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# Knowledge-based process design for pad-polishing of precision optics

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## Abstract

This paper addresses the polishing of precision glass optics as well as mirrors made of advanced ceramics with the so-called pad polishing process, a sub-aperture technology. Smaller and smaller lot sizes, an increasing demand for customized optics as well as raising price pressure by Asian competitors challenge the European manufacturer. To withstand these challenges and for manufacturing highly specialized prototypes, a gain in efficiency is required, which can be reached by knowledge-based process design.

The contribution of this work consists in the presentation of an theoretical tool for the analytical compensation of systematic process deviations. The tool will substitute the empirical try-outs in process required for the compensation kinematic effects.

The local distribution of material removal is calculated based on Preston’s equation and takes into account the influence of the major input parameters.

The resulting distribution of local material removal is used for the realization of compensation strategies. The necessary experimental investigations, the mathematical model and application examples are presented. The given experimental results on a 6-axis cnc-polishing machines show a significant reduction in shape deviation applying these methods compared to a polishing process without any compensation.

## 1 Technological Background

Pad polishing is applied on many types of polishing machines and typically used for both pre-polishing and figuring. A small polishing tool is moved across the surface. The high flexibility enables machining of diverse materials. Depending on the machine tool and applied control system various tool path can be realized [1]. All applications have in common the required compensation of kinematic effects. The application of a spiral tool path with a rotating work piece, similar to slow tool turning, offers a number of advantages: less marks on the surface, higher removal rates and highly symmetrical results. On the other side, changes in the polishing conditions between the edge and the centre must be compensated, right know by empirical try-outs. That means, at least one additional sample for every new geometry or new set of process parameters is required. Figure 1 shows a typical change in the radius of curvature without compensation by moderating the feed rate.

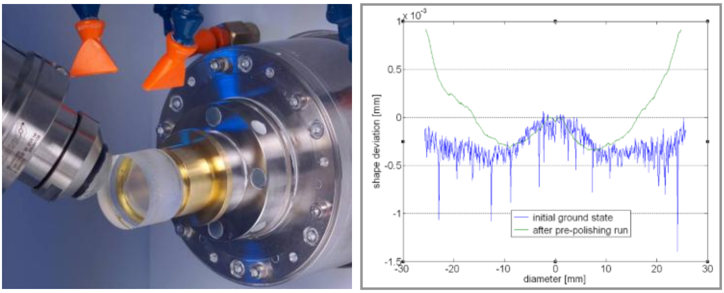


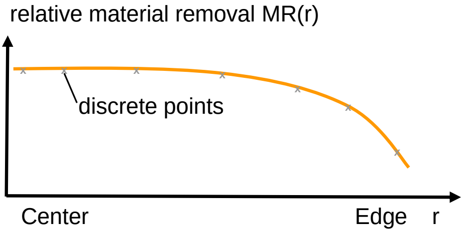
Figure 1: Motivation: Compensating the systematic form deviation in spiral polishing

## 2 Description of the analytical method

In contrast to the corrective polishing algorithms [2], the here proposed tool looks for an easy and efficient description of the influence of the most significant process parameters on the local material removal for defining the required moderation. An data interface enables the feedback to the control of the machine tool.

### 2.1 Modeling approach

The chosen approach bases on the calculation of the material removal MR(r) (Figure 2) dependant on the site on the radius.



**Approach**

1. Calculate MR(r) according to Preston‘s equation
2. Repetition for numerous points from center to edge

➔ Input for moderation

Figure 2: General approach and outcome of the model

The repetition for a discrete number of points results in a description of the local differences in material removal. This profile can substitute the prior used empirical profiles as well as forms the basis for controlling the material removal by moderating the feed rate, spindle revolutions or the spot size.

### 2.2 Calculation of local material removal

The calculation of the material removal at a given site MR (r) bases on Preston's equation [3]: It states that the material removal in polishing depends on the relative velocity between tool and sample v, the contact pressure p and the polishing time dt. Several researchers developed modifications or extensions of his equation. But here, the major changes are in the local dwell time, relative velocity and pressure, which are considered in the basic equation sufficiently. Our experiments showed that only an extension by exponents of the relative velocity and pressure is necessary to consider non-linearities. The here addressed spiral tool path results in a number of contact periods, within a single spot is touched by the tool. Geometrical considerations enable the calculation of the contact time and the relative velocity according to the given process parameters as well as lens design and tool geometry. Combining these with Preston's equation the material removal at the point r can be described by the following sum of several contact periods:

$$MR(r) = \sum^{n} \int_{0}^{t\max} f\left(v_{rel}(R,r,n)\right) dt$$

There is no analytical antiderivative without further restrictions, so that the calculation requires a numerical approach, which was implemented finally in Matlab. The Matlab environment also contains a graphical user interface and data interfaces to the machine tool control system.

In summary, the model enables the prediction of the influence of change in process parameters on the centre and edge effects as well the overall change in the shape. Furthermore, it can be used to calculate an appropriate compensation strategy by changing feed rate, spindle revolutions or contact area dynamically.

## 3 Application

All the experimental work was conducted on a 6-axis-polishing machine (Zeeko IRP 200 / Satisloh AII). A typical pressure-inflated membrane tool was used. Figure 3 shows the results of an application test. The moderation of the feed rate was made on basis of a calculated profile instead of an empirically determined one. The polishing time was approximately ten minutes and the geometry was a mild asphere. The result with a moderation based on the calculated material removal profile (right chart) shows, that the previously observed change in the radius of curvature (left chart) was compensated.

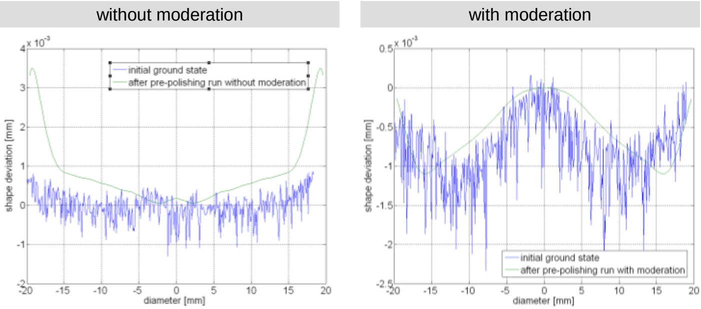


Figure 3: Polishing results without (left) and with calculated (right) moderation

## 4 Conclusion

The presented theoretical tool can be applied for the analytical compensation of the systematic influences in spiral-polishing. The tool provides a relative description of the irregularities in material removal for given process parameters. The benefits are the reduction of necessary test samples after a change of part geometry or of the process parameters as well as considering the changes in the contact zone, when polishing aspheres. The next development steps will take into account the effect of contact pressure, which was assumed as constant right now.

## References:

[1] Freeman, R., “Bonnet Polishing and Fluid Jet Polishing“, Zeeko Ltd (2008).

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[3] Preston, F., “The Theory and Design of Plate Glass Polishing Machines,” Journal of the Soc. of Glass Technology 11, 214-256 (1927).