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Effects of process parameters on the replica shape in glass hot embossing

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Abstract

Hot embossing is a promising replication technology for precision manufacture of glass micro optical components. However, the optical performance of thermally imprinted micro optical components is significantly deteriorated due to the warpage formed on their global surfaces. The control of surface roughness and replica thickness are also vital in practical applications. This study attempts to experimentally evaluate the effects of different process parameters (i.e., embossing temperature, embossing force, isothermal pressing time, annealing rate, maintenance force and fast cooling point) on the shape parameters (i.e., curvature radius, surface roughness and thickness) of glass replica. The results provide an important means for minimizing the warpage, reducing surface roughness and controlling replica thickness in hot embossing. In this study, a series of glass hot embossing experiments were conducted by a commercially available precision glass molding machine. The surface topography was measured on both the top and the bottom surfaces of embossed glass replicas. The thickness and diameter of the replicas were also measured. The experimental results were then analyzed for quantifying the effects of different process parameters on the shape parameters. The results of this study provide optimal process parameters for practical hot embossing applications.

Keywords: Glass Hot embossing, Warpage, Process Parameters, Precision Manufacture, Optimization

1. Introduction

Micro optics are gaining significant attention from engineers and researchers due to their capabilities of miniaturizing the devices, enhancing integration and precision, and saving energy for modern optical systems. Glass becomes a popular material candidate for micro optics, due to its abundant raw materials, high recyclability, desired thermal and chemical stability, satisfactory mechanical properties and excellent optical transmittance in the visible region. Among the processing techniques for production of glass micro optics, hot embossing is a promising one, because of its high manufacturing efficiency, high replication fidelity and simplicity in tool development [1].

Glass hot embossing technique also allows a wide range of adjustable processing parameters, which determine the final shape and optical performance of the glass replica. Zhao et al. [2] found that higher cooling rates led to larger refractive index drops but less dispersion variations in glass replicas. Fischbach et al. [3] suggested that the glass-to-mold sticking force could be significantly reduced by decreasing pressing time, increasing cooling time and decreasing pressing force. Zhou et al. [4] numerically and experimentally investigated the influence of pressing temperature on the friction coefficient between mold and glass. The friction coefficient was determined by using the barrel compression test which involved the experimental recording of axial displacement history and maximum diameter expansion history, and the simulation of the friction calibration curve. Gleason et al. [5] conducted design of experiment (DOE) analysis and pointed out that the repeatability of replica thickness could be maximized under slow heating and cooling rates, long soaking time and low pressing force.

Micro optics have stringement requirement of surface quality in terms of shape parameters, such as low warpage, low surface roughness and low thickness error. However, the effects of process parameters (e.g., embossing temperature, embossing force, isothermal pressing time, annealing rate, maintenance force and fast cooling point) on the surface quality of replica in glass hot embossing have merely been reported. This study aims to bridge this research gap, and the research findings are expected to facilitate the engineering optimization of the glass hot embossing process.

2. Typical glass hot embossing process

A typical glass hot embossing process involves five stages: presetting, heating, embossing, cooling and demolding, as illustrated in Figure 1. Initially, the glass disk is positioned on the lower mold and left a gap of $-Z_A$ for avoiding contact with the upper mold insert. In order to protect mold from oxidization at the elevated temperature, vacuum is applied to the chamber for the removal of air, followed by the introduction of nitrogen gas. When the gaseous environment is stablized, the mold inserts and glass wafer are heated simultaneously from initial temperature T_0 to the target embossing temperature T_B, and soaked at this temperature for reaching a more uniform temperature distribution.

At the beginning of the embossing stage, the lower mold is moved upward to make the glass disk touch the upper mold, and the compression is kept until the isothermal embossing force F_D is reached. The isothermal pressing enables the softened glass disk to deform and fill the cavities of the upper mold insert. In this fashion, the patterns on the upper mold insert are transferred to the top surface of glass disk.

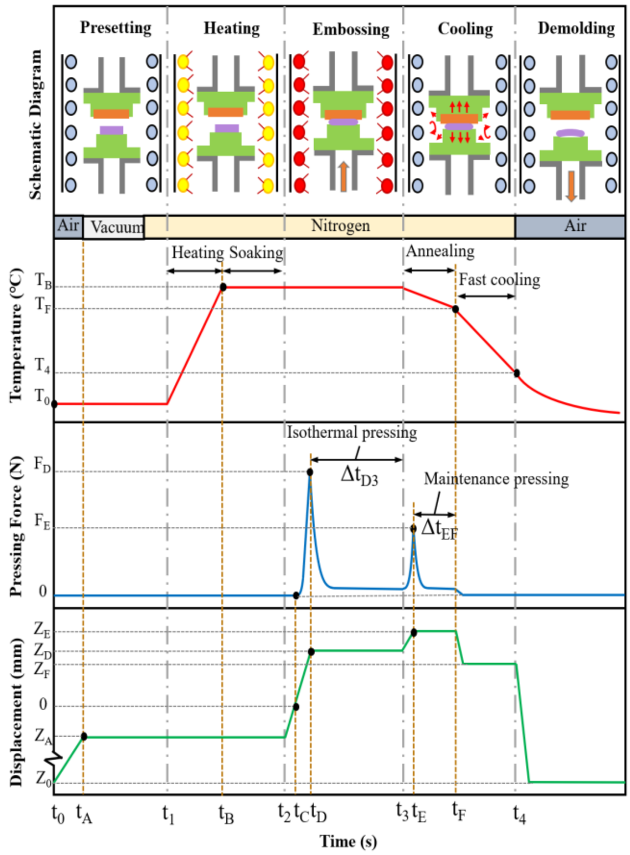

Figure 1. Schematic diagram for a typical glass hot embossing process.

A small force of F_E is loaded on the glass replica for maintaining the shape of patterns on the replica as soon as the cooling stage is started. Initially, a low annealing rate of r_{anneal} is set to minimize the thermal stress inside the embossed glass replica. Once the temperature decreases to the fast cooling point T_F (approximately the T_g of glass), the force on the replica is removed and a rapid cooling rate is applied for fastening the thermal cycle. At a relatively low temperature T_4 (i.e., ~$220\ ^{\circ}C$), the maintenance pressing force is completely taken off, and the lower mold is moved downward for demolding. Meantime, a forced convection flow of nitrogen gas is introduced for faster cooling. When the temperature of the embossed glass replica is lower than 160 $^{\circ}C$, it can be taken out for quality assessment.

3. Experimental

3.1. Design of experiments

In this study, the N-BK7 glass plane-parallel-plate (PPP) disks are acquired from SCHOTT. The average diameter and thickness of these glass disks are 5.05±0.01 mm and 1.05±0.01 mm respectively, and their top and bottom surfaces are mechanically polished to have a local roughness of about 1 nm, a flatness of less than 40 nm and a parallelism of below 5 arc-second. The glass hot embossing experiments are conducted on the Toshiba GMP-311V machine (see Figure 2a and Figure 2b). By following the glass hot embossing process described in Section 2, the parameter design can be seen in Table 1. The process history of experiment condition 1 is provided in Figure 2c. Except that in experiment condition 7 the value of Z_E remains the same as that of Z_D, the values of Z_A, Z_D, Z_E and Z_F in other experiment conditions are set to be -0.996 mm, 0.09999 mm, 0.19999 mm and 0.09598 mm respectively.

Table 1 Conditions for the glass hot embossing experiments

Experiment conditions	T_B (°C)	F_D (N)	Δt_{D3} (s)	r_{anneal} (°C/s)	F_E (N)	T_F (°C)
1	670	500	100	0.45	300	550
2	690	500	100	0.45	300	550
3	710	500	100	0.45	300	550
4	670	750	100	0.45	300	550
5	670	1000	100	0.45	300	550
6	670	500	50	0.45	300	550
7	670	500	0	0.45	300	550
8	670	500	100	0.83	300	550
9	670	500	100	1.75	300	550
10	670	500	100	0.45	200	550
11	670	500	100	0.45	0	550
12	670	500	100	0.45	300	530
13	670	500	100	0.45	300	570

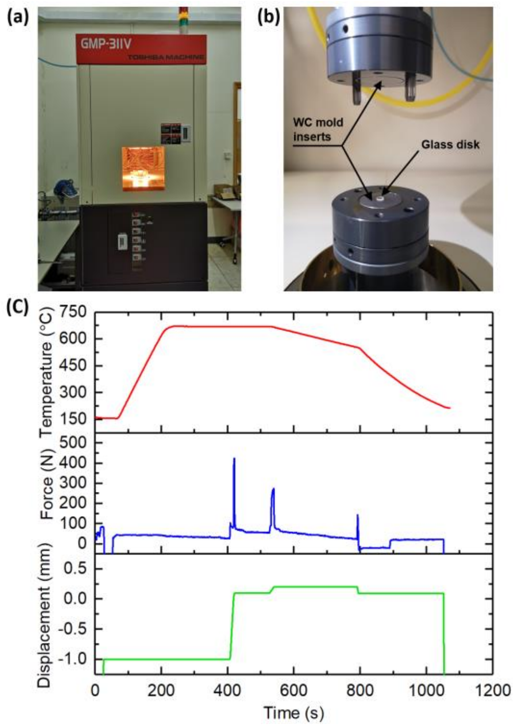

Figure 2. (a) The Toshiba GMP-311V machine. (b) The experimental setup. (c) The process cycle of experiment condition 1. The displacement at which the upper mold just touches the glass disk is set to be 0 mm.

3.2. Surface characterization of embossed glass replica

Figure 3 shows the surface topography of the top and bottom global surfaces of the embossed glass disks, which was measured by using the white light interferometer (Bruker Contour GT-X). The RMS repeatability of the interferometer is lower than 0.03 nm, which satisfies the requirement of this study. By surface fitting with a sphere, the curvature radius of sphere (R_C) and the mean of the absolute value of roughness for fitted surface (S_a) can be determined. The warpage can be roughly indicated by the absolute value of curvature radius, $|R_C|$. It is interesting to note that negative (positive) value of R_C infers the warpage is convex (concave) in this study. Since the warpages of WC mold inserts and raw glass disks are neligibale, the curvature on the surfaces of replicas are assumed to be generated during the glass hot embossing process. Furthermore, the thickness (t) and diameter (d) of these embossed glass replicas were measured by a vernier caliper, which had an uncertainty of 0.01 mm.

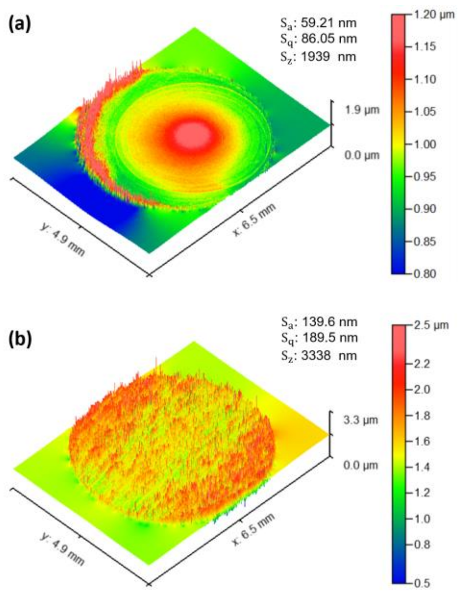

Figure 3. Surface topography of glass replica embossed in experiment condition 1: (a) top surface and (b) bottom surface. The surface texture of replica is mostly transferred from that of mold insert.

4. Results and discussions

4.1. Effects of isothermal embossing temperature, force and time

Figure 4 reveals that the top and bottom surfaces of the glass PPP disks become convex and concave, respectively after hot embossing process, and the bottom surfaces are found to have smaller warpages than those of the top surfaces. Figure 4a suggests that increasing the isothermal embossing temperature notably aggrandizes the warpage and surface roughness of both the top and the bottom surfaces of the replicas and thus deteriorates their flatness. In the embossing temperature range, the glass viscosity decreases expotentially with increasing temperature. As a result, glass disks at higher temperature are more prone to deformation, and consequently have lower thickness and larger diameter.

As a shown in Figure 4b, the increase of curvature and surface roughness, and the decrease of thickness can be clearly seen when the isothermal embossing force increases from 500 N to 750 N. However, the embossing force above 750 N does not have an obvious effect on the shape parameters.

Glass replica that undergoes zero isothermal pressing time shows a relatively large curvature on the top and the bottom surfaces, a desirable surface roughness and a notably high thickness as shown in Figure 4c. As the isothermal pressing time prolongs, the warpage of top surface decreases continuely, while the warpage of bottom surface slightly decreases first and then increases moderately. Compared to the short isothermal pressing time (i.e., 50 s) , the long counterpart (i.e., 100 s) enables less increase of surface roughness but almost the same reduction of thickness.

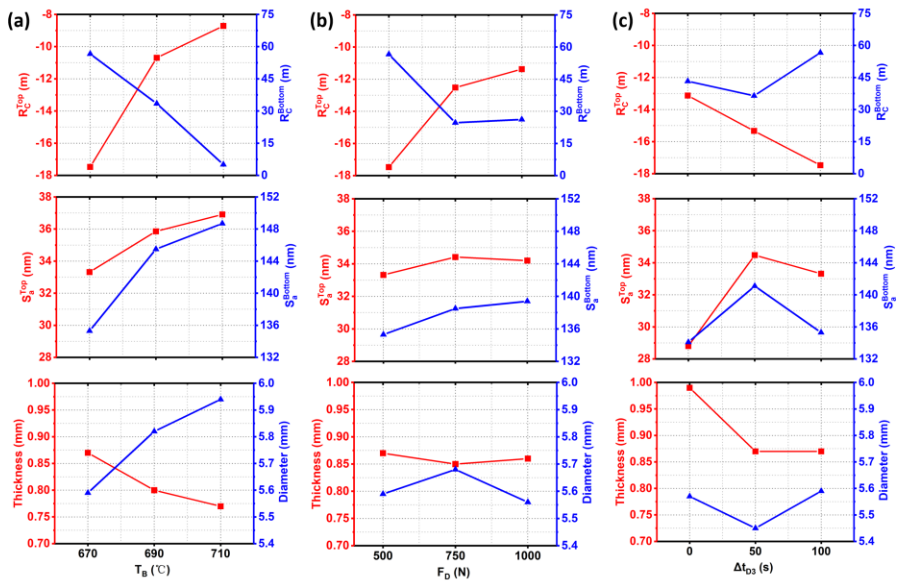

Figure 4. Comparison of shape parameters of glass replicas embossed in (a) experiment conditions 1, 2 and 3, (b) 1, 4 and 5, (c) 1, 6 and 7.

4.2. Effects of annealing rate, maintenance force and fast cooling point

As shown in Figure 5, it is interesting to note that the waparge on the top surface becomes highly small when the warpage of the bottom surface is convex. The warpage is expected to be readily formed at high annealing rate due to the large non-uniform expansion or shrinkage. However, the experimental results show that the smallest warpage on top surface is generated at a moderate to the lowest annealing rate. Moreover, lower surface roughness appears at higher annealing rate as shown in Figure 5a. Since the slower annealing rate allows the glass PPP disks to be compressed under elevated temperature for longer time, replica annealed at lower rate has lower thickness but larger diameter.

The application of moderate maintenance force is capable of producing the smallest warpage on the top surface of replica without significantly affecting its surface roughness as shown in Figure 5b. The mean surface roughness of bottom surface decreases as the maintenance force increases, which is attributed to the flattening of the peaks on the surface roughness profile. Unsurprisingly, the higher maintenance force results in a lower thickness, because of the larger axial deformation of glass disks. It is evident from Figure 5c that an increase of the fast cooling point significantly decreases the warpage of top surface but has an opposite effect on that of the bottom surface. Besides, a higher fast cooling point results in a higher roughness of the top surface. Furthermore, the fast cooling point has little influences on the roughness of the bottom surface, the thickness and the diameter of glass disks.

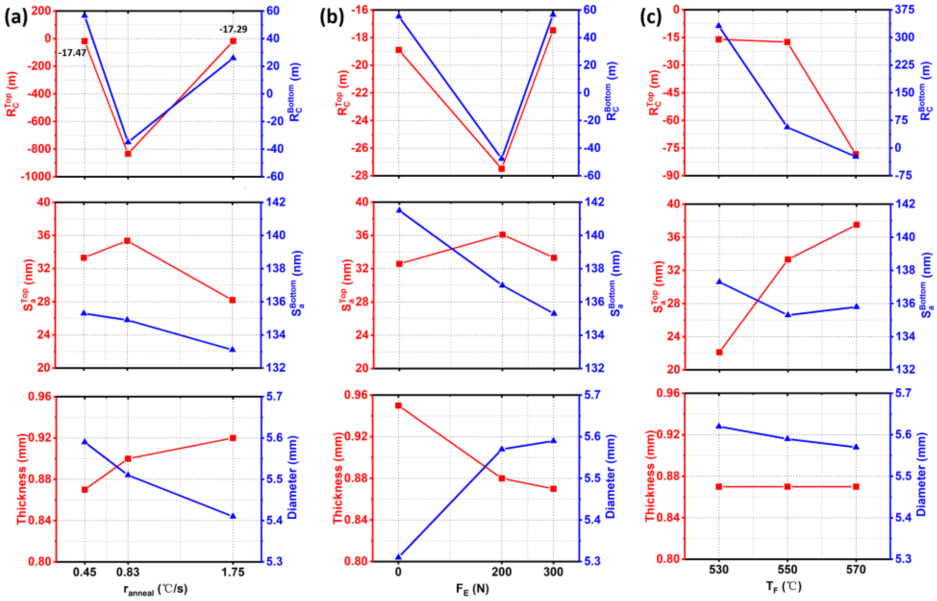

Figure 5. Comparison of shape parameters of glass replicas embossed in (a) experiment conditions 1, 8 and 9, (b) 1, 10 and 11, (c) 1, 12 and 13.

4.3. Optimal process parameters for practical hot embossing applications

In practice, the target micro/nanostructures are generally located on the upper mold insert, and a flat and smooth surface is created on the lower mold insert. Although the bottom surface of the embossed glass replica may suffer from large warpage and high roughness, it is subjected to the post-finishing treatment at ease. Thereore, it is reasonable to attach more importance to the curvature radius and surface roughness of the top surface in parameteric design.

Figure 4 and Figure 5 suggest that low embossing temperature, low embossing force, long isothermal pressing time, moderate annealing rate, moderate maintenance force and high fast cooling point enable small warpage to be formed on the top surface of the replica. On the other hand, low surface roughness can be observed on the top surface of the glass replica that is treated with low embossing temperature, zero isothermal pressing time, relatively high annealing rate and low fast cooling point. Moreover, the roughness of top surface is somewhat insensitive to the embossing force and maintenance force. In applications for minimizing the warpage and surface roughness of the top surface of the replica, one recommendable set of process parameters including low embossing temperature, low embossing force, relatively long isothermal pressing time, moderate cooling rate, moderate maintenance force and low fast cooling point.

The control of replica thickness can be of high significance. In glass hot embossing process used in this study (except for experiment condition 7), the target thickness of glass replica is 0.85 mm. It is interesting to note that the replica thickness shows considerably low sensitivity to the embossing force and the fast cooling point. As a result, the selection of other four parameters is critical to gain the desirable replica thickness. From the experimental results, the target thickness of the replica is more likely to be controlled and produced under low embossing temperature, long isothermal pressing time, slow annealing rate and high maintenance force.

5. Conclusions

This study experimentally evaluated the effects of process parameters on the shape parameters of the replica in a specially designed glass hot embossing process. The findings and results are given below:

1) The top surfaces of all embossed replicas are convex, while the bottom surfaces are concave in most cases. Furthermore, the warpage on the top surface is usually higher than that on the bottom surface.
2) Under some special process parameter settings, the bottom surface becomes convex, and the warpage on top surface is almost imperceptible.
3) Warpage of the top surface can be minimized under low embossing temperature, low embossing force, long isothermal pressing time, moderate annealing rate, moderate maintenance force and high fast cooling point.
4) The top surface of glass replica shows lower surface roughness when it is treated with low embossing temperature, zero isothermal pressing time, relatively high annealing rate and low fast cooling point.
5) The replica thickness shows considerably low sensitivity to the embossing force and fast cooling point.

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