Journal of
Materials
Processing
Technology

Journal of Materials Processing Technology 113 (2001) 189–195

www.elsevier.com/locate/jmatprotec

A statistical experimental study of the injection molding of optical lenses

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Abstract

In the injection molding of plastic optical lenses, the processing conditions have critical effects on the quality of the molded lenses. Since there are many process parameters involved in an injection molding process, and more importantly, an optical lens needs precisely controlled surface contours, determination of the processing conditions for lens molding is very complicated. The objective of this work is to investigate experimentally some effects of the molding conditions on the surface contours of injection molded lenses. A spherical lens was molded using polycarbonate. The surface profiles of the lenses molded under different processing conditions were measured using a laser interferometer. The birefringence of the lenses was measured using a specially designed polarimeter to characterize the residual stress in the lenses. Statistical methods were employed in the experimental studies in order to systematically analyze the effects of various process parameters on the lens contour errors. The process parameters studied include injection speed, holding pressure and mold temperature, etc. The contour errors were correlated to the mold shrinkage and the residual stress in the molded lenses. The study shows that in addition to the mold shrinkage the stress also plays a vital role in determining the lens surface contours.

Keywords: Injection molding; Optical lenses; Molded

1. Introduction

The injection molding technique is now used increasingly more widely in the manufacturing of precision plastic parts, such as optical lenses. This trend is driven primarily by the strong needs for the manufacturing of these parts at high production rates and low cost. An optical lens needs precisely controlled surface contours to realize its optical design. In general, the injection molding process is not ideal for such products since excellent replication of the mold contour is very difficult to be achieved using this process due to free mold shrinkage and stress induced distortion, especially when highly viscous molding materials are used. Injection–compression molding has been proven to be a better solution for the molding of high-end plastic optical lenses [1]. On the other hand, it has also been proven that through proper mold design and process optimization, an injection molded lens can achieve reasonably well controlled surface contours, although not exactly replication of that of the mold, which provides a low cost solution for the manufacturing of plastic optical lenses. In this case, the injection molding conditions have critical effects on the quality and productivity of the molded lenses [2,3]. Since there are many process parameters involved in an injection molding process, determination of the processing conditions for lens molding is very complicated, and no established design rules are available.

Deviation of the contours of a molded lens from those of the mold caused by free mold shrinkage has been studied previously [4]. If the shrinkage is uniform, although it may cause the thickness and radii of curvatures of a lens to deviate from those of the mold, but the resultant contour errors are predictable and can be well corrected in the mold design stage. Practically, the mold shrinkage is, however, non-uniform, which may cause not only undesirable variation in lens thickness and hence contour errors, but also frozen-in stresses and hence further distortion of the products. For optical lenses, a very small distortion may result in relatively large deviation of the lens contours from those designed.

There is another source of residual stresses in injection molded parts. During an injection molding process, polymer melt is forced to flow in a narrow channel by high pressures. This may result in an anisotropic structure of the polymer melt, and it may be frozen in moldings to some extent. The influences of the anisotropic polymer structure on properties of the molded plastic lenses are twofold. Firstly, the products may display flow-induced birefringence. Secondly, associated with the anisotropic structure, stress is present in

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the molded lenses, which may also cause distortion of the products. In this case, since the stress is directly related to the birefringence, study of the effects of process parameters on the birefringence patterns can provide important clues for process optimization. It is worth noting that the birefringence is also material dependent. The most commonly used optical plastic, polycarbonate, has a relatively large positive stress–optical coefficient [5]. It is, therefore, an ideal candidate for injection molding process studies.

The objective of this work is to study some effects of injection molding conditions on surface contours of a molded polycarbonate lens. In order to systematically analyze the effects of various process parameters on the lens contours, statistical methods were used in conducting the experiments. The contour errors were correlated to mold shrinkage and the level of the flow-induced stress in the molded lenses to evaluate the importance of these two factors in determining the lens contours.

2. Experimental work

2.1. Molding materials

The material used in this study was a commercially available injection-molding grade of polycarbonate. The material was pre-conditioned at 120°C for 4 h using a dehumidifying drier before molding. The trade name, manufacturer and melt flow index of the material are shown in Table 1.

2.2. Part geometry and mold design

All of the molding experiments were conducted using a two-cavity test mold especially designed for this study. The product is a mono-axis spherical lens. The designed geometry and dimensions of the test part are shown in Fig. 1.

The test mold includes two pairs of inserts to form the lens contours. Each of the concave and convex inserts was fabricated separately using tool steel Assab Stavax HRC40-52. The mold was designed with a cold round runner system of diameter 6 mm and a sprue of diameter 8 mm. An edge gate of dimensions 10 mm × 5 mm × 3 mm was used.

2.3. Injection molding process

The molding experiments were performed on a 100 t HP 1000-220/Netstal injection molding machine. The experiments were conducted under various designs of experiments, as explained in the following sections. Under each set of process conditions, 10 shots were made to ensure that the process was stable before samples were collected. If no significant variation was observed during these first 10 runs, the molded parts from the next five runs were collected as the samples for product characterization.

Table 1
Molding material used in this study

Material name	Polycarbonate
Category	General purpose
Manufacturer	Mitsubishi
Trade name	Iupilon
Grade	S-2000
Melt flow index (g/10 min)	10

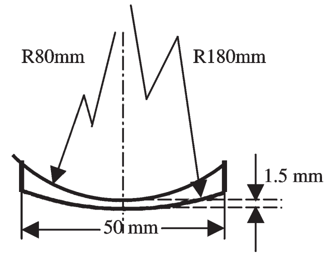

Fig. 1. Designed geometry and dimensions of the test part.

2.4. Design of experiments (DOE)

Full two-level three-factorial (2^3) molding experiments were designed to determine the effects of various process parameters on the sample weight, and the radii of curvature of the molded lenses and the level of the flow-induced stress in the lenses. The process parameters under consideration were the injection speed, the holding pressure and the mold temperature. The high and low levels of these process parameters are tabulated in Table 2. Other process parameter settings were held constant throughout the experiments, as listed in Table 2.

After the 2^3 experiments, molding experiments were further conducted to study the effects of two-stage holding pressure and pressure holding time on the quality of the molded lenses. Three types of holding pressure profiles were used, as shown in Fig. 2. For the second type of two-stage holding, the holding times used were 5, 7.5, 10, 12.5, 15 and 20 s, respectively. The other processing parameters used in these experiments were the same as those in the 2^3 molding experiments.

2.5. Product characterization

In this study, it has been observed that there are slight differences in product quality between the lenses molded in cavity I and cavity II, which is due to their difference in cooling efficiency. To focus on the major task of this study, in this paper only the characterization data for lenses molded in the cavity I are discussed. All the data presented in this paper corresponds to lenses obtained from cavity I.

2.5.1. Part weight

Before weighing, the runner systems were carefully trimmed from the lens samples. For each set of process conditions, all five collected parts were weighed and the average part weight was calculated. Among the five samples,

Table 2
Process parameters used in full two-level three-factorial (2^3) molding experiments

Factor	Low level	High level
Injection speed (mm/s)	20	100
Holding pressure (bar)	1000	1560
Mold temperature (°C)	60	140
Other process parameters		
Screw rotation speed	100 mm/s	
Back pressure	100 bar	
Feed stroke	50/52 (for suck back)	
Cushion setting	12 mm (V/P switch over at 8 mm)	
Holding pressure time	5 s, one-stage	
Cooling time	30 s	
Barrel temperature setting	300°C (melt), 300°C (nozzle), 300°C (cylinder head), 300°C (metering zone), 270°C (compression zone), 270°C (feed zone), 50°C (feeder throat)	

the part with a weight closest to the average value was chosen for the further measurements described below.

2.5.2. Radius of curvature

A GPI XP laser interferometer was used to measure the radii of curvatures of the mold inserts and molded lenses. The maximum peak to valley (PV) measurable using the interferometer is 10 μm at 320 pixels and 20 μm at 640 pixels. The surface profiles of the mold inserts were measured at normal resolution, i.e., 320 pixels. The surface profiles of the mold lenses were measured at a higher resolution, i.e., 640 pixels.

In this study contour error was used to quantify the quality of the molded lenses in terms of their radii of curvature, which is defined as

$$\text{Contour error} = R_{\text{lens}} - R_{\text{insert}}$$

where R_{lens} and R_{insert} represent the radii of curvature of a lens and that of the corresponding mold insert, respectively.

2.5.3. Photoelastic stress analysis

The photoelastic stress analysis system used in this study was custom-built. It consists of a conventional polarimeter, a CCD camera and an IBM PC with photoelasticity stress analysis software.

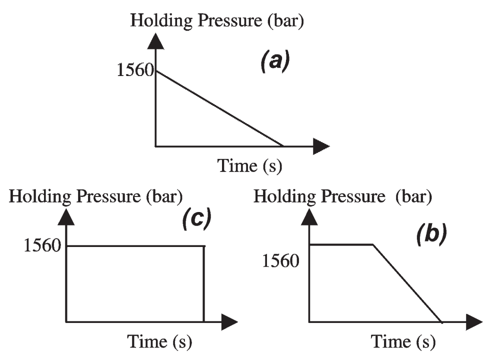

Fig. 2. Holding pressure profiles used in this study: (a) one-stage holding; (b) two-stage holding, type I; (c) two-stage holding, type II.

In the quantitative stress analysis of the plastic lenses, firstly an immersion fluid was made [6], which has exactly the same refractive index, n, as that of the part under test. Since polycarbonate has a refractive index of 1.586, the immersion fluid used in this study was made by mixing silicone oil ($n = 1.5568$) and diiodomethane ($n = 1.7$). The lens was then immersed in the fluid in a stress-free glass container and put under the polarimeter to let polarized light pass through the sample. The optical images were recorded by the CCD camera when using a different combination of polarizers and analyzers, and then analyzed using the photoelasticity software. The radii of curvature, diameter and center thickness of the lens were input into the computer to account for the thickness of the lens at a particular point. In multi-fringe analysis the fringe number was assigned by the operators [7,8].

Qualitative stress analysis was conducted in a similar way, but after the optical images were recorded no further analysis was done. The images were compared to each other visually and assigned as low, medium or high stress level, based on the number of fringes observed. All of the parts collected from the eight molding experiments were rated based on the observed birefringence patterns. The rating of 0.0 was given to the parts with a low level of stress, and 0.5 and 1.0 to the parts with a medium and a high level of stress, respectively. Two representative birefringence patterns for the low and high level of stresses are shown in Fig. 3 as examples.

2.6. Data analysis

In this study, the method adopted to analyze the full two-level three-factorial experiments (2^3) was to treat the data as a series of paired comparisons, one parameter at a time [9]. The comparisons were carried out under various conditions for the other factors. The effect of the jth factor (E_j) was calculated using the equation

$$E_j = \frac{\sum_{i=1}^{n}(l_{ij} \times R_i)}{\sum_{i=1}^{n} R_i} \quad (j = 1, 2, \ldots, n) \qquad (1)$$

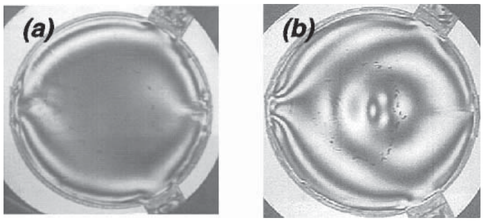

Fig. 3. Representative birefringence patterns observed: (a) low level of stress; (b) high level of stress.

where i is the combination number, n the total number of combinations (i.e. the total number of experiments; for the 2^3 design, n equal to 8), R_i the responsible variable for the ith combination, l_{ij} equal to -1 for low level of the jth factor, $+1$ for high level of the jth factor and $\sum_{i=1}^{n} l_{ij} = 0$.

The interaction between the jth and kth factor (I_{jk}) was calculated using the equation

$$I_{jk} = \frac{\sum_{i=1}^{n}[(l_{ij} \times l_{ik}) \times R_i]}{\sum_{i=1}^{n} R_i} \quad (j = 1, 2, \ldots, n) \tag{2}$$

The product characterization results were analyzed using the conventional 2^3 matrix [9].

3. Results and discussion

3.1. Sources of contour errors

In the lens manufacturing industry, the contour errors of a lens refer to the deviation of the lens surface contours from the designed contours. The contour errors for a molded plastic lens may come from three sources. Firstly, the contours of a mold insert may deviate from the designed contours. The test mold inserts used in this study were fabricated using conventional machining and polishing techniques. The contours and surface finish of the inserts were measured using the laser interferometer. The maximum peak-to-valley measured for the inserts is less than 10 μm, although the edge regions of the convex inserts were out of range during the measurements. The measurement plots for the two inserts used to form cavity I of the test mold are shown in Fig. 4.

The radii of curvatures of the test mold inserts measured using the interferometer are tabulated in Table 3. These values deviate significantly from the designed values. Nevertheless, the focus of this paper is to study the effects of the

Table 3
Radii of curvature of the mold inserts measured using the laser interferometer at room temperature

	Radius of curvature	
	Concave surface	Convex surface
Cavity I	176.12	80.42
Cavity II	178.93	81.31

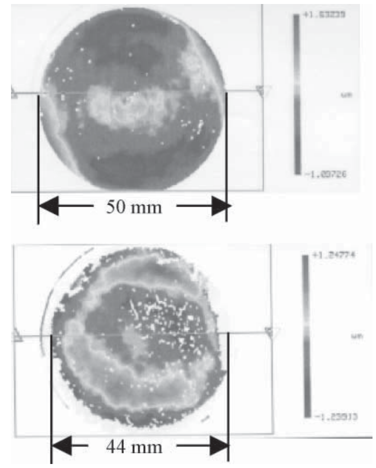

Fig. 4. Surface roughness map of the test mold inserts measured using the laser interferometer: (a) concave insert for cavity I, having a maximum peak-to-valley of 2.670 μm; (b) convex insert for cavity I, having a maximum peak-to-valley of 2.487 μm.

molding process parameters on the contour errors of the molded lenses. Therefore, these inserts can still serve the major purpose of this study. In this work, the contour errors of a lens refer to the deviation of the radii of curvature of a molded lens from those of the mold inserts, rather than the designed values.

It is also worth noting that the radii of curvature shown in Table 3 were obtained at room temperature. At relatively high mold temperature, thermal expansion of the inserts may also cause deviation of the mold surface contours from the designed contours, but such deviation is usually fairly small. When the radii of curvature are relatively large compared to the diameter of the mold, the surface contours of the mold, especially that of the center area, would not be affected by this significantly, which is the case in this study.

For the molding of high-end optical lenses, ultra-precision machining is required for making high precision molds. In a parallel research to this work, the authors have used a single-point diamond turning machine to make aluminum test mold inserts. The surface profiles of the inserts were also measured using the laser interferometer. In contrast to those fabricated using conventional machining methods, in this case the entire insert surface, including the edge region, has a very good surface finish. The maximum peak-to-valley was less than 0.2 μm, which is about 15 times better than the inserts used in this study. Despite the high precision achievable by the diamond turning machine, the short tool life for an aluminum insert makes it a costly option. At present, how to achieve high precision for a lens mold at a reasonably low price is still a great challenge faced in the mold manufacturing industry, although the topic is beyond the scope of this paper.

The second source of contour errors of a molded lens is the free mold shrinkage of the lens. As mentioned in Section 1, both uniform and non-uniform mold shrinkage can cause severe contour errors for the molded lenses. Flow simulation and systematical process study may help to minimize such contour errors, although this is also beyond the scope of the present paper. In this work, sample weight was used to indirectly characterize mold shrinkage, therefore non-uniformity of the shrinkage is not under consideration. Only the average effect of mold shrinkage on contour errors will be discussed.

Thirdly, the flow-induced stress may also cause distortion of a plastic lens in the mold and hence contour errors. The same as the free mold shrinkage, the stress is also very much dependent on the processing conditions. In this study, the authors will mainly discuss the effects of the processing conditions on the lens contour errors and their relations to the mold shrinkage and flow-induced stress.

3.2. General observation

In general, the molded lenses have slightly poorer surface finish compared to the corresponding inserts. The maximum peak-to-valley is between 10 and 20 μm. In addition, for most lens samples, only the center sections of the lens surfaces, typically with a diameter of 25 mm, fall within measurable peak-to-valley range for the instrument. Therefore, all the radii of curvature of the lenses reported in this paper refer to the values for the center sections of the lenses.

For the lens design used in this study, if considering only uniform mold shrinkage, the contour errors would occur in the form of

$$R_{\text{concave}} \geq R'_{\text{concave}}, \qquad R_{\text{convex}} \leq R'_{\text{convex}}$$

where R_{concave} and R'_{concave} are the radii of curvature of the concave surface of the lens and the corresponding insert, respectively, and R_{convex} and R'_{convex} are the radii of curvature of the convex surface of the lens and the corresponding insert, respectively.

However, in this study, for all of the molded lenses, it was found that

$$R_{\text{concave}} \leq R'_{\text{concave}}, \qquad R_{\text{convex}} \leq R'_{\text{convex}}$$

The situation is illustrated schematically in Fig. 5. Such a shrinking pattern indicates that stress plays a very important role in the determination of the lens contour errors. The stress causes the lens warp in the mold. The stress could be induced by non-uniform shrinkage or flow-induced orientation. In this paper, the two components are not separated.

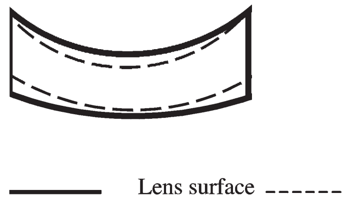

Fig. 5. A schematic diagram of the contour errors of a molded lens.

Table 4
Process parameter matrix and product characterization results

Process parameter			Responsible variable		
Injection speed	Holding pressure	Mold temperature	Sample weight	Contour error	Stress level
+ [a]	+	+	7.44	−5.4	1.0
+	+	− [a]	7.65	−2.4	0.5
+	−	+	7.25	−4.4	0.5
+	−	−	7.38	−2.4	0.0
−	+	+	7.43	−3.4	1.0
−	+	−	7.59	−1.4	0.5
−	−	+	7.14	−4.4	0.5
−	−	−	7.36	−2.4	0.0
Average value			7.41	−3.3	0.5

[a] + and − represent the high and low level of the process parameters, respectively.

3.3. Factorial analysis based on product characterization

To study the effects of process parameters on contour errors and their relation to mold shrinkage and residual stress, a factorial experimental study was conducted. The detailed experimental design and production characterization methods have been illustrated in Section 2. The experimental results are shown in Table 4. In the table, the contour error was measured from the concave surface of the lenses.

The effect of each process parameter was calculated using Eq. (1) described in Section 2. For example, the effect of a process parameter on the stress level was calculated such that a rating of 1.0 was given to high level of birefringence and 0.0 to birefringence patterns with less fringe number. The effect of the holding pressure on the stress level is +50%, which means that an increase of holding pressure from the low to high level will cause an average stress rating increase of 50% of the average level. Note that the effect of each process parameter is an averaged value over eight experiments. An interaction between parameters exists when the difference in the response variables between the low and high levels of each parameter is not the same at all levels of the other parameters. The interactions were calculated using Eq. (2) described in Section 2. When the interaction is large, the effect of a single process parameter has little practical significance.

The results of the 2^3 factorial analysis are listed in Table 5, from which can be seen clearly the effect of an individual process parameter on the contour error.

From Table 5, it can be seen that the contour error is influenced dominantly by the mold temperature. As the mold temperature increases from the low to high level the contour error will increase by 34%, i.e. the radius of curvature of the concave surface of the lens will be 34% smaller than the average value for the eight run experiments, which is −3.3. The large effect of the mold temperature on the contour error can be attributed to both free mold shrinkage and stress. This can be seen clearly from the relatively large effect of the mold

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