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APPROACHES TO COST-EFFECTIVE MANUFACTURING OF PRECISION ASPHERES

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ABSTRACT

Precision aspheres are used in a wide range of technical applications. Their admissible form deviation typically shows less than 1µm pV which allows a separation to the quality class of mid performance aspheres. Common applications containing precision aspheres are e.g. objectives for SLR cameras and microscopes as well as binoculars. With respect to the required performance of the optical systems, generative manufacturing technologies such as precision molding / bright molding, are not an option due to induced material inhomogeneities and stress birefringence. Thus, cutting manufacturing technologies such as grinding and polishing are used exclusively.

The aim of this paper is to gain insight into the process chain for the production of precision aspheres and the manufacturing technologies used. The process chain to discuss is in accordance with figure 1.

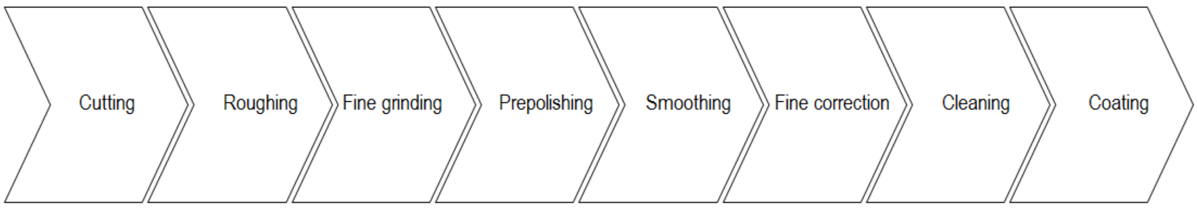

Fig. 1: Common process chain for the manufacturing of precision optics

Furthermore, deficiencies of current manufacturing technologies are shown and needs for action are derived. The emphasis of this discussion is set on current technologies for prepolishing and smoothing. The state-of-the-art manufacturing technology for prepolishing processes is called Bonnet Polishing. It uses a flexible subaperture tool body which provides a (relatively) small contact zone. The removal rate of a polishing tool correlates with the size of its contact zone. Thus, Bonnet Polishing leads to long processing times which turn out to be the cost driver for the manufacturing of precision aspheres. Furthermore, polishing tools with small contact zones are prone to generate mid frequent form deviations in a spatial wavelength range of 0.5 – 2mm. The subsequent smoothing process does not provide an effective way to remove the tool fingerprint. At present, time-consuming fine correction is the only way to eliminate remaining high frequent form deviations.

In order to reduce manufacturing costs, this paper provides three considerable approaches to discuss:

- optimized process parameters for an increased removal rate;
- a multi-tool setup for simultaneous processing with at least two polishing tools;
- a full aperture active-adaptive polishing tool.

Every approach shows specific pros and cons with regard to the manufacturing process as well as technical complexity, installation space, etc. Thus, a comparison and evaluation of all three approaches is given. Finally, this paper presents a concept of the preferred approach.

1. INTRODUCTION

The quality class of precision aspheres or precision optics in general can be classified by two major characteristics: the performance of the optical system as well as the measuring technology required for the manufacturing process. A detailed discussion on the optical performance was already given by [1], [2], [3] as well as [4] and does not represent the subject for further research.
The measuring technology used in the process chain for the manufacturing of optical components strongly depends on admissible shape deviations (form and surface) of the workpiece.
Numerous technical applications allow form deviations in the range of several µm. Hence, state-of-the-art Coordinate Measuring Machines (CMM) are likely used because:

1. their measuring uncertainty is absolutely adequate for this task;
2. they possess an enormous flexibility;
3. they require short set-up times / programming times;
4. they allow short processing times.

Optical components that can be qualified by CMMs are generally classified as mid performance optics. Typical applications of this class are, for instance, ophthalmic devices, common microscopy applications as well as consumer camera objectives just to name a few.

Admissible form deviations of less than the measuring uncertainty of a state-of-the-art CMM cannot be qualified safely. Therefore, form deviations of less than usually 1µm are measured interferometrically. Interferometric test benches used therefor comply with the principle of a Twyman-Green Interferometer [4]. The verification of spherical optics requires interferometer objectives with a suitable focal length and aperture to adapt the wave front corresponding to the surface curvature. However, aspheres and freeform optics necessitate the usage of a Computer-Generated Hologram (CGH) to shape the wave front corresponding to the optical surface to be verified.

2. STATE-OF-THE-ART POLISHING TECHNOLOGIES FOR PRECISION ASPHERES

Aim of this chapter is to gain insight into state-of-the-art polishing technologies for the manufacturing of precision aspheres by pointing out the three major downsides of the existing technologies. Fading out several grinding processes that are conducted before, the analysis starts with a fine grinded asphere. It shows a matte and opaque surface (ref. Fig. 1) which is due to a 15 – 25µm thick layer of micro-cracks, called SubSurface Damage (SSD) arising from the grinding process [4]. This layer is to be removed by a so called prepolishing process providing a constant removal height over the whole surface. The state-of-the-art polishing technology for aspheres is called Bonnet Polishing (ref. Fig. 2). For this purpose, multi-axis CNC machines/robots as well as polishing tools and controls therefor are commercially available. Process times for prepolishing aspheres amount to multiple times of comparable spheres, depending on the local curvatures and slope variations.

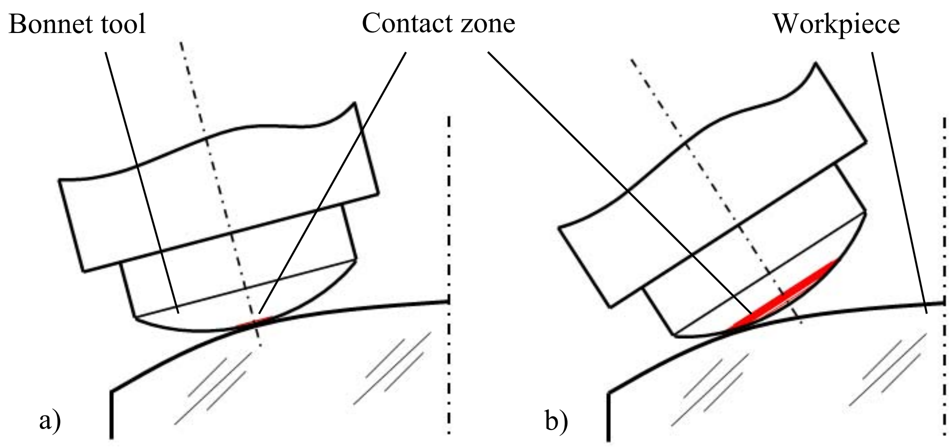

Fig. 2: Bonnet polishing: a) classical, b) off-axis

These additional processing times, derived from tool geometry and processing kinematics, are one of the major cost drivers for the manufacturing of aspheres and freeform optics. It is mandatory that the tool curvature radius is possessed smaller-sized or equal to the tightest local curvature of the workpiece. This allows to retain the form generated by the previous fine grinding process, but limits the polishing tool diameter concurrently. This in turn leads to a small-sized contact zone between workpiece and polishing tool. As a consequence, this leads to three major disadvantages that are to be discussed subsequently:

1. The removal rate directly depends on the size of the contact zone under the assumption of constant pressure and relative speed. Thus, small-sized contact zones lead to a **low removal rate** resulting in long processing times.
2. Small-sized contact zones are subject to the generation of **mid frequent form deviations** induced by the fingerprint of the tool. At present, there is no technology for an efficient removal of these structures.
3. Small-sized contact zones lead to **high erosion** of the polishing pad. Hence, a short durability necessitates a periodic change of the bonnet causing increased setup times.

An effective approach to increase the tool life by an off-axis polishing was patented by [5]. It is characterized by a defined displacement between the rotary axis of the tool and the contact zone. This yields to major advantages as the relative speed in the contact zone never shows 0m/s (like it does without off-axis), the deviation of minimum and maximum relative speed is far less, and finally, the tool life is increased significantly by the generation of a ring shaped tool wear profile (ref. Fig. 2 b)) with a multiple times bigger-sized surface area. Optimizations concerning the surface finish by "Continuous Precessing" [6] or the variation of processing parameters were conducted by [7], [8] as well as [9]. The remaining drawbacks like the low removal rate (ref. disadvantage no. 1) as well as the subject to the generation of mid frequent form deviations (ref. disadvantage no. 2) cannot be eliminated by the off-axis technique.

The subsequent smoothing process of aspheres uses flexible multilayer tools. These generally consist of a stiff carrier plate equipped with an elastic interlayer and a polishing pad of foamed polyurethane foil. The stiffness of the multilayer tool can be varied by the shore hardness and the thickness of the interlayer and polishing pad, to influence the spatial wavelengths to be smoothed. The maximum diameter of the smoothing tool is limited by the tightest local curvature of the workpiece also. Thus, ripples generated by the Bonnet Polishing cannot be removed in an effective manner. In fact, a decrease of the amplitude can be achieved but due to specified form tolerances a fine correction is still necessary. A strong demand for a time and cost efficient production of aspheres leads to a general need for action in terms of technology and process development.

3. APPROACH

The following chapter discusses three approaches for a cost effective production for aspheres. An evaluation concerning prospect of success, effort of execution as well as flexibility is given subsequently.

OPTIMIZED OF PROCESS PARAMETERS FOR AN INCREASED REMOVAL RATE

The achievable removal rate strongly depends on the three major process parameters pressure, relative speed as well as dwell time. The Preston equation delivers a good tool for the prediction of removal heights (ref. eq. 1).

$$\Delta h = k * p \int v(t)\, dt \tag{1}$$

Δh … Removal height
k … Preston constant
p … Polishing pressure
$v(t)$ … Relative speed
t … Dwell time

A targeted material removal requires a state of mixed friction whereat slide friction as well as fluidic friction occur in proportion. Hence, a prediction of removal heights demands for stable friction conditions. Thus, an increased removal rate requires a tuning of process parameters. Investigations by [10] deliver two major interrelations:

1. An increased polishing pressure leads to a higher friction coefficient.
2. An increased relative speed leads to a lower friction coefficient.

It can be derived that an increased removal rate can be achieved by a balanced increase of polishing pressure and relative speed, assuming unmodified tool composition and processing kinematics. Investigations by [10] confirm this theory. However, this tuning is limited by close tribologic boundaries. Thus, an increased removal rate of 20 – 25% (depending on material) can be achieved. The major disadvantage of this is a higher sensibility of the tribologic system – concerning altering process parameters such as the wear of the polishing pad, the temperature of the polishing abrasive, etc. – which results in a decreased predictability of the removal height.

Thus, the variation of the process parameters pressure and relative speed is of limited suitability. Even as off-axis polishing reduces the deviation of minimum and maximum relative speed significantly, the remaining difference in speed (within the contact zone) can lead to critical hydrodynamic circumstances. Likewise, local pressure differences caused by the form adaption of the polishing pad can lead to the same situation. Thus, a constant removal rate during the whole polishing process cannot be achieved. Furthermore, the disadvantages of mid-frequent form deviations (ref. disadvantage no. 2) as well as high erosion of the polishing pad (ref. disadvantage no. 3) still remain.

MULTI-TOOL SETUP FOR SIMULTANEOUS PROCESSING WITH AT LEAST TWO POLISHING TOOLS

A multi-tool setup promises a significantly higher removal rate. For this, a simultaneous processing of at least two polishing tools is required. Fig. 3 shows a suitable concept that allows to derive several boundary conditions for the polishing process and construction design:

- The longer the simultaneous processing of both polishing tools in proportion to the overall processing time, the bigger the effect on the processing time.
- Due to limited installation space, the simultaneous processing of both polishing tools cannot be accomplished in the apex zone of the workpiece. Thus, the relative processing time reduction is in proportion with the workpiece diameter.
- The workpiece needs one degree of freedom, coincident to its optical axis. This axis has to be driven, preferably electromechanically (ref. Fig. 3 Z_{rotWpc}).
- The tool arms require lateral guideways and drives for movement in z-direction. This can be implemented in adjacence to the polishing tool (ref. Fig. 3 $Z_{transTool1}$ / $Z_{transTool2}$) and/or as a direct mount to the support frame (ref. Fig. 3 $Z_{transTool}$).
- The tool arms require lateral guideways and drives for movement in x-direction (ref. Fig. 3 $X_{transTool1}$ / $X_{transTool2}$)
- Each polishing tool requires a rotational axis and drive in y-direction to track the tool in accordance to the curvature of the workpiece (ref. Fig. 3 $Y_{rotTool1}$ / $Y_{rotTool2}$).
- An off-axis polishing is possible by a constant offset angle in x-direction (ref. Fig. 3 $X_{rotTool1}$ / $X_{rotTool2}$) or out of the local workpiece surface normal by a constant offset angle in y-direction (ref. Fig. 3 $Y_{rotTool1}$ / $Y_{rotTool2}$).

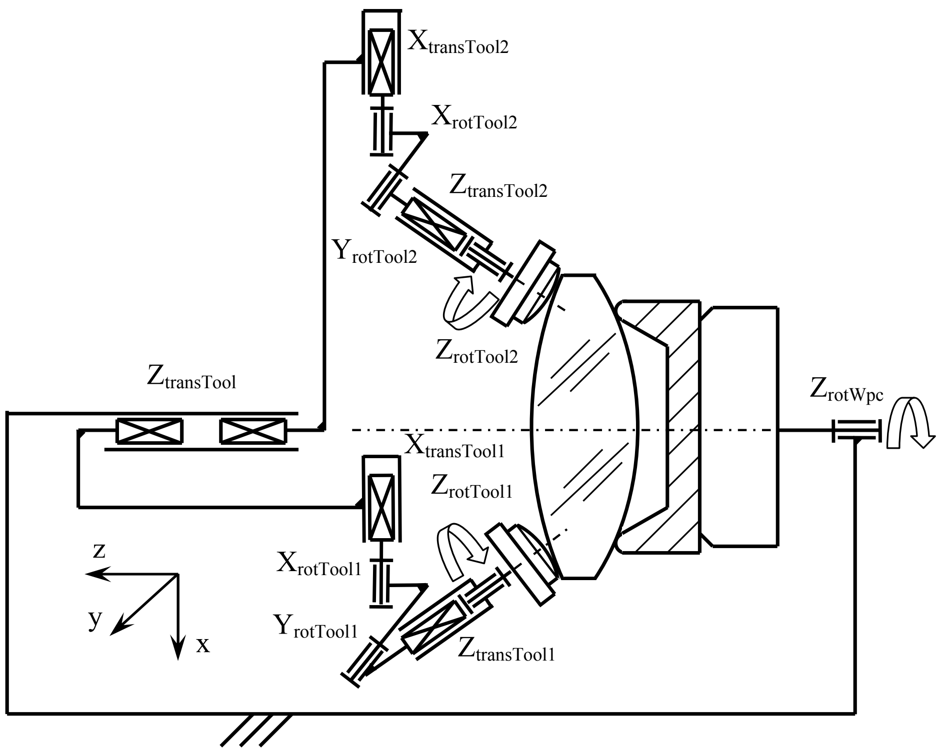

Fig. 3: Concept of a multi-tool setup

Setups with three or more polishing tools are feasible in principle. Due to limited installation space, the typical diameter range of precision aspheres does not allow a simultaneous processing of all polishing tools. Hence, the aspired process time reduction cannot be met. Furthermore, every additional polishing tool leads to a more complex setup in terms of mechanics, controls and programming.
Precision aspheres for semiconductor applications are a major target group of this multi-tool setup as they possess large diameters, large curvature radii as well as moderate slope variations. In summary, the multi-tool setup with simultaneous processing of at least two polishing heads promises a significant processing time reduction of almost 50 percent. Nevertheless, the disadvantages, specified in chapter two still remain the same as they tend to mid frequent form deviations (ref. disadvantage no. 2) as well as the high erosion (ref. disadvantage no. 2) of the polishing pads cannot be solved by this approach.

FULL APERTURE ACTIVE-ADAPTIVE POLISHING TOOL

Full aperture polishing tools – as used for polishing of spheres and planes – possess several advantages. As the removal rate is directly depending on the surface area of the contact zone, a maximum removal rate can be achieved by a full aperture polishing. Furthermore, the form deviations induced by the polishing tool can be easily removed by correction polishing as they are low frequent and low amplitude. Finally, the surface area used for polishing is a multiple of the surface area used in bonnet polishing. Thus, Synchrospeed tools offer a much higher durability.

The demand for active polishing tools with large contact zones for aspheric surface manufacturing is nothing novel. About 30 years ago [11] and [12] investigated in active tools for the polishing of primary mirrors for astronomy applications. These “Stressed Lap” (SL) tools featured a characteristic diameter of about 1m in combination with a mm range travel. By constant enhancements over the years in terms of mechanical design and control, this technology became essential for today’s primary mirror segment production for astronomy [13], [14]. Latest SL tools possess diameters of about 1.5m. For the development of full aperture active and / or adaptive polishing tools for aspheres, this technology offers very limited usability. Thus, a parallel branch of development for deformable polishing tools started out in year 2005 with theoretical investigations by [15].
First practical results for active deformable tools followed by [16] and [17] by using a full aperture polisher with evenly distributed piezo actuators over the whole surface area. By this, the form of the tool can be manipulated. Biggest disadvantage of this development is the limited piezo travel of about 30µm as well as a residual form deviation of 4 – 8µm RMS which limits the usability of this tool for very slight aspheres. Hence, every asphere geometry requires a special best fit radius polishing tool.

The adaptive full aperture polisher developed by [18] and [19] features a membrane which is brought into contact with the workpiece either by compressed air or by a magnetic field in combination with ferromagnetic balls underneath the membrane. Practical results show very low removal rates due to the polishing pressure of ~0,1bar. Furthermore, the results show a non-uniform removal profile which could be improved by the rotational speed ratio of tool and workpiece.

Up to now, publications in the field of full aperture polishing tools for aspheres feature either an active form variation or an adaptive (passive) polisher that emulates the form of the workpiece to be processed. Though, none of these setups provides a combination of both approaches, which would lead to several advantages for the polishing process:

- Less requirements for the actuators concerning dynamics, smallest step size and installation space
- Remaining form deviations of the active deformed polisher will be compensated by the adaptive layer. Thus, an almost homogeneous pressure distribution within the full aperture contact zone allows an overall constant material removal.

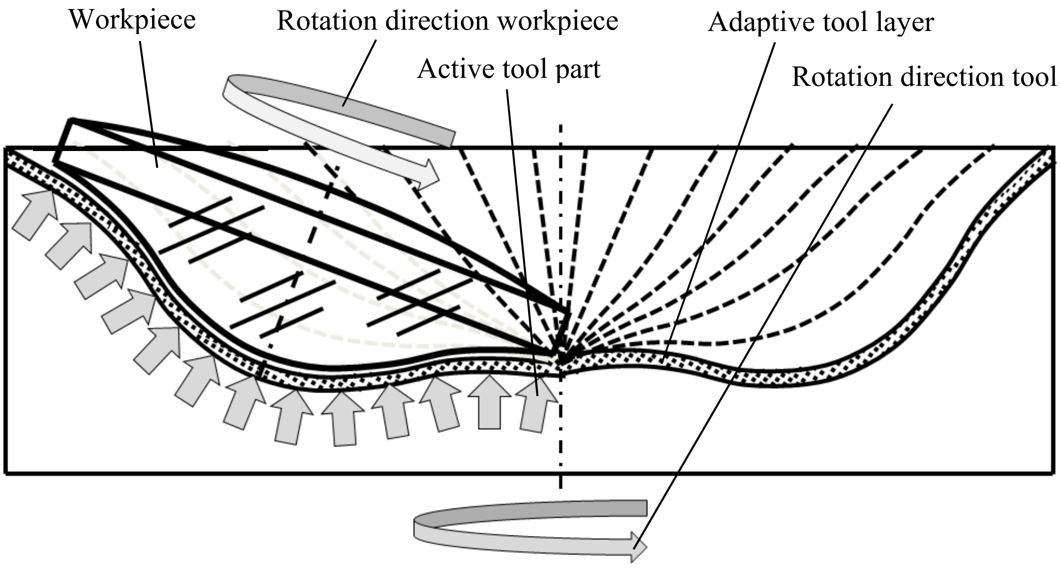

Fig. 4: Concept of a full aperture active-adaptive polishing tool

Fig. 4 illustrates a possible layout of a full aperture active-adaptive polishing tool in full section view. To fulfill the requirements concerning form deviations and pressure distribution, a serial composition of active and adaptive part of the tool is a necessity.

EVALUATION OF THE APPROACHES

Tab. 1 shows an evaluation of the three approaches concerning their prospect of success, effort of realization as well as flexibility. The approach of a full aperture active-adaptive polishing tool promises the greatest process time reduction. Nevertheless, it takes a huge effort of realization due to the development of a completely new technology. Furthermore, the approach features a limited flexibility as the travel ranges of the actuators are limited. The remaining approaches promise a decrease of the downsides of subaperture tools presented above but do not eliminate their source.

Tab. 1: Evaluation of the approaches

Rating criteria \ Approach	**Optimized process parameters**	**Multi-tool setup**	**Full aperture active-adaptive tool**
Prospect of success	o	o	+ +
Effort of realization	+ +	–	–
Flexibility	+ +	+	o

+ + excellent + good o satisfactory – sufficient – – insufficient

4. CONCLUSION

The aim of this paper was to give a review of state-of-the-art polishing technologies for precision aspheres in order to specify disadvantages and identify cost drivers in the production of precision aspheres. From this, three approaches for a cost effective manufacturing of precision aspheres were developed, presented and summarized, providing a recommendation for further research.

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