Deterministic Polishing of Smooth and Structured Molds

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Abstract. The replication of ultra precise optical components requires molds with an extremely low surface roughness, a minimum of defectivity and high shape accuracy. To meet these demands polishing is essential. In comparison to other fields of application, polishing molds combines high demands and new geometries, e.g. aspherical cavities or structured surfaces for cylindrical lens arrays. Due to a lack of suitable polishing strategies, tools and innovative tool machines, the molds often have to be polished manually. In this chapter the authors discuss the major aspects for deterministic polishing starting from basic investigations on the material removal mechanisms to process strategies, tool development and design of innovative polishing tool machines. The materials dealt with reach from steel to advanced ceramics and tungsten carbide. The addressed geometries are smooth molds with a continuous surface as well as structured surfaces. The discussed issues look at the needs in replication of both plastic and glass optics.

1 Introduction

One key to success in the replication of plastic and glass optics represents the mold inserts. Therefore, deterministic, powerful and automated manufacturing processes for the mold making are required. Polishing forms the most frequently

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E. Brinksmeier et al. (Eds.): Fabrication of Complex Optical Components, LNPE, pp. 99–117.
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used technology if high surface quality in terms of low roughness and high surface integrity is demanded. In many applications polishing secures the functionality of the samples. Due to its position at the end of the manufacturing sequence, it determines the sample quality substantially. For long-time polishing has been established in the conventional manufacturing of optics by grinding and polishing. In the fields of metal sheet forging or plastic injection molding, molds and dies have been polished manually for many years.

The manufacturing of molds for the replication of optics combines the high demands in terms of accuracy of the optics manufacturing with complex geometries, partly dealt with in mold and die making industry.

Within the SFB / TR4 several projects focused on the development of appropriate polishing machines, automated processes and the required fundamental understanding of polishing necessary for finishing mold inserts. Figure 1 provides an overview of the major influences, which determine the polishing result in terms of form accuracy, surface quality, sub-surface condition and efficiency (material removal rate).

Understanding the fundamental mechanisms of the material removal in polishing presents the key for the systematic development of polishing processes and helps to explain the causes of process instabilities and defects on the polished surfaces. This will be presented for the different mold materials in the next section.

In the field of mold and die making industry logical explanatory models are missing for describing defects like pull-outs which are the reason for many judicial issues. Process strategies for manufacturing 'defect free' high gloss polished tool steel surfaces will be shown and a defect chart with advices for avoiding defects will be presented in the second section.

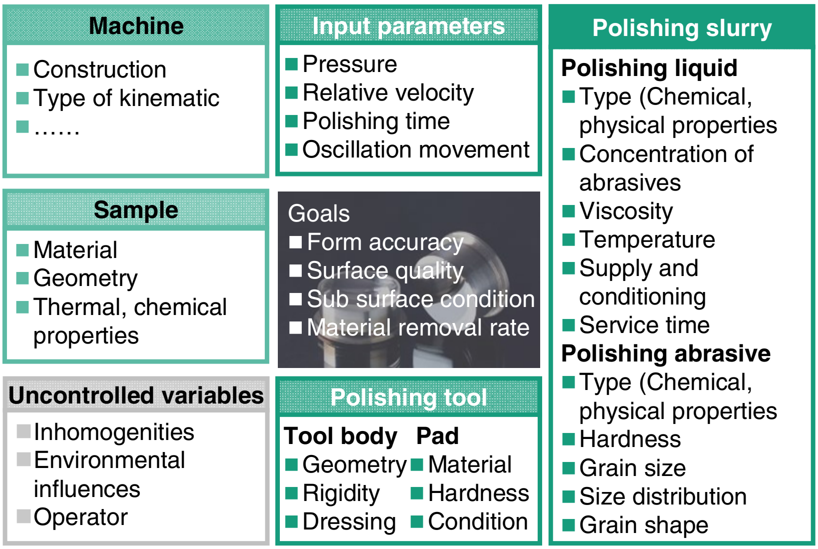

Fig. 1 Overview of major influences on the polishing results

The following chapter describes an innovative polishing tool machine for local polishing of smooth, free formed surfaces. New membrane based tools are designed and analytical simulations support the choice of the most suitable polishing kinematic in regard to the final surface texture and shape accuracy.

Optical and medical industries are demanding a large variety of optical elements exhibiting complex geometries in the shape of localized cavities or grooves. The authors finally present the development of a new abrasive polishing process for finishing structured molds, which is exclusively realized by vibration motion [Bri09, Schu09, Bri10]. The absence of rotational tools opens up the possibility to machine new types of surface geometries.

2 Fundamental Mechanism in Polishing

Four hypotheses about material removal mechanisms in polishing emerged from the investigations on the chemical and physical phenomena in polishing [Ham01, Eva03]. These are the hypothesis of abrasion, the flow hypothesis, the chemical hypothesis and the friction wear hypothesis. Recent research activities focus on the interaction between the system components [Xie96, Kom97, Luo04, Cha08], for example the interaction between an abrasive grain, the sample surface and the polishing pad. *Evans et al.* provide an extensive discussion of the two-component and three-component interactions in the process area [Eva03].

In the following discussion, fundamental differences in material removal mechanisms are expressed by grouping them into two categories: a merely mechanical removal mechanism and a chemical-mechanical one. The mechanical removal mechanism refers particularly to the abrasion and flow hypothesis as well as the abrasive wear theory. *Samuels* stated that the difference between grinding and polishing is only in terms of scratches' and chips' magnitude, but not in terms of removal mechanisms [Agh70, Sam03]. The flow hypothesis, developed by *Beilby*, *Tabor* and *Bowden* [Bei21, Bow50], assumes the occurrence of material displacements and the formation of an modified surface layer.

The chemical-mechanical removal mechanism combines chemical and mechanical effects for explanation of material removal. Examples are the friction wear theory or the developed understanding of chemical-mechanical planarization (CMP) in wafer processing [Kom96, Jia01, Eva03].

Preston's equation represents the basis for modeling the polishing process [Pre27]. It states that the material removal rate dz/dt is proportional to the applied pressure p and to the relative velocity v_R between the sample and the polishing pad:

$$\frac{dz}{dt} = K_P \cdot p \cdot v_R \tag{1}$$

The design of many polishing machines and of nearly all polishing processes is based on Preston's equation. Additionally, more complex predictive models were developed [Xie96, Luo04, Cha08, Wan08], particularly in CMP.

By the design of the polishing system the occurrence of a specific material removal mechanism can be influenced. The polishing system is defined by the sample material, the polishing liquid, the polishing agent and the polishing pad. In the following, the basic mechanisms and their effects on the surface and sub surface area in polishing steel, advanced ceramics and tungsten carbide are explained when applying one specific material removal mechanism.

2.1 Polishing of Steel

Within the SFB / TR4 best results in polishing steel were achieved with diamond slurries. Based on the assumption that the material removal is predominantly of abrasive nature, the chip formation mechanism can be modeled as follows: The polishing grain penetrates the work piece surface and scratches across the surface, embedded in the polishing pad [Dam05, Klo06a]. Both the resulting normal and tangential load generate stresses in the form of pressure, tension and shearing. As soon as the yield strength of the material is exceeded, the stresses lead to plastic deformation [Klo05]. The grooving grain displaces material and, once, the maximum formability is reached, chip formation occurs. A detailed analytical calculation of the penetration depth of a single abrasive grain and the resulting material flow stresses can be found in [Klo08a]. Further chemical aspects in polishing steel are discussed in [Dam05, Klo06b].

In order to draw conclusions on removal mechanisms and chip formation, hardened and unhardened CrMo-steels were investigated [Klo05, Dam05]. One astonishing result is, that hardened steels shows higher material removal rates (MRR) than unhardened ones. The experiments also revealed, that a better surface roughness is reached with hardened steels than with unhardened ones [Klo05].

According to *Zum Gahr*, different chip formation mechanisms can be characterized from the ratio of the displaced volume to the volume of the cutting trace [Gah98]. In the so called micro ploughing only material displacement takes place. In contrast, in micro cutting the removed volume equals the volume of the cutting trace. The findings on the MRR correspond with *Zum Gahr's* wear theory. In polishing ductile, unhardened steel the degree of plastification and material displacement is higher than in polishing brittle, hardened ones. A higher ratio of micro ploughing occurs and the amount of removed material is lower. Contrarily, because of the high dislocation density in hardened steels no significant material displacement appears, but cutting of material occurs instantaneously [Dam05, Klo05].

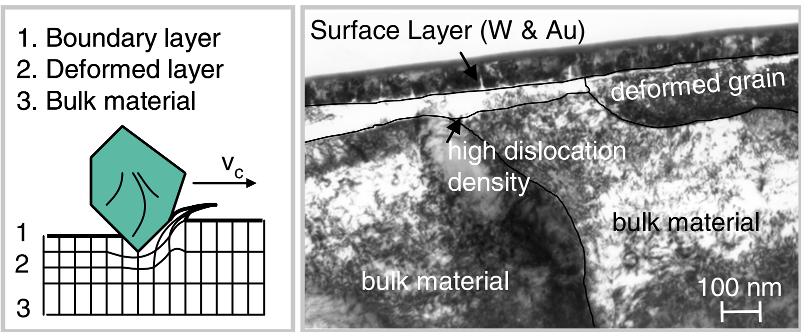

Fig. 2 Sub surface condition of an unhardened steel after polishing with diamond (TEM, right)

TEM analyses confirm that hardened steel, with its martensitic structure, is less subject to plastic deformation. In terms of unhardened steel a boundary layer close to the surface can be identified with strongly deformed grains and significantly higher dislocation density (Figure 2). In deeper regions, no influence of the polishing process on the lattice structure can be observed. In terms of hardened steel, a boundary layer with a high amount of dislocations can not be identified [Dam05].

2.2 Polishing of Advanced Ceramics

Both silicon carbide and silicon nitride are widely known for superior material properties. In specific applications, for example molds, polishing of these advanced ceramics is required to ensure low surface roughness and damage free subsurface regions.

To clarify the effects of both distinguished material removal mechanisms, investigations on polishing silicon carbide (SIC) and silicon nitride (HIPSN) are summed up [Klo07a, Klo09a]. Three different types of slurries were employed: water-glycol with diamonds (synthetic, 2-4 µm), and two water based slurries with ceria (Opaline by Rhodia) resp. with zirconia (CC10TM by Saint-Gobain). The usage of a diamond slurry results obviously in a mechanically dominated removal mechanism [Kom97, Eva03, Dam05, Klo09a]. Ceria and zirconia slurries feature chemical-mechanical interactions [Kom96, Klo07a]. Due to their lower hardness compared to the ceramics pure abrasion can be excluded.

The occurring material removal mechanism effects the MRR, the surface quality and the influence of machining parameters. Figure 3 indicates the dependency of MRR on material and material removal mechanism, determined by the design of the slurry [Klo09a].

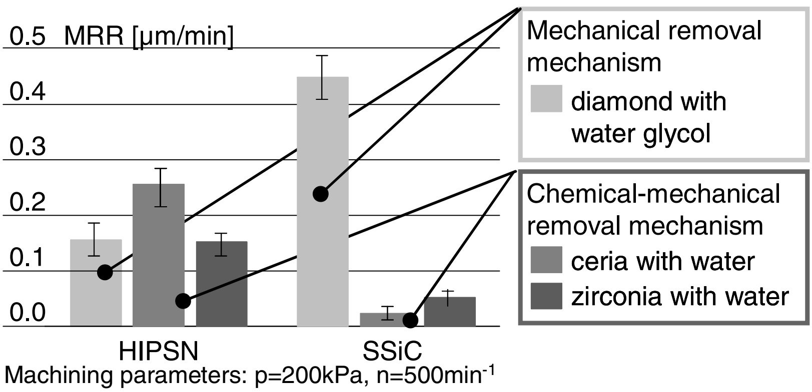

Fig. 3 Average MRR in polishing silicon based ceramics with various polishing agents

Apparently, employing diamond is the best choice for polishing silicon carbide. In contrary, the usage of the water based ceria slurry was an efficient choice in processing silicon nitride.

An statistical analysis of the influence of pressure and relative velocity on the MRR indicates that they do not show the same effect for all material removal mechanisms. In diamond polishing an increase of both input parameters results in a similar effect on the MRR which correlates with the Preston's equation. Whereas, if using ceria or zirconia, the relative velocity does not effect significantly the MRR in the same manner as the applied pressure. Therefore, the actual removal mechanism has to be considered regarding the choice of machining parameters [Klo09a].

In addition to the empirical investigations, the influence of the material removal mechanism on the surface and sub surface area was investigated by SEM, TEM, and AFM [Klo09a]. After polishing with diamond, the subsurface layer of both ceramics reveals dislocations up to 100 nm. They reach deeper in HIPSN than in SIC. The high toughness of silicon nitride implicates that the applied polishing work is converted to form the dislocations before any micro chipping occurs. In contrary, the high brittleness of silicon carbide leads primarily to micro chipping and cracking [Klo09a].

Following the general argumentation for chemical-mechanical polishing of HIPSN, the silicon nitride surface is worn by hydrolysis with the aid of ceria as a catalyst [Kom96, Jia01, Hah99]. In a second step, ceria removes the formed oxide layer. Own investigations revealed several indicators for the validity of this hypothesis, e.g. an observed increase of pH and a measured amount of ammonia in the slurry [Klo09b]. After chemical-mechanical polishing TEM analyses show a complete absence of any dislocations in the subsurface layer and the surface seems to be free of scratches on AFM images [Klo09a].

2.3 Polishing of Tungsten Carbide

Binder less tungsten carbide represents a common choice of material for the molds and dies in precision glass molding. That is why the previous explained methodology is extended on binderless tungsten carbide. The investigated type shows a ratio of binder below 0.30 % and an ultrafine texture with an average grain size below 200 nm. Due to the high chemical wear resistance of the material, the investigation focuses on a mechanical dominated material removal mechanism.

The effects of the relative velocity and the applied pressure on MRR (Figure 4) show that the Preston's equation can also be applied to describe the material removal when polishing tungsten carbide. But both parameters do not effect the resulting surface quality significantly in terms of roughness parameters. The values of Rms are below 2 nm and the peak to valley roughness below 20 nm (diamond grit size 2-4 µm, polyurethane polishing foil). This result implies that binder less tungsten carbide can be polished with high removal rates without decreasing surface quality, which is not given in polishing steel and advanced ceramics.

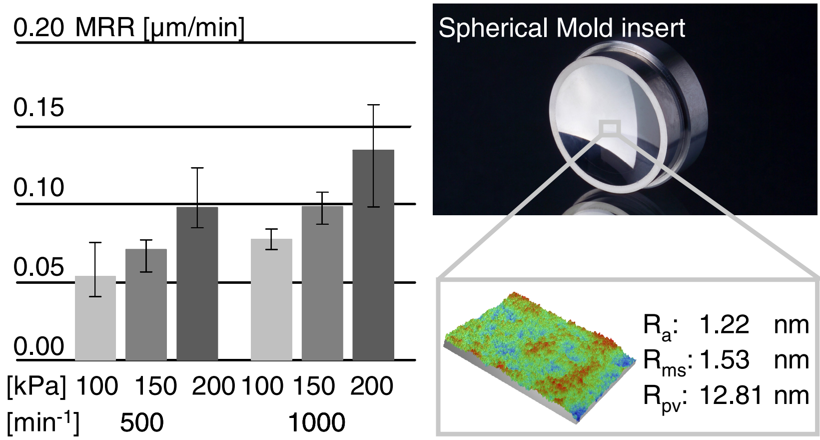

Fig. 4 Influence of applied pressure and spindle revolution on MRR (left) and average surface roughness (right)

The fundamental investigations were applied on spherical mold inserts, shown on right side of Figure 4, which confirms the feasibility of polishing tungsten carbide in short time with a high surface quality.

3 Polishing Processes for the Mold and Die Making Industry

The polishing process in the mold and die making industry is mainly done manually. The quality of a manual polished mold strongly depends on the worker's skill and experience. In order to reduce this dependency, the main goal of the research at Fraunhofer IPT consists in the automation of the polishing process in order to support the worker up to 80% of his manual, monotone work. But previous to the automation a complete understanding of the polishing process and the influencing parameters is essential.

An important aspect is to find logical explanatory models for describing the appearance of imperfections which are a knock-out criterion for the required surface of the final plastic part and the reason for many judicial issues between polisher, steel manufacturer, mold maker and end user.

In the transfer project named SFB/TR4-T3, process strategies for manufacturing of defect free high gloss tool steel surfaces were developed in purpose to get robust strategies for avoiding the imperfections and/or giving advices about what to do when surface imperfections appear.

3.1 Polishing Strategies and Influencing Parameters

To gain a complete understanding of the polishing process, many experiments on different tool steels have been executed in order to analyze the influencing parameters on a polished surface in a scientific manner. The following relevant parameters have been examined during the project:

- steel composition and structure,
- manufacturing process,
- polishing kinematics,
- cleaning strategies and
- polishing systems.

Experiments with different steel compositions gave evidence that small differences in the alloying elements such as manganese, molybdenum and vanadium don't affect the polishing result. Although, differences in microstructure and steel manufacturing show clearly that the number of carbides and non-metallic inclusions are decisive for the quality of the polishing result.

In this context pull-outs might be the most interesting defects, as they appear as peaks on injection molded plastic parts, which therefore are rejected. They occur, as the name indicates, when carbides or non-metallic inclusions breaks out of the steel matrix. Four different scenarios are imaginable for the interaction between a diamond grain and a steel matrix containing carbides (Figure 5, left):

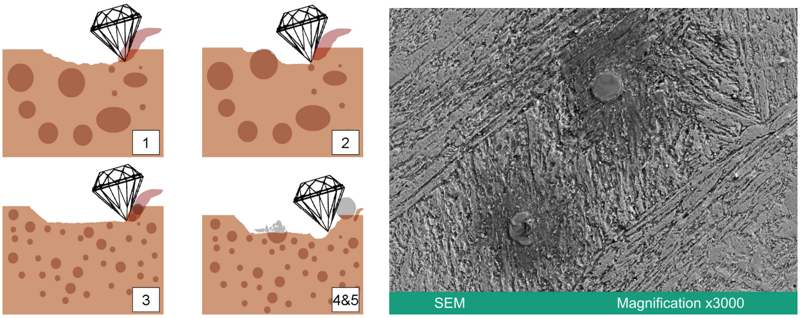

Fig. 5 Interactions with diamond grain and steel surface (left) [Dam05], Non-metallic inclusion (right)

1. A typical mechanical abrasion of steel caused by a diamond grain (no carbide particles involved),
2. A diamond grain strikes a large primary carbide, which stays in the surface as it is still enclosed by the steel matrix,
3. Secondary carbides, which are smaller than the diamond grain, are removed out of the steel matrix and will not affect the surface quality,
4. Carbides having the same size as the diamond grain, or even larger, are not easily removed out of the steel matrix, but will be cut into pieces/or pulled-out by the diamond grain.

Another reason for the pull-outs are non-metallic inclusions (NMI), e.g. oxidic and/or sulphidic particles occurring as line shaped or globular inclusions. NMI can, as carbides, break out and leave holes or stay in the steel matrix, but in some cases only the softer material around the NMI is removed leaving a "stuffed hole" with the disadvantage that water can enter, leading to corrosions around actual inclusions (see Figure 5 right).

3.2 Defect Chart

As a first step towards an uniform polishing vocabulary, Fraunhofer IPT has created a defect chart in cooperation with the Swedish University of Halmstad [Reb09] on the basis of the European standard EN ISO 8785 [Eni99].

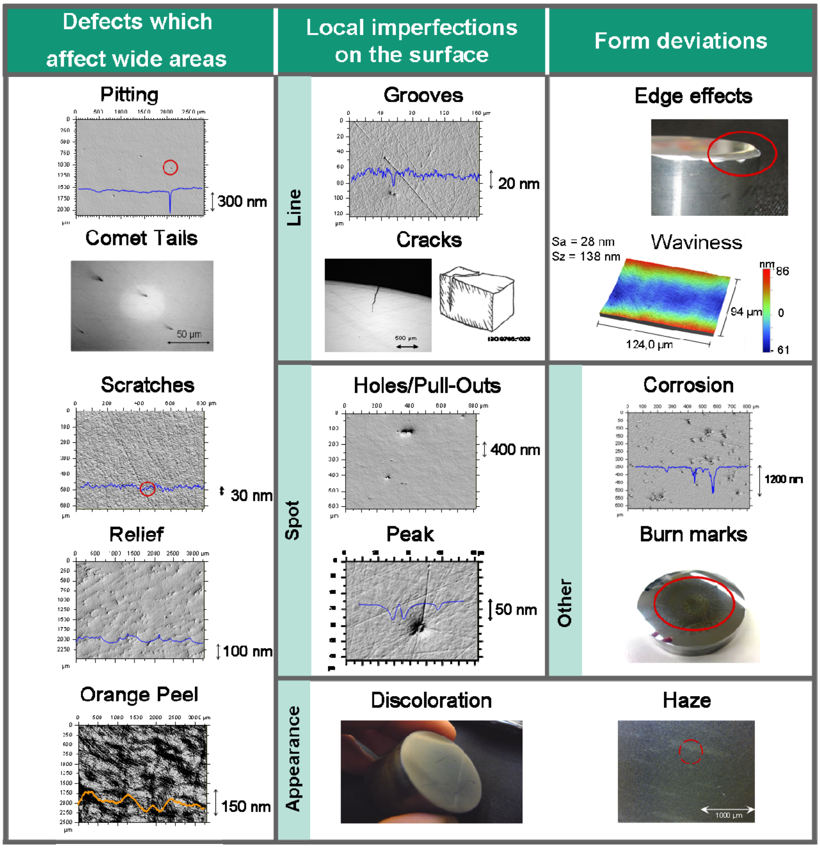

Fig. 6 Classification of surface imperfections – defect chart

With this table and the according manifold experiments, polishing strategies for various examined steel grades were formulated and are presented on the SFB/TR4 homepage.

On the basis of these results, the aim of further research at Fraunhofer IPT is the development of automated, integrated and robotic polishing systems to compensate the disadvantages of manual processing and to support the manual polisher in his monotone work. The goal is to automate up to 80 percent of the polishing process so that only 20 percent of the work will still be performed manually. This was already shown on parts with freeform surfaces in a robot cell with an integrated force-controlled polishing spindle [Klo10].

4 Computer Controlled Polishing of Free Formed Surfaces

Replication technologies, such as the injection molding of plastics or the embossing of glass, bear a very high potential for a cost effective high quality mass production of such complex optical components. The key component within this complex process is the mold insert itself. However, little knowledge about the replication processes and insufficient possibilities of simulating the exact behavior of the deformed material cause a difficult and cost intensive ramp up. Due to the lack in calculation the shrinkage and inner tension related deformations of the replicated optics, the mold inserts has to be tested and iteratively adopted. The form correction machining of the molds for the optimization needs to be able to remove material in a range of a few microns to several tens of Nanometers in order to assure maximum shape deviations below a 100 nm PV. Usually, chemically and mechanically highly withstanding metals or even ceramics are used. A surface finish of down to 2 nm Ra are requested. Conventional path controlled machining such as milling or turning operation does not reach out to this level of accuracy.

4.1 Dwell Time Controlled Polishing

Different from conventional milling or grinding operation, the locally applied polishing is a dwell time controlled process. The material removal is controlled by the feed-rate of the tool on the surface. The more material has to be removed, the slower the feed-rate is adjusted. For little removal the feed-rate is increased. This approach turns the achieved precision on the work piece away from the accuracy of the applied machine tool towards the process stability and a sophisticated pre-calculation of the pursuit polishing strategy. Presupposing the above, defined form corrections in the sub-micron range are possible on materials used in the optical mold making. The pre-calculation is conducted in an off-line mode prior to the actual polishing by an algorithm. As input data, the supposed geometry of the mold insert is needed. This geometry usually differs from the one of the final replicated optic due to the influence of shrinkage and inner tension that needs to be corrected. In addition, a shape measurement of the part taken either interferometrical or tactile is used to determine the local error map of the insert that needs to be corrected. The third requested input is the so called influence function of the locally applied polishing tool, describing the material removal profile in dependence of adjustable process parameters such as pressure and relative velocity. With the above three input variables the subsequent calculation of the polishing algorithm is based on an optimization assisted division of the influence function and the error profile, generating the ultra-precise polishing strategy. Of fundamental importance for the functionality of this machining approach with a pre-calculated dwell time map is a stable, reproducible and deterministically adjustable influence function. For the insurance of the control over the polishing influence function, extensive knowledge about the process itself especially including tribo-mechanical interactions is needed. Beyond this understanding, a machining system is necessary providing and controlling constant process parameters even on complex form shapes.

4.2 Machining System – Adaptive Polishing Head

At the Fraunhofer IPT a new, adaptable polishing head based on a parallel-kinematic-structure has been developed for the locally applied polishing. The machining system is capable of providing all the relevant kinematics for the polishing tool. The work piece does not have to be driven separately. Due to the kinematic setup of a specially designed Double-V-Parallel-Kinematic-Structure, eccentric movements, angles of precession and dynamic adaptations under consideration of the process relevant eccentricity can be realized. On account of the independence of a work piece rotation or linear movement, the process conditions are ideally stable, also on complex free-form shapes. A more detailed description of the mechanical setup and its control system can be found in [Wec04, Bre05]. Figure 7 shows the final design of the test bench used for the process parameter investigation.

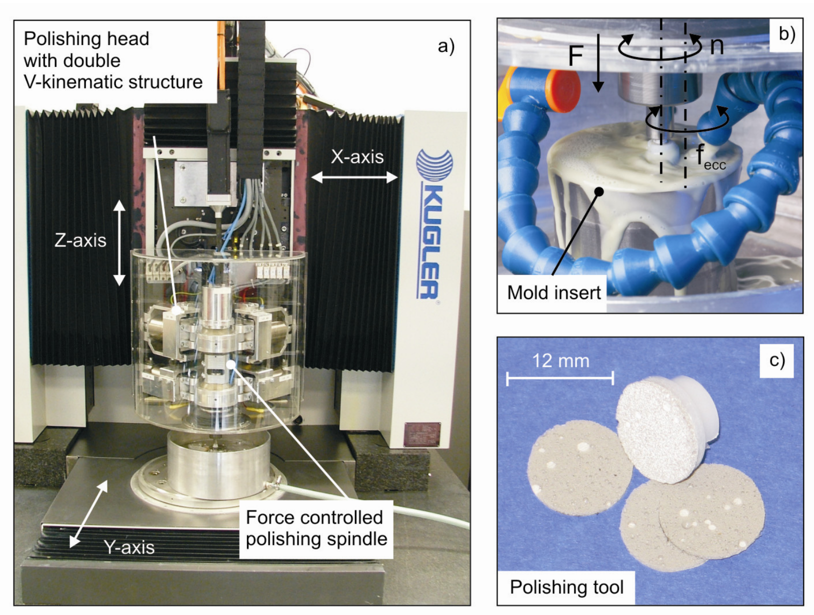

Fig. 7 a) Machine tool setup used for investigations of the zonal polishing process, b) closer view on the polishing tool and process kinematic, c) polishing pad with polyurethane foil.

The overall machine system consists of a 3-Axis base machine and the attached adaptive polishing head with in addition have 5 DOF. The adjustable parameter ranges are given in table 1.

Table 1 Parameter range of the polishing head

Polishing force F	0.5 - 20 N
Force increment	0.2 N
Eccentric frequency f_{ecc}	1 - 10 Hz
Eccentric radius r_{ecc}	0.2 - 4 mm
Spindle revolutions n	500 - 5000 min^{-1}

4.3 Process Development for the Zonal Polishing

Numerous polishing strategies which determine the process conditions and hence the result of the finishing are used for scientific experiments regarding the influence function.

Taking *Preston's* equation for granted (Formula 1), a linear increase of the MRR should be realized starting from the center of the rotating tool. Figure 8 a) shows the accruing characteristic W-profile by the adjusted process parameters pressure p and relative velocity v_r which are based on theoretical conversion of former specified values.

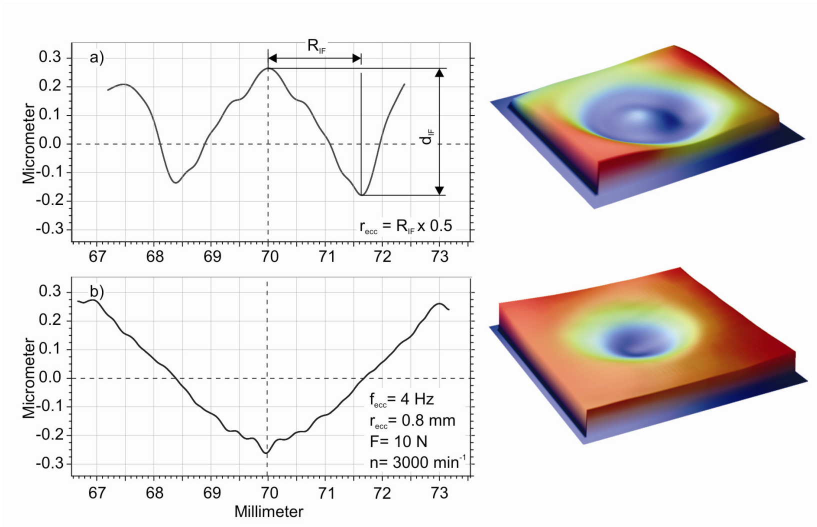

Fig. 8 Determination of eccentric radius as the main parameter for achieving the required (b) Gaussian profile of the influence function »Footprint« - Process development on a silicon Nitride sample (Si_3N_4)

However, the maximum material removal is not found on the outer diameter but at one half to two thirds of the radius of the polishing tool, forming the influence function. Looking further towards the boundary of the influence function, the removal depth declines steadily. This simple trial emphasizes the fact that either an inhomogeneous pressure profile or an influence of the relative velocity in the gap between the tool and the sample is influencing the geometrical formation.

The influence function is characterized by depth d_{IF} and radius R_{IF} which in this case can be identified as 1.6 mm. Preliminary investigations on polishing of steel have shown that this dimension can be used for setting up the eccentricity of the polishing tool movement in order to achieve a Gaussian profile of the influence function [Bre05, Klo08b]. Further investigations lead to a ratio of R_{IF} and eccentric radius r_{ecc} of about 1:2. By using this value and an experimentally identified value for the eccentric frequency f_{ecc} of 4 Hz the required Gaussian profile for the dwell time algorithm can be achieved as shown in figure 7 b). The appropriate volume of removed material V_{IF} was computed by importing the 2D-graph of a Form TalySurf in a specially developed Matlab program and amounts to 0.005 mm³ on average (after polishing time of 240 s).

With the adaptive polishing head, a machine base is given to intensively investigate the formation of the influence function of a locally applied polishing tool. In terms of the machine parameters, the eccentric frequency shows only a small impact for the profile formation. However, the eccentric radius, the applied normal force and the relative velocity do have significant impact on the formation of the influence function determining the process efficiency. This kind of process development is of vital importance in order to conduct form corrections on high precision molds for replication purposes in plastic injection molding or embossing of glass.

5 Polishing of Structured Molds

Optical and medical industries are demanding a large variety of optical elements exhibiting complex geometries and multitude opto-functional areas in the range of a few millimeters [Eva99]. Therefore, mold inserts made of steel or carbides must be finished by polishing for the replication of glass and plastic lenses [Klo07b]. For polishing these complex components in the shape of localized cavities or grooves the application of rotating polishing pads is very limited [Bri07]. Established polishing processes are not applicable, so state of the art is a time consuming and therewith expensive polishing procedure by hand. Therefore, a new abrasive polishing process for finishing these complex mold geometries to optical quality was developed. The necessary relative velocity in the contact area between polishing pad and workpiece surface is exclusively realized by vibration motion which is an advantage over vibration assisted rotating polishing processes. The absence of rotation of the pad opens up the possibility to machine new types of surface geometries.

5.1 Polishing Machine

The vibration polishing device is powered by two voice-coil actuators, see figure 9. These two actuators enable frequencies up to f = 150 Hz and amplitudes up to A = 250 µm in two axes and were implemented into a conventional machine tool [Bri10].

During the design process a large area of applicable machining frequencies and amplitudes was considered to achieve a multifunctional and flexible system.

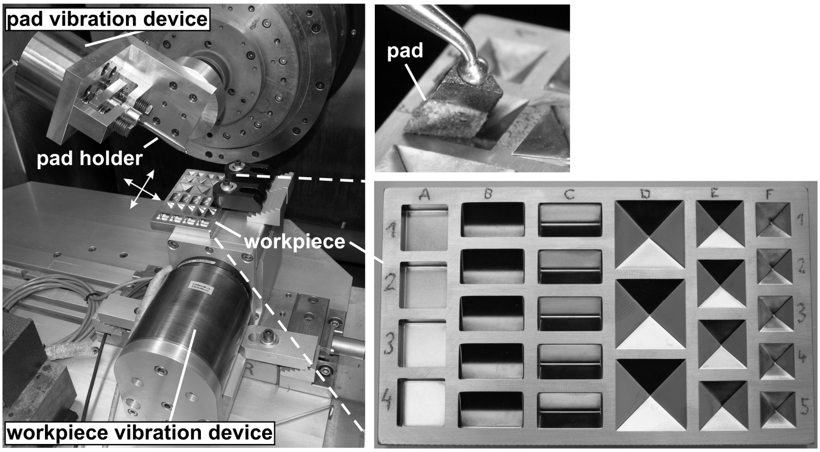

Fig. 9 Vibration polishing test set up: voice-coil actuators on workpiece side and pad side [Bri10]

On pad side the control is realized open loop with spring return and variable stiffness as this concept enables the maximum vibrational frequency. On work piece side the control is realized closed loop with a position sensor.

5.2 Vibration Polishing Material Removal Characterization

During material removal characterization the polished surface area (material removal function – “footprint”) is divided into profile sections. The tip of the profilometer loaded with an adjustable normal force drives along these profiles with continuous speed. The height position of the tip is continuously recorded and with this information the surface contour for each profile section is created. By interpolation between the single profiles the 3D-shape of the measuring area can be evaluated. The data determined with this procedure realizes primarily the material removal calculation. The method for analyzing material removal is described on basis of one single profile section in figure 10 [Bri10]. The workpiece material below the reference height h_{ref} is shown hatched. The remaining areas represent the void volume above and below h_{ref}. The distance l_{tot} is the overall length of the measuring profile. The length l_{ref} represents the measuring section, on which no material removal appeared. For calculating the removed material volume the difference from the average void volume of the reference length $V_{void,ref}/l_{ref}$ and the average void volume of the total distance $V_{void,tot}/l_{tot}$ is identified and multiplied with the total distance l_{tot}.

The material removal of one single profile is calculated as follows:

$$PMR\,(\,profile\ material\ removal\,) = \left(\frac{V_{void,tot}}{l_{tot}} - \frac{V_{void,ref}}{l_{ref}} \right) \cdot l_{tot} \qquad (2)$$

If this procedure is applied to the entire measured area the material removal is calculated as follows:

$$FMR(\,field\ material\ removal\,) = \left(\frac{V_{void,tot}}{A_{tot}} - \frac{V_{void,ref}}{A_{ref}} \right) \cdot A_{tot} \tag{3}$$

The process parameters pressure p, polishing time t and relative velocity v_r were characterized regarding their linear dependence on material removal [Scu09], which can be expected according to Preston's equation (Formula 1).

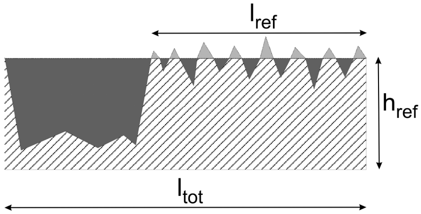

Fig. 10 Parameter definition for material removal characterization

For validating the linear material removal behavior the parameters were varied on three levels. The polishing system consisted of a synthetic felt pad and an oil-based polishing slurry with diamond abrasives of a size of 1 µm. This system showed a good applicability and low variances. The experiments were accomplished with four repetitions at each level.

Figure 11 (left) shows the linear increase of the material removal dz over polishing time t. The stability index $R^2 = 98{,}6$ % indicates the fit of the measured values to the linear smoothing function. The error bars show the 66,7 % confidence region of the average values of the repetitions. The influence of the polishing time conforms the Preston's equation with variables kp, p and v_r kept constant.

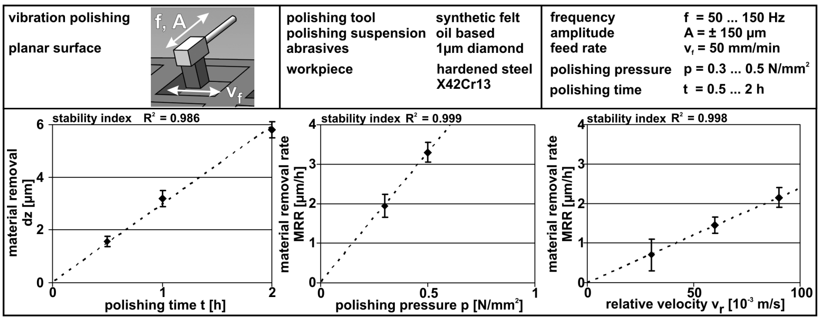

Fig. 11 Verification of Preston's equation: influence of polishing pressure, relative velocity and polishing time on material removal [Schu09]

The polishing pressure was analyzed at two levels with four repetitions each. A pressure larger than p = 0.5 N/mm² is not practible because of the limited power of the vibration polishing head. A pressure smaller than p = 0.3 N/mm² would lead to very low material removal and therefore non detectible volumes. Figure 11 (center) shows the linear behavior of the polishing pressure within the covered pressure range and confirms also the Preston's equation.

The average relative velocity between polishing pad and workpiece is calculated from the total distance s and time t for one vibration period (1/frequency). The polishing pad covers s = 4 ·A (amplitude) during one period of oscillation. Hence, the value of relative velocity is calculated by

$$v_r = \frac{ds}{dt} = \frac{4 \cdot A}{f^{-1}} = 4 \cdot A \cdot f \tag{4}$$

In order to change the relative velocity both the oscillating amplitude and the oscillating frequency can be varied. The material removal rate was examined in dependence of the frequencies f = 50 Hz, 100 Hz and 150 Hz.

It is evident from figure 11 (right) that a linear dependence of frequency - and thus also the relative velocity - and the material removal rate is applicable. Therefore, Preston's equation can be applied to vibration polishing within the analyzed parameter range without restriction.

Figure 12 shows a polished rectangular slot which was machined to optical quality by vibration polishing [Bri09].

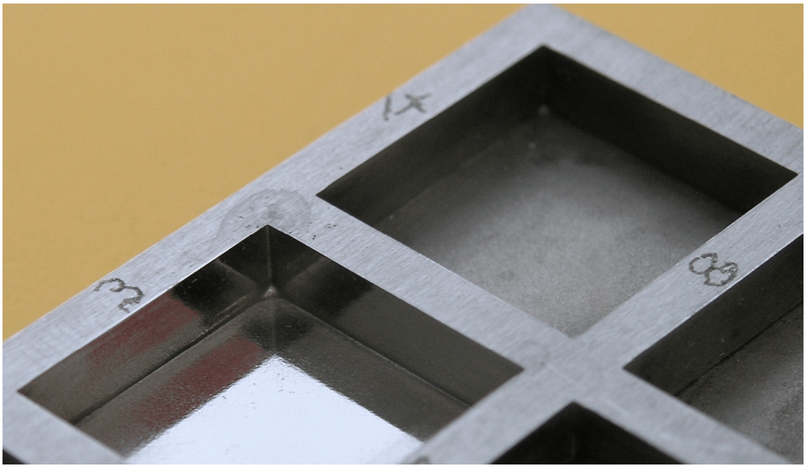

Fig. 12 Reference workpiece with vibration polished slot [Bri09]

6 Conclusion

This chapter started with a fundamental discussion on the material removal mechanisms in polishing with regard to common mold materials. On the one side, the effects of a mechanical removal mechanism, occurring when using diamond abrasives, on the surface and sub surface were discussed. On the other side, a damage-free chemical-mechanical removal mechanism for polishing silicon nitride was presented. The scientific driven first section was developed to an application ready state for polishing steel molds in the second section. With the explained defect chart and the development of robust process strategies a first step towards a common understanding of the polishing step is made with the goal of an international standardization.

With the adaptive polishing head developed at the Fraunhofer IPT, a machine base is given to intensively investigate the formation of the influence function of a locally applied polishing tool. The machine in combination with the process development enables form corrections on high precision molds, which result in higher accuracies of the molded optics with less iteration in mold making process.

Finally, for finishing complex shaped optical mold inserts a novel polishing process was presented, which operates without the classical rotating motion of the polishing pad and therefore can be used more flexibly at finite-dimensional opto-functional surfaces.

Acknowledgement. The authors like to thank the German Research Foundation (DFG) for funding this work as a part of the Transregional Collaborative Research Center SFB/TR4 "Process Chains for the Replication of Complex Optical Elements".

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