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Paper: "*Efficient mold manufacturing for precision glass molding*", Olaf Dambon, Fei Wang, Fritz Klocke, Guido Pongs, Bernd Bresseler, Yang Chen, and Allen Y. Yi. Journal of Vacuum Science & Technology B 27, 1445 (2009).

Introduction

Precision glass molding is an efficient near net shape fabrication method for high volume production of aspherical optical glass components. Up until now, the mold manufacturing is still the most cost- and time-consuming process partly due to the fact that the shrinkage error of glass has to be compensated for by means of multiple molding trials and mold modifications.

In this paper, an efficient mold manufacturing process with integrated numerical simulation is presented in the form of a case study of an industrial molding example. Taking into account the shrinkage error predicted by process simulation, revised molds are manufactured directly with compensated design. After molding test with the compensated molds, the surface figure of the molded glass lenses was in good agreement with the desired shape within 1 μm, which matched the original accuracy requirement and no further mold compensation was needed.

Glass material property

During the precision molding process, glass is heated together with the mold assembly to a temperature above its transition temperature (Tg). At this temperature the glass material is viscoelastic and the stresses in glass relax very quickly. Viscoelastic behavior is a time dependent response of a material to stress or strain. To describe this stress relaxation, a generalized Maxwell model (Fig. 1) is commonly used, where E_0 and E are the instant initial elasticity and actual elasticity, σ and ε are stress and strain, τ_i are the relaxation times, and ω_i are their corresponding weighting factors.

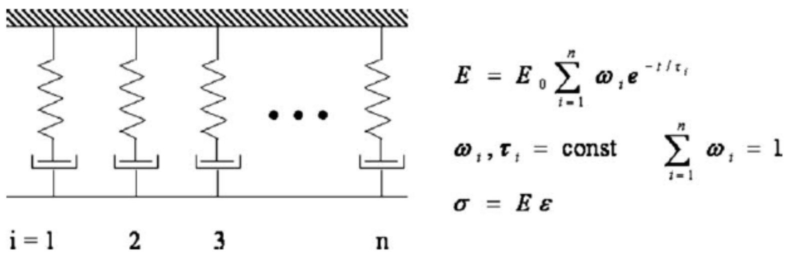

Fig. 1. Generalized Maxwell model.

For the temperature range from room temperature to molding temperature, the thermorheologically simple approximation of studied glass material P-SK57 can be described very well by the following shift function.

$$a(T) = \frac{\eta}{\eta_r} = \frac{\tau}{\tau_r} = \exp\left[\frac{\Delta H}{R}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right],$$

where η and τ are viscosity and relaxation time of the glass material, ΔH and R are the activation energy and ideal gas constant.

The relaxation behavior of an optical glass and its temperature dependence provide the analytic foundation for process simulation of precision glass molding process. Besides the viscoelasticity, another influencing material property for the final shrinkage error is thermal expansion coefficient, which can be measured by using a dilatometer to dilatrometrical soften point. Thermal conductivity and specific heat capacity of both glass and mold materials are also required for the calculation of temperature distribution, which is critical to the relaxation speed and the degree of thermal expansion.

Process simulation

In this paper, a numerical simulation method is developed in a commercial FEM software (ANSYS) to predict geometrical deviation of the molded lens and provide compensation information for the mold manufacturing in advance. The general simulation model includes two separated physical models (Fig. 2): thermal model for the calculation of heat transfer and temperature distribution and the mechanical model for the calculation of thermal expansion, glass relaxation, and form filling procedure.

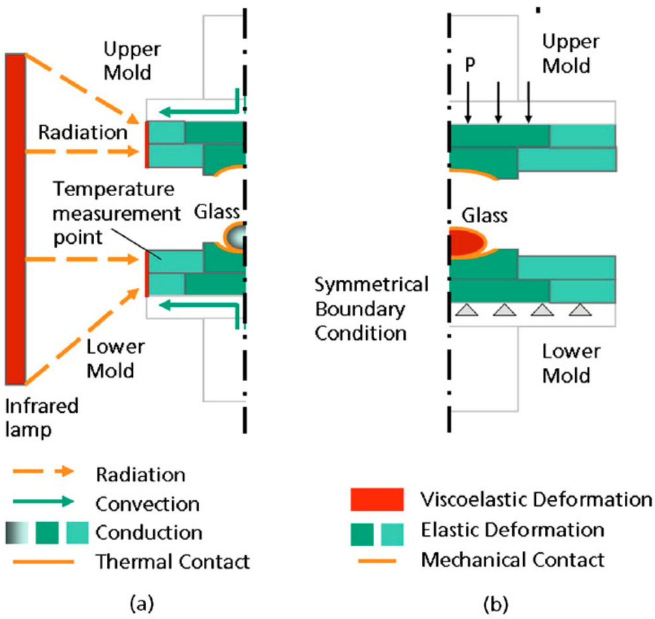

Fig. 2. (a) Heat transfer model of glass molding process.
(b) Mechanical model and the boundary conditions.

Based on the thermal and mechanical models, a calculation algorithm for the entire molding process was established in the commercial FEM software ANSYS multimode model. The molding process simulation included three major steps: heating, molding, and cooling, which are analogous to the real molding process.
The developed numerical simulation method was implemented to predict the glass shrinkage error for an industrial molding job, where a biconvex lens with aspherical surface on both side was molded. The lens has a diameter of 22 mm and thickness of 8.5 mm. The form accuracy required by the optical design is peak to valley error smaller than 2 μm. A sketch of the lens design can be seen in Fig. 3. The molding job was to be carried out on a commercial Toshiba molding machine (model GMP-211V) and the molding temperature was 545 °C for the selected glass type (P-SK57).

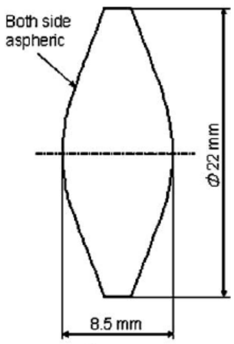

Fig. 3. Lens design for the molding trial.

Simulation result

In this simulation, the mold geometry was constructed in ANSYS directly according to the above mentioned mold design. The optical surface was described by the standard aspherical equations. In the meshing procedure, adaptive meshing and zonal refinement were carried out on both the mold and glass surface for better accuracy. Glass preform in ball shape was selected for its simplicity and the diameter was calculated from the desired lens volume. As shown in Fig. 4, the final result showed a maximum deviation of 5.5 μm on the optical surface and a maximum residual stress of about 20 MPa at the corner of molded lens.

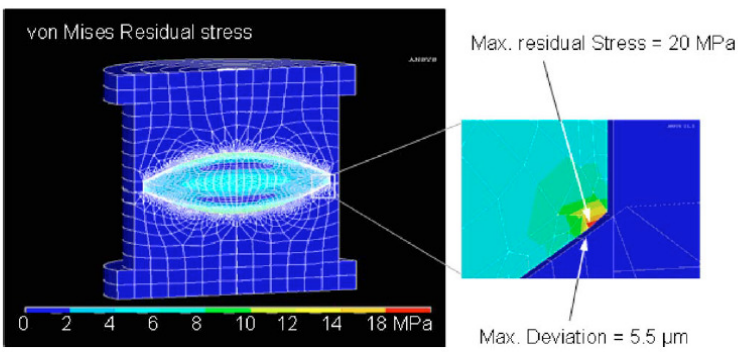

Fig. 4. Simulation result for an industrial molding job.

Mold compensation

Figure 5(a) shows the integration of simulation in the mold design and manufacturing process. First of all, the initial mold design was done before simulation based on the desired optical form, and would be used as geometrical boundary conditions in the FEM simulation. After the process simulation, the calculated glass form deviation was used as the feedback for mold design modification. Based on the modified mold design, the first mold set was manufactured, with which first group of molding tests were then carried out and the surface accuracy of the molded lens were measured. If the desired requirements were satisfied by the figure accuracy on the molded lens, no more compensation iteration would be needed. Otherwise, additional compensation cycles would be required based on the measurement result.

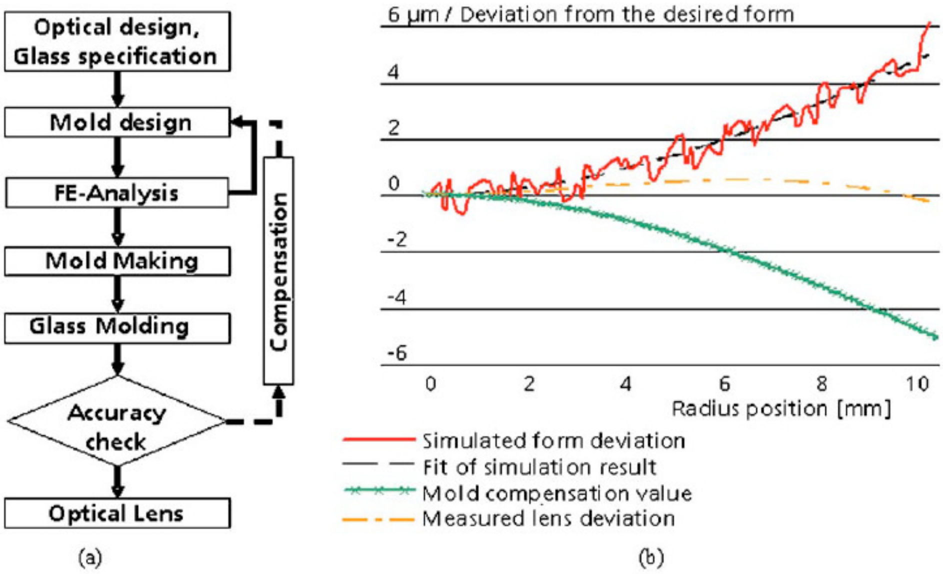

Fig. 5. (a) Flowchart of the integrated simulation in the mold design and manufacturing. (b) Comparison of simulated form deviation, mold compensation, and molded lens.

After the process simulation, the calculated glass form after shrinkage is compared to the desired form, which showed a maximum deviation of about 5.5 µm as can be found in Fig. 5(b). For an efficient compensation the simulation result is fitted into standard aspherical equation, and the amount of deviation is directly mirrored on the mold surface as compensation value.

Molding result

A trial molding was carried out on the Toshiba precision glass molding machine GMP-211V. The entire molding process consists of three main steps. The heating and cooling processes were under nitrogen atmosphere whereas the main molding process was done under vacuum. The molding process had a total duration of over 20 min and the main molding force was up to 3 kN. Toward the end of the molding cycle, a very low holding force of 0.5 kN was applied to the lens to prevent glass breakage due to internal stresses inside glass generated during uneven cooling process. The molded lens was measured on the Taylor Hobson PGI 1250 profilometer, the result showed a peak to valley error smaller than 1.5 μm on both aspherical surfaces (Fig. 6), which met the design requirements thus no more compensation iteration was necessary.

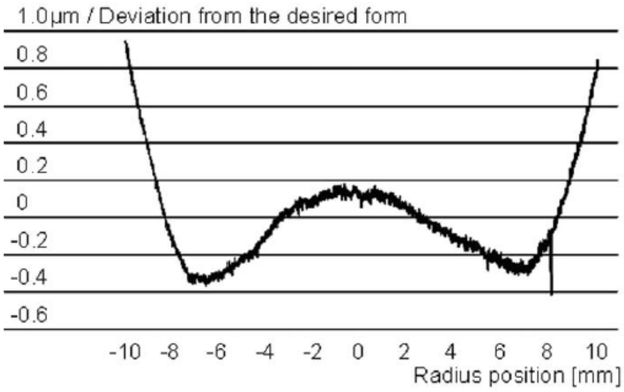

Fig. 6. Measured surface error on the molded lens relative to the original design.

Conclusion

An effective mold manufacturing method for precision glass molding with process simulation was developed. A case study was performed for an industrial molding job to evaluate the efficiency of the mold manufacturing using the simulation results. Measurement results after the trial molding showed excellent form accuracy on the molded lenses. Future work would include the development of a widely usable glass relaxation material model in the simulation to achieve better predict accuracy and an user friendly interface with automatic compensation algorithm for an enhanced combination between the simulation, mold design, and measurement result.

Reference

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