Experimental Study of the Aspheric-plano Lens Fabrication using Compression Glass Molding

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The effects of the process parameters in the molding of aspheric glass lenses for camera phone modules have been investigated experimentally. The molding conditions were optimized with respect to the form accuracy (PV) (the response variable) of the molded lens. The experimental conditions were obtained by employing a factorial design method. From the analysis of variance (ANOVA) and *P*-value (significance level), the slow cooling rate was found to affect the response variable most significantly. The lens molded under the optimum molding condition showed a transcription ratio of 93.4 %.

Keywords : Aspheric glass lens, Glass molding press (GMP), Design of experiments (DOE)

1. INTRODUCTION

Aspheric glass lenses offer many optical advantages, including superior optical performance and reduced optical aberrations. The key process used for aspheric glass lens fabrication in conventional lens manufacturing is polishing. Magnetorheological finishing (MRF) and precision polishing are two automatic polishing methods that are commercially available. Due to the complexity of these processes and the long cycle times involved, the overall costs for medium- to high-volume productions of aspheric lenses are very high[1-3].

The use of a glass molding press (GMP) has recently become an attractive approach alternative to the traditional glass lens manufacturing process. This hot-forming compression method has many advantages. For instance, it is a simpler process than polishing and lenses can be pressed into shape without requiring the usual subsequent finishing operations. Finally, it allows the fabrication of aspheric glass lenses that cannot be created using traditional method-polishing.

The GMP method has resulted in the mass production of aspheric glass lenses being possible. Thus, in cases where the process parameters are properly designed, the GMP method is considered to be one of the most reliable methods for the fabrication of aspheric glass lenses.

However, due to the extremely high hardness (R_c>90) of popular mold materials such as tungsten carbide (WC) and silicon carbide (SiC), the grinding process used to fabricate such molds becomes expensive. In addition, it is sometimes difficult to control the many parameters of the molding process (e.g., the pressing force, cooling rate, and cooling range, etc.). Thus, to reduce the number of case studies required, an efficient strategy for the process design is required, and the related results should be analyzed systematically.

One solution would be to use, the design of experiments (DOE) method. This statistics-based tool is useful for the process design and analysis of complicated industrial design problems. The DOE method has facilitated an understanding of the process characteristics and has helped in the investigation of how each parameter affects the response variables. In addition, the DOE method has successfully been used to systematically determine the optimum process parameters using fewer testing trials.

Extensive parameter studies related to molding processes have previously been carried out, but they focused on issues concerning the injection molding of plastic products[4-6]. By contrast, this study deals with the optimization of the GMP process with regard to the form accuracy (PV) of molded aspheric glass lens intended

Table 1. Processing conditions for the fabrication of the tungsten carbide mold.

Grinding process	
Wheel configuration	SD 2000, Resin bond
Workpiece speed	200 rpm
Grinding wheel speed	30,000 rpm
Feed rate	0.25 mm/min
Depth of cut	0.1 μm
Polishing process	
Diamond paste (Grain size)	Rough: 2 μm; Finish: 1 μm
Polishing medium	Nylon

for a 3-megapixel camera phone module. From the results of the analysis, both the effect of each process parameter on the response variable and the optimum parameter values for the GMP process were determined.

2. EXPERIMENTS

2.1 Lens design and mold fabrication

The aim was to produce a plano-aspheric convex singlet lens with a diameter of 4.0 mm (clear aperture 3.0 mm), intended for a 3-megapixel, 2.5 magnification zoom camera phone module. The aspheric convex side of the lens was optically designed using the following aspheric equation:

$$z = \frac{C \cdot x^2}{1 + \sqrt{1 - (1 + K) \cdot C^2 \cdot x^2}} + \sum_{i=1}^{n} A_i \cdot x^i \qquad (1)$$

where K (= −0.298) is the conic constant, $C = 1/R$ (where R [= 2.934 mm] is the vertex radius of the aspheric surface), and A is the constant for the aspheric form.

Tungsten carbide (WC; 002K, Everloy Co., Japan) that contained 0.5 wt.% cobalt (Co) was used to build the mold. The mold surface was ground and polished using an ultra-precision aspheric processing machine (ASP01, Nachi-Fujikoshi Co., Japan) and an aspheric polishing machine (KRF-2200F, Kuroda Co., Japan), respectively. Diamond-like carbon (DLC), 80 nm in thickness, was coated onto the processing surface in order to protect the mold from the extreme working conditions during the molding process. The aspheric surface of the fabricated mold showed form accuracy (PV) of 0.199 μm. All of the mold surface processing conditions are summarized in Table 1 for completeness.

Table 2. Thermal properties of the glass preform.

Transition temperature (T_g)	498 °C
Yielding point (A_t)	549 °C
Annealing point (AP)	488 °C
Strain point (StP)	464 °C

Table 3. Parameters of the GMP process in this study.

Parameter	Delay time	Pressing process		SC* process
		Step 1	Step 2	
Force (N)	–	Variable (*A*)	300	Variable (*C*)
Time (sec)	30	10	Variable (*B*)	–
Temperature (°C)	Molding	Rapid cooling point	Release	Rate (°C/sec)
	555	Variable (*D*)	200	Variable (*E*)

*SC : Slow Cooling

2.2 Experimental design for the GMP process and surface analysis

A ball-type preform (L−BSL7, Ohara Co., Japan) was used as the glass material for the lens fabrication. The thermal properties of this glass are shown in Table 2. This and other glasses suitable for the GMP lens fabrication method have lower transition temperature than standard glasses, and they are lead (Pb) free. Ten test lenses were molded under the same condition using a precision glass molding machine (Nano-Press S, Sumitomo Co., Japan). The form accuracy (PV) and the surface roughness (Ra) of each aspheric surface were measured using an ultra-high accurate three-dimensional (3-D) profilometer (UA3P, Panasonic Co., Japan) and a white light interferometer (Newview5000, Zygo Co., USA) with a vertical resolution of 0.1 nm, respectively. Table 3 reveals the details of the GMP process and the five parameters selected in this study. The heated glass preform was pressed in two different steps and then slowly cooled. All of the parameters of the slow cooling process were used as input variables. In case of the pressing process, the two most significant design parameters, pressing force in step 1 (*A*) and pressing time in step 2 (*B*), found from a preceding study were selected[7,8]. Since the lens produced after the pressing process is immediately cooled slowly from the molding temperature to the rapid cooling point, the rapid cooling point is related to the temperature range of the slow

Table 4. Levels and factors used in the factorial design.

Sign	Factor	Low level (−1)	High level (+1)
A	Step1-Pressing force (N)	100	200
B	Step2-Pressing time (sec)	10	20
C	SC-Pressing force (N)	50	200
D	Rapid cooling point (°C)	460	490
E	SC-rate (°C/sec)	0.4	4.0

Table 5. Estimated effects and coefficients on the form accuracy (PV) (coded units).

Term	Effect	Coef.	SE Coef.	T	*P*
Constant		0.31266	0.001943	160.94	0.000
A	0.01306	0.00653	0.001943	3.36	0.001
B	0.00944	0.00472	0.001943	2.43	0.018
C	−0.06746	−0.03373	0.001943	−17.36	0.000
D	0.04257	0.02129	0.001943	10.96	0.000
E	0.10497	0.05249	0.001943	27.02	0.000
$A \times B$	0.00906	0.00453	0.001943	2.33	0.023
$A \times C$	−0.01856	−0.00928	0.001943	−4.78	0.000
$A \times D$	−0.01871	−0.00936	0.001943	−4.82	0.000
$A \times E$	0.01759	0.00879	0.001943	4.53	0.000
$B \times C$	−0.02096	−0.01048	0.001943	−5.39	0.000
$B \times D$	−0.02469	−0.01235	0.001943	−6.36	0.000
$B \times E$	0.00949	0.00474	0.001943	2.44	0.017
$C \times D$	0.01491	0.00746	0.001943	3.84	0.000
$C \times E$	−0.03957	−0.01978	0.001943	−10.18	0.000
$D \times E$	0.01858	0.00929	0.001943	4.78	0.000

cooling process. In conventional glass-forming method, the slow cooling step involves cooling from the annealing point to the strain point. To verify this effect, the high and low levels of the rapid cooling point were determined based on the annealing and strain points of the glass material, respectively. The values corresponding to the high and low levels of the selected design parameters are listed in Table 4. The form accuracy (PV) of the aspheric surface of the molded lens in the clear aperture was used as a response variable of the input parameters.

Experiments were performed by using a statistical design of experiments approach, which included a screening for fractional factorial design as well to estimate the relative influences of the five aforementioned factors and their possible interactions with the analytical response, taken as arbitrary units of the peak area. The number of experiments in the fractional factorial design ($N_{\text{fractional}}$) increases exponentially

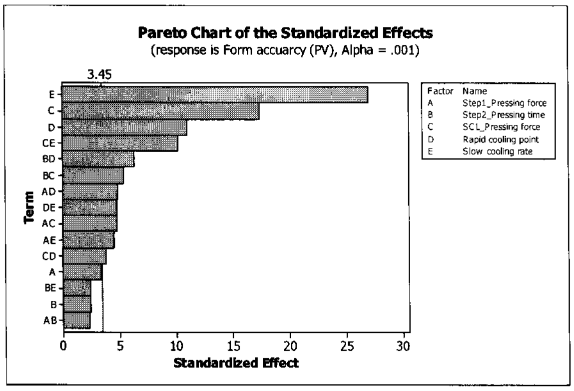


Fig. 1. Pareto chart of the standardized effects for the form accuracy (PV) of the aspheric surface of the molded lenses.

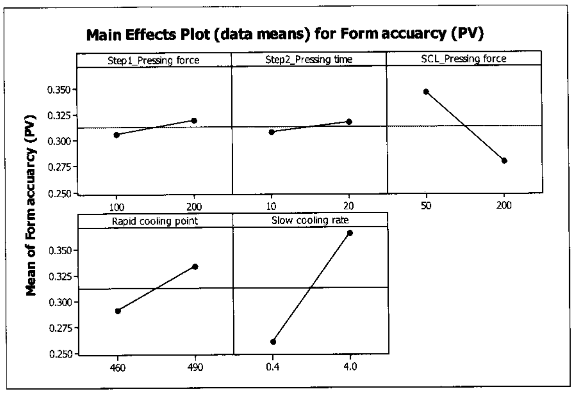


Fig. 2. Main effect plot for the form accuracy (PV) values of the aspheric surfaces of the molded lenses.

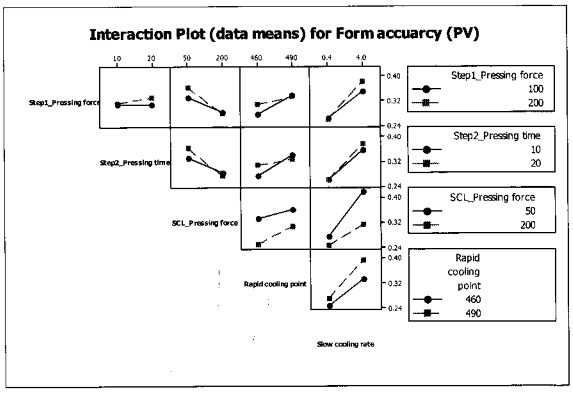


Fig. 3. Interaction plot for the form accuracy (PV) values of the aspheric surfaces of the molded lenses.

as follows:

$$N_{\text{fractional}} = m(n_l)^{k-q} \tag{2}$$

where q is the degree of fractionation, k is the number of factors to be investigated, n_l is the experiment level, and m is the number of replicates. In this study, the values of these parameters were as follows: $k = 3$, $n_l = 2$, and $m = 10$. Hence, there were 160 runs in the experiment resulting from repeating sixteen designed conditions ten times.

3. RESULTS AND DISCUSSION

Two-way ANOVA and P-value (significance level) were used to check the significance of the effects on the form accuracy (PV) of the aspheric surface of the molded lens. Ten lenses were molded under the each set of designed conditions and a mean value of the form accuracy (PV) was quoted for the statistical analysis. The P-value obtained from the analysis and the significance level value ($\alpha = 0.001$) were compared to

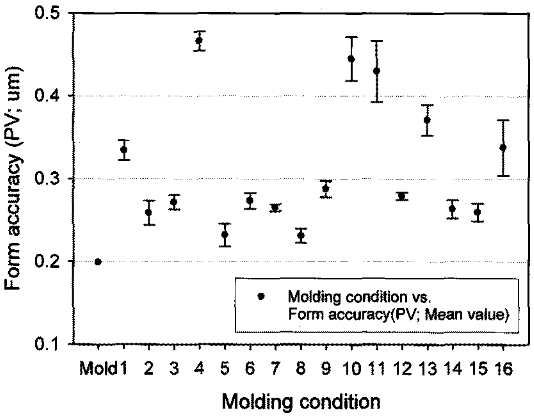
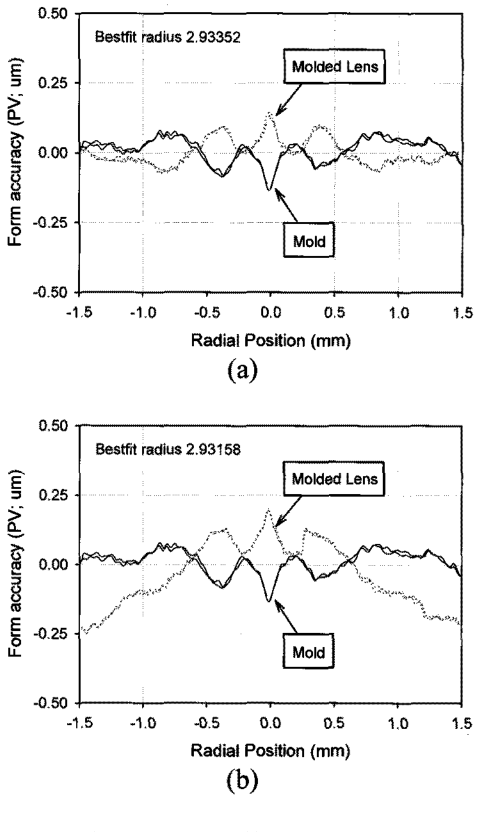


Fig. 4. Mean form accuracy (PV) value and standard deviation according to the designed molding conditions.

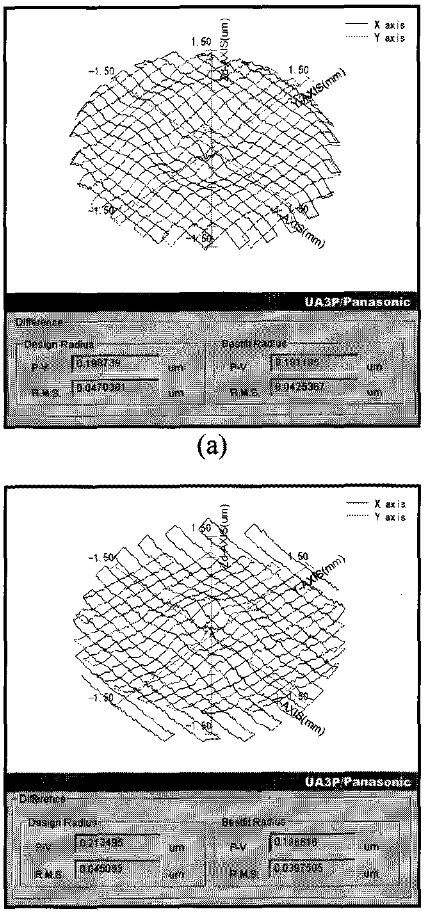
verify the significance of each factor. The estimated effects of the five main effects and the ten two-way interactions, as well as their statistical significance at a 99.9 % confidence level ($P < 0.001$) on the form accuracy (PV), are shown in Table 5. Figure 1, the Pareto chart, points out that all of the slow cooling parameters and the interaction between SC-pressing force (*C*) and SC-rate (*E*) significantly influenced the form accuracy (PV) of the molded lens. Figures 2 and 3 show how the main effect and the interaction, respectively, influence the form accuracy (PV) of the molded lens. The SC-rate represents the most significant variable, inducing the deepest variations in the form accuracy (PV) of the molded lens, whereas the pressing process parameters had little effect on the response variable. The optimum molding condition is the combination of the parameter level to make low the form accuracy (PV) value of the molded lens. Figure 3 indicates that the pressing force in the slow cooling process (SC-pressing force (*C*)) has comparatively little influence on the form accuracy (PV) when slow cooling rate (SC-rate (*E*)) is at its low level. Figure 4 reveals the mean form accuracy (PV) and standard deviation for each combination of factors. The form accuracy (PV) of the lens molded under the optimum and the unoptimized



(a)

(b)

Fig. 5. Form deviation profiles between the molds and the lenses molded using: (a) the optimum condition and (b) the unoptimized condition among the designed conditions.



Difference
Design Radius
P-V 0.198739 um
R.M.S. 0.0470381 um
Bestfit Radius
P-V 0.181135 um
R.M.S. 0.0425367 um

(a)

Difference
Design Radius
P-V 0.213495 um
R.M.S. 0.045089 um
Bestfit Radius
P-V 0.186616 um
R.M.S. 0.0397505 um

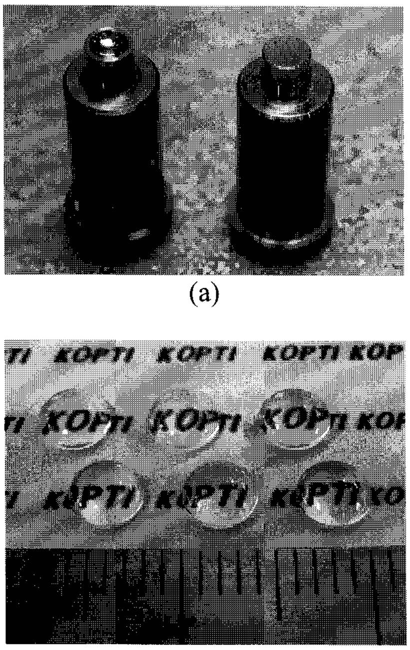
(b)

Fig. 6. Form accuracy (PV) of the aspheric surfaces of: (a) the mold and (b) the lens molded under the optimum condition.

molding condition among the experiment points designed by fractional factorial were 0.23 and 0.47 μm, respectively. In addition, the standard deviation for each condition is less than 10 % of the corresponding form accuracy (PV). This indicates that the experiments are highly reproducible. Figure 5 shows the form deviation profiles between the molds and lenses molded using the optimum and the unoptimized molding conditions. The best-fit radius of the molded lens is lower than that of the mold due to glass shrinkage during the cooling process. The more the best-fit radius of the lens is decreased, the more the form accuracy (PV) is increased.

The form accuracy (PV) of the molded lens was measured using an ultra-high accurate 3-D profilometer, which operates using the repulsive forces between the atoms of the scanning probe and the test surface. The measured form accuracy (PV) values for the aspheric surfaces of the mold and the lens molded under the optimum molding conditions are depicted in Fig. 6(a) and (b), respectively. The form accuracy (PV) values are found to be 0.199 and 0.213 μm against the design radius (2.934 mm), respectively. The percentage transcription ratio is calculated as the ratio of the form accuracy (PV) against the design radius between the mold and the molded lens. It is calculated to be around 93.4 % for the optimum molding condition.

Figure 7 shows photos of the fabricated mold (a) and the lenses (b) molded under the optimum molding condition.



(a)

(b)

Fig. 7. Photos: (a) the WC mold and (b) the lenses molded under the optimum condition.

4. CONCLUSIONS

The experimental verification of the slow cooling process parameters in the molding of aspheric glass lenses for optimum process design is presented. In addition, transcription characteristics were ascertained by comparing the topographies of the form accuracy and the roughness between the lens and the mold surface.

- All of the slow cooling process parameters appear to significantly influence the form accuracy (PV) of the lens. The slow cooling rate (SC-rate) was found to be the most significant parameter.

- The condition that result in the molded lens with the lowest form accuracy (PV) value are as follows:

  Step1-Pressing force : level “-1” (100 N)
  Step2-Pressing time : level “-1” (10 sec)
  SC-Pressing force : level “+1” (200 N)
  Rapid cooling point : level “-1” (460 °C)
  SC-rate : level “-1”(0.4 °C/sec)

- The interaction between the pressing force in the slow cooling (SC-pressing force) and the slow cooling rate (SC-rate) was the most significant factor. The interaction plot indicates that the SC-pressing force has comparatively little influence on the form accuracy (PV) when the SC-rate is at its low level.

- The lens molded under the optimum molding condition showed a transcription ratio of 93.4 %. This value is obtained by comparing the form accuracy (PV) values of the mold and the molded lens. This value is sufficient for fabricating the precision optical component for our system.

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