

# FEM simulation of the effect of cooling rate on prediction of surface deviation of compression molded glass lenses

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**Abstract.** For precision compression glass molded lenses, surface deviation is vital for the quality check. In this research, the effects of cooling rates on the prediction of surface deviation in glass lenses by precision compression molding were studied. Two types of cooling method with many different cooling rates were investigated. Based on the simulation results, two steps cooling method is better. And slower the cooling rate cause larger surface deviation.

## 1. Introduction

Compression glass molding is an ideal manufacturing technique for precision glass optical elements because of its net shape forming and high production manufacturing capabilities [1-4]. Due to the hot pressing and cooling, surface deviation was inevitable introduce to the molded glass lenses. The surface deviation will cause the lens's unnecessary refraction and lead to a decline in quality. Finite element method (FEM) has been applied to simulate and investigate the influence of the process parameters in compression molding method on the quality of glass lenses [2-4]. The Tool-Narayanaswamy-Moynihan (TNM) model [5, 6] was used to simulate the glass structural relaxation behavior in cooling stage. In this research, the FEM method with TNM model was used to study the surface deviations of compression molded glass lenses. Based on different cooling methods and different cooling rates, the surface deviations of aspherical and spherical surface studied. Based on the results, a two steps cooling method was chosen. However, the cooling rate at the first step should be considered carefully, because of the side effect for residual stresses.

## 2. Numerical simulation

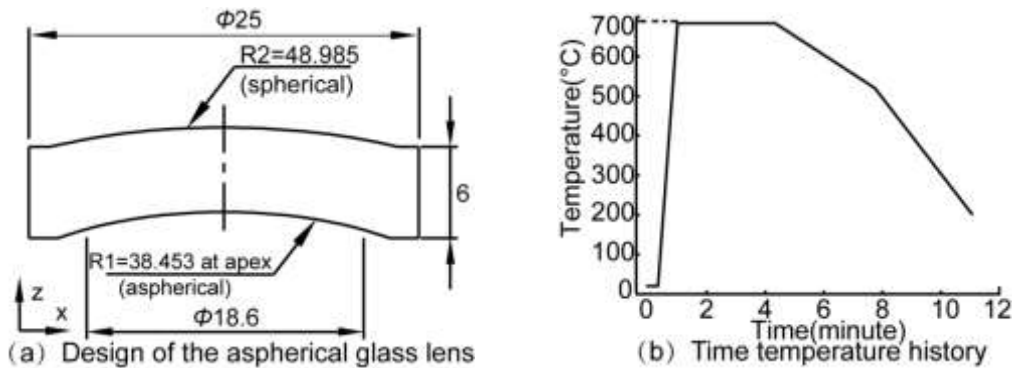
The compression molding proceeds in two stages called heating and hot pressing of glass blank, and cooling. The glass blank was first heated to the molding temperature  $T_{\text{molding}}$ , higher than the glass's glass transition temperature  $T_g$ , in the heating and molding stage. In  $T_{\text{molding}}$ , the glass was simulated as a Newtonian fluid. Because of the non-linear properties of the glass material associated with its current temperature and temperature history in cooling stage, the glass was molded by using the TNM model.

Figure 1 (a) illustrates the design drawing of the glass lens in mm. The convex side is spherical surface and the concave side is aspherical surface.

Figure 1(b) illustrates an example of two steps cooling procedure for the compression molding process. Hot pressing was executed at 684 °C, and maintaining the temperature for 4 minutes to release stresses due to pressing. The next step is to cool the molds and glass lens to room temperature. In Figure 1(b), the cooling procedure was divided into two parts: from the pressing temperature to

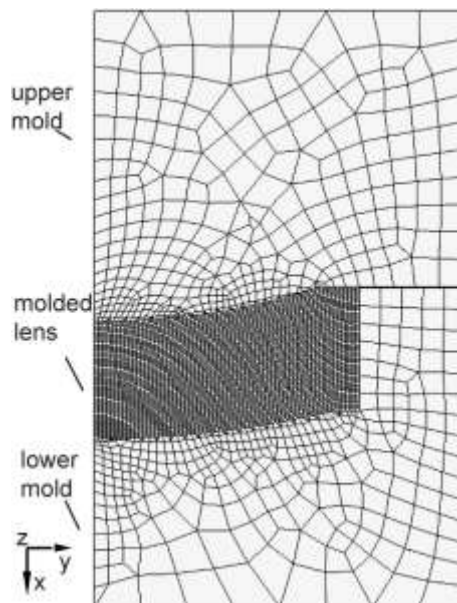


520 °C was implemented on a cooling rate of 0.8 °C/s, then from 520 °C to 200 °C was carried out on a cooling rate of 1.6 °C/s. Then the molded glass lens was taken out for room temperature cooling when the temperature achieved 200 °C [2, 7].



**Figure 1.** (a) Design drawing of the aspherical glass lens in mm, (b) An example of two steps cooling procedure

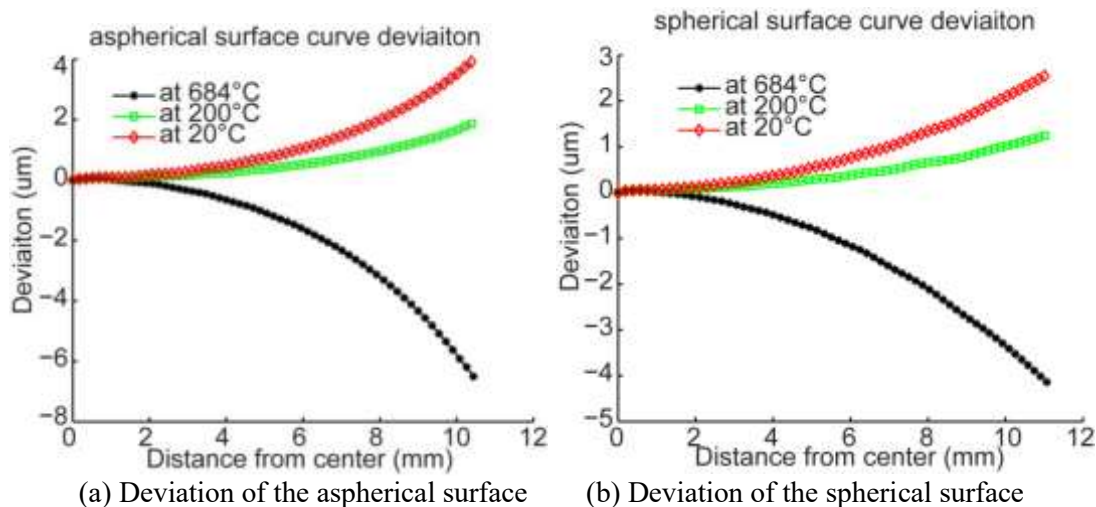
In FEM simulation, a two dimensional (2D) axisymmetric model was applied in this research based on the axisymmetric properties of glass lens and experimental environment. And a four-node isoparametric quadrilateral elements was used to mesh the glass and molds[7-9]. The upper mold, glass lens and lower molds were meshed into 381, 3,500 and 365 elements, respectively. Figure 2 illustrates the moulded lens and molds model after the molding procedure.



**Figure 2.** FEM model of the moulded glass lens and molds after molding procedure

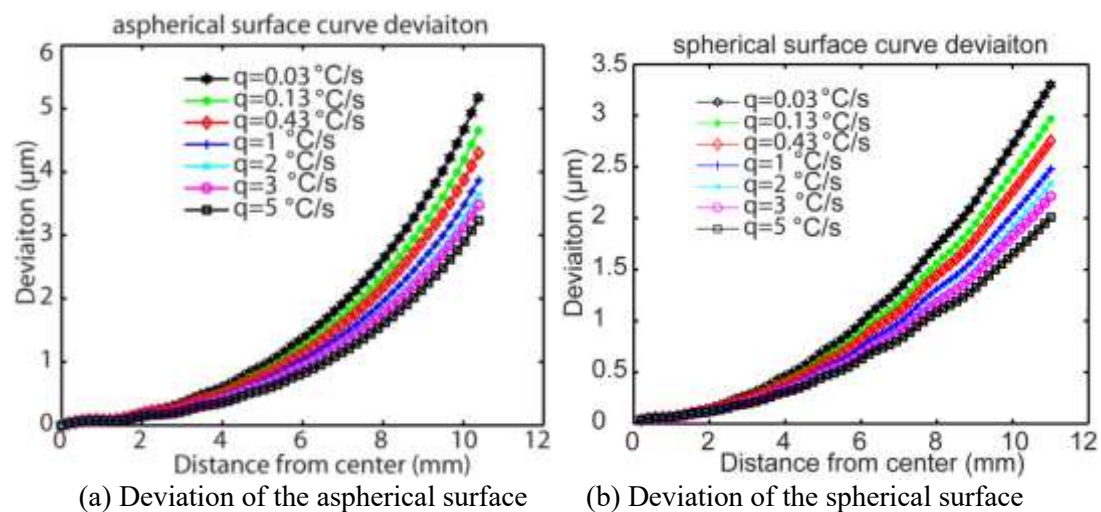
### 3. Simulation results and discussion

Figure 3 illustrates the deviations of aspherical surface and spherical surface at different temperature stage during the cooling process. The deviation means difference between the lens's surface and its designed surface. The cooling process was started with a cooling rate of 0.8 °C/s from molding temperature to 520 °C, then the cooling rate was changed to 1.6 °C/s until the temperature reached 200 °C. Then a room temperature natural cooling was followed by taking out the glass lens. In Figure 3, black dot denotes the deviations at molding temperature. Red diamonds denotes the deviations at 200 °C. Green square means the deviations under room temperature.



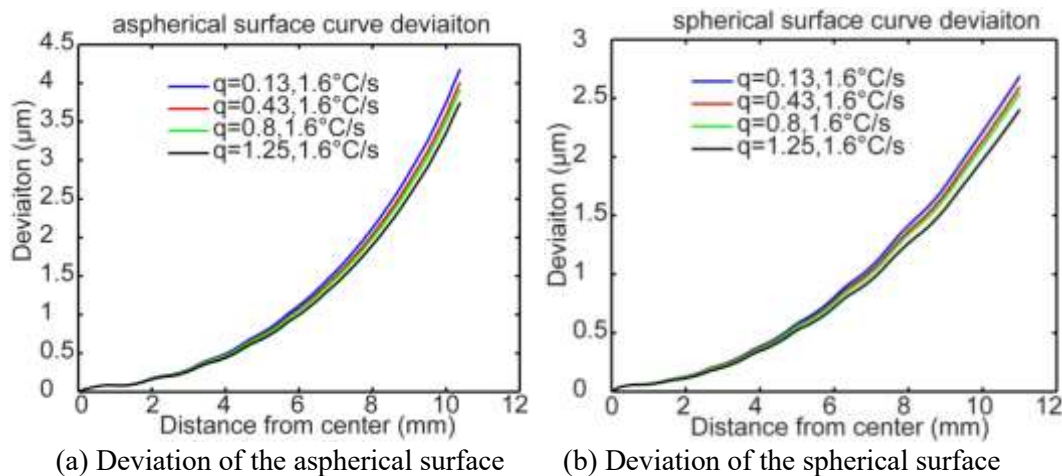
**Figure 3.** Deviations of the glass lens at aspherical and spherical surface at different temperature stage during cooling process

Figure 4 shows the deviations of aspherical and spherical surfaces under different cooling rates. The lenses were cooled to 200 °C with a constant cooling rate. The cooling rates were set as 0.03 °C/s, 0.13 °C/s, 0.43 °C/s, 1 °C/s, 2 °C/s, 3 °C/s, 5 °C/s, respectively. It can be seen that slower cooling rate causes larger deviations on both aspherical and spherical surfaces.



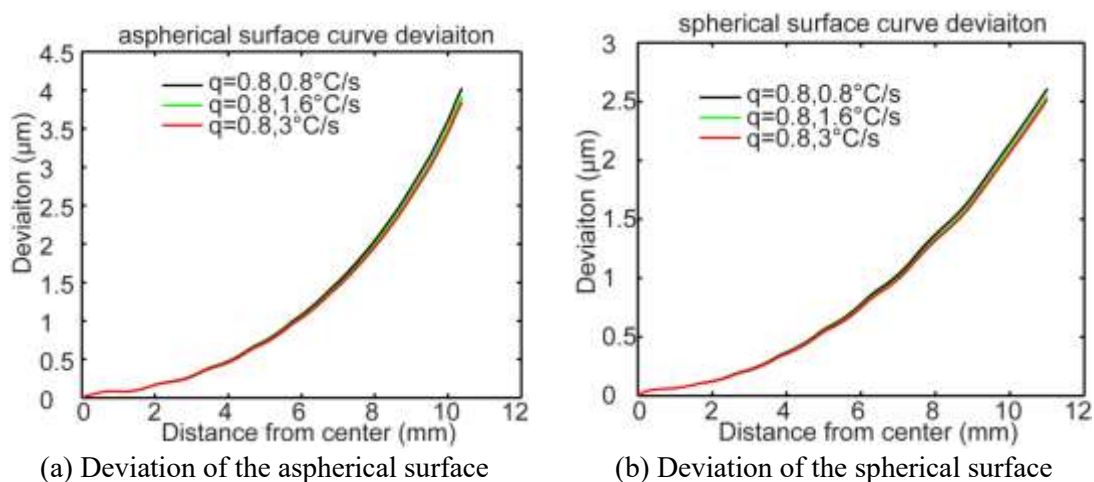
**Figure 4.** Deviation of the glass lens at room temperature by using different cooling rates

Figure 5 shows the deviations of aspherical and spherical surfaces by using two steps cooling method with different first step cooling rates. The first step cooling rates were set as 0.13 °C/s, 0.43 °C/s, 0.8 °C/s, 1.25 °C/s, respectively. The lens was cooled with the first step cooling rate from molding temperature to 520 °C. Then a second cooling rate was followed until 200 °C. The second cooling rate was set as 1.6 °C/s. Then the lens was removed from molding machine for room temperature cooling. It can be seen that the largest difference of deviations at both aspherical and spherical surfaces by different first step cooling rates were about 1 μm.



**Figure 5.** Deviation of the glass lens at room temperature by using two steps cooling method with different first step cooling rates

Figure 6 shows the deviations of aspherical and spherical surfaces by using two steps cooling method with different second step cooling rates. First, the lens was cooled from molding temperature to  $520^\circ\text{C}$  with the first step cooling rate. And the first step cooling rate was set as  $0.8^\circ\text{C/s}$ . Then the cooling rate was changed to the second step cooling rate until the temperature reached  $200^\circ\text{C}$ . The second step cooling rates were set as  $0.8^\circ\text{C/s}$ ,  $1.6^\circ\text{C/s}$ ,  $3^\circ\text{C/s}$ , respectively. Then the lens was taken out for natural cooling. It can be seen that there is no significant change in surface deviation at both aspherical and spherical surfaces by different second step cooling rates.



**Figure 6.** Deviation of the glass lens at room temperature by using two steps cooling with different second step cooling rates

Based on the results in Figures 4 and 5, the cooling rate between the molding temperature and  $520^\circ\text{C}$  shows a big influence on surface deviation. The slower cooling rate, the larger deviation. However, the cooling rate at the second step gives smaller influence. There is only  $0.1\ \mu\text{m}$  changes in deviation when the cooling rate at the second step raised from  $0.8^\circ\text{C/s}$  to  $3^\circ\text{C/s}$ .

#### 4. Conclusions

The surface deviation of compression molded glass lenses were investigated by using FEM. The results showed that cooling rate before the transition temperature has larger effect on surface deviation and should be chosen carefully. And the slower cooling rate cause larger surface deviation. When the temperature cooled under the transition temperature, the cooling rate shows smaller effect. Therefore, two steps cooling method is a way to keep small surface deviation while decrease cooling time.

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