out tests on the products themselves. In addition, there is the wide range of optical materials and their sometimes very different machinability.

## 3 CMP–how to get initial parameters–new methodical approach

With the novel methodical procedure presented in the following, it is possible for the user to identify the most efficient initial parameter combinations for his CMP application. Based on this setting, the process can be further adapted.

The foundation for this is formed by uniformly and comparably conducted preliminary tests. Their preparation, execution and evaluation are described below.

### 3.1 Preparation

The polishing technology used for parameter determination is the widely used synchro-speed process, as its technical design allows equally precise and continuous adjustment of all process parameters. In addition, a slurry supply unit is needed. Prior to each test, the entire system must be cleaned to be as free as possible from old slurry residues. These could otherwise falsify the test result.

The preparation of the polishing tool, the slurry and the test specimens must always be carried out uniform and according to the specifications listed in Table 1. After the preparation of the individual components, the conditioning of the polishing pad and the slurry can be started. This is necessary because both components change their properties and behaviour considerably during their initial time in the process. To obtain stable process conditions, a sample (sacrificial sample) of the investigated glass material is polished three times for 20 min with the freshly conditioned slurry and a fresh pad. An intermediate setting of the process parameters is used, namely a polishing pressure of 50 kPa and a relative speed of 2.09 m/s. This causes agglomerates in the slurry to be ground up and the surface of the polishing pad to absorb polishing agent and be smoothed. Between runs, the pad is brushed out to prevent glazing. The components are sufficiently prepared when a constant MRR has been established.

### 3.2 Execution

After a stable state of slurry and pad has been reached, the experiments can be started. For this purpose, test specimens are polished successively with different process parameters. Based on a preliminary investigation, parameter combinations with high pressure and low relative speed are neglected, as they have not proven useful in the development of the methodology, since process results in this range are subject to very large fluctuations. This results in a total of six parameter combinations of polishing pressure and relative speed to be used, which are shown in Figure 2a.

The sequence of the required individual tests is shown in Figure 2b. According to the methodology, each combination is to be performed twice in random order, which means that 12 test specimens are required as a foundation. Each test specimen is processed for 300 s with the selected parameter combination. After processing each test specimen, it is mandatory to brush out the pad.

### 3.3 Evaluation

After the machining process, the test specimens are cleaned and the surface roughness (RMS), the MRR, the surface quality, and the change in surface shape are determined. Table 2 summarises the target values to be measured as well as the measuring methods and procedures to be used for this purpose.

**Table 1:** Specifications for the preparation of the slurry, the polishing tool and the test specimens.

| Slurry | Polishing tool | Test specimens |
|---|---|---|
| – Prepare the slurry with deionized water to a concentration of 1.025 g/cm³<br>– 2 l slurry is needed<br>– Ensure a volume flow of 0.5 L/min<br>– Temperature 22 °C ± 0.5 °C | – Pad attached to the tool according to manufacturer's instructions<br>– Dressing the pad with a diamond tool to an axial play of ±2 μm<br>– Store the tool in water over 24 h | – Prepare 12 plan samples with a diameter of 40 mm and a thickness of 10–12 mm<br>– Edges faceted (1 × 45°)<br>– Numbered and pre-weighted<br>– Pre-polished to a shape of 2.5(0.5/0.5) |

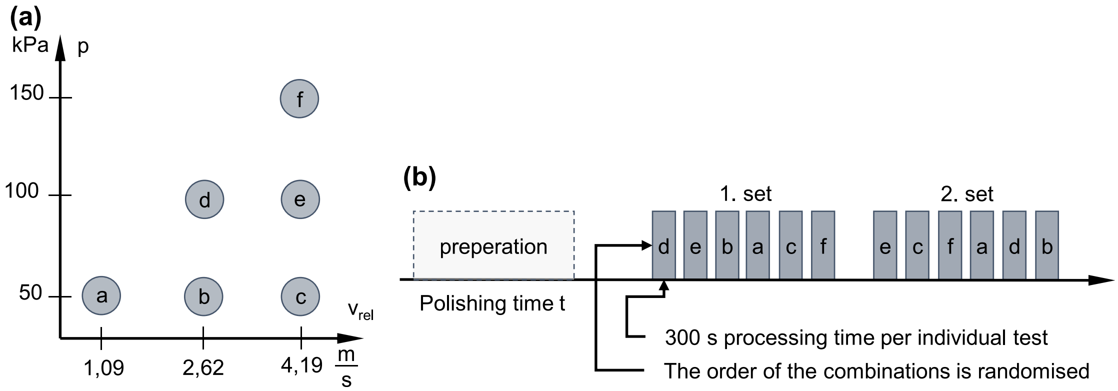


**Figure 2:** Design of the test procedure. (a) Combinations of polishing pressure and relative speed selected for implementation. (b) Sequence of individual tests. The order of the parameter combinations is randomised. Each specimen is polished for 300 s.

**Table 2:** Compilation of the target variables to be measured as well as the measurement methods and procedures to be used for this purpose.

| Surface roughness | MRR | Surface quality | Change in shape |
|---|---|---|---|
| – Determination of the RMS at nine points evenly distributed on the surface<br>– e. g. by using white light interferometry<br>– Calculate mean value and standard deviation over all measuring points | – Determination of material removal by weighing the samples before and after machining<br>– Calculation of MMR in µm/min | – Searching for surface defects (DIN ISO 10110-7) [19]<br>– Manually or automated e. g. by using an ARGOS system<br>– Documentation of the maximum defect size $L_{max}$ | – Measurement of the surface shape before and after machining (SAG, IRR, and RSI)<br>– e. g. by using interferometry<br>– Calculation of the deformation |

For all recorded test values, the mean value from the identically processed test specimens is calculated and documented. The change in shape is not a hard criterion for evaluation, as the movement sequences in the process are rigidly set, this can have a negative effect on the change in shape. However, the values provide an impression of how much the polish carrier affects the shape of the product. After the evaluation of the experiments, the comparative presentation of the results can be started.

## 3.4 Visualisation

The clear illustration of the test results forms the basis for a quick selection of suitable start parameters. It is therefore necessary to combine the three remaining parameters in one presentation. In the following, this will be illustrated using experimental data obtained according to the procedure presented above.

The properties of the components used are summarised in Table 3. In the experiments, the glass material FCD1 was processed with the polishing agent Opaline™ and four different pads. This process was repeated two times.

Figure 3 summarises the test results in a diagram specific to the novel methodology. For clarity, only three of the six implemented $p/v_{rel}$-combinations are shown. The results for MRR, RMS and $L_{max}$ are combined in one graph. Along the abscissa the MRR is plotted in µm/min. The positive direction of the ordinate shows the raw roughness data (RMS) in nm without applying any filter and the negative direction the maximum defect size $L_{max}$ in mm.

**Table 3:** Properties of the investigated components.

| Polishing pad | | Polishing agent | | Glass material | |
|---|---|---|---|---|---|
| **Type:** | **Hardness:** | **Type:** | **Material:** | **Type:** | **Hardness:** |
| Unalon LP-66 | 80 shore A | Opaline™ | Ceroxid 99.9% | FCD1 | 345 HK |
| Unalon GR-25 | 81 shore A | **pH value:** | **Particle size D90:** | **Density:** | **Thermal conductivity λ:** |
| Exterion™ C74A | 78 JIS-A | 7.0 | 0.5–1.0 µm | 3.70 g/cm³ | 0.837 W/m·K |
| Exterion™ C76C | 86 JIS-A | | | | |

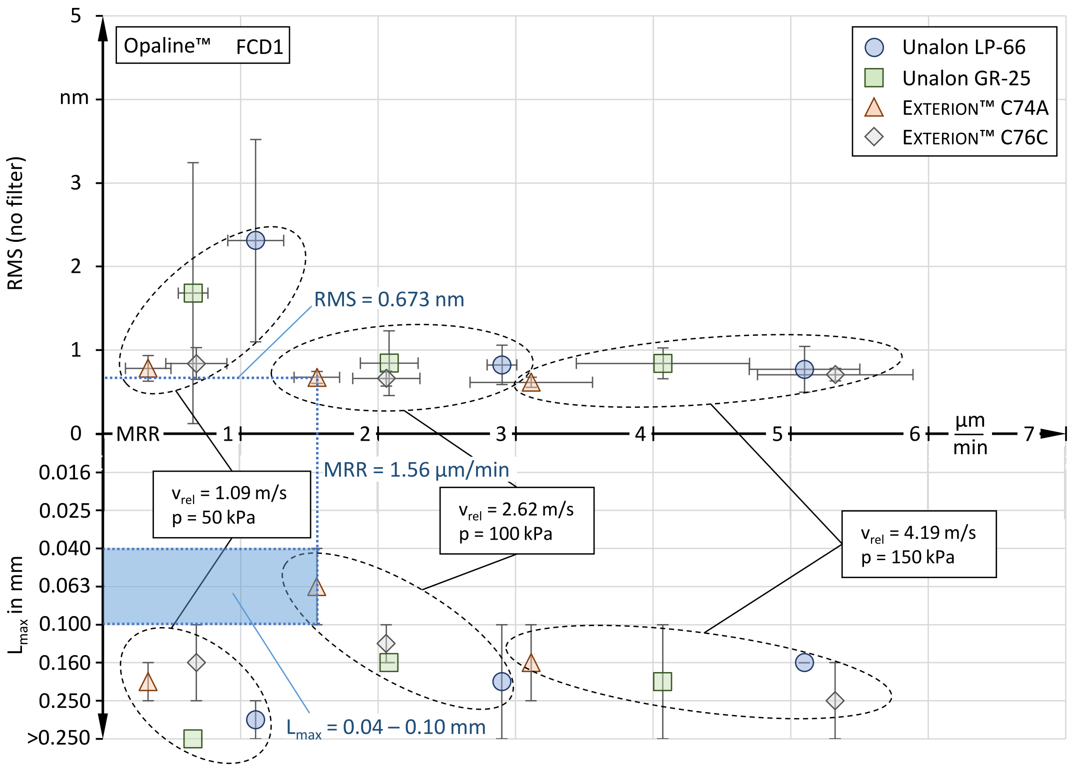


**Figure 3:** Illustration of the test results generated using the presented method and the components from Table 3. For a better overview, only selected parameter combinations are shown. The values of the three target variables MRR, RMS and $L_{max}$ are shown in the graph.

For each parameter combination, the results are illustrated by a pair of symbols which are located opposite to each other, with the MRR being the connection variable. The indication of the defect length is not continuous but within the gradations according to DIN ISO 10110-7. Therefore, the error bar displayed does not indicate the standard deviation, but the identified minimum and maximum for $L_{max}$.

In Figure 3 one parameter combination is highlighted by dotted blue lines to illustrate how to read the data shown in the diagram. This is done as follows: Using the process parameters $p$ = 100 kPa and $v_{rel}$ = 2.62 m/s, the Exterion™ C74A pad achieves an MRR of 1.56 µm/min with a surface roughness of 0.673 nm RMS and a maximum defect size of $L_{max}$ = 0.04–0.1 mm.

## 3.5 Selection

The choice of a starting parameter for a CMP process is always based on the optical requirements (shape, roughness and maximum defect size) and the desired material removal rate. In order to demonstrate the applicability of the new method in practice, a German optics manufacturer has provided a demonstrator. This is a concave-convex lens made of the material FCD1 with a required shape accuracy of λ/10. The subsequent process design is based on the following requirements:

- The surface roughness should be below **2 nm RMS (P3).**
- The maximum allowed size of defects $\mathbf{L_{max}}$ **is 0.1 mm (5/3×0.1).**
- The MRR should be more than **0.4 µm/min.**

The defined boundary conditions are displayed as red lines in Figure 4. A suitable start parameter setting must therefore be chosen from within the green highlighted zone. In this case, three parameter combinations are suitable for the application example, as they are completely enclosed by the zone.

The selection of the combination used in the further course was again made by the optics manufacturer. Since the Exterion™ C76C pad exhibits good behaviour in combination with the process parameters $p$ = 50 kPa and $v_{rel}$ = 2.62 m/s, this combination was used for the initial design of a process.

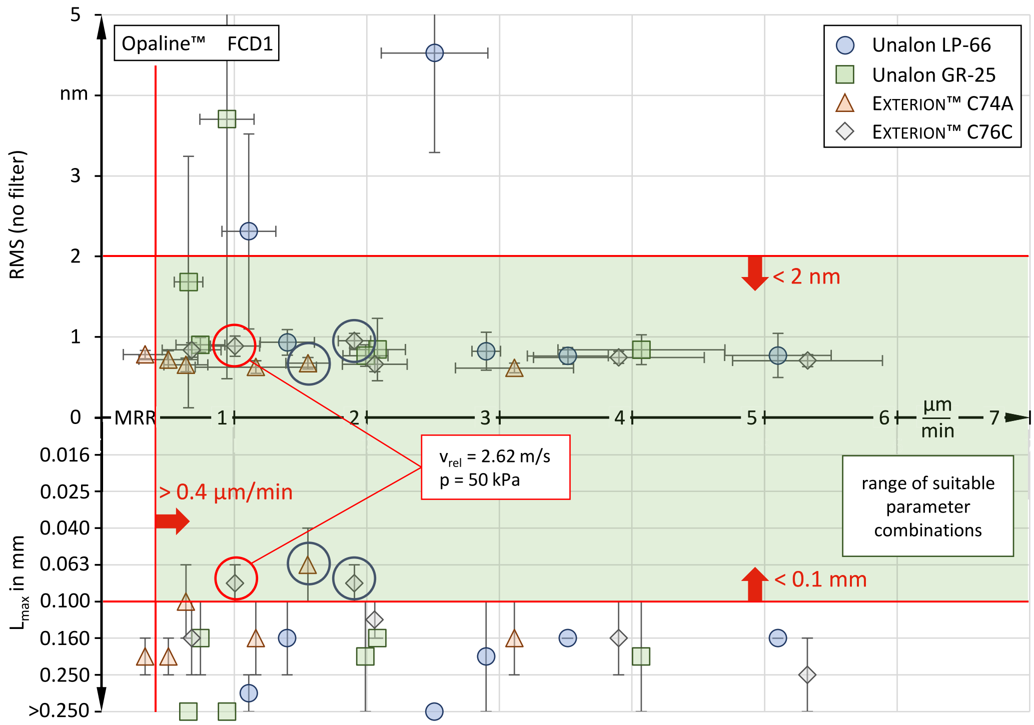


**Figure 4:** Illustration of the test results generated using the presented method and the components from Table 3. The boundary conditions for the target variables MRR, RMS and $L_{max}$ are marked by red lines. The zone in which all requirements are met is highlighted in green. All suitable parameter combinations are highlighted. The selected set is additionally outlined in red.

## 3.6 Application

The selected parameters must be adapted mathematically to the geometry to be machined. A corresponding adaptation will be demonstrated by means of a convex–concave lens, which was processed during validation tests in the production line of an optics manufacturer. The geometry of the lens and the process setup are outlined in Figure 5.

Based on the required relative speed $v_{rel}$, the diameter of the lens $d_{lens}$, the radius of curvature $R$ and the polishing

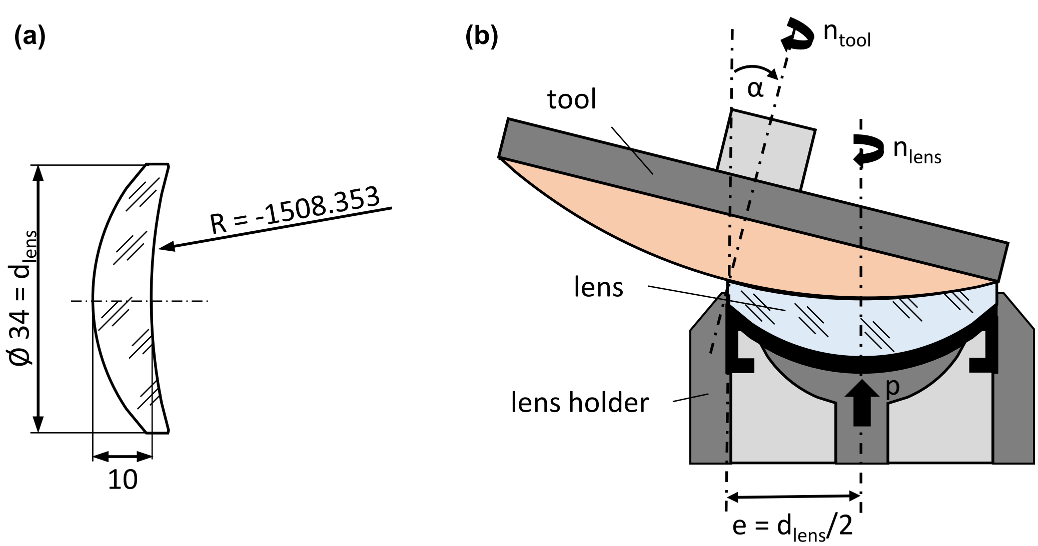


**Figure 5:** Boundary conditions for the application of the methodological approach. (a) Sketch of the lens to which the parameters are to be transferred. The drawing is not to scale. Only data approved by the manufacturer is shown. (b) Sketch of the process setup.

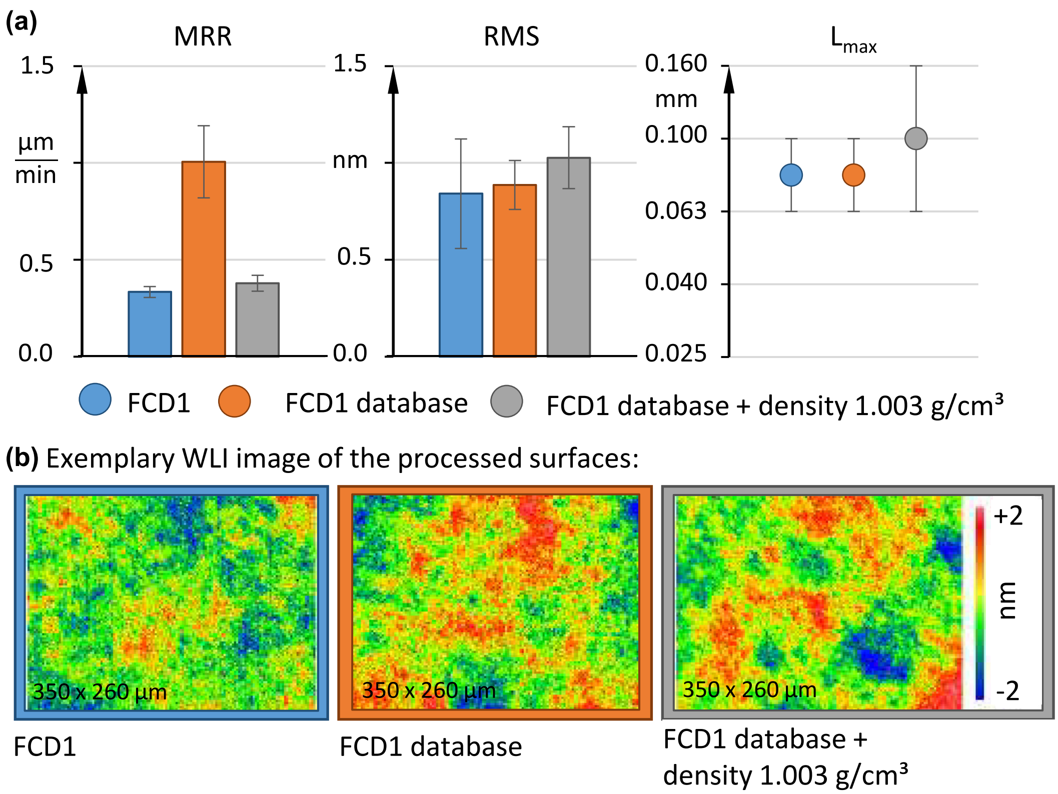


**Figure 6:** Results from the application of the methodological approach. (a) Comparison of the values of the target quantities for MRR, RMS and Lmax achieved in the preliminary tests with a slurry density of 1.025 g/cm³ (left column, blue), in the validation tests with a slurry density of 1.003 g/cm³ (middle column, orange) and in supplementary tests with a slurry density of 1.003 g/cm³ (right column, gray). (b) WLI images of the machined surfaces (Zygo NewView; 20x Mirau).

pressure $p$, the rotational speeds of tool $n_{tool}$ and workpiece $n_{lens}$, as well as the adjustment angle $\alpha$, must be derived mathematically. The following equations can be used for this purpose [20].

$$n_{tool} = \frac{v_{rel}}{\pi \cdot d_{lens}} \quad \text{with} \quad d_{tool} = 2 \cdot d_{lens}$$

$$\alpha = \arcsin\left(\frac{d_{lens}}{2 \cdot |R|}\right)$$

$$n_{lens} = \cos\alpha \cdot n_{tool}$$

This results in the following settings for the polishing machine:

- $n_{tool} = 1472.46\ \text{min}^{-1}$
- $\alpha = 0.6457$
- $n_{lens} = 1472.36\ \text{min}^{-1}$
- $p = 50$ kPa

Due to machine limitations, the adjustment angle α had to be set to a value of 0.7503°. Also, the rotational speed of the tool had to be set to a value of 1250 $\text{min}^{-1}$. Both results in a rotational speed of the lens of 1249.83 $\text{min}^{-1}$. The 15% reduction in relative speed compared to the start parameter is tolerable and only leads to a reduction in MRR.

In the following, the machining results are compared with the values of the initial tests.

From the graphs in Figure 6 it can be seen that the values for RMS and $L_{max}$ of the preliminary tests on plane surfaces hardly differ from those when transferred to the lens geometry shown in Figure 5a. Nevertheless, the MRR is two thirds lower in comparison. This is because the density of the polishing slurry during the polishing of the lenses was only 1.003 g/cm³ (fixed value by the optics manufacturer) instead of 1.025 g/cm³ which was used during the preliminary tests, resulting in a significant decrease in MRR.

To confirm that exclusively the slurry density was causing the decrease in MRR, the preliminary tests with the selected parameter set were performed again with a slurry density adjusted to the industrial values. The results for MRR compare well between the validation tests and the supplementary tests. Thus, the transferability of the results from uniformly performed preliminary tests to the processing of different geometries is proven. Furthermore, this is supported by the results for RMS and $L_{max}$.

After the initial design of the process, it may be necessary to make further fine adjustments in order to achieve the desired stability, for example. Compared to the conventional methods for designing CMP, however, no major test series are necessary for this. Smaller adjustments can be made directly in the running process.

The mathematical adaptation of the process parameters from the preliminary tests to the target process and a comparable condition of the polishing pad and polishing slurry is decisive for the application of the method. This results in comparable conditions in the effective gap. This in turn results in comparable process results. Particular attention should therefore be paid to the preparation and control of the polishing medium carrier and polishing suspension.

The presented approach has already been successfully used several times in the industrial environment. For example, an ideal combination of polishing slurry and polishing pad as well as suitable process parameters for polishing $CaF_2$ with RMS <1 nm could be found. Furthermore, the method was used to develop an optimal formula for a polishing agent for processing hard glass materials.

## 4 Conclusions

Chemical-mechanical polishing processes are subject to many different influences. These have been extensively studied scientifically and are well documented. However, it is difficult to transfer the findings to the production environment. There is often a lack of detailed information about the properties of the products used, such as slurries and pads. In addition, there is a lack of time, equipment, and personnel to carry out even larger test series. The novel method presented here enables the manufacturers and distributors of the consumables, but also the end user, to carry out tests according to a uniform procedure. The user thus has the possibility to design his processes based on his own tests or the manufacturer's data. At the same time, different approaches can be compared, and the most efficient solution selected. The procedure is particularly useful when processing new glass materials or when searching for alternative consumables. It was proved that, process windows developed in this way can be transferred to all moderately curved surfaces. This enables processes developed centrally in high-wage regions to be applied to production sites worldwide without the need to send highly qualified personnel. In addition, no costly measurement technology is required on site. Both can significantly reduce the development costs for new CMP processes.

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