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Hot Embossing of Parallel v-Groove Microstructures on Glass

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A series of parallel v-groove microstructures was embossed on glass at an elevated temperature. The effects of glass temperature, applied pressure, holding time, and demold temperature on the conformity between the product and the tool were studied. We found that very precise microstructures can be fabricated on glass at temperatures about 35°–55°C above the glass transition temperatures. However, careful attention should be paid to the demold temperature and the mold release agent in order to prevent the tool from sticking to the glass.

I. Introduction

Advances in the semiconductor manufacturing technique have accelerated the development of microcomponents and systems in almost every conceivable field. In optical applications and communication systems, this trend is no exception. Thus the need to fabricate precise microstructures on glass is clear. Hot embossing, which requires only simple equipment, possesses advantages such as the ability to fabricate delicate structures over a fairly large area and having a very short material flow distance. As such, it has been adopted as one of the most suitable manufacturing methods for producing microcomponents.

Many hot-embossed optical devices use polymers, because they are low weight and their glass transition temperatures (T_g) are lower than those for glasses. However, compared with polymers, glasses have better transparency and chemical stability, making them an obvious choice in many applications. Studies on the hot embossing of polymers have revealed the importance of uniform embossing temperature and pressure. Lin and colleagues[1–3] investigated the possibility of hot embossing for producing microstructures. Scheer and Schulz[4] studied polymer behavior during hot embossing. Koro and colleagues[5–7] investigated the deformation behavior of the glass, but their devices had geometric features of a much larger scale. Youn and colleagues[8–11] used glassy-carbon (GC) micromolds to investigate the surface profile and filling rate of microstructure hot embossing on glass. In order for the structural patterns of the tool to be precisely duplicated on glasses, the temperature of the glasses must be above their respective T_g values. If the temperature is too low, glass flow tends to be retarded, and the detail of the structure will be obscured. On the other hand, if the temperature is too high, then the rapid cooling rate after embossing tends to cause the glass to crack. Thus, the temperature of the glass during embossing is critical in the process. Furthermore, the pressure applied to the glass must be retained for a certain period of time to reduce the formation of voids in the tool cavity caused by material shrinkage during cooling. Specific embossing conditions like temperature, pressure, and holding time with respect to forming materials have not been thoroughly studied. Thus, the purpose of this study was to further investigate the effects of the aforementioned parameters on the embossed products.

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II. Experimental Procedure

Glasses selected for the experiments were FCD 1 (Hoya) and SF2 (Ohara), and their physical properties are listed in Table I. Both glasses have a glass transition temperature (T_g) lower than 500°C.

Experimental parameters chosen in this study include glass temperature, holding pressure, holding time, and parting temperature of the glass (the demold temperature). After several preliminary tests, the ranges of the parameters were selected, and the experiments were conducted with the conditions shown in Table II.

The microstructure to be fabricated on the glass was an array of parallel v-grooves. The microstructure patterns were obtained by cutting into the surface of a 10.0-mm-thick brass plate with a precision diamond cutter, which in turn functioned as an electrode to produce a thin nickel plate. Figure 1 shows the detail dimension of the microstructure.

The nickel plate was used as an embossing die, and was attached to a copper heating plate, which in turn was fastened to the ram of the press, and was spaced off with an insulating layer. The glass, on which the structures were to be duplicated, was positioned on the top of another copper heating plate, which in turn was fixed to the bolster of the press with an insulator in between.

The temperatures of each heating plate were automatically adjusted by signals fed back from three thermo couples embedded in the plate. Temperature variation over the entire area of the heat plate (250 mm × 125 mm) was controlled with a precision of ±1°C. The embossing pressure and the holding time were numerically controlled. The maximum load of the press was 5 tons. The glasses were heated in an oven to the temperature specified for the experiment, after which they were moved to the heating plate for 5 min, thereby allowing the heat to be evenly distributed before the pressure was applied.

After embossing, the glass was removed from the heating plate and left to air cool. The dimensions of the v-grooves on the glasses were measured by a Kosaka ET-4000 (Kosaka Laboratory Ltd., Chiyoda-ku Tokyo, Japan) surface profiler. We collected a surface profile for five 0.8 mm sections (Fig. 2). The average peak was then calculated and converted to a percentage of the original tool groove depth (h/H%), as shown in Fig. 3.

Table I. Physical Properties of FCD1 and SF2 Glasses

Glass	Hoya FCD1	Ohara SF2
Glass transition temperature (T_g)	455°C	430°C
Yield temperature	485°C	465°C
Average index of refraction	1.49700	1.64769
Linear coefficient of thermal expansion	$\alpha_{-30°\text{ to }70°C}$: 133×10^{-7}	$\alpha_{-30°\text{ to }70°C}$: 88×10^{-7}
	$\alpha_{100°–300°C}$: 155×10^{-7}	$\alpha_{100°–300°C}$: 98×10^{-7}
Specific weight	3.7	3.85
Hardness (H_k)	345	400

Table II. Experimental Conditions

Glass temperature (°C)	480	485	490			
Embossing pressure (MPa)	5	10	15	20		
Holding time (s)	60	90	120	150	180	240
Glass thickness (mm)	4	5	6	7	8	
Demold temperature (°C)	150	160	170	180		

III. Results and Discussion

The purpose of embossing is to duplicate the tool form on the surface of glass. The better the conformity is between the glasses and tools, the better the quality of the product. Figure 4 is a plot of the percentage of the groove depth ($h/H\%$) versus embossing pressure at various glass temperatures. Pressure holding time was set at 120 s. It is clear that for FCD1 at 490°C, the percentage of the groove depth increased with the applied pressure and reached a maximum of 80% for pressures above 15 MPa. The result indicates that high temperature and high pressure promote better conformity for FCD1 glass.

Figure 5 is the percentage of the groove depth duplicated on a 4.0-mm-thick FCD1 glass at various holding times. The glass temperature was kept at 490°C, and the applied pressure was 15 MPa throughout the embossing process. We found that increasing the holding time meant that the percentage of the fill-up of the mold cavities also increased. For holding times longer than 180 s, the groove depth on the glass surface could achieve 96% of the actual profile.

For FCD1 glass that was thicker than 4.0 mm, as depicted in Fig. 6, the percentage of groove depths imprinted was less satisfactory. This might arise from the fact that the thicker the glass is, the more difficult it becomes to direct flow of the glass in the horizontal direction, thus restricting the fill-up of the mold cavity.

The cooling rate of the glass after embossing must be carefully controlled in order to avoid the formation of a crack. In the above experiments, the embossed glasses were left to cool at room temperature. We found that demold temperatures higher than 160°C promoted the initiation of cracks, as shown in Fig. 7.

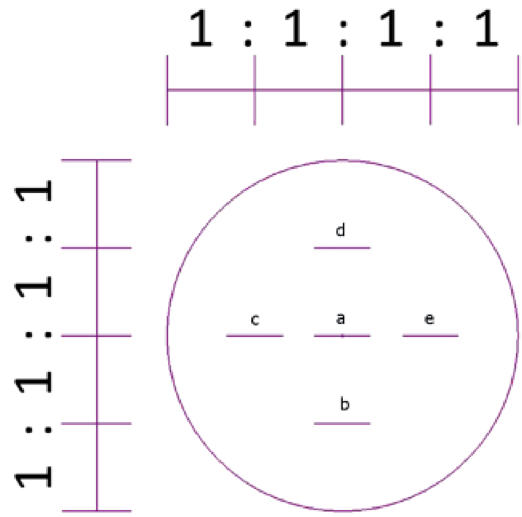

Fig. 2. Illustration of surface profile sampling sections.

Some of the cracks started from the glass surface, while others initiated within the glass. Additionally, sticking sometimes occurred between tools and glass surfaces at high temperatures, as shown in Fig. 8. In this case, a suitable boron nitride-based mold release agent can be helpful.

For SF2 (Ohara) glass, which has a lower glass transition temperature but higher softening temperature (564°C) than FCD1 (Hoya), embossing must be carried out at an even higher temperature (520°C) to avoid crack formation. One possible explanation is that the difference in the thermal expansion coefficient between the tool and the SF2 glass is larger than it was for FCD1.

IV. Conclusions

An array of parallel v-groove microstructures was fabricated on FCD1 and SF2 glasses at elevated temperatures. For FCD1, a

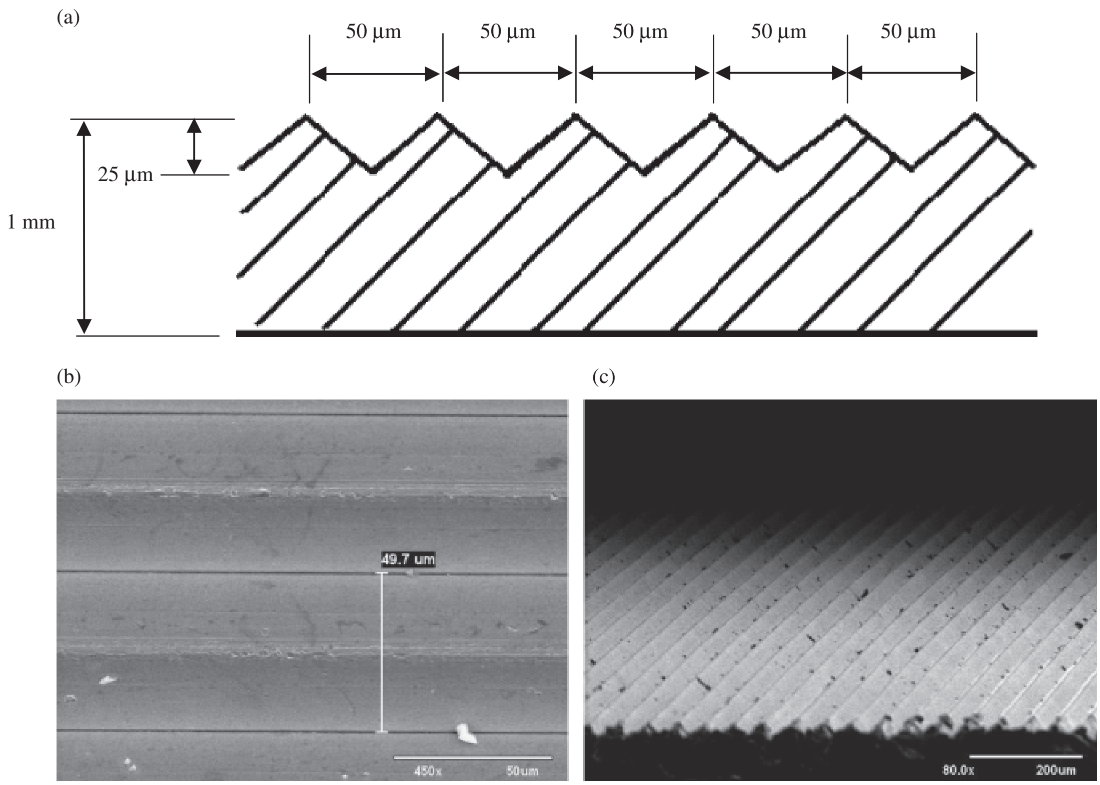

Fig. 1. A series of parallel arrays of v-grooves on a nickel plate: (a) dimensions of the v-groove; (b) top view; (c) side view.

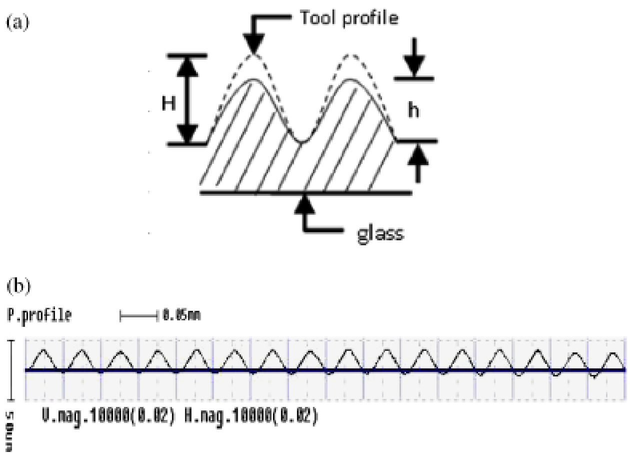

Fig. 3. (a) Illustration of the percentage of the original tool groove depth (h/H%). (b) Example of surface profile data measured by the Kosaka ET-4000.

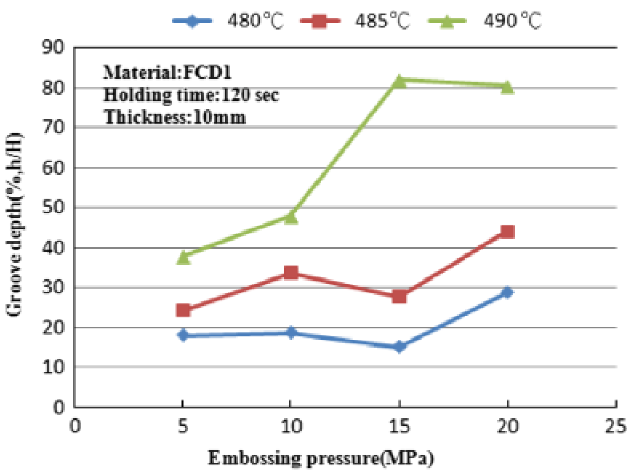

Fig. 4. Groove depth versus embossing pressure at various glass temperatures.

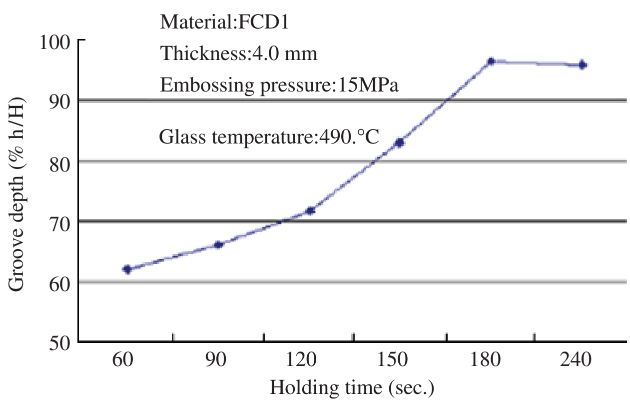

Fig. 5. The effects of holding time on groove depth.

very precise duplication of the templates could be fabricated at a temperature of about 35°C above its glass transition temperature, with a medium pressure and a longer holding time. On the other hand, for SF2, which has a lower T_g but higher softening temperature than FCD1, embossing needs to be carried out at 55°C above T_g in order to obtain a satisfactory duplication of the template. Finally, a mold release agent was helpful in preventing sticking between glasses and tools at elevated temperatures.

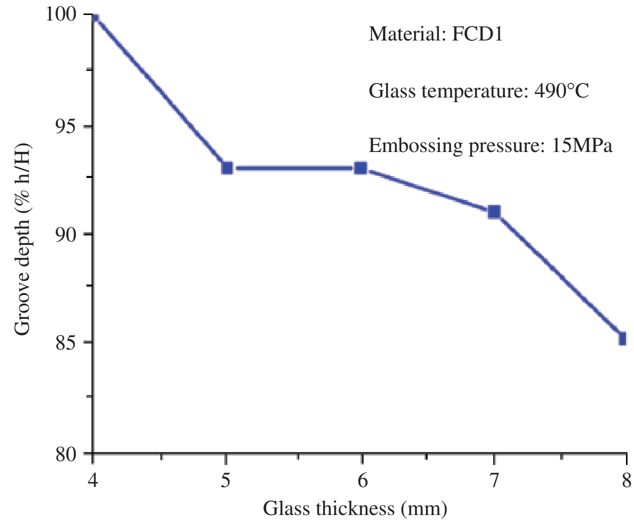

Fig. 6. Groove depth for various glass thicknesses.

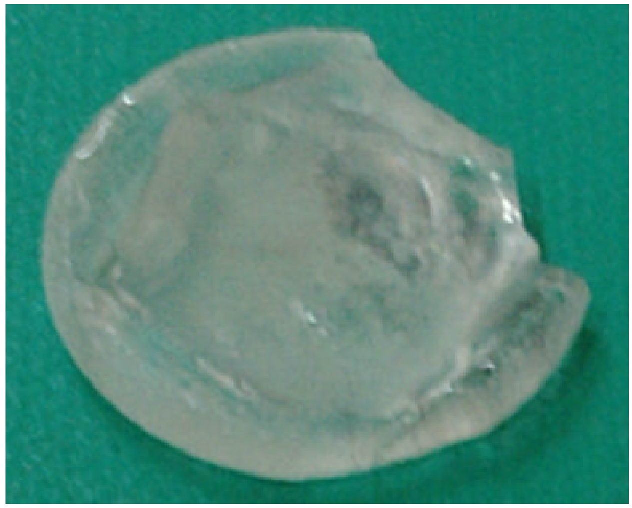

Fig. 7. The appearance of cracking when the demold temperature was 180°C.

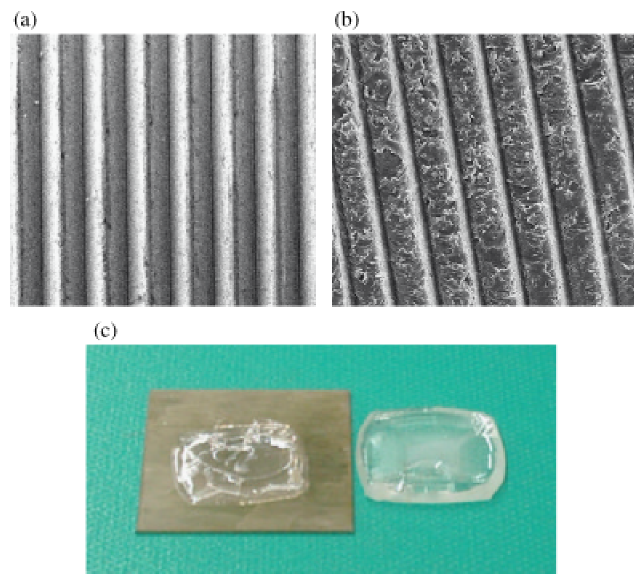

Fig. 8. (a) SEM image of a normal product's surface. (b) SEM image of a glass surface with sticking. (c) Sticking occurred between the tools and the glass surfaces at high temperatures.

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