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Numerical simulation of glass rolling process for cylindrical lens array

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A simulation study was conducted to analyze the filling deformation of the rolled cylindrical lens array in glass rolling process. A thermal-displacement coupled finite element analysis was carried out on the glass rolling stage, in order to obtain the simulation results of forming stress, temperature distribution, filling ratio, and warpage. The results demonstrate that the plate temperature and radial displacement are the most influential factors for filling ratios among the processing parameters. The feed velocity has a little influence on filling ratios. In addition, radial displacement loading is the most dominating factor among three factors in determining the warping deformation of the rolled glass. When the radial displacement is beyond 0.2mm, the warpage of the rolled glass increases significantly. The warpage is sensitively proportional to the feed velocity, but increases slightly with greater temperature. Besides, overlarge forming stress easily induces crack growth of the rolled glass. These simulation results have certain guiding significance in getting an overall understanding of the processing parameters influence on the rolled glass quality, thus will help make decision in optimizing the processing conditions.

1. Introduction

Cylindrical lens array plays an important role in the field of illumination, laser welding, fiber coupling and optical communication owing to the functionality of light beam shaping and uniformity control. Traditional machining of glass cylindrical lens array involves cutting, grinding, polishing process etc., which is cumbersome and time-consuming. Glass roller to plate hot embossing is an effective and potential method for mass-production and low-cost manufacturing of glass cylindrical lens array [1]. Compared to the plate-to-plate glass molding process, glass rolling process presents a unique line contact filling mode, which can reduce the radial loading and realize large-area continuous manufacturing [2]. In the roller-to-plate hot embossing process, a polished glass plate is firstly placed in the lower plate mold, then heated to specific temperatures, next rolled to the desired shape by precision roller and plate mold, finally slowly cooled to the room temperature.

Because the ambient environment is very high during glass rolling process, it is extremely difficult to measure and monitor the temperature distribution of glass workpiece at actual time. To investigate and predict the glass rolling process, finite element method (FEM) is a convenient and effective visualization way. Jain et al. [3] predict the performance of a precision glass aspherical lens molding process by incorporating stress relaxation parameters into FEM software, and demonstrated that numerical simulation can be used to predict the residual stress of the molded glass components. Ananthasayananam et al. [4] systematically studied the sensitivity analysis on the shape deviation of molded lens by FEM. Li et al. [5] used FEM to predict the temperature gradient and displacement change of molded glass cylinder, and demonstrated that the temperature difference has a great influence on the deformation behaviors and stress distribution. Zhou et al. [6] analyzed the influence of the dimension on the quality of a plano-concave molded glass lens by simulation, and indicated that residual stress has a great relationship with diameter and center thickness ratio. The above-mentioned literatures demonstrated that FEM is an effective and flexible approach to predict and analyze the residual stress, temperature distribution, and shape evolution of the molded glass in glass molding process. Hence, numerical simulation is a reliable approach to study the glass rolling process.

Until now, there are few simulation researches about glass rolling process. According to the physical model of glass molding process, the simulation model on the glass rolling process can be built. But it is worth noting that the boundary conditions and contact behaviors of glass rolling process have a great difference from the glass molding process. Lan et al. [7] developed a roller-to-plate imprinting machining and investigated the filling mechanism of the plastic microstructures. The results demonstrated that the processing optimization of the hot embossing is the key to control the optical quality and shape accuracy of rolled microstructures. Youn et al. [8] evaluated the replication quality of large-area rolled structures, and indicated that the roller temperature has a great influence on the forming accuracy of microstructures. However, glass has a much higher transition temperature than polymer. The viscoelastic characteristics and embossing conditions of glass are also different from the polymer. Therefore, the theory and process system of polymer roller-to-plate embossing is inadequate for the glass rolling process. To our knowledge, no systematic numerical simulation of the rolled glass in the rolling process has been reported before.

The aim of this study is to investigate the glass filling behaviors during glass rolling stage by FEM. First, a thermal-displacement coupled finite element analysis was conducted on the glass rolling process, in order to get the displacement, temperature, and stress distribution of the rolling system. Then, the filling ratio of rolled glass was evaluated by extracting and calculating the deformed profile. Besides, the deformation behavior of glass plate during rolling stage was analyzed and discussed.

2. Simulation procedure

Roller-to-plate hot embossing process can complete large-area manufacturing of glass cylindrical lens array by replicating the structures of mold core. Fig. 1 shows the illustration of glass cylindrical and basic dimensions of mold core characteristic size. The width and sag of mold core are 0.6 mm and 0.15 mm, respectively. The outer and inner diameter of the roller are 80 mm and 50 mm, respectively. The width and length of plate is 80 mm. In this study, to predict the deformation behavior of glass cylindrical lens array, finite element analysis model was established based on the above geometry of rolling system.

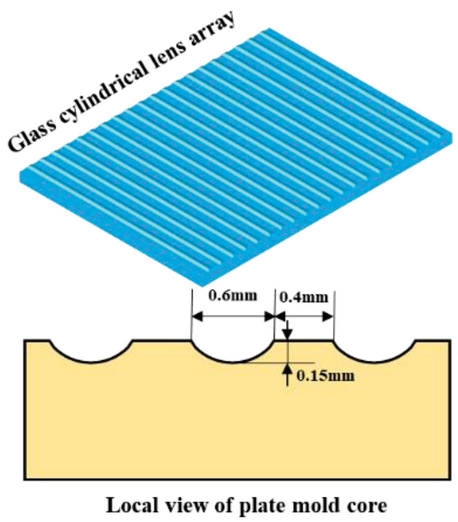

Fig. 1 The illustration of the glass cylindrical lens array and basic dimensions for plate mold core.

Fig. 2 shows the finite element model of the glass rolling process. The model includes the roller, glass blank, and plate mold core. A thermos-displacement coupled analysis is conducted on the rolling system. The roller and plate are modelled as elastic material, while glass is modelled as viscoelastic above transition temperature. All the bodies are treated as deformable and meshed in first-order quadrilateral elements. In the simulations, the boundary condition of roller is fixed in radial and axial direction at the heating stage, and rotating in axial direction at rolling stage. The boundary and loading conditions of plate is fixed in vertical direction at heating stage, and moved in vertical and radial direction at rolling stage. The temperature boundary condition is conducted the inner surface of roller and lower surface of plate. The contact surface is modeled as hard contact with frictional penalty formulation. The friction coefficient was set as 0.3 on the Coulomb friction model.

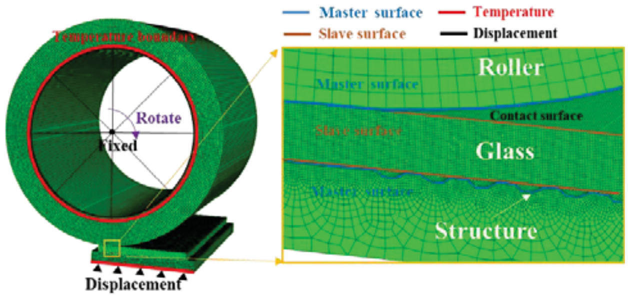

Fig. 2 Finite element model of the glass rolling process

The roller and plate are made of tungsten carbide (WC). The mechanical and thermal properties of glass and tungsten carbide are listed in Table 1.

Table 1 Mechanical and thermal properties of WC and P-SK57

Material properties	P-SK57	WC
Young's modulus (GPa)	93	590
Poisson ratio	0.25	0.22
Density (kg/m^3)	3010	14700
Heat conductivity (W/m.℃)	1.01	65
Specific heat (J/kg.℃)	314	760
Expansion coefficient	<100: 8.8×10^{-6} <500: 10×10^{-6} <620: 60×10^{-6}	4.9×10^{-6}

During the heating stage, glass is heated between transition point and softening point by heat conduction. The heat conduction between mold and glass is set as 2800 W/(m^2.℃).The viscoelastic material is modeled as general Maxwell model, and its temperature is treated as thermally rhetorical simplicity (TRS) model by using empirical William-Larry-Ferry equation [9] . The structural relaxation characteristic of viscoelastic glass is modeled as Narayanaswamy-Moynihan (TNM) model [10]. The stress relaxation and structural relaxation function parameters are shown in Table 2 [6]. In the simulations, the roller temperature is set as 550℃, and the plate temperatures are changed from 550 to 580℃. The feed velocities are set as 1, 5, 10, and 20 mm/s. The radial displacement loadings are set as 0.1, 0.2, 0.3, and 0.4 mm. The different combined processing parameters are input into simulation software. Finally, the simulation result of glass rolling process can be obtained after calculating.

Table 1 Stress and structural of P-SK57 glass

Stress relaxation		Structural relaxation	
φ_i	τ_i	ω_i	τ_{wi}
0.585	13.93	0.0186	0.0008
0.41	50.3	0.0401	0.0045

0.005	10331.86	0.0949	0.0146
WLF parameters		0.2296	0.0373
C_1	28.6	0.4177	0.0792
C_2	507	0.1991	0.1382
T_{ref}=507℃		T_{ref}=560℃	

3. Results and discussions

Fig. 3 shows the simulation results of glass rolling process. It can be seen that the glass rolling process is a dynamic continuous filling and demolding process. When the temperatures of the roller and plate are 570℃ and 550℃, the temperature distribution and expansion displacement of the rolled glass at the heating stage is shown in Fig. 3(a). Owing to the temperature difference between the roller and plate, the upper surface temperature of glass is different from the lower surface at the heating stage. The expansion accumulation displacement of rolling system is about 0.04mm. And, the volume change vs temperature curve is shown in Fig. 3(a). It is noteworthy that the glass plate has to be placed at least 0.1mm away from the roller surface at heating stage. Because the overlarge expansion deformation would result in glass breakage. In addition, the compensation of displacement loading should be considered in the actual manufacturing process.

Fig. 3(b) shows the displacement color pictures of glass rolling process at different stages. To complete the filling deformation, a specific radial displacement loading is firstly applied on the plate. Then, the roller and plate form a certain feed loading to achieve the manufacturing process. From the enlarged view of displacement color image at rolling stage, the glass has not completely filled in the mold structures. It can be concluded that the processing parameters have a great influence on the filling deformation during rolling stage.

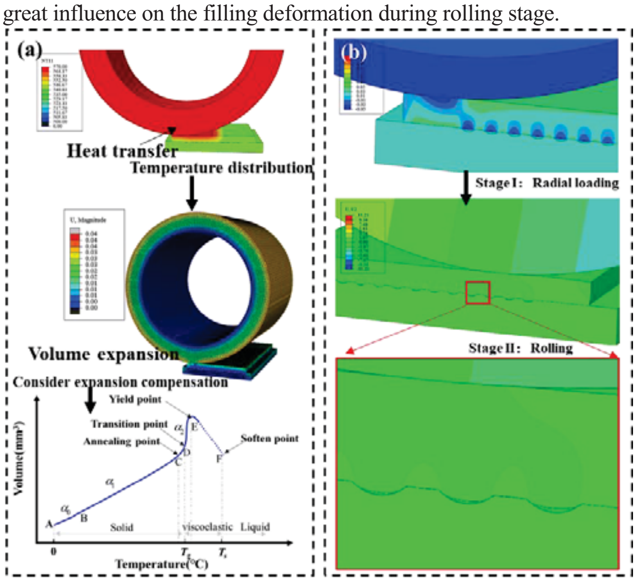

Fig. 3 The simulation results of glass rolling process, (a) The temperature distribution and thermal expansion of glass rolling system, (b) The deformation displacement of the glass rolling process.

To study process parameters influence on filling deformation of rolled glass during rolling stage, the filling ratios are obtained and calculated form the simulation results. The filling ratios at different plate temperature is shown in Fig. 4(a). Glass exhibits a deformation characteristic of temperature-dependent viscosity. With the increase of the plate temperature, the lower surface temperature of rolled glass increases, which accelerates the filling of cylindrical lens array. When the temperature of roller and plate, feed velocity, and radial displacement loading are 550℃, 5mm/s, and 0.2mm, the filling ratios of rolled glass cylindrical lens array is about 65%. As temperature rises, the elastic storage is reduced and viscous flow is increased. When the plate temperature is 570℃, the filling ratios during rolling stage is reached about 98%. The greater the plate temperature is, the larger the filling ratios achieve. But when temperature is reached a specific threshold, the filling ratio is basically unchanged. When the temperature and feed velocity are held constant, the filling ratios increases with the radial displacement loading, as shown in Fig. 4(b). It is easily understood that the more displacement loading is, the larger filling ratio is. As the displacement loading is increasing, more free deformation volume becomes available.

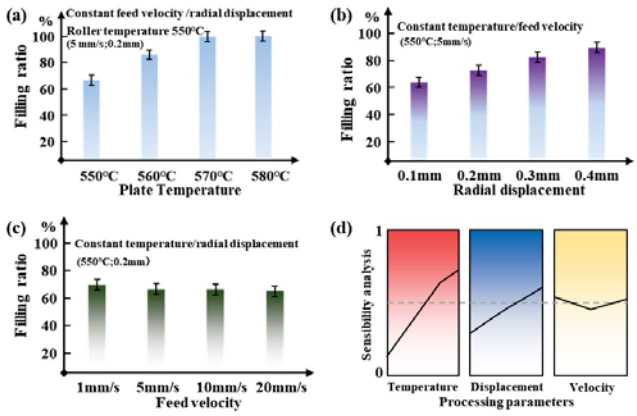

Fig. 4 The filling ratios analysis of glass rolling process, (a) Plate temperature, (b) Radial displacement, (c) Feed velocity, (d) Main effects plot for filling ratios.

Fig. 4(c) shows the filling ratios of rolled glass at different feed velocities. The filling ratio slightly decreases with the increase of feed velocity. The lower the feed velocity is, the more deformation time is. At the same temperature and radial displacement, the deformation of rolled glass would slightly increase due to the effect of structural relaxation. At the supercooled liquid region, the viscoelastic deformation of the rolled glass increases with the increase of relaxation time. At lower rolling temperatures, the increase of the deformation needs a longer structural relaxation time. This is why feed velocity has not a great influence on the filling deformation. The analysis outcome of response in the filling ratios is shown in Fig. 4(d). It is observed that temperature is the most dominating factor in affecting the filling ratios of cylindrical lens arrays during the rolling stage. The higher temperature induces the lower viscosity and elastic modulus of the rolled glass, which accelerates the glass flow deformation during the pressing stage. Furthermore, radial displacement loading has also a great influence on the filling ratio of glass cylindrical lens array. Among all the process parameters, the feed velocity is an important factor in the glass rolling process but has the least contribution to the filling ratio.

In the glass rolling process, the glass plate would occur warpage and crack due to the shear motion and the out-of-balance of mechanical force distribution. Fig. 5(a) shows the warpage image and stress distribution of rolled glass during the rolling stage. To study the process conditions' effect on the warping deformation, the maximum warpage displacement is extracted and estimated from the simulation. Fig. 5(b) shows the processing parameters' effect on the warpage. It is easily observed that radial displacement loading is the most dominating factor among the three factors in determining the warping deformation of the rolled glass. When the displacement is beyond 0.2mm, the warpage is greatly increased. Besides, the warpage is slightly increased with the increase of feed velocity. And, the plate temperature has little influence on the warpage. To make a summary in this part, the warpage is mainly affected by displacement loading.

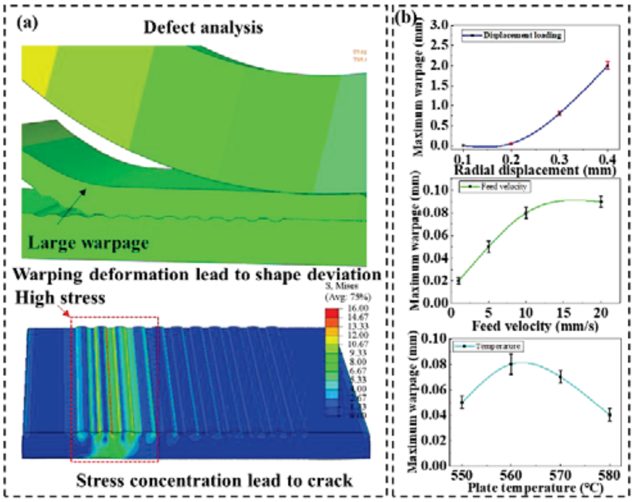

Fig. 5 Defect prediction analysis of rolled glass, (a) The color pictures of rolled glass, (b) The parameters effect on the warpage.

In the glass rolling process, localized stress concentration would induce glass crack, as shown in Fig. 5(a). The forming stress increases as temperature decreases and displacement increases. When the stress is beyond a threshold, the rolled glass easily occur breakage. Hence, optimization of processing parameters is very important for the glass rolling process. In addition, the residual stress and shape deviation of glass cylindrical lens array are also two important indexes in estimating forming quality. In the succeeding work, the cooling and demolding stage in the whole glass rolling process will be deeply investigated.

4. Conclusions

In this study, a numerical simulation of the glass rolling process for cylindrical lens array is conducted. The results show that the filling ratio of the rolled glass is sensitively proportional to the plate temperature and radial displacement, but decreases slightly with the feed velocity. In addition, the radial displacement has a great effect on the warping deformation during the rolling stage. The warpage is proportional to the feed velocity but increases slightly with greater plate temperature. These findings are fundamentally meaningful in getting a better understanding of the glass rolling process. Moreover, it also can provide a theoretical guideline for the practical glass rolling process

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