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Injection Compression Molding of Wedge-shaped Plates: Effects of Processing Parameters

SHIH-JUNG LIU* AND KUN-YEH LIN

Polymer Rheology and Processing Lab

Department of Mechanical Engineering

Chang Gung University, Tao-Yuan 333, Taiwan

ABSTRACT: Thermoplastic wedge-shaped plates have been widely used as a light guide module in thin film transistor (TFT) liquid crystal display (LCD). This article studied the injection compression molding of thermoplastic wedge-shaped plates. The effects of various processing parameters on the dimensional quality of molded parts were studied including melt temperature, mold temperature, melt filling pressure, short shot size, packing pressure, compression pressure, and cooling time. The material used was general-purpose polystyrene. Injection compression molding experiments were conducted on a modified injection-molding machine equipped with a melt compression unit. After molding, the quality of parts was evaluated by the deviation from mold dimensions. An experimental study, based on the Taguchi orthogonal array design, was conducted to identify the relative significance of all these parameters. Among the processing parameters in this study, short shot size and melt temperature were found to be the principal parameters affecting the dimensional accuracy of molded parts. The effects of the compression stage on the birefringence of molded plates were also investigated. The final goal of this study was to better understand the effects of various processing factors on the injection compression molding of wedge-shaped plates, so that steps could be taken to optimize the molding process. This provides significant advantages in terms of improved product quality.

KEY WORDS: wedge-shaped plates, TFT-LCD, injection compression molding, processing parameters.

INTRODUCTION

THIN FILM TRANSISTOR liquid crystal display (TFT-LCD) [1] has been considered to be one of the leading technologies in high-quality displays because of its high brightness, low thickness, and low power consumption. Wedge-shaped plates made of amorphous thermoplastics have been one of the important components in the light guides of TFT-LCD module. Figure 1 shows schematically the light guiding function of the wedge-shaped plate in the display system. The light guide requires accurate dimensions and high surface quality, as well as good optical behavior. Due to its differential thickness distribution, the wedge-shaped plate has been found difficult to be successfully molded by the conventional injection molding process.

*Author to whom correspondence should be addressed. E-mail: shihjung@mail.cgu.edu.tw

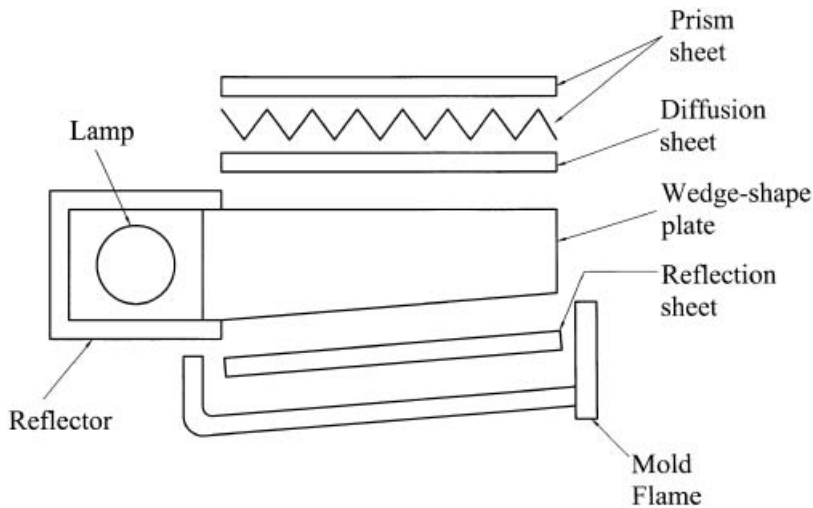


Figure 1. Schematic of the wedge-shaped plate in a thin film transistor liquid crystal display.

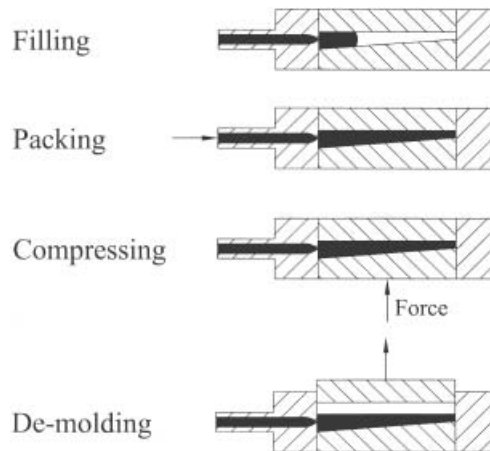


Figure 2. Schematic of the injection compression molding process.

Injection compression molding [2] has the advantages of decreasing molding pressure, reducing residual stress and warpage, minimizing molecular orientation, and reducing part density variation, as well as improving dimensional accuracy [3]. It is widely used to mold precision plastic parts such as connectors, compact discs, and lenses. During cavity filling and the first stage of packing, the process is exactly the same as in conventional injection molding. With some delay after the gates are naturally frozen or mechanically shut-off, a movable mold wall is used to compress the resin, which was injected and partially packed in the cavity previously. Cooling continues to take place as the resin is compressed up to the instant that the mold opens. The injection compression process can thus be divided into the following stages: filling, packing, compression, and cooling. Figure 2 shows schematically the injection compression molding process. The control capacity and flexibility of the injection compression molding technique is significantly greater than that of conventional injection molding. It thus has the potential to produce parts with better

dimensional control. Though precision parts usually have simple geometrical shapes such as disks, plates, or cylinders, dimensional accuracy and stability must be strictly satisfied for these precision parts [4].

This paper studied the injection compression molding of thermoplastic wedge-shaped plates [5]. The material used was general-purpose polystyrene. Injection compression molding experiments were conducted on a modified injection-molding machine equipped with a melt compression unit. After molding, the dimensions of molded parts were measured and compared to the dimensions of the mold. The effects of various processing parameters on the dimensional quality of molded parts were studied including melt temperature, mold temperature, melting filling pressure, short shot size, packing pressure, compression pressure, and cooling time. An experimental study, based on the Taguchi orthogonal array design, was conducted to identify the relative significance of all these parameters. The effects of the compression stage on the birefringence of molded plates were also discussed.

MATERIALS AND EXPERIMENTAL SETUP

Materials and Experimental Setup

The resin used in this study was general-purpose polystyrene with a melt flow index of 8.5. Injection compression molding experiments were conducted on a modified injection-molding machine equipped with a melt compression unit. The molding machine has the highest injection rate of $109 \text{ cm}^3/\text{s}$. A wedge-shaped plate cavity of $100 \times 80 \text{ mm}^2$ with a movable mold wall was used for all experiments. To achieve a uniform flow during melt filling, a coat-hanger manifold as well as a film gate was designed before the plate cavity near the thick side of the wedge-shaped plate. Figure 3 shows schematically, the structure of the mold and the compression unit [5], as well as the dimensions of the wedge-shaped plate. The temperature of the mold was regulated by a water-circulating mold temperature control unit. Due to the small size of the film gate compared to that of the plate, the gate for melt filling was naturally frozen before the compression force was applied to the resin.

During molding, the polymer melt was first injected into the cavity followed by a packing stage. Upon completion of the melt packing process, a compression force was applied to the parts via the movable mold wall. The moving rate (compression rate) was kept constant for all experiments. Five specimens were performed for each test trial. After molding, the thickness at six positions along the centerline of the plates were measured and compared to the dimensions of the mold. The deviation d of molded parts from mold dimensions was defined as follows:

$$d = \sum_{n=1}^6 (t_{\text{part}}^n - t_{\text{mold}}^n) \quad (1)$$

Experimental Parameters and Design

Seven different processing parameters were selected as factors for evaluation, including melt temperature, mold temperature, melting filling pressure, short shot size, packing

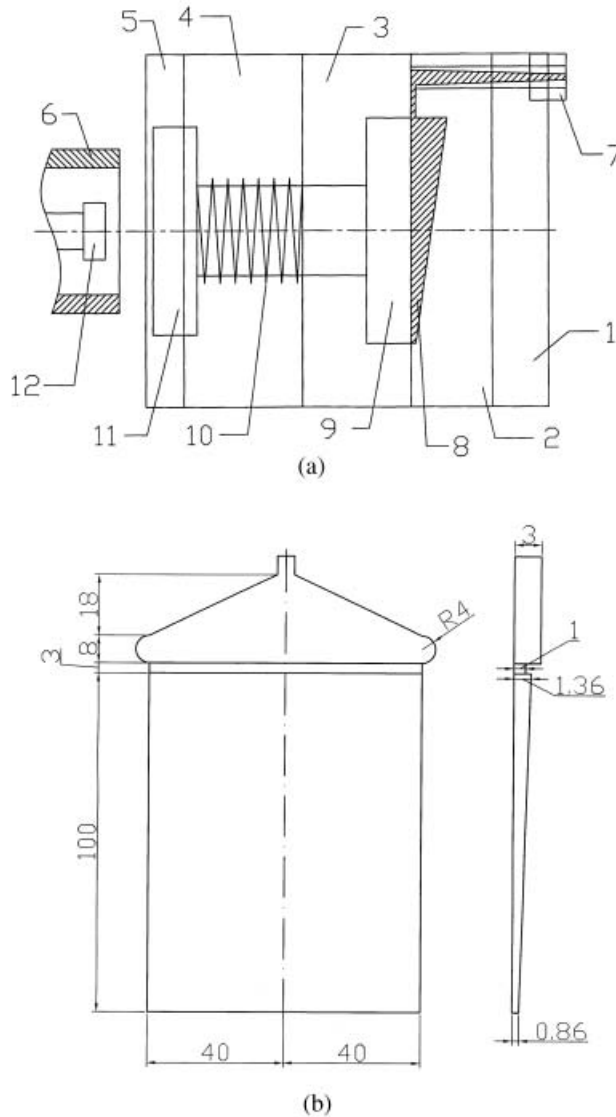


Figure 3. (a) Structure of the mold and the compression unit (1. clamp plate, 2. cavity plate, 3. core plate, 4. spacer, 5. clamp plate, 6. compression cylinder, 7. sprue bushing, 8. cavity, 9. compression plate, 10. spring, 11. compression plate, 12. plate for mounting compression mechanism) and (b) dimension of the wedge-shaped plate.

pressure, compression pressure, and cooling time. The melt temperatures selected were 220, 235, and 250°C. The mold temperature for the parts was set at either 50, 60, or 70°C. Three different short shot sizes were used: 92%, 97% (under fill), and 102% (overfill) of the mold cavity. The melt injection pressure was 105, 113, and 120 MPa. The compression pressure was maintained at either 184, 245, or 306 kPa. The cooling time was set at 10, 20, and 30 s. Finally the melt packing pressure was maintained at 98.8, 127, and 155 MPa.

Table 1. Factors and levels selected in the main experiment.

	Level 1	Level 2	Level 3
A – Melt temperature (°C)	220	235	250
B – Mold temperature (°C)	50	60	70
C – Short shot size (%)	92	97	102
D – Melt injection pressure (MPa)	105	113	120
E – Compression pressure (kPa)	184	245	306
F – Cooling time (s)	10	20	30
G – Packing pressure (MPa)	98.8	127	155

Table 1 lists the processing parameters and parameter levels selected in the main experiment.

RESULTS

Injection compression molding experiments were conducted on a modified injection-molding machine equipped with a melt compression unit. All molded wedge-shaped plates exhibited larger than mold-dimension size at the thick side, while exhibiting smaller than mold-dimension size at the thin side of the plates.

Effects of Processing Parameters on Dimensional Accuracy

Various processing variables were studied in terms of their influence on parts dimensional quality: melt temperature, mold temperature, melting filling pressure, short shot size, packing pressure, compression pressure, and cooling time. The dimensional deviations obtained from each test trial are analyzed statistically. In the analysis, a signal-to-noise (S/N) ratio is the statistical quantity representing the power of a response signal divided by the power of the variation in the signal due to noise [6]. The S/N ratio is derived from the loss function and assumes different forms depending on the optimization objectives. The maximization of the S/N ratio leads to the minimization of any property that is sensitive to noise. In order to minimize the dimensional deviations of injection compression-molded wedge-shaped plates, the equation describing the smaller-the-better characteristic can be used for the analysis [6]:

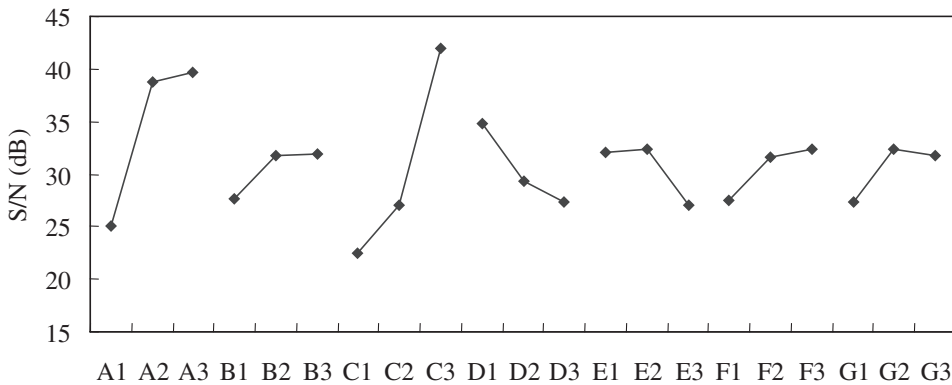
$$\frac{S}{N} = -10 \log_{10} \left[\left(\frac{1}{n} \right) \sum_{i=1}^n d_i^2 \right] \quad (2)$$

where d_i is the dimensional deviations of molded plates, and n corresponds to the number of samples in each test trial. An L'18 experimental matrix based on the Taguchi method [6] was designed. Table 2 lists the experimental array design. The optimum factor levels with the largest S/N ratios can then be obtained, which will minimize sensitivity over the range of noises [6].

The variation of the dimensional deviations for different processing parameters and noise were analyzed according to the methods developed by Taguchi [6]. The S/N ratios for the main experiment were calculated and the results are shown in Figure 4. Based on

Table 2. $L'18 (3^7)$ orthogonal array used in this study.

Run	A	B	C	D	E	F	G
1	1	1	1	1	1	1	1
2	1	2	2	2	2	2	2
3	1	3	3	3	3	3	3
4	2	1	1	2	2	3	3
5	2	2	2	3	3	1	1
6	2	3	3	1	1	2	2
7	3	1	2	1	3	2	3
8	3	2	3	2	1	3	1
9	3	3	1	3	2	1	2
10	1	1	3	3	2	2	1
11	1	2	1	1	3	3	2
12	1	3	2	2	1	1	3
13	2	1	2	3	1	3	2
14	2	2	3	1	2	1	3
15	2	3	1	2	3	2	1
16	3	1	3	2	3	1	2
17	3	2	1	3	1	2	3
18	3	3	2	1	2	3	1

**Figure 4.** Variation of the S/N ratio with factor level for injection compression-molded wedge-shaped plates.

the figure, the optimum factor levels that could statistically result in the minimum dimensional deviations for the injection compression-molded wedge-shaped plates were predicted to be A3/B3/C3/D1/E2/F3/G2. These optimized factor levels represented a melt temperature of 250°C, a mold temperature of 70°C, a 102% short shot size, a melt injection pressure of 105 MPa, a compression pressure of 245 kPa, a cooling time of 30 s, and a packing pressure of 127 MPa.

Effect of Compression on Birefringence

In addition to the part dimensional accuracy, the birefringence developed in polymeric materials was also an important quality especially for optical parts such as wedge-shaped plates. It can be expected that compression adds thermal-induced birefringence to the

molding. However, the magnitude of birefringence introduced by compression is less than that introduced by packing, especially packing after the peak cavity pressure. This means that it is possible to maintain the same degree of shrinkage control with reduced orientation through a proper combination of packing and compression.

The effect of compression pressure and compression hold time on the birefringence of molded wedge-shaped plates was studied. Figure 5 shows the birefringence of molded plates subjected to different compression pressures by the movable wall, while Figure 6 shows the molded birefringence subjected to different compression times. The birefringence of molded wedge-shaped plates can be reduced by increasing the compression forces and the compression time.

With conventional molding, if two moldings are molded with the same filling condition by different packing pressures, the one with higher packing pressure will have a higher level of molecular orientation. This is due to the packing-induced orientation. In injection compression molding, since the compensation for shrinkage is mainly a result of the compression, packing can be shortened and flow-induced orientation can be reduced. With a compression mechanism available, the shrinkage compensation can be decoupled from frozen molecular orientation.

Significance of Processing Parameters

To identify the relative significance of the processing parameters on the dimensional accuracy of injection compression-molded plates, a standard analysis of variance (ANOVA) has been performed according to the methods developed by Taguchi [6]. Table 3 lists the calculated results for molded parts. The variance ratio, denoted by F in

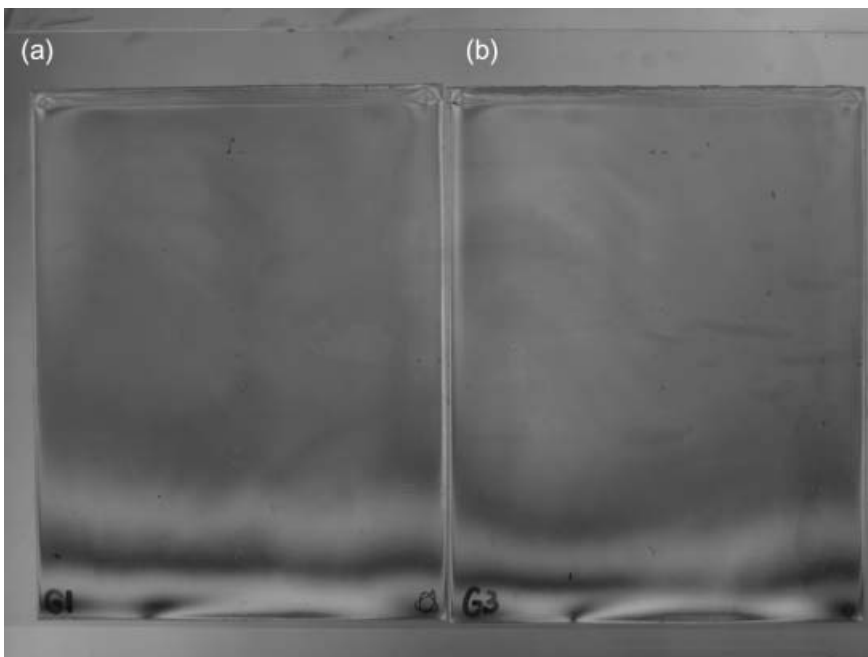


Figure 5. The birefringence of molded plates subjected to different compression pressures: (a) 180 and (b) 300 kPa.

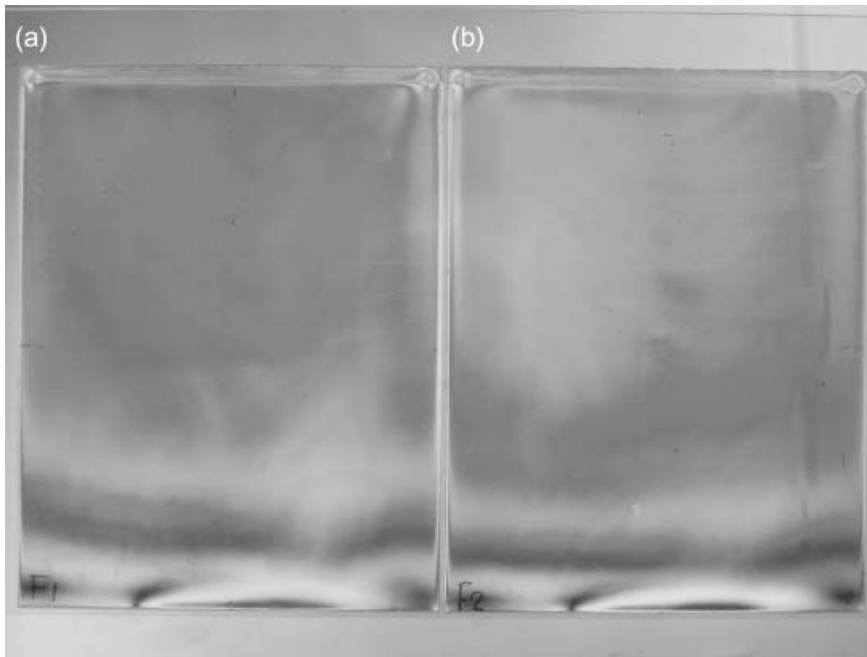


Figure 6. The birefringence of molded plates subjected to different compression times: (a) 0 and (b) 10 s.

Table 3. ANOVA table of injection compression-molded plates.

Factor	Degree of Freedom	Sum of Square	Variation	F	Order of Significance
A	2	0.012713	0.006357	6.012322	2
B	2	0.000842	0.000421	0.398259	7
C	2	0.03331	0.016655	15.75305	1
D	2	0.002684	0.001342	1.269396	3
E	2	0.000951	0.000476	0.449874	6
F	2	0.000985	0.000493	0.465995	5
G	2	0.001309	0.000654	0.618845	4
Error	75	0.081409	0.001085		
Total	89	0.134203			

Table 3 is the ratio of the mean square due to factor and the error mean square. A larger value of F means the effect of that factor is larger compared to the error variance. The larger the value of F, the more important that factor is in influencing the process response. The significance of each processing factor on the dimensional accuracy of injection compression-molded wedge-shaped plates can therefore be judged by the values of F in Table 3.

Based on Table 3, the relative significance of each processing parameter on the dimensions of molded polystyrene plates was arranged in the decreasing order of short shot size ($F=15.75$), melt temperature ($F=6.01$), melt injection pressure ($F=1.27$), packing pressure ($F=0.62$), cooling time ($F=0.47$), compression pressure ($F=0.45$), and mold temperature ($F=0.40$). For the factors selected in this study, short shot size and melt

temperature were found to be the two principal parameters affecting the dimensional accuracy of molded wedge-shaped plates.

DISCUSSION

Role of Compression

Up to the present, the wedge-shaped plates have been made by conventional injection molding. During the molding process, after the cavity is filled, a high pressure is applied on the upstream of the gate to force additional melt into the cavity. The compressibility of the melt allows the core to be compressed. Packing raises the melt density in the cavity and compensates for the shrinkage during subsequent cooling. This stage, called packing (or holding), starts from the instant the cavity is filled to the instant the gate is frozen. Packing is the dynamic nonisothermal flow during the post-filling process [7].

Such a packing-based densification introduces packing orientation, which affects dimensional stability and optical properties. It has been proposed [8,9] that the development of the birefringence of a polymeric material could be related to the stress state during flow under states that the birefringence is linearly proportional to the principal stress difference, i.e.

$$\Delta n = C(\sigma_1 - \sigma_2) \quad (3)$$

where C is the stress-optical coefficient, and σ_1 and σ_2 are the stresses in the principal directions [10].

Compression can provide another densification mechanism to conventional molding and can be used to mold parts of good densification without a high degree of frozen-in orientation. The compression mechanism can pressurize the melt without inducing molecular orientation. The injection compression molding process incorporates both packing-based and compression-based densification in sequence. Injection compression molding retains the advantages of conventional molding, such as smooth material feeding and easy automation. With both densification mechanisms, injection compression has enabled precision molders to meet the dual requirement of accurate dimensional control with little frozen orientations.

In this study, the molded birefringence was found to decrease with the compression pressure (Figure 5) and the compression hold time (Figure 6). This might be due to the fact that the compression mechanism applies direct force on a movable mold wall to compress the melt inside the cavity. The pressure is not applied at isolated points, but on the whole projected area. The pressure is not transmitted by the melt, but is applied directly to the melt on the wall. Compression only causes uniform compressive strain and there is no flow-induced birefringence in the compression-molded part. The flow-induced residual stress [11,12] as well as birefringence [3] in molded plates can thus be reduced.

Processing Parameters and Dimensional Accuracy

In injection compression molding, additional processing parameters are involved when compared to those of conventional injection molding. These new processing parameters

include the amount of melt injection (short shot size), compression pressure, and compression hold time. For the parameters selected in this study, short shot size was found to be the most significant parameter affecting the dimensional accuracy of molded plates. The optimum short shot size was found to be 102% of the mold cavity for the levels selected in this study (Figure 4). During the injection compression molding process, the mold cavity was first filled with polymer melt followed by the application of compression via the moving wall. If the short shot size is smaller than optimum, molded parts exhibit smaller than mold dimension size. However, if the short shot size is too big, the high pressure of the excessive polymer melts pushes the moving wall backward and molds parts with greater than mold dimensions.

The second most important parameter affecting the dimensional accuracy of a molded plate was the melt temperature. As soon as the melt begins to enter the cavity it starts to cool and undergoes volumetric shrinkage. It becomes more difficult for the polymer melt to be compressed as the temperature falls. Increasing the melt temperature decreases the cooling rate of the materials and keeps the polymer melt hot for a longer time. The viscosity of the materials decreases accordingly. This will help the moving wall to compress the material and mold a precise plate, as suggested by the experimental result in Figure 4.

Increasing the packing pressure and the packing time helps mold precision parts. During injection compression molding, a packing (hold) pressure is applied to the materials to push them against the mold wall and minimize the shrinkage during the cooling process. One can thus increase the molded part accuracy by increasing the packing pressure or the packing time. However, if the packing pressure is too high, it pushes the moving wall backward and molds an over-sized plate.

The post-filling process primarily controls the quality of a precisely molded part. As long as the polymer melt enters the cavity, it begins to cool and undergoes volumetric shrinkage. A compression-based pressure control mechanism is not coupled to the natural freezing mechanism. It thus remains functional even after the gate freezes, allowing direct pressure control over post-filling for quality. This enhances the control capacity over the post-filling process, which affects part quality significantly. Increasing the compression pressure should minimize the shrinkage of the polymer melt and decrease the molding deviation of the wedge-shaped plates. It should be noted here that although compression can reduce the frozen-in birefringence in molded wedge-shaped plates, its effect on part dimensional accuracy is not as significant as that of conventional packing. Therefore an appropriate combination of packing and compression would be even more important in successfully molding a precise plate with minimum birefringence.

To obtain high dimensional quality parts, the temperature of the melt must remain high enough for a period sufficient for the polymer melt to be compressed by the moving wall. This is aided by having a high mold temperature so that the melt will not cool too rapidly (Figure 4).

Increasing the cooling time can keep the part inside the cavity for a longer time before de-molding. This should help the materials take the contour of the cavity and increases the molding dimensional accuracy, as suggested by the experimental result in Figure 4.

Finally, it should be noted that all molded plates in this study exhibited greater than optimal thickness at the thick side while exhibiting less than optimal thickness at the thin side of the plates. This might be due to the fact that the compression unit used in this study applied a uniform pressure on the plate. Such a uniform pressure may not be enough to compress the polymer melt at the thick side of the plates and may be too much for the thin side of the plates. For future work, a compression unit with variable compression

pressures across the plates should be developed to mold a wedge-shaped plate with a better dimensional accuracy.

CONCLUSIONS

This report has examined the effect of different processing factors on the dimensional accuracy of injection compression-molded wedge-shaped plates. The following conclusions can be drawn based on the current study.

1. One can increase the dimensional accuracy of the molded parts by increasing the cooling time, packing pressure, melt and mold temperatures, melt injection pressure and compression pressure, and by adopting an appropriate short shot size.
2. Among the various processing factors in injection compression molding, short shot size and melt temperature were found to be the principal factors affecting the dimensional accuracy of molded plates.
3. The birefringence in molded plates decreases with the compression pressure and compression hold time, mainly due to the compression providing a better control capability of the post-filling without the coupling of frozen-in birefringence.

In this study, the effects of the processing factors have been investigated and the mechanism of melt densification has been explained, and steps can thus be taken to ensure that the dimensional accuracy can be optimized. This provides significant advantages in improving product quality of injection compression-molded wedge-shaped plates.

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