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MATERIAL INFLUENCE OF SILICON NITRIDE AT MAGNETORHEOLOGICAL FINISHING (MRF)

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ABSTRACT

Precision glass molding (PGM) is used to produce high precision optical components in medium quantities. Premise is to manufacture accurate press molds of difficult to machine materials like silicon nitride. Magnetorheological Finishing (MRF) makes it possible to finish PGM molds to high precision in an economical, steady and efficient way. Therefore a study of the material influence during the process condition changes with controlled variation of process parameters was undertaken and is shown in this work. This work indicates the influence of the material needed for PGM at the MRF to produce precise molds.

Keywords: Material influence, silicon nitride, MRF, Magnetorheological Finishing, Precision glass molding, PGM

1. INTRODUCTION

Precision components used in leading technological applications are increasing. Therefore, new manufacturing chains are needed to fulfill the exalted demands in a short production time with cost-effective levels. Especially production techniques for quantities in the medium and great lots are required. One possibility for mass-production of quality optical components like lenses is the reproduction technique such as the PGM that forms primarily low TG glasses in press machines. Especially for aspheric and free-form elements the press process has certain advantages. It is only possible to manufacture such high precision units by using accurate moulds.

The press moulds, which feature only small figure errors, may be made of hard and brittle silicon nitride (SSN) ceramics or other advanced materials. These ceramics have to be machined in economic and stable process chains. Therefore, several manufacturing steps, such as grinding, lapping and polishing have to be used. However, due to the complex form geometries and the corresponding shape accuracy, an error dependent sophisticated polishing, commonly known as MRF, may be required to achieve the postulated requirements.

2. MAGNETORHEOLOGICAL FINISHING (MRF)

MRF is a precision computer controlled polishing (CCP) process for finishing nonmagnetic materials[1]. Modern manufacturing chains use MRF to improve already conventional pre-polished workpieces like optical components or moulds made from advanced materials. The MRF process is based on a magnetorheological fluid, which consists of magnetic carbonyl iron (CI) particles, nonmagnetic polishing abrasives like diamond and liquids like water with stabilizers[2]. A magnetic field causes the fluid ribbon to stiffen on the wheel, which is used as a polishing tool. Since the fluid is in a circuit and continuously conditioned it is almost considered as wear less during its lifetime of some weeks.

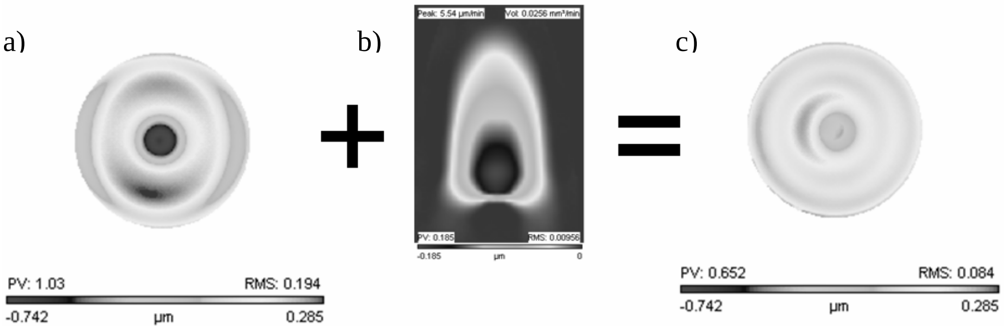

Figure 1. Steps at CCP for precision components. Initial figure error a), influence function b) and finial figure error c)

A CNC controlled positioning unit maneuvers the mould through the stiffened fluid on the wheel and through the simultaneous rotation the whole leading surface may be polished. The amount of material removed from each point depends on the time duration for which each point is in contact with the fluid and the machine setting parameters. The material removal is defined and further included in the influence function – in the MRF terminology also called the ‘spot’. Changing the process parameters modifies the removal, which is presented through values like peak and volume removal rate.

For the correction of a surface to be polished a computer-controlled polishing (CCP) process is used which normally consists of following steps also demonstrated in Figure 1. The first step is measurement of the optical surface to obtain its figure error. Based on the influence function and the figure error, an individual polishing tool dwell time profile may be calculated as second step. The next step is the actual polishing procedure followed by the final quality check. If necessary, the lens may be polished again.

3. PREPARATION OF THE TEST SERIES

At the beginning of the experiments, a spherical form geometry was machined in the leading side of samples with diameter 20 mm and a concave curvature radius of –50 mm. The shape was manufactured using several conventional process steps. At first the forms were conventional ground using a five-axis CNC grinding center. Then the samples were pre-polished with loose abrasives to form smooth surfaces necessary for interferometer measurements.

The smoothed moulds obtained were then used for the final experiments with MRF. During the testing stage with a QED Q22-X* polishing unit the material influence were determined with the machine set up at the Laboratory of Optical Engineering using default settings resulting from previous definitions for brittle materials[3]. The material removal is measured through the influence function peak removal value, which quantifies the maximum material removed over a defined time period.

4. RESULTS AND DISCUSSION

The machining with loose abrasives has many impacts to be considered. A major impact for the process and also for the achievability of high precision components is the material and the corresponding individual process behavior. For optimization further knowledge of the influence is necessary. Preston was the first who postulates a mathematical model for the material removal at loose abrasive machining called “Preston’s law”[4]

$$R_V = k \cdot p \cdot v$$

where k is the Preston coefficient and v is the relative velocity between lens and fluid in the polishing zone and p is the original pressure at the contact zone. For the MRF the equation was expanded by Zhang Feng to include the process parameters depending on the physical properties of the MR Fluid on the wheel which results in a complex equation for the pressure distribution [5]. The material properties itself are not included into the equation by their own parameter. They are summarized in the Preston coefficient k, which can be seen as the product of factors containing further information like machine set up, MR Fluid, workpiece geometry and the material properties.

4.1. Material influence

The material machined with the MRF technique features a major impact due to the properties like young modulus, fracture toughness or hardness a strong impacts on the material removal and figure error is caused. For optimization of the process further knowledge of the material and its influence is necessary. Assuming that the material factor f_{mat} features a value of one at standard optical glass the other factors can be approximated through a linear relation as applied in the following.

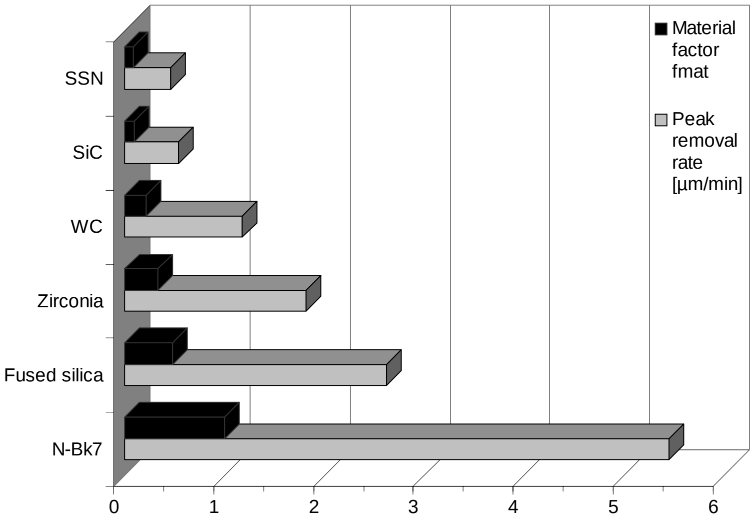

Figure 2. Material factor f_{mat} and peak material removal of some brittle materials in comparison to standard optical glass N-Bk7.

The results shown in
Figure 2 give the influence of the material on the material removal. The peak removal rate varies from ~5.5 µm/min at standard optical glass N-Bk7 to ~2.6 µm/min at fused silica to ~1.8 µm/min at zirconium to ~1.2 µm/min at tungsten carbide (WC) to ~0.54 µm/min at silicon carbide (SiC) ~0.46 µm/min at silicon nitride (SSN). Additional the material factor varied form ~1 at standard optical glass N-Bk7 to ~0.5 at fused silica to ~0.3 at zirconium to ~0.2 at tungsten carbide (WC) to ~0.1 at silicon carbide (SiC) and silicon nitride (SSN). It is clearly visible that the finishing of very tough and brittle materials is more complex and complicated. But one big advantage of brittle material remains: The critical depth of cut responsible for ductile material removal is much higher at brittle materials and hence a brittle fracture may not occur because of the low removal rate.

4.2. Process parameters

Having a low material removal the polishing time will increase more because the complete surface has to be polished. Additional to the longer polishing time errors of the process set-up may generate mid frequency surface errors. This has to be minimized through optimization of the influence function used. A study of the influence of the process parameters may expand at this justice the knowledge.

Further impact is given through the material removal behavior of each material at different machine and process parameters. Each material has it own influence on the removal at a specific set. An examination series was performed to analyze the coherence between the MRF process parameters, the depth of cut, magnetic field strength, wheel speed, pump speed, viscosity of the MR Fluid and the spot peak removal rate.

Figure 3 shows the peak removal rates vs. the MR fluid flow rate for the process parameters to be verified. The peak removal rate varied from ~0.2 µm/ to ~0.6 µm/min at the depth of cut from ~0.4 µm/ to ~0.63 µm/min at the wheel speed from ~0.35 µm/ to ~0.5 µm/min at the MR Fluid viscosity from ~0.46 µm/ to ~0.53 µm/min at the pump speed and finally from ~0.45 µm/ to ~0.5 µm/min at the magnet field strength. It is identifiable that the biggest influence is given through the depth of cut followed by the wheel speed, which changes the cutting speed. A median influence is present at the MR Fluid viscosity and the pump speed. Only a small influence is given through the magnetic field strength, which is not equal to results achieved at standard optical glass. The gradient of the graphs in Figure 3 indicate the gravity: more steeply means more influence. An explanation for the median impact parameters may be drawn as follows. The parameters not only influence the fluid’s stiffness but also the fluid’s shape on the wheel. The higher the MR fluid ribbon is the less pressure appears in the contact zone between tool and workpiece and therefore a lower removal will succeed.

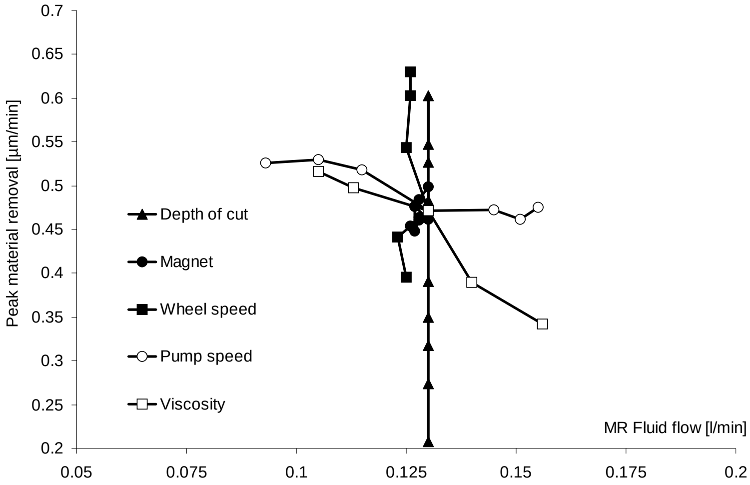

Figure 3. Influence of changing process parameters at silicon nitride on the MRF peak removal rate

5. CONCLUSION

From the results obtained from examination of the material influence of at the Magnetorheological Finishing (MRF) the following conclusions may be drawn:

- The MRF is a sophisticated technique, which exhibits an individual controllable material removal process for the optical surfaces.
- The MRF process shows a great material influence nevertheless also tough and brittle materials, which are more complex and complicated to finish, can be polished successfully.
- An individual material factor fmat could be derived from the machined samples, which shows a possibility to include the material influence into the Preston coefficient
- Process parameter analysis evinces the important parameters for the peak removal rate. At this the greatest influence is through depth of cut, wheel speed, pump speed, viscosity~~,~~ and magnet field.
- It is demonstrated that the MRF is an economical, steady and efficient technique for silicon nitride

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