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Tribological wear analysis and numerical lifetime prediction of glassy carbon tools in fused silica molding

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ABSTRACT

Precision Glass Molding (PGM) is currently the standard manufacturing process for medium-lot-size fabrication of complex shaped, high-quality lenses. During each molding cycle in PGM, the molding tools experience thermal and mechanical loads. Degradation mechanisms caused by these loads limit the molding tool life. Therefore, acquiring a deeper knowledge of the fundamental degradation mechanisms of molding tool surfaces is of high-interest.

In this work, the tribological wear mechanisms of the surfaces of glassy carbon tools used for fused silica molding were investigated. Both an experimental study and a finite element method (FEM) simulation are presented, and their results were correlated. In the experimental study, the progressive wear process on glassy carbons surfaces was investigated using scanning electron microscopy (SEM). In addition, atomic force microscope (AFM) measurements of the sizes of surface defects such as notches were analyzed. Experimental results were compared with a FEM simulation of the tensile stresses and sliding velocity that arise during each fused silica molding cycle. Using this approach, the dimensions of wear can be calculated after any given number of molding cycles and the lifetime of the molding tools can be predicted.

1. Introduction

Optical components made of fused silica are essential due to the outstanding properties of this material. Fused silica has a broad transmission range for electromagnetic radiation from 180 nm to 3.5 μm wavelengths. Through this, fused silica will be applicable for ultraviolet, visible and near infrared radiation. Additionally, the low-coefficient of thermal expansion ($\sim 0.5 \cdot 10^{-6}\,\mathrm{K}^{-1}$), the low thermal conductivity ($\sim 1.4\,\mathrm{Wm}^{-1}\,\mathrm{K}^{-1}$) and the high glass-transition temperature ($\sim 1300\,^{\circ}\mathrm{C}$) facilitate the application of fused silica in high-temperature environments. Furthermore, the material has a high chemical resistance and a high laser induced damage threshold (LIDT), which especially qualifies fused silica optics to be used for high-power lasers [1].

Optical components consisting of glass are traditionally manufactured by grinding and polishing processes [2]. This production method is well established and suitable for the production of planar and spherical shaped optical components. However, for the production of complex optics (e.g. aspheres, diffractive optics or freeform lenses) the technology of Precision Glass Molding (PGM) is more convenient [3]. PGM is a replicative technology for producing high-precision optical lenses in medium and high-volumes [4]. High-quality lenses with complex geometries and decreasing dimension are in growing demand, which is driven by the wide-ranging applications in laser technology, biomedicine and consumer electronics [5].

In PGM, glass preforms are placed between a pair of molding tools and heated up in vacuum. At the molding temperature, the glass is pressed firmly for several minutes until the mold form is homogeneously filled with glass. After a controlled cooling with applied pressure for shrinkage compensation, the pressed lens keeps the desired optical and geometric properties, with no need for post-processing steps. The machining of the complex molding tools with high accuracy is extensive and costly. However, the costs for one optical glass component decrease with the increasing numbers of manufactured optics. For this reason, several investigations focus on enhancing the lifetime of molding tools. Determining an appropriate wear prevention the chemical and mechanical interactions between molding tools and glass were analyzed [6–11].

PGM of fused silica, in comparison to the common optical glasses, is considerably more challenging. The reason for that is the high molding temperature at about 1360 °C, whereas the molding

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temperature of common optical glasses ranges from 400 °C to 700 °C. The high molding temperature causes high thermo-mechanical loads and hence restricts the number of suitable mold materials due to wear. A promising material for molding tools is glassy carbon due to its chemical inertness and high-temperature resistance [12,13]. The influence of the process parameters temperature and pressing force on the wear of molding tools made of glassy carbon was analyzed in [14]. Silicon residues were detected on the molding tools after molding tests. However, no silicon diffusion was measured in the glassy carbon tools.

For establishing PGM of fused silica in production technology, an extensive knowledge about the wear mechanism during the molding process is mandatory. In this work, an experimental study was performed in order to examine the progressive wear process on glassy carbon molds. Moreover, a finite element method (FEM) simulation was performed for investigating the tensile stress and compressive stress during each fused silica molding cycle. A comparison of experimental and simulation results enables the calculation of the dimension of wear and thus the numerical prediction of the molding tool lifetime.

2. Experimental setup

2.1. *Molding tools/molds*

Molding tools of glassy carbon material from Tokai Carbon Co., Ltd, were used. Glassy carbon is a convenient material for molding tools, because amorphous carbon is chemically inert and has a high-temperature resistance [13]. In this experimental study, simple cylindrical molds with diameter 30 mm and height 10 mm were used to exclude the influence of the sample geometry. The plane contact surface of the molds was polished to optical quality down (roughness Ra < 5 nm) using a Phoenix 4000 made by Buehler GmbH and silicon dioxide polishing suspension with grain size < 0.05 μm.

2.2. *Fused silica*

The glass blanks used were cylinders with a diameter of 10 mm and a height of 5 mm made of fused silica grade SQ1. Fused silica grade SQ1 (~1200 ppm OH content, other elements ≤ 0.4 ppm) is a high-purity material, so that chemical reactions between molding tools and fused silica glass can be neglected. The material is typically applied to optical elements such as lenses, mirror substrates and wafers [15].

2.3. *Molding process*

Molding experiments were examined in order to analyze wear mechanisms. Each pair of molding tools, upper and lower mold, was used for a certain number of molding cycles. Fig. 1 (left) shows the schematic set-up of the molding experiment. The glass molding experiments were performed on a commercial Toshiba Glass Molding Press GMP-207HV. The molding process is an isothermal process due to the fact that the molding tools and the glass blank have the same temperature throughout the process. An example chart of the process parameters temperature, tool position and force during the molding experiments are shown in Fig. 1 (right).

The molding process starts with an evacuation of the molding chamber to an atmosphere pressure below 3 Pa in order to remove oxygen and water and thus prevent the oxidation of the molding tools. The heating is done by using infrared lamps. The heating and cooling process phases are performed under a nitrogen environment for faster heating and cooling by means of convection accompanied by infrared radiation. After reaching the molding temperature (1360 °C), the entire molding tool assembly with the glass blank is soaked at this temperature. Then the lower molding tool is driven in contact to the upper molding tool at a constant velocity of 3 mm/min until the stated molding force (2 kN) is reached. Now a constant molding force is applied for the molding time of 240 s. After the molding phase the glass is cooled down to a temperature below the transition temperature of the glass under the load of a small molding force (post-pressing force). Throughout the cooling phase, glass shrinkage is avoided by using nitrogen at a controlled flow rate. The entire chamber is finally cooled down at maximal nitrogen flow rate. This molding process is repeated for a certain number of molding cycles.

2.4. *Analysis of the wear*

To analyze the wear of the molding tool surfaces, scanning electron microscope (SEM) measurements were taken with a Zeiss Neon 40 EsB. SEM pictures with different magnifications were received. In order to obtain the surface topography with high-resolution, atomic force microscopy (AFM) images were carried out by Central Facility for Electron (GFE) Microscopy of RWTH Aachen University.

3. Experimental results

In order to investigate the progressive wear process, the glassy carbon surface was scanned by SEM being polished, after 10 and 20 molding cycles (Fig. 2). The glassy carbon molding tool was marked to compare the wear process at the selected surface area. Double-digit nanometer defects in the form of notches were visible at the polished surface. Thus either the polishing might lead to small surface defects or these defects are already in the raw material in the form of voids, respectively. After 10 molding cycles, these small defects enlarged. The defect size increased to several hundred nanometers. During the next ten molding cycles, the

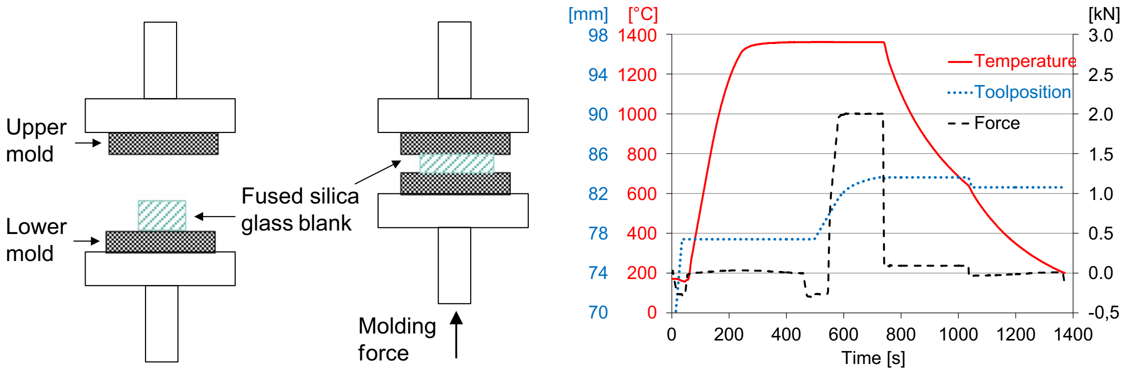

Fig. 1. Schematic structure of the molding experiment (left) and process parameters in the molding tests (right).