

Technical note

Development of a new apparatus for ultrasonic vibration-assisted glass hot embossing process

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ABSTRACT

A new apparatus for an ultrasonic vibration-assisted glass hot embossing process has been developed. The upper die constitutes the ultrasonic vibrating device, and a cooler is provided to protect the transducer from the high operating temperatures. An ultrasonic horn originally designed for use at room temperature was modified to ensure correct operation of ultrasonic vibrating device for high temperature use. Because the load cell is located inside a vacuum chamber, the detection of the force applied to the glass during the forming process is not significantly impacted by external forces, and thus, a precise force history of the forming glass can be obtained. Flat hot embossing experiments were performed to investigate the effect of ultrasonic vibration on the amount of force required during forming, and Fresnel structure hot embossing experiments were then conducted to investigate the improvement in molding accuracy gained through ultrasonic vibration. The experimental results are taken to validate the manufacturing potential of the developed apparatus and the improvement in formability achieved by applying ultrasonic vibration.

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1. Introduction

Optical glass hot embossing is crucial for the mass production of optical elements. In this process, the glass is firstly heated above a specific temperature, then embossed using molds with well-machined spherical or aspherical surfaces and replicates the shapes of the surfaces, and finally cooled to room temperature to form the final product. The ability to produce large numbers of precise replicas makes glass hot embossing technology an ideal choice for the fabrication of optical elements [1–4].

This technique was recently extended to the manufacture of optical elements with complex structures. Saotome [5] used a silicon mold to make V-grooves on K-PSK100 and K-PG375 optical glass and found that the glass exhibited sufficient microformability for use in micro- or nano-forming processes. Yi [6] fabricated a diffractive optical element made of glass using a fused silica mold and K-PG325 glass, which is noted for its low transition temperature (T_g). The results proposed glass molding as an effective alternative manufacturing method for high-quality, low-cost optical components.

Although the industry will eventually adopt hot embossing for the production of glass optical elements, several problems must be solved. First, the glass does not readily fill the microcavities of complex molds, thus lowering the quality of the resulting

optical elements. The cost of producing the molds is also high, and the molds can be damaged under excessive loads with insufficient molding temperatures. Load can be reduced by raising molding temperatures, but this means longer heating times and decreased production efficiency. The life-span of the molds is also shortened by higher temperature heating and cooling cycles.

To increase formability in the hot embossing of polymers, ultrasonic vibration has proven effective [7,8]; however, there is a concern that glass may break if directly subjected to such vibrations. This problem can be avoided by raising the molding temperature well above the T_g of the glass. That, however, changes the material properties of the ultrasonic horn and shifts its resonant frequency, causing a mismatch with the frequency generator. Another problem is that, to prevent oxidation, the glass hot embossing process must be performed in a vacuum or nitrogen-rich environment, either of which is difficult to incorporate into an experimental apparatus. The choice of mold material is also restricted because whatever material is used must not only resist high working temperatures but also endure the alternating mechanical stresses of ultrasonic vibration. Hence, seldom works have focused on the ultrasonic vibration-assisted glass hot embossing process.

The preliminary results of one experiment with the ultrasonic vibration technique revealed that vibration improved the formability of V-groove and Fresnel structures on glass material [9]. However, the ability of the experimental apparatus to measure the forces applied was affected by several problems. First, the load cell was installed outside the vacuum chamber at the bottom of the moving die causing the die to be pulled by the vacuum during the

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Fig. 1. Apparatus for the ultrasonic vibration-assisted glass hot embossing process.

forming process. Second, the O-ring seals between the moving die and the vacuum chamber applied an additional shrinkage force on the moving die. Because of these external forces, the apparatus was unable to monitor the applied forces precisely enough to obtain a force history for glass deformation, resulting with a compression tester that could not adequately regulate the embossing force. In addition, the infrared heaters were installed inside the vacuum chamber, where the high working temperature rendered them easily broken. In the design proposed by Fukuyama [10], the load cell is housed in the forming chamber, and the pressure fluctuations in the forming chamber have little effect on the output of the load cell.

For this study, a new apparatus for ultrasonic vibration-assisted glass hot embossing was built to address these difficulties. In this design, the ultrasonic vibrating device is built into the upper die. In addition, the load cell is located inside the vacuum chamber to enhance the accuracy of force detection during the forming process. Two types of experiments were conducted with this apparatus. First, flat hot embossing experiments were performed to investigate the impact of ultrasonic vibration on molding forces. Second, Fresnel structure hot embossing experiments were performed under a different ultrasonic frequency compared to the previous study to assess the manufacturing potential of the apparatus and to validate the enhanced formability possible through the use of ultrasonic vibration.

2. Experimental apparatus

Fig. 1 shows the new hot embossing apparatus developed for this study. A heating furnace and an ultrasonic vibrating device are

Table 1
Specifications of molding apparatus developed for this study.

Maximum mold temperature	600 °C
Maximum vacuum	2×10^{-1} Torr
Displacement accuracy	4 μ m
Driving resource	Servomotor
Maximum load	50 kN
Ultrasonic frequency	35 kHz \pm 500 Hz
Ultrasonic power	900 W
Ultrasonic vibration amplitude on booster in 25°	3 μ m

attached to a compression tester. The heating furnace heats both the molds and the glass specimens and provides a vacuum environment for the embossing process. The compression tester controls the embossing displacement with feedback signals from an optical encoder and a load cell. Vibrations are applied to the glass specimen by an ultrasonic vibrating device built into the upper die of the furnace. Table 1 lists the specifications for this apparatus.

2.1. The heating furnace

Fig. 2 shows a cross-sectional diagram of the heating furnace. A quartz tube is integrated into the vacuum chamber wall. In conjunction with the moving flatbed of the compression tester, the lower die moves in and out of this quartz tube to load the glass specimen, emboss it, and unload the product. Infrared heaters surround the quartz tube outside the chamber wall, and the infrared light penetrates through the quartz to heat the molds and the specimen inside.

The lower die contains a load cell, which is cooled by a lower cooler to prevent from being damaged by the high working temperatures in the chamber. The load cell (LW-20100, Interface, Inc.) has a compensated temperature range of 16–71 °C, but because its temperature during the glass hot embossing process does not exceed 35 °C, sensor calibrations for elevated temperatures are deemed unnecessary. The load cell is donut shaped, with the central tunnel accommodating the pipes for the water circulating in the lower cooler and the vacuum pumping for the chamber. During the forming process, the load cell is inside the vacuum chamber. The force

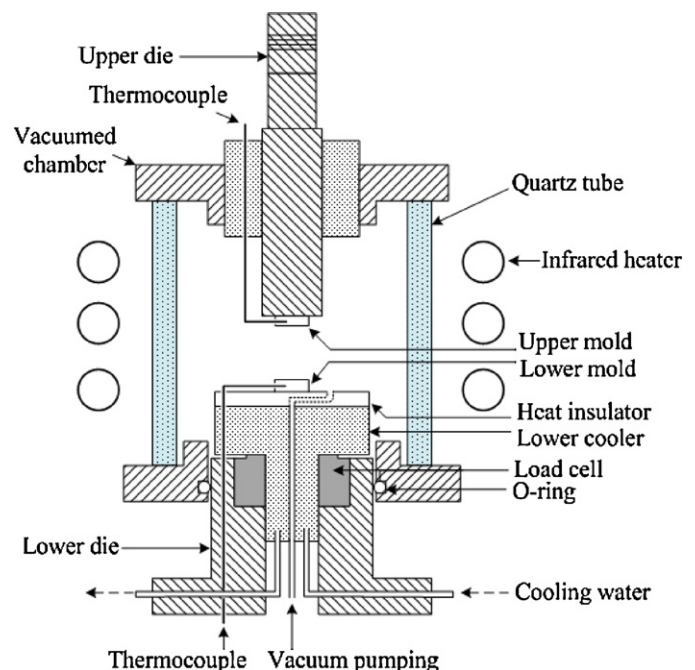


Fig. 2. Cross-sectional diagram of heating furnace.

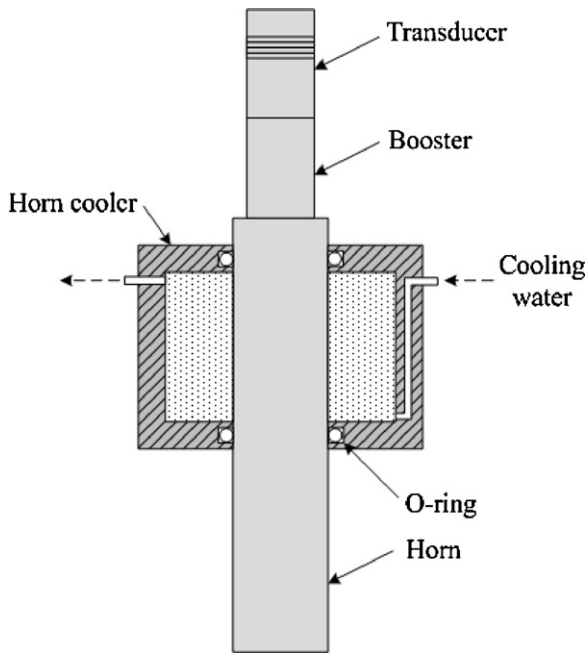


Fig. 3. Design of horn cooler for ultrasonic vibrating device.

applied can therefore be detected free of external forces, enabling a precise force history for the forming glass.

The infrared heaters are placed outside the vacuum chamber to increase their lifetimes. A frame with the circulated cooling water supports six heaters in a semi-circle that surrounds the chamber in three layers. The maximum power of these heaters is 7.8 kW. During the embossing process, the zone inside the quartz tube is pumped to form a vacuum, and radiation from the heaters passes through the quartz tube to the molds and glass specimen inside the chamber. The output power of the heaters is supplied by an SCR and is controlled by a UP150 program temperature controller (Yokogawa Electric Co.) that receives feedback signals from a K-type thermocouple installed into the mold.

2.2. Ultrasonic vibrating device

The ultrasonic vibrating device is designed to work properly at 35 kHz. The frequency generator (King Ultrasonic Co.) is set to operate with automatic frequency tracking at $35 \text{ kHz} \pm 500 \text{ Hz}$. For thermal protection, a horn cooler is mounted outside the ultrasonic horn, as shown in Fig. 3. O-rings placed between the ultrasonic horn and the horn cooler to form a water seal do not significantly affect the ability of the ultrasonic device to vibrate.

The ultrasonic horn was originally designed for use at room temperature and had a diameter of 40 mm and a length of 209 mm. In the glass hot embossing process, however, the material properties of the horn are affected by the higher temperatures, causing the resonant frequency of the vibrating device to shift beyond the tracking range of the frequency generator. Therefore, based on the compensation method proposed in [9], the length of the ultrasonic horn was reduced to 202.5 mm, and the maximum working temperature of the ultrasonic vibrating device was raised from 150°C to 450°C to accommodate the molding temperatures used in the process.

3. Experiment

3.1. Procedure

Fig. 4 shows the experimental procedure, which progressed as follows: (1) the glass and molds were simultaneously heated to the molding temperature (approximately $20\text{--}40^\circ\text{C}$ above T_g); (2) the mold began embossing the glass at a preliminary speed of 0.1 mm/min to ensure that the temperatures on the contact surfaces of the molds and the glass were identical; (3) when the embossing displacement reached 0.1 mm , the embossing speed was increased to 1.5 mm/min ; (4) when the embossing displacement reached 1.5 mm , ultrasonic vibration was applied; (5) when the embossing displacement reached 2 mm , ultrasonic vibration ceased and both stages were held at their final positions for 30 s; and (6) the glass was released from the molds and left to cool to room temperature.

K-PSK-100 (Sumita Optical Glass, Inc.) glass with 7 mm in diameter and 6.5 mm in height was used in this study. According to the manufacturer's report, the T_g and the yielding point (A_t) of the batch of glass were 398°C and 426°C , respectively.

3.2. Flat hot embossing

Stainless AISI304 molds were used for the flat hot embossing experiments with the molding surfaces polished, as shown in Fig. 5. Flat molds were used in both the upper and lower dies. Table 2 lists the experimental parameters, and Fig. 6 shows the force–displacement curves. Curves P1, P4, and P8 represent the results for the conventional glass hot embossing process at three molding temperatures. The data show that when the molding temperature was increased, less force was required to emboss the glass. When the ultrasonic vibration was applied, the required force dropped rapidly while the displacement continued to increase. At the final displacement of 2 mm , an increase in force reduction was observed as the molding temperature decreased.

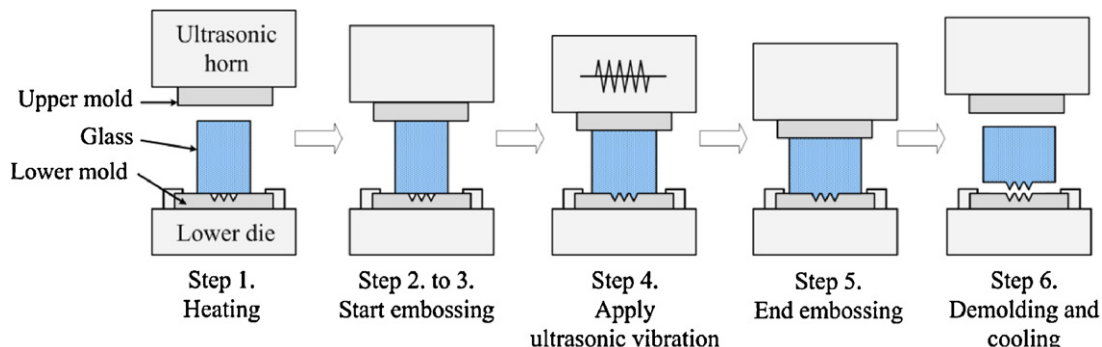


Fig. 4. Experimental procedures for ultrasonic vibration-assisted glass hot embossing process.

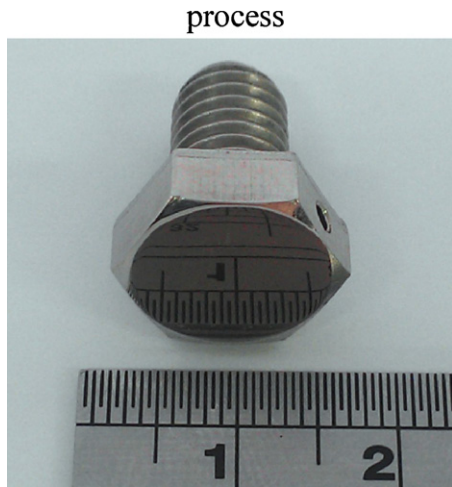


Fig. 5. Flat mold.



Fig. 8. Fresnel mold.

Table 2
Parameters for flat hot embossing experiments.

No.	Apply ultrasonic vibration	Lower mold temperature (°C)	Upper mold temperature (°C)
P1	No	420	427
P2	Yes	420	428
P3	Yes	420	427
P4	No	425	432
P5	Yes	425	432
P6	Yes	425	433
P7	Yes	425	432
P8	No	430	435
P9	Yes	430	434
P10	Yes	430	434

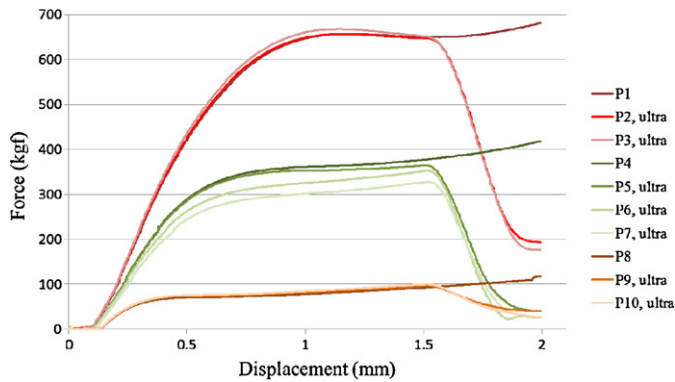


Fig. 6. Force–displacement results for flat hot embossing experiments.

3.3. Fresnel structure hot embossing

The Fresnel molds were formed by electroforming NiCo on a specially designed Fresnel structure, which was machined by ultra-precision machining on Ni. The Fresnel molds were coated with PtIr to prevent the glass from adhering to the molds during the hot embossing process. Fig. 7 shows the design dimensions and Fig. 8 shows the actual Fresnel mold. In Fig. 7, several step heights are defined, and the measurements for these step heights were taken from the mold and the molded glass after the embossing process was complete. In the hot embossing process, the Fresnel mold was fixed to the lower die, and a flat mold similar to that used in the flat hot embossing experiment was mounted to the upper die. The molding temperatures were 431 °C and 435 °C in the upper and lower molds, respectively. Fig. 9 shows an example of the molded glass.

The Fresnel structures were measured using an apparatus consisting of a LK-H020 laser displacement sensor (KEYENCE Co.) and a servo linear actuator (ANIMATICS Co.), as shown in Fig. 10. Fig. 11 shows the measurement results for the Fresnel mold, and Fig. 12 shows an example of the measurements for the molded glass. Each piece of molded glass was scanned cross-directionally, so that every step of the Fresnel structure yielded four measured values. The step heights were recorded as the average of these values. Fig. 13 shows the three inner step heights of the mold and the molded glass. These data shows that the heights for the ultrasonic vibration-assisted hot embossing process are higher than those for the conventional process without ultrasonic vibration.

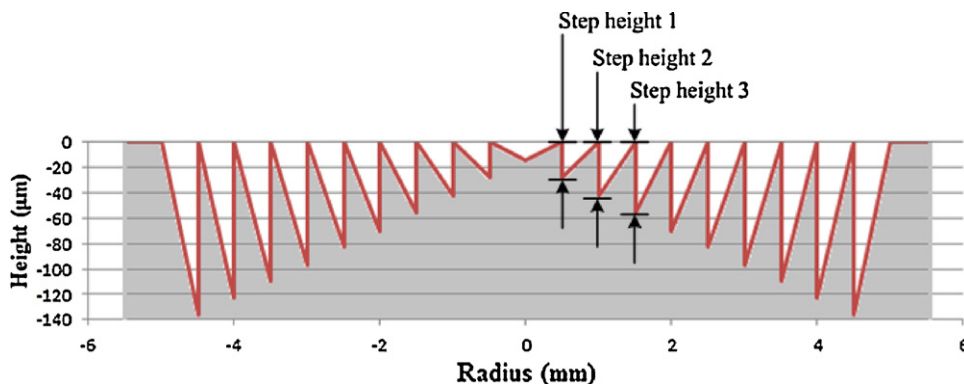


Fig. 7. Design dimensions of Fresnel structure.

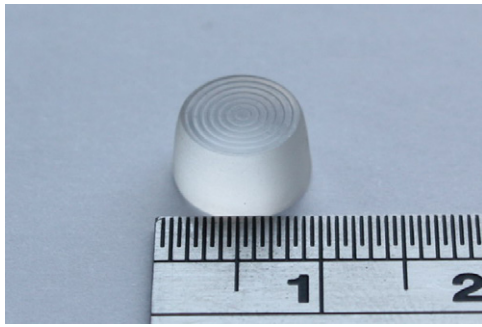


Fig. 9. Molded Fresnel structure.

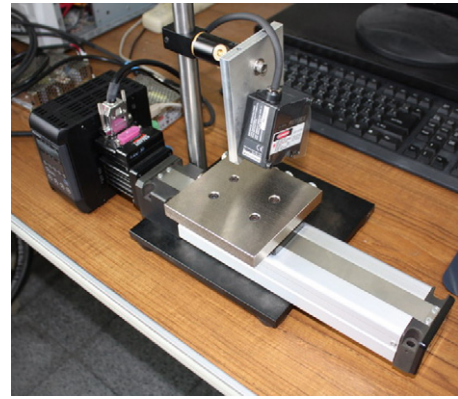


Fig. 10. Apparatus for structural measurements.

4. Discussion

The apparatus developed for this study overcame the difficulty of acquiring accurate force data in a vacuum environment, which is critical for monitoring product quality during the glass hot embossing process. The new apparatus can yield precise measurements of the force history of the glass during forming and generate accurate material properties of glass. Furthermore, the compression tester allows for greater control of the applied force than in earlier designs, and therefore, product quality is improved.

A cooling system is necessary to prevent damage to the transducer caused by the high temperature, but the additional mass of a cooler in direct contact with the ultrasonic horn would dampen the vibrations and change the resonant frequency of the ultrasonic

vibrating device. Hence, the designed cooler does not contact the ultrasonic horn directly, and O-rings are adopted to seal the cooling water surrounding the horn. This system delivers cooling water to the horn surface with insignificant changes in the resonant frequency.

In the flat hot embossing experiments, ultrasonic vibration significantly reduced the force required. This may be because ultrasonic vibrations raised the local temperature between the molds and the glass, thus softening the glass to the point where flow conditions were comparable to those observed at higher molding temperatures in the conventional hot embossing process. With lower required molding temperatures, heating time is shortened,

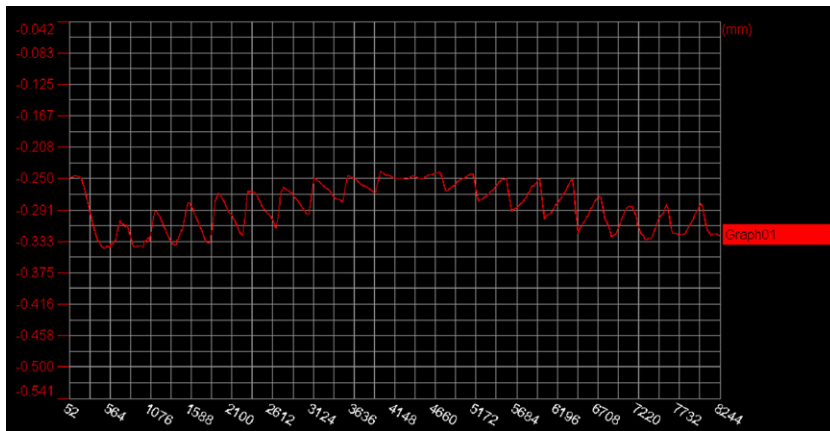


Fig. 11. Measurement results for the Fresnel mold.

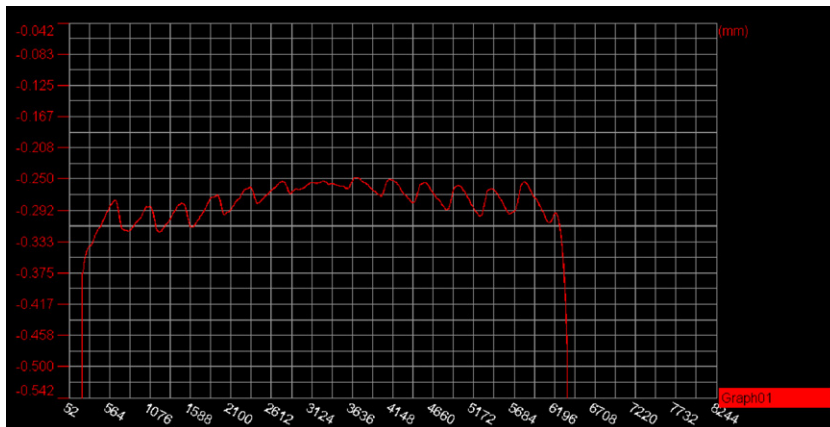


Fig. 12. Measurement results for a molded structure on the glass.

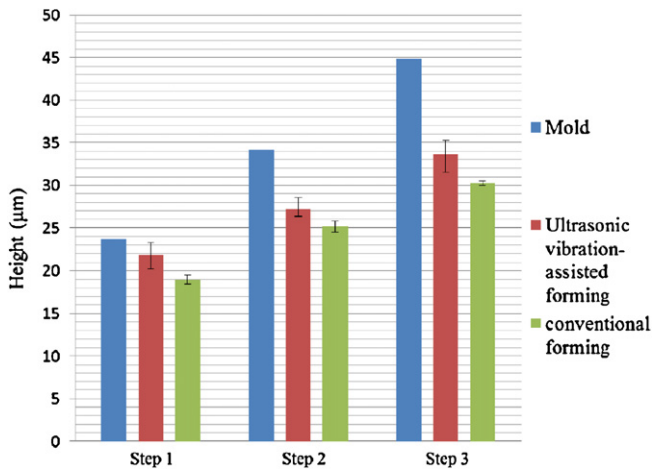


Fig. 13. Measured step heights of mold and molded glass.

and efficiency is improved. In addition, embossing forces are lowered, reducing wear on the molds and extending mold life.

In the Fresnel structure hot embossing experiments, ultrasonic vibration enhanced the step heights of the molded Fresnel structures by further softening the glass and facilitating its flowing into the mold cavities.

5. Conclusion

This study successfully demonstrated the effectiveness of a new apparatus designed for use in the ultrasonic vibration-assisted glass hot embossing process. A quartz tube is incorporated into the vacuum chamber wall. Infrared heaters surround the quartz tube outside the chamber, and radiation from the heaters penetrate through the quartz tube to heat the molds and the glass specimen inside the chamber. The load cell is inside the lower die and is protected by a cooling system. Because the load cell is inside the vacuum chamber during the forming process, the effects of external forces are negligible; thus, the load cell obtains a precise force history for the forming glass. The ultrasonic vibrating device is in

the upper die, and a cooler protects the transducer from high temperatures. An ultrasonic horn originally designed for use at room temperature was modified to ensure proper function at the high temperatures required by the hot embossing process.

With this apparatus, flat hot embossing experiments were performed to investigate the effect of ultrasonic vibration. The results show that forming forces drop rapidly as ultrasonic vibration is applied, thus indicating that the glass is softened. Fresnel structure hot embossing experiments were also conducted with the same apparatus, and the step heights of the molded glass structures were enhanced by ultrasonic vibration. These results are taken to validate the manufacturing potential of the developed apparatus and confirm that ultrasonic vibration improves formability in glass hot embossing.

References

- [1] Meden-Pielinger GAA, Van de Heuvel JHP. Precision pressed optical components made of glass and glass suitable modeling. US Patent 4,391,915 (1983).
- [2] Taniguchi Y. Mold for molding optical element. US Patent 5,855,641 (1999).
- [3] Firestone GC, Jain A, Yi AY. Precision laboratory apparatus for high temperature compression molding of glass lenses. *Review of Scientific Instruments* 2005;76:063101, <http://dx.doi.org/10.1063/1.1921367>.
- [4] Yi AY, Huang C, Klocke F, Brecher C, Pongs G, Winterschladen M, et al. Development of a compression molding process for three dimensional tailored free-form glass optics. *Applied Optics* 2006;45:6511–8, <http://dx.doi.org/10.1364/AO.45.006511>.
- [5] Saotome Y. Microformability of optical glasses for precision molding. *Journal of Materials Processing Technology* 2003;140:379–84.
- [6] Yi AY, Chen Y, Klocke F, Pongs G, Demmer A, Grewell D, et al. A high volume precision compression molding process of glass diffractive optics by use of a micromachined fused silica wafer mold and low Tg optical glass. *Journal of Micromechanics and Microengineering* 2006;16:2000–5.
- [7] Mekarum M, Noguchi T, Goto H, Takahashi M. Effect of applying ultrasonic vibration in thermal nanoimprint lithography. *Microsystem Technologies* 2008;14:1325–33, <http://dx.doi.org/10.1143/JJAP.46.6355>.
- [8] Lee CH, Jung PG, Lee SM, Park SH, Shin BS, Kim JH, et al. Replication of polyethylene nanomicro hierarchical structures using ultrasonic forming. *Journal of Micromechanics and Microengineering* 2010;20:035018, <http://dx.doi.org/10.1088/0960-1317/20/3/035018>.
- [9] Tsai YP, Hung JC, Yin LC, Hung C. Ultrasonic vibration-assisted optical glass hot embossing process. *International Journal of Advanced Manufacturing Technology* 2012;60:1207, <http://dx.doi.org/10.1007/s00170-011-3669-8>.
- [10] Fukuyama S, Fujiwara S, Sugiura Y. Press forming machine for glass. US Patent 7,503,189 (2009).