Finishing Complex Surfaces with Zonal Polishing Tools

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Abstract

High quality surfaces in terms of low roughness and high form accuracy are achieved by polishing as the essential finishing step. The machining is usually limited to planar or spherical geometries. Finishing of complex geometries require high efforts concerning machine tool and process development. The objective of this paper is to present first results to overcome these limitations indicated by processing advanced ceramics. In order to shorten the process development, a technology transfer of known parameters and conditions from 2-dimensional to zonal polishing is used. This first approach can be used for corrective polishing of zonal form deviations of ceramic samples in the future.

Keywords:

Polishing; Manufacturing; Transfer; Ceramic

1 INTRODUCTION

Advanced ceramics feature high hardness, remarkable corrosion resistance, low thermal expansion, high thermal shock resistance and low weight. These material properties allow their usage in adverse environments and applications. Popular examples are silicon nitride balls in bearing components and silicon carbide mirrors for astronomical optics devices. Furthermore, these non-oxide ceramics can be used by mold manufacturers for molding complex optics components out of glass. In order to achieve the low roughness requirements of the optical systems, a defect free surface and an accurate form is indispensable.

In spite of diverse scientific investigations and developments regarding machines for computer controlled polishing [1, 2, 3] the variety of robust process strategies is still insufficient. This deficit is due to the high amount of time and effort needed for the design of robust strategies, especially for small samples and complex geometries up to free forms.

In this paper, results of investigations of the transfer of polishing strategies (parameters and polishing system) from a conventional process (referred to as 2-dimensional) to a computer controlled process for zonal polishing are presented. The main objective is an efficient design of polishing strategies and a successful technology transfer in order to determine stable process conditions and high material removal rates (MRR) for the zonal correction of complex geometries.

2 EXPERIMENTAL SETUP

2.1 Materials

The transfer of process strategies from “2-dimensional to zonal” is exemplified by processing of silicon nitride (hot isostatically pressed silicon nitride) as one of the most popular non-oxide ceramics. The specimen were ground by using diamond grinding wheels (2-dimensional) and polished for the investigations of influence functions (zonal), respectively. The polishing systems were specified by using polyurethane foils as tools and ceria slurry with a deionized water base.

The efficiency of the polishing systems were evaluated by using different machining parameters in respect of process stability and reproducibility while maintaining high MRR and surface quality.

2.2 Methods

In comparison to zonal polishing (figure 1) the 2- dimensional process has a number of advantages in terms of process development and scientific investigations, such as high MRR, clearly measurable or even visible effects with respect to technological interactions and straightforward use of metrology of the processing results. Hence, the scientific understanding of technological aspects can be elaborated with reasonable efforts and used to develop polishing strategies for commonly used materials.

However, this specific process is not capable of polishing free form surfaces which becomes more and more important in a variety of innovative applications. To overcome these limitations, the zonal polishing process can be used. Unfortunately, an apparent lack of understanding and the intricate procedure of investigations hinder the holistic development of polishing strategies for the zonal process.

Therefore, the approach of this paper is to use the polishing strategies developed with an established 2-dimensional polishing process and transfer these to a zonal polishing machine tool. Based on theoretical considerations the optimization of the zonal process include practical investigations concerning the variation of pressure and relative speed as well as specific zonal process parameters such as eccentric frequency and radius on the formation and stability of the influence function. These preliminary investigations are of vital importance for establishing a stable correction process of zonal form deviations on complex geometries based on an adapted polishing system as former investigations on the polishing of steel already proved [4].

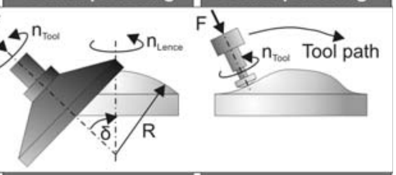
	2-dim. polishing	Zonal polishing
Process kinematic		
Material removal rate	High	Low
Measurement of MRR	Easy	Difficult
Process time	Fast	Slow
Process stability	Mostly state-of-the -art	High research efforts
Metrology	Easy metrology	Limited metrology
Form correction	Limited	Dwell time polishing
Geometry complexity	Low (planar, sperical)	High (asperical)
Conclusion	High efficiency in scientific research of technological interactions	Decisive for every complex component with optical surface quality

Figure 1: Advantages and disadvantages of different polishing processes at a glance.

2.3 Machine

The studies for the development of an efficient polishing system were carried out on a CNC-controlled polishing machine (2-dimensional). The subsequent investigations took place on an adaptable 5-axes polishing module (figure 2a) which was developed at the Fraunhofer IPT [4, 5]. The setup and its related control system for synchronizing the module to a 3-axes machine provides the required flexibility for investigations of polishing complex geometries (figure 2a).

Due to the double V-kinematic structure featuring five degrees of freedom the module is capable of adjusting its alignment to continuously ensure a perpendicular angle of contact between tool and surface of the workpiece. Furthermore, an individual eccentric movement can be superimposed to the rotating polishing tool at different angles (figure 2b), decisively influencing the characteristic removal profile of the tool. The polishing module is capable of different eccentric movements specified by radius and frequency (table 1). This specific tool movement can be superimposed to the rotation of the spindle (figure 2b). Thus, heterodyne velocity profiles can be realized. In addition to the position-controlled mode of the z-axis, the system can change to force-controlled mode in order to permanently assure a steady allocation of pressure in the process zone (table 1).

Table 1: Parameter range for the DoE.

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}

In order to realize a corrective zonal polishing process with this machine tool setup a dwell-time based algorithm is used prior to the actual polishing task. As input data for this algorithm, the supposed geometry of the surface is needed. In addition, a form measurement taken either by optical or tactile metrology is used to determine the local error map of the sample. The third required input is the influence function of the zonal polishing tool, describing the material removal profile dependent on the adjustable process parameters such as pressure and relative speed. The subsequent calculation of the algorithm results in a dwell-time controlled path of the polishing tool over the sample and particular process parameters of the polishing process. In order to allow correction of form deviations on complex surfaces a stable, reproducible and deterministically adjustable influence function is of great importance.

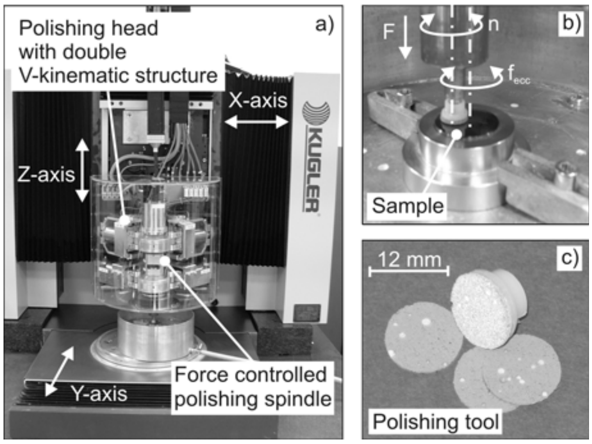


Figure 2: a) Machine tool setup used for investigations of the zonal polishing process, b) closer view on the polishing tool, c) polishing pad with polyurethane foil.

The applied polishing tools (figure 2c) consist of a flat plastic base body with a diameter of 12 mm, covered with different polishing foils. The polishing head allows the usage of further polishing tools like rubber based body materials or even tools with an bulb formed membrane, which will be taken into account in further scientific work.

2.4 Metrology

The MRR for developing efficient polishing strategies are quantified by weight measurements of the samples (2-dimensional process) and mathematically estimated by measuring the geometry of the influence function (zonal process), respectively. The latter is realized by using a Form TalySurf (tactile) measurement device. The surface quality was determined by a white light interferometer.

3 RESULTS AND DISCUSSION

3.1 Removal mechanisms

Former investigations [6] reveal satisfying results using ceria and diamond based slurries in a conventional polishing process (2-dimensional). Material removal rates of up 0.3 µm/min can be achieved. The surface qualities of both polishing systems are highly reproducible and yield optical surfaces in the range of 1-2 nm Ra and 20-30 nm Rt. However, ceria slurry tends to result in a more efficient polishing step than diamond slurry due to less machining efforts, i.e. same applied pressure though less revolutions, and certainly less monetary effort.

It is assumed that the advantage of polishing with ceria slurry is based on an interaction of chemical and mechanical removal mechanisms as outlined in figure 3. The beneficial process conditions can be explained by hydrolysis of the silicon nitride surface in aqueous solutions in combination with the so called "chemical tooth" ability of ceria [3, 6, 7, 8]. An indicator of the oxidation of silicon nitride by forming sodium hydroxide is shown by an increase of pH (figure 3).

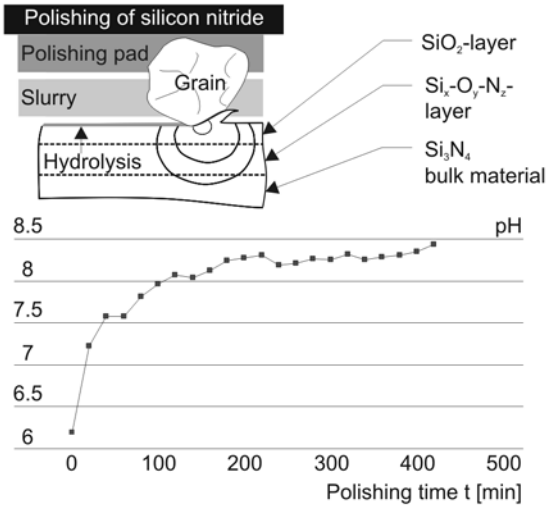


Figure 3: Assumed removal mechanisms of polishing silicon nitride with ceria slurry (2-dimensional process).

3.2 Tool influence function by zonal polishing

The previously identified polishing strategies which determine the process conditions and hence the result of the finishing are used for first experiments regarding the influence function of the zonal process. Taking the Preston Hypothesis for granted (formula 1), a linear increase of the MRR should be realized starting from the center of the rotating tool. Figure 4a 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. The Preston coefficient K_P represents various other influences on the process.

$$MRR = K_P \cdot p \cdot v_r \quad (1)$$

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 [2]. 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 can be achieved as shown in figure 4b. 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).

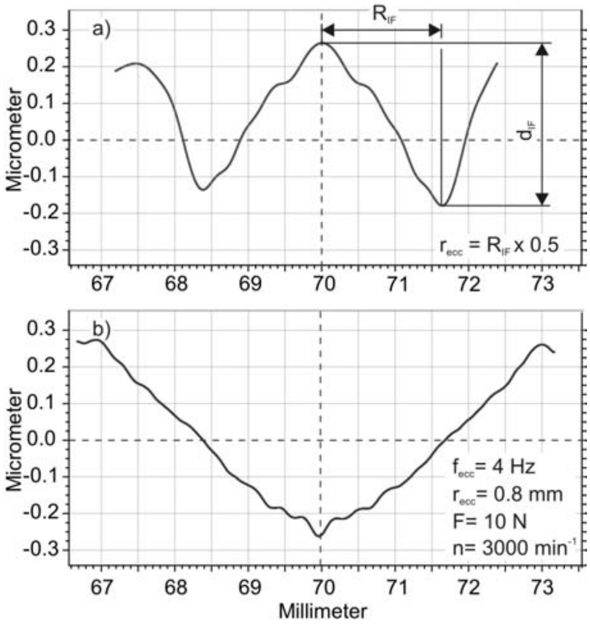


Figure 4: a) Determination of eccentric radius as the main parameter for achieving the required (b) Gaussian profile of the influence function.

3.3 Investigation of typical process parameters

As the process parameters lead to reproducible Gaussian profiles of the influence function the time related stability and corresponding MRR are verified. Figure 5 shows a non-linearity between the removed material V_{IF} after 120 s and 240 s, which can be explained by incomplete saturation of the polishing foil with ceria slurry after a process duration of 120 s. Therefore, a preparation of the polishing tool before starting the intrinsic polishing process was established. A linear increase of the material removal with increasing dwell-time (figure 5) is a main requirement for a form correction.

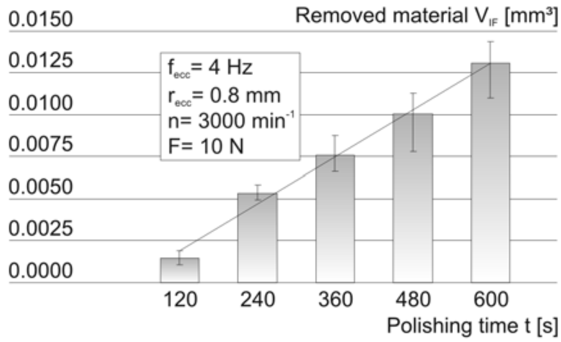


Figure 5: Evaluation of process stability by different processing durations and volume of removed material.

The overall process stability was proven by a long-term run of the polishing tool under real process conditions and can be estimated by up to 3 hours. After that duration the influence function matches the one of the beginning of the process.

Seeking a further understanding, a variation of the tool revolutions over constant applied pressure and vice versa have been conducted. Unlike the results of investigations of the steel polishing process [4], the influence of changes of relative velocity on MRR is far more sensitive. The increase of revolutions strictly involves the increase of the MRR (figure 6a). Furthermore, figure 6 shows that an increase of normal force and applied pressure, respectively, leads to rising MRR (figure 6b). The behavior is approximately linear.

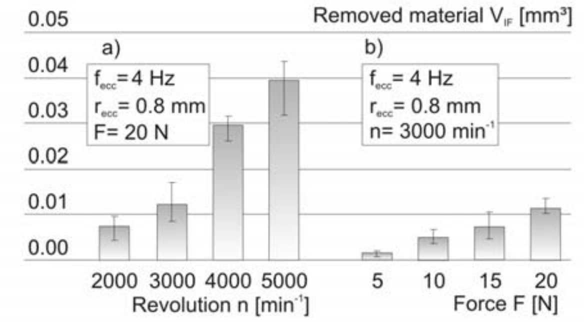


Figure 6: Dependency of material removal on parameters (a) relative velocity v_r and (b) force F (Preston hypothesis).

3.4 Enhancement of process efficiency

Due to its high stability, e.g. compared to felt as another popular polishing tool, polyurethane foil revealed the potential to further increase process normal forces. However, the stability of the process has to be ensured first.

The influence function in figure 4b changes from Gaussian to W-shaped profile with the increase of pressure. Moreover, the radius R_{IF} is increasing as shown in figure 4a and figure 7a. This phenomena can be explained by a growing deformation of the polishing tool. An adjustment of the eccentric radius r_{ecc} to 80% of the R_{IF} allowed the realization of reproducible influence functions with Gaussian profiles.

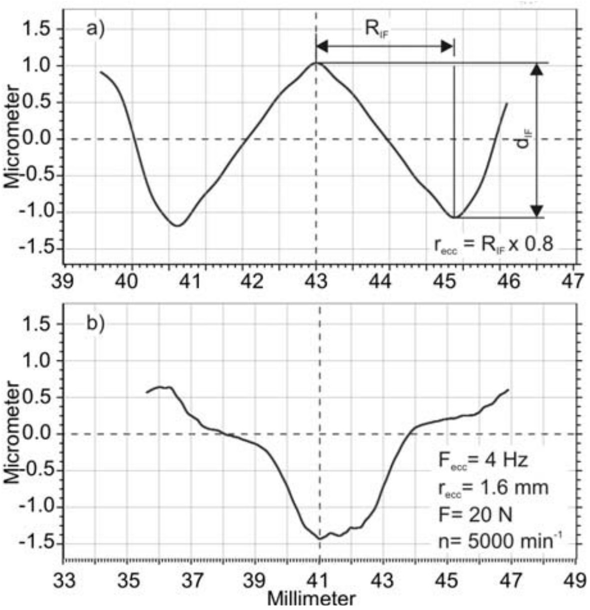


Figure 7: Influence function (a) before and (b) after adjusting specific corrective values for maximized removal rate.

It is assumed that the linearity of the MRR (figure 6b) and applied normal force allows the doubling of the MRR with the zonal process. Due to the different contact area the pressure of 2 bar equals roughly 360 N (2-dimensional process) and 10 N (zonal process), respectively. Hence, the use of the maximum of 20 N (table 1) would lead to doubled MRR for the zonal polishing compared to the 2-dimensional. A verification with specific parameters (figure 7b) results in a maximized MRR of 0.62*10^{-3} mm^3/min (normalized to 1 mm^2) which indeed marks the double of the normalized MRR of 0.31*10^{-3} mm^3/min for the 2-dimensional process.

4 CONCLUSION

This paper showed the results of scientific studies with the goal of shortening the development of a stable and reproducible polishing process for corrective machining of complex ceramics samples. The transfer was successful by rendering unnecessary intensive preparatory work on polishing strategies and resulted in satisfying overall results with a high and reproducible MRR and surface quality. 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. These investigations establish the basis for a correction of form deviations on complex geometries of ceramic samples, which is the objective of ongoing scientific work and will be presented in future publications.

5 ACKNOWLEDGMENTS

We sincerely thank the German Research Foundation (DFG) for financial support of the Collaborative Research Center SFB/TR4 (RWTH Aachen and University Bremen (Germany), Oklahoma State University at Stillwater (USA)).

6 REFERENCES

[1] Bingham, R.G., Walker, D.D., Kim, D.-H., Brooks, D., Freemann, R., Riley, D., 2000, A Novel Automated Process for Aspheric Surfaces, Proc. SPIE, 4093/10:445-450

[2] Yi, A., Hezlep, M., Pol, T., 2004, A Computer Controlled Optical Pin Polishing Machine, J. Materials Processing Technology 146/2:156-162.

[3] Evans, C.J., Paul, E., Dornfeld, D., Lucca, D.A., Byrne, G., Tricard, M., Klocke, F., Dambon, O., Mullany, B.A., 2003, Material Removal Mechanisms in Lapping and Polishing, CIRP Annals, 52/2:611–633.

[4] Brecher, C., Wenzel, C., 2006, Kinematic Influences on the Formation of the Footprint During Local Polishing of Steel, WGP Annals, XIII/1:23-26.

[5] Weck, M., Wenzel, C., 2004, Adaptable 5-axes Polishing Machine-head, Production Engineering, 11/1:95-98.

[6] Klocke, F., Zunke, R., Dambon, O., 2007, Chemo-mechanical Polishing of Silicon Nitride, Proc. euSPEN, 2:356-359.

[7] Jiang, M., Komanduri, R., 1998, On the finishing of Si_3N_4 Balls for Bearing Applications, Wear, 215/1:267-278.

[8] Hu, Y.Z., Gutmann, R.J., Chow, T.P., 1998, Silicon Nitride Chemical-mechanical Polishing Mechanisms, J. Electrochem. Soc., 145/11: 3919-3925.