Process Chain for the Replication of Complex Optical Glass Components

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Abstract. Precision glass molding is becoming a promising technology for fast production of complex optical glass components in high volume. It is a replication process and becomes economical after a few batches. The glass molding process can be holistically described by a process chain which starts with the design of the optical component and modeling of the glass molding process using numerical simulation. An ultraprecision grinding process is applied to manufacturing the molds. Chemically insert coatings are necessary in order to prolong mold life because the mold has to withstand high mechanical and thermal loads. The parameters of the subsequent molding steps such as temperature or pressure depend on the type of glass and the size of the optical component. The last step of the process chain is the qualification of the optical components by measuring their optical properties using precision metrology.

1 Introduction

The demand for high-precision, complex-shaped optical components is rapidly growing worldwide. Such components are used in classical metrology applications, such as camera lens modules in mobile phones, optical systems in automobiles or for optical storage media in information technology.

The traditional production method for optical components is grinding, followed by a polishing step. This method is not economical for manufacturing of complex shaped components such as aspheric lenses, free-form lenses or lens arrays in medium to large quantities. The final polishing step is extremely costly and therefore it is only selected for very high-quality components in small volume.

As optical materials, glasses offer many advantages over optical polymers. Glasses have not only higher transparency but also lower susceptibility to

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E. Brinksmeier et al. (Eds.): Fabrication of Complex Optical Components, LNPE, pp. 119–132.
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corrosion and higher strength. Another advantage of glasses is the higher power density they allow. This is necessary for high-energy laser and high power lighting applications. In addition, glasses provide a greater range of refraction indices than optical polymers. On the market different glasses are available. These differences in their composition result in different optical properties.

The precision molding technology is an established technology for fast and economical production of complex optical components in large quantities. A glass preform and the molding tools are heated up to the molding temperature and pressed into the desired shape. In a single step, an optical component with double-sided functional surfaces and high accuracy is produced, without the need for subsequent finishing. Since the mold production by grinding and polishing is costly, and the precision glass molding is a replication process, the entire process chain only becomes economic after a minimum number of batches. By using multi-cavity tools, multiple optical components can be molded in one batch, thus increasing the efficiency of the process.

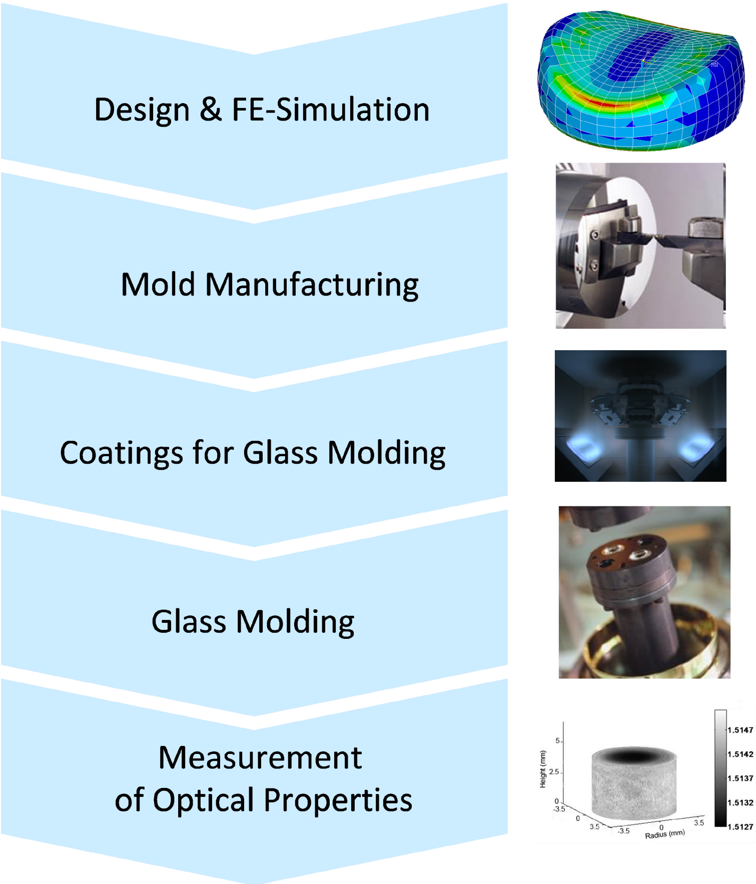

Fig. 1 Process chain for the replication of glass components

Figure 1 describes the complete glass molding process. In the first step, the optical component is designed and the molding process simulated. Due to the different thermal properties of glass and mold, the lens has a non-negligible deviation from the desired shape after the pressing process because of the shrinkage of the glass during cooling. Using FEM simulation, the shrinkage of glass and changes of its optical properties such as refractive index after molding can be calculated. Taking this into account, the mold is manufactured. High demands are placed in the form accuracy and roughness of the mold, since any form deviations will be transferred to the optical component. To prolong the mold lifetime, protective coatings that prevent wear and thus increase the profitability of the process are deposited on the mold. The parameters of the pressing process such as temperature or pressure depend on the type of glass and the size of the optic. After the molding process, the quality of the lenses is controlled by measuring of their optical properties using precision metrology.

2 Design and FE-Simulation

2.1 Objective of Simulation

In precision molding process, glass raw material is first heated to a temperature above its transition temperature (e.g., B270, Tg=533°C, forming temperature 625°C) and subsequently pressed into a lens shape, and then carefully cooled down together with the mold inserts. During pressing and cooling, many factors such as thermal expansion and stress relaxation affect molding process and thus lead to form deviation in final geometry and variation in refractive index. Therefore, by mold design, the surface deviation should be compensated on the mold surface based on the original lens design by adding a slight amount of correction, so that the molded lens matches both the geometrical and optical specifications. Traditionally, the amount of compensation is determined by costly- and time intensive trial and error molding. In recent years, numerical modeling is implemented to assist the mold making process to predict these errors before the actual mold manufacturing.

2.2 Thermal and Mechanical Modeling

The process simulation of precision glass molding is developed based on FE method and consists of a thermal model predicting the actual temperature distribution and a mechanical model to predict the visco-elastic deformation and thermal shrinkage of the molded glass lens.

The thermal model considers all three heat transfer mechanisms occurring in a typical glass molding process (conduction, convection and radiation), in order to determine the temperature distribution and variation rate inside both the glass and mold volumes during the entire molding process. The temperature distribution determines the visco-elastic material behavior of glass material.

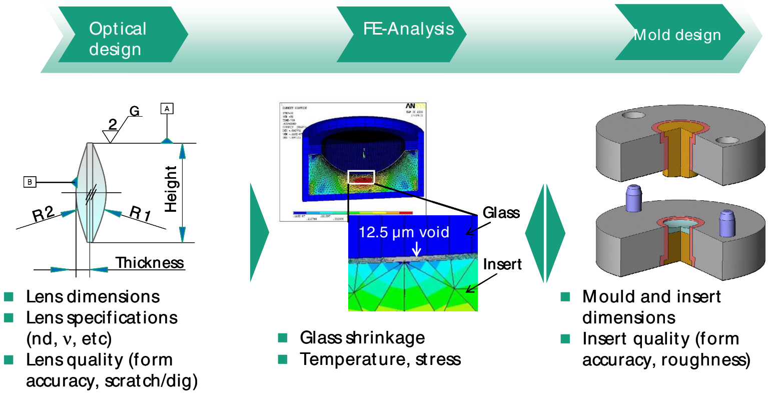

Fig. 2 Design of molded optical glass components with the assistance of FE-simulation

For a typical visco-elastic material, such as glass at the molding temperature, the application of a constant load will lead to material deformation, which consists of instantaneous deformation (elastic effect) and continuous deformation over time (viscous effect). The visco-elastic property will cause decay of the applied load and this decay is called stress relaxation, which determines the deformation behavior of glass. To describe the visco-elastic behavior, a generalized Maxwell model expressed in Eq. 1:

$$G(t) = 2G\sum_{i=1}^{n} w_i exp(-t/\tau_i) \tag{1}$$

can be used to model the stress relaxation of glass at transition temperature [Dam09, Jai05, Jai06], where G(t) is the stress relaxation module, ω_i are weighting factor and τ_i are the corresponding relaxation times under certain temperature.

2.3 Index Variation Modeling

The refractive index of an optical glass changes after precision compression molding mainly due to structural relaxation in glass. In the past the phenomenon of group index drop has been studied using the Tool-Narayanaswamy-Moynihan (TNM) model for different heat treatment and cooling rates [End99]. Meanwhile inhomogeneous temperature distribution inside the glass during cooling can cause structural distortion and thus refractive index variation after cooling. According to Su et al.'s previous research, the refractive index variation inside the molded glass will also introduce substantial wavefront deviation for precision glass components [Nar71]. This index variation could be modeled by the famous Lorentz-Lorenz equation [Rit55]:

$$\frac{n^2 - 1}{n^2 + 2} = \frac{4\pi}{3}\frac{N_A \rho}{M}\alpha \tag{2}$$

where M is molar weight, N_A is Avogadro number, ρ is density and α is mean polarization. Using this equation, refractive index distribution of a molded glass lens could be determined by calculating the density change. This prediction of index variation during molding is especially necessary for precision imaging optics, so that the variation can be compensated during the optical design stage.

2.4 Mold Design and Manufacturing

After the process simulation in the FEM code like ANSYS, ABAQUS or MSC MARC, the calculated glass lens shape after shrinkage is compared to the desired form, which shows a maximum deviation of about several up to a hundred micrometer depending on different lens surface shape and diameter. For efficient compensation, the simulation result of shape deviation will be combined with the compensation value of the index drop and then fitted into standard non-spherical equation. The amount of deviation is directly mirrored on the mold surface as the compensation value. Based on this compensation, the mold inserts made of alloys and ceramics will be manufactured on precision grinding machine (e.g. Toshiba ULG-100D SH3), thus the molded glass lenses match the specification directly without any finishing steps.

3 Mold Manufacturing

Optical glass is molded between 350 and more than 800 °C depending on the glass type and its chemical composition. While so called low-Tg glasses can be molded using nickel plated mold materials, ceramic molds are used for the majority of optical glasses. In order to guarantee the highest accuracies and a long mold lifetime ceramics are most suitable to be used as mold materials. Their hardness, chemical resistance, thermal stability and low coefficient of thermal expansion qualify them as the forming tools for the glass molding process. On the other side, those properties make it hard to machine these materials.

While in the past molds made of silicon carbide and other ceramics were used, today a binderless tungsten carbide with fine grains is the first material of choice. In comparison to conventional hard metals those special grades contain just a very small amount of nickel or cobalt, which is used as a metallic binder. Thus, very dense (15,57 g/cm³), hard (2825 HV10) and materials can be produced with the proper properties a glass molding tool needs.

Due to its hardness, tungsten carbide can only be machined by grinding and polishing [Mei09, Bri07, Bri09]. Here, diamonds are typically used as abrasives.

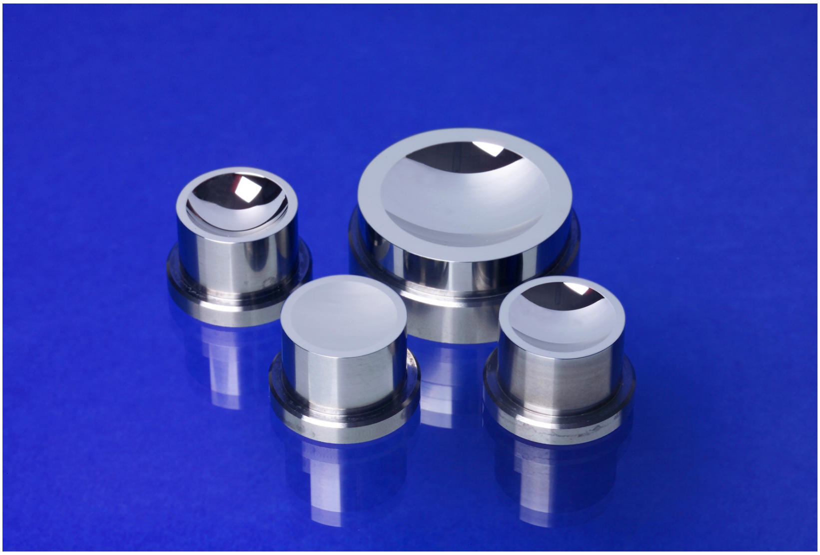

Fig. 3 Ground tungsten carbide molds for precision glass molding

Since the molds need to be very accurate with optical surface finish, a ductile machining process as described by Bifano [Bif88], Grimme [Gri07] and others [Liu03, Liu01] is necessary. In ductile mode cutting the process parameters are chosen in a way to enable plastically deformation of the material. Thus, cracking of the surface is avoided and a very smooth and shiny surface finish is obtained. Characteristics of ductile mode cutting processes are very small depth of cut and feed rates as well as round instead of sharp cutting edges. Thus, the chip thickness is smaller than the so called critical chip thickness, which is an indicator for ductile mode cutting and depends on the mechanical properties of the material. In addition to the abovementioned process parameters compressive stresses and high temperatures in the cutting zone have positive effects on ductile machining.

To manufacture the molds, an ultraprecision grinding process [Bri10, Che03] is applied. Therefore, ultraprecision machines with highly accurate guideways and air bearing spindles are needed. For the machining of the tungsten carbide materials, resin bonded grinding wheels are used. Typically, the abrasives in the bonding are 3 to 5 μm in diameter. The concentration of diamonds is usually rather high, so high number of cutting edges can machine the material and therefore guarantee a small chip thickness. Thus, a mirror finish can be generated on the tungsten carbide surface showing less than 10 nm roughness (Ra).

Since a grinding wheel is continuously effected by wear, the mold manufacturing process usually needs several iterations to reach the final form accuracies. Typically, the mold is ground and then the form of the mold is measured. Based on this metrology data and their characteristics of the machine setup, the grinding wheel position e.g. can be determined. In the final steps the metrology data is also used to generate the tool path with compensation of the existing errors on the mold [Luo97, Che10, Mei10]. Thus, form accuracies of up to 150 nm (PV) and irregularities of less than 100 nm can be achieved.

After grinding, the mold surface already shows an optical finish but there are still some regular structures on the mold caused by the grinding process characteristics. These regular structures can effect the quality of the optic. To eliminate them a subsequent polishing process is needed. Since the large number of the molds are rather small or steep, there is no automated polishing process capable to machine the molds. Therefore, the majority of the molds are polished by hand.

Based on the current state of the art, a large spectrum of mold geometries of different sizes can be machined including rotationally symmetric molds with spherical and aspherical shapes, cylindrical shapes, either spherical or aspherical, and freeforms such as non rotationally symmetric parts and arrays.

4 Coatings for Glass Molding

A crucial requirement for the successful application of the precision glass molding technology in practice is the protection of the optical surfaces of the molds through the application of suitable coatings [Ma08]. The production of the molds in the extreme form accuracy required for optical applications is technically difficult and therefore expensive. Protective coatings that can withstand the high mechanical, thermal and chemical stresses during the molding process are essential.

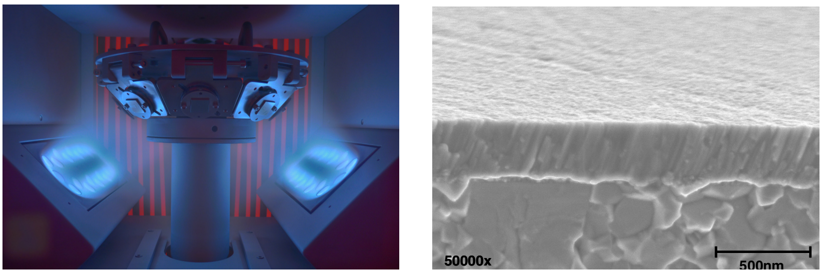

Fig. 4 Coating process (left); PtIr coating (right)

There are two main failure modes of the molding tools that need to be addressed by coatings:

The first one is glass adhesion on the tool surface. Due to the high temperature and the long contact time between molding tool and glass, sometimes glass sticks to the mold surface. This phenomenon is the result of chemical interactions between the glass and the mold surface. These chemical interactions are accelerated by diffusion processes between glass, coating and substrate that take place near the surface during multiple pressing cycles. Therefore, coatings with the least possible chemical reactivity towards glass, like noble metal coatings, are preferred [Fis10]. Alloys of Platinum and Iridium are being successfully used in this application [Pat87]. Furthermore, substrates don't contain elements that diffuse easily, like binderless tungsten carbide, are also preferred. Since different glasses can have significantly different compositions, each coating should ideally be optimized for a specific glass type.

The second failure mode is the deterioration of the surface quality of the molding tool (increased roughness, cracks, scratches etc.). The coatings applied should be hard enough to prevent scratching during handling and resilient against mechanical and thermal cyclic loads in order to prevent such defects.

For the deposition of suitable protective coatings, there is a multitude of technologies that could be used. There are however several necessary characteristics that the selected coating technology should exhibit:

- During cooling, there is usually a difference in the shrink rate of the glass and the mold, due to different coefficients of thermal expansion. The adhesion of the coating to the substrate should be higher than the adhesion of the coating to the glass, in order to avoid coating delamination in this situation. Parameters that affect the adhesion are the cleanliness and activation method of the substrate prior to coating, as well as the deposition parameters [Mat10].
- The coating should not increase the surface roughness. This depends on the deposition technology and parameters, as well as the coating thickness [Mat10].
- The coating should be as defect-free as possible. Especially in-situ coating defects (droplets, clusters, pinholes etc.) should be minimized in order to meet the defect density specifications of the optical component.
- The coating thickness should not have large variation across the molding tool surface. A lot of effort is required to produce molding tools with form accuracies down to 150nm (PV or peak to valley). A coating thickness variation of a few hundred nm would derail this effort. Low coating thicknesses (well below 1µm) and suitable substrate rotation during coating can be used to prevent this problem.

By using the above mentioned characteristics as selection criteria, the most suited coating technology is sputtering. This PVD (physical vapor deposition) process is able to provide smooth, defect-free coatings with low coating thickness variation and is extremely flexible regarding possible coatings and substrates [Mat10].

5 Glass Molding

Several hot forming technologies for glass products have been developed during the last decades. The most precise of them is called precision glass molding, or precision pressing and was originally developed in Asia and the United States approximately at the same time [Yi07, Klo04].

Sometimes the process is described as 'isothermal' process. This refers to the fact that the molding tools and glass have the same temperature throughout the process. The system itself is exposed to a heat cycle from room temperature to 700° in some cases and is therefore not strictly isothermal. The material input for the precision glass molding process consists of a glass preform with polished or fire-polished surface quality. As a general rule, the surface quality of the final molded product cannot be better than the preform or the mold surface. Drops of glass can be formed directly from the melt or glass can be cut, ground and polished into balls, disks or spherical lenses. The molding tools with the preform in between are heated up to pressing temperature by infrared radiation in a process chamber. The process chamber is first evacuated and then purged with nitrogen to prevent oxidation on the tools. The pressing temperature is chosen in the range between the yield point and the softening point so that the viscosity of the glass is between 1010 and 107 dPa s. After reaching the pressing temperature a homogenizing phase is added to achieve a uniform temperature distribution within the molds and the glass. The glass does not absorb much of the infrared light and is mainly heated by thermal conduction over the contact area or convection by the nitrogen flow. Thereafter the glass is pressed between the molds. The pressing cycle is mainly force controlled, in combination with the glass viscosity this leads to strain rates of a few mm/ minute. To achieve the desired center thickness of the lens, several end conditions are used. As the temperature control is very exact, a defined pressing time can be used to achieve a defined strain. Alternatively, position control can be employed and an end position for pressing can be defined. When the molding tools engage during pressing in a way that a closed cavity is formed, the center thickness is defined to a large amount by the preform volume.

After the pressing phase, the tools are cooled by nitrogen gas flow. A holding force is applied and the glass is cooled via the heat transfer over the molds. The holding force compensates the shrinkage of the glass when in viscoelastic regime and suppresses deformation due to internal stresses when approaching the elastic regime. The cooling phase is divided in two steps. A first step with a slow, controlled cooling rate and a second step of fast cooling once the glass has been cooled down under the transition temperature. The process ends at approximately 200 °C, the process chamber opens, the molded glass part is removed from the molds and a new preform is put in. The overall cycle time is around 15 to 25 min depending on the size and geometry of the product. To increase throughput, several molding tools can be used in one process. The advantages of this specific glass molding technology is the ability to mold double-sided parts with a lateral alignment of 5 µm and angular alignment of 50 arcseconds using many types of optical glasses.

6 Measurement of Optical Properties

Structural relaxation is the non-linear time dependent response of glass material properties (e.g., volume, density and enthalpy) to temperature change [Sch86]. The structural response depends on the thermal history, current temperature and the direction of the temperature change. The optical properties such as refractive index of an optical glass will change after molding due to structural relaxation in glass [Su10]. This requires appropriate process conditions in manufacturing to minimize the impact due to refractive index change. Figure 3 illustrates a three dimensional (3D) measurement setup [Zha09].

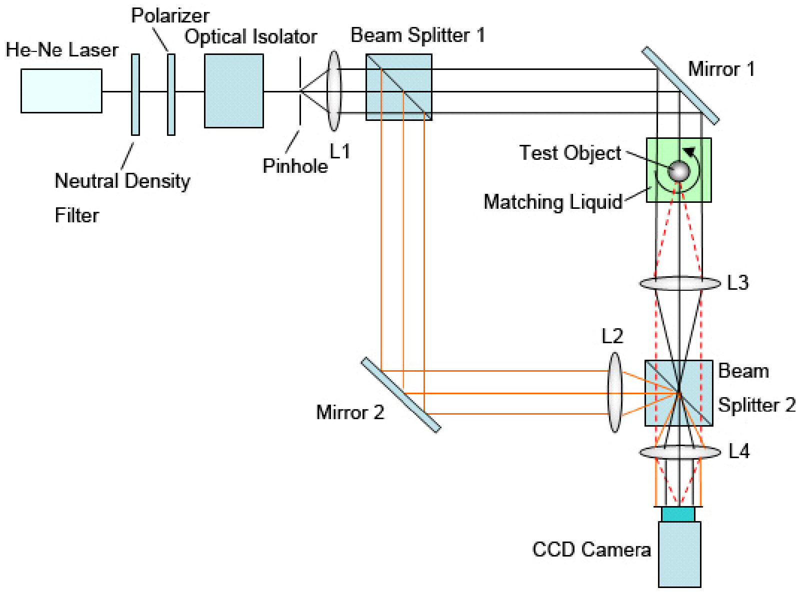

Fig. 5 Optical setup for 3D refractive index distribution measurement [Zha09]

The 3D measurement shown here is based on computed tomography, a nondestructive method that is widely used to generate 3D images of a specific property inside of an object from a series of two dimensional (2D) projections taken around a single axis of rotation. Details of computed tomography used in glass molding study can be found in [Zha09]. Using this setup, refractive index change down to 10^{-4} can be precisely measured.

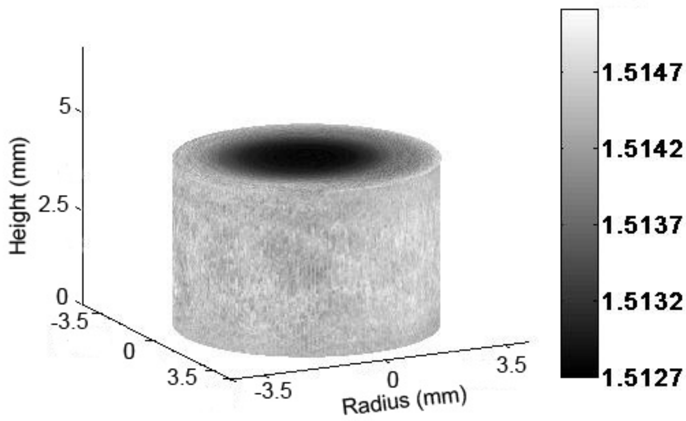

Fig. 6 3D refractive index map of a molded BK-7 lens [Zha09]

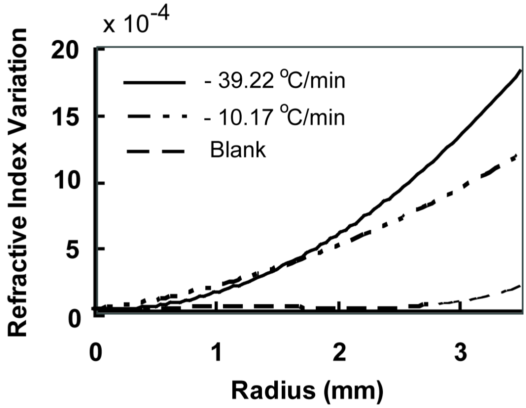

Fig. 7 Refractive index variation of molded glass lens under different cooling rate [Zha09]

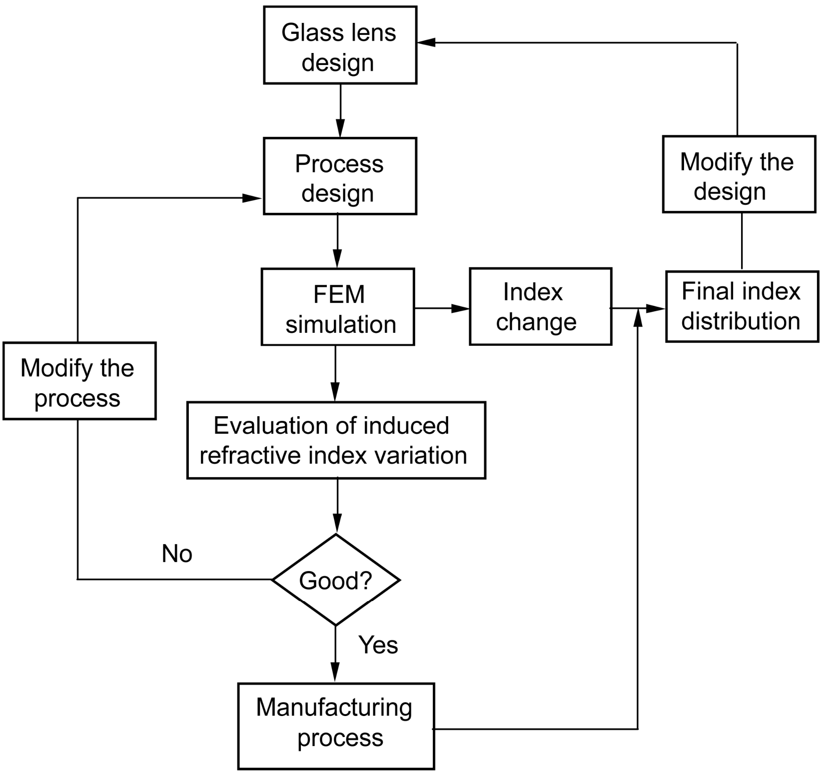

Fig. 8 Flow chart of FEM assisted glass molding process optimization [Su10]

Figure 4 shows a 3D refractive index distribution map of a molded BK-7 glass lens. The cooling rate for this lens was -39.22 °C/min. The 3D computed tomography shows that the refractive index distribution of the thermally treated glass is no longer uniform. The index variation could be as large as $2x10^{-3}$.

As a comparison, a second BK-7 glass sample was thermally treated with a cooling rate of -10.17 °C/min, and its refractive index distribution was also reconstructed by use of 3D computed tomography, shown in Figure 5 with an untreated glass blank. The refractive index variation under -10.17°C/min cooling was about 1.3×10^{-4}, smaller than the variation for the higher cooling rate (=-39.22°C/min) but still much larger than that of a blank, shown in the dashed line in the same figure, indicating that refractive index variation in a molded glass lens depends on cooling rate and geometry of the lens.

The optical property change is crucial for process compensation in designing glass molding process. Figure 6 is the process flowchart showing how the index variation information can be utilized. Specifically, finite element method (FEM) assisted numerical simulation is adopted to calculate the refractive index changes [Su10]. This information is then incorporated into the optical lens design so the optical lens geometry can be modified to compensate for the index variation due to cooling. This arrangement allows high volume, low cost and high precision optical lenses to be manufactured by eliminating the need for the costly trial and error approach. Similarly, other optical properties such as stress induced birefringence and dispersion also experience different degree of change during cooling thus can be measured and potentially compensated for in manufacturing process using similar strategy.

7 Conclusion

Driven by demand for high-precision and low cost optical glass components the precision glass molding technology offers a good possibility for fast production of precision optical glass components in medium and high volumes. The manufacturing process is holistically described by the process chain for replication of complex optical glass components. Each of the process steps has a crucial impact on the final result.

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

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