Research Article

The effect of packing phase and mold temperature on the directional warpage of spherical lenses using the injection molding process

H. Barghikar[1] · P. Mosaddegh[1] · M. Masoumi[2] · M. Ranjbar[3]

Abstract

This study investigated the directional warpage on bi-convex and bi-concave spherical lenses by experimentally monitoring the changes in the pressure and temperature of mold cavity and comparing them with the simulation results. Warpage was investigated in the direction of the introduction of molten materials into the cavity of the mold, and when it was perpendicular to the direction of the fluid wave front. Packing conditions, including packing time and packing pressure, and mold temperatures are among the important factors influencing lens warpage and their geometric quality. In this research, these factors were investigated in a full factorial design of experiment. Also, simulation results are in good agreement with the experimental results obtained by the vision measuring machine apparatus. According to the results of this study, the least warpage values in bi-convex and bi-concave lenses in the direction of the fluid wave front were 180 and 200 microns, respectively; while these values were 172 and 198 microns when the lenses were perpendicular to the fluid wave front. The experimental values of these in the direction of the melt in the entrance of the mold for bi-convex and bi-concave lenses were 149 and 186 microns, respectively, while these values were 143 and 180 microns when the lenses were perpendicular to the flow front direction. In addition, the results of the pressure diagram inside the mold cavities indicated the correlation with the warpage, such that when the slope of the pressure graph was lower, the lens warpage was less too.

Keywords Warpage · Polymeric lens · Injection molding · Packing pressure · Mold cavity

1 Introduction

The injection molding process is very important for the mass production of polymeric lenses due to the high production rate and the low cost of the final products. The application of these lenses is obvious in optoelectronic devices such as mobile phones, tablets, and so on. There is, however, a complex relationship between the injection parameters and the quality of molded plastic spherical lenses in the injection molding process [1–3]. So, characteristics such as warpage, shrinkage, residual stress and birefringence need to be addressed. So far, various factors influencing injection molding parameters have been considered, such as injection velocity, melt temperature, mold temperature, packing pressure and cooling time, to get the optimum geometric quality of polymeric lenses [2, 4–6]. Lu and Khim [7], studied the warpage of meniscus concave lens, finding an optimal level of injection parameters to improve the geometric quality with 3 factors of injection parameters; these included injection velocity, packing pressure and mold temperature at 2 different levels, according to the research carried out in this field. According to the results, the mold temperature could be regarded as the most important parameter affecting the

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contour error (warpage) of the molded lens. Tsai et al. [8] studied the geometric quality and warpage of a plano-convex lens in order to find the optimal level of parameters with 8 factors in 3 different levels. The results of this study indicated that the most important factor in the warpage of the lenses was packing pressure. Spain et al. [9] also investigated the warpage of a plano-convex lens and a bi-convex lens with the changes in the injection parameters, and the peak to valley (PV) level was measured; finally, a model for improving the quality of lens production was presented. The results of this research showed that the most important factors affecting the total warpage were packing pressure and packing time. Tsai et al. [10] also studied the warpage of a plano-convex lens and investigated the pressure profile in the mold cavity. The results of this study showed that the melt and mold temperature and packing time were the most important parameters influencing the warpage and the accuracy of lenses. Mosaddegh et al. investigated the geometric and optical quality of a bi-convex lens produced by the injection molding process. According to their results, the factors simultaneously affecting the geometric quality and the optical quality of these types of lenses were the melt temperature, packing time, injection pressure and packing pressure, respectively. These factors indicated that the simultaneous control of the pressure, in the mold cavity, both during the injection and at the packing stage, could be the solution for suitable injection with the minimal optical errors [11].

Warpage is due to the different volumetric shrinkage along the piece. In fact, the warpage in the piece can be due to the differential effects or area shrinkage and directional effects. Shrinkage changes from one region to another, which is because of the difference in the cooling rate of the piece, refer to the differential shrinkage. Differential shrinkage arises from the calculation of volumetric shrinkage in the entire lens, resulting in the total warpage [12–15].

As it is known, several parameters play a role in determining the geometric quality of the lenses, especially their warpage. Among them, the packing phase has the greatest effect. The mold temperature is also considered a priority due to the direct impact of the polymer melt. Therefore, this research focused on these factors. The directional effects are due to the variations in the volumetric shrinkage along the molten flow and in a direction perpendicular to it, which can be parallel or perpendicular to the flow of materials. What has been studied in this research is the existence of these directional effects on the lens warpage; in fact, the less the directional warpage and the closer its magnitudes to each other, the better the geometric quality of the lens; also, the dimensional tolerances for installing in the optic systems are better. A careful study of the directional effects of warpage can improve the geometric quality of polymer lenses and dimensional tolerances, especially in the injection molding process.

Table 1 Factors and levels used in the experiments

Factors	Level 1	Level 2
Mold temperature (°C)	80	90
Packing pressure (MPa)	90	100
Packing time (s)	8	12

Table 2 Values for other injection parameters

Melt temperature(°C)	230
Injection pressure (MPa)	90
Injection time (s)	6.5
Cooling time (s)	100

2 Methodology

Various factors contribute to the formation of warpage in the polymer lenses. 2 factors of packing (holding) pressure, including packing time (packing conditions in the injection molding) and mold temperatures have the greatest impact on the overall complexity of the lenses. Of course, parameters such as the melting temperature of the polymer also play a role in this regard. The main focus of this study was, therefore, to examine the injection conditions in the packing phase. With several experiments, a 2 level process window was developed for these 3 factors, based on Table 1. Other injection parameters including the injection pressure, the injection time and the constant cooling time were fixed and considered based on Table 2. To investigate the effect of these three parameters, the full factorial method with 8 (2 ^ 3) tests was designed.

The basis for selecting levels was a large number of experiments. The filling of the cavities should be consonant, without any air trap or weld lines in the molded lenses. For example, the packing time was chosen in such a way that, firstly, the cavities would be 100% filled; second, the molten gate of the polymer could be blocked to the mold cavity. Also, according to the initial analysis results, it took about 100 s for 100% of the layers to freeze and reach the glass transition temperature, which was the basis for choosing the cooling level. The temperature range of the mold was chosen in such a way to show an interferometry pattern of lenses surface with a minimum peak to valley (PV) value less than 10 microns. This means that selecting temperatures below 80 °C and more than 90 °C, according to the injection conditions and the experimental results,

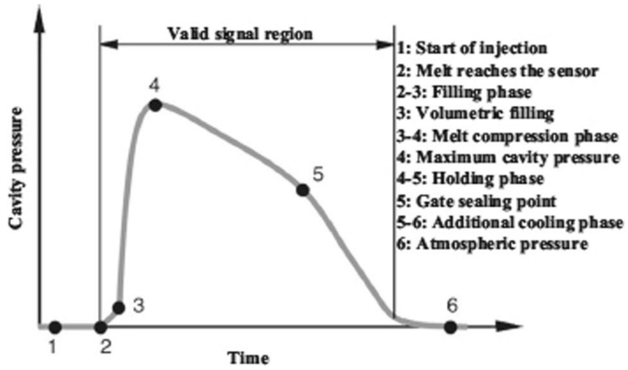


Fig. 1 Determining different injection phases based on a schematic of the trend of mold cavity pressure

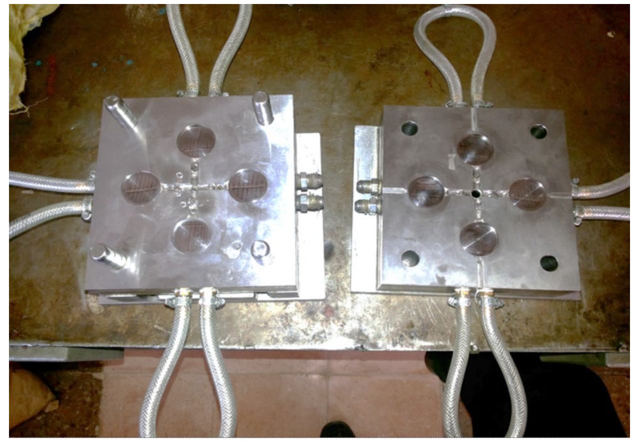


Fig. 2 The 4-cavity mold for injecting bi-convex and bi-concave spherical lenses

will not lead to the desired surface quality of spherical lenses.

The material used in this study was PMMA (Sumipex HT55X) amorphous polymer [16]. Also, the Kistler 6189A temperature–pressure sensor was located in the mold cavity of both lenses. The main application of this sensor was to record the pressure changes during the injection up to the end of the packing time.

Finally, the main objective of this study is to investigate irregular surface by measuring directional warpage, focusing on three main parameters of injection molding for spherical lenses. The lowest directional warpage and its maximum value are discussed with the trend analysis of the pressure diagram inside the mold cavity. Using this method to prevent the high cost of measuring lenses individually can be reliable, From the study of the trend of the molding cavity pressure variations, details of the injection conditions can be found [10]. Figure 1 shows a schematic diagram of the mold cavity pressure.

The molded lenses from the experiments were accurately measured with the vision measuring machine (profile projector); the results were compared with the simulations obtained from the Moldflow Insight software. Then, the least warpage in the direction of flow and that perpendicular to it has been discussed.

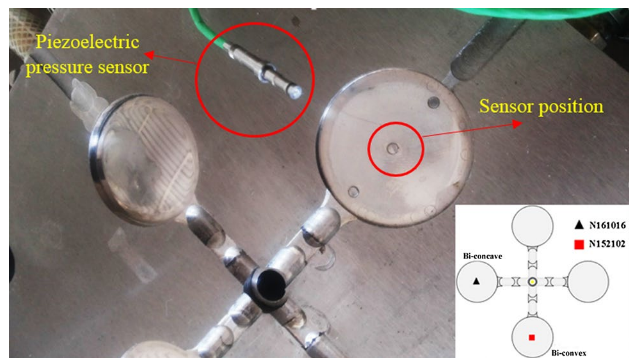


Fig. 3 The position of the sensor in the lens mold cavity

Table 3 The main values of the lens geometry designed for this research

	Radius curvature (mm)	Lens thickness (mm)	Lens diameter (mm)
Bi-convex	220	4.22	36.5
Bi-concave	220	3.98	36.5

3 Experiments

These experiments were performed with a 4-cavity mold, as shown in Fig. 2. The pressure sensor was installed in the middle of the lenses, as illustrated in Fig. 3. The cavities of this mold were two by two geometrically identical and opposite of each other. The main parameters of the lenses geometry are presented in Table 3 and Fig. 4.

The injection process parameters were obtained according to the conditions of the tests in Table 4. Figure 5 shows bi-convex and bi-concave molded lenses as well as the desired direction of measurement. The lenses were measured twice, once parallel to the melted polymer flow, and once in a vertical position, by the vision measuring machine. The results of these measurements are presented in Table 5.

Due to the shape of the holes in the mold, the Y axis for the bi-convex lenses was parallel to the material flow and the X axis was perpendicular to it, while it was opposite for the bi-concave lenses. It is clear from Table 5 that for both lenses, the experiment no. 2 had the highest

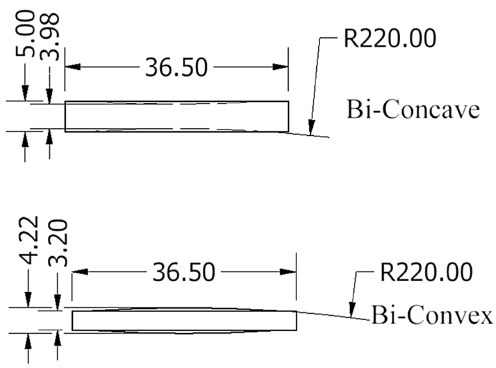


Fig. 4 Geometric dimensions of bi-convex and bi-concave spherical Lenses

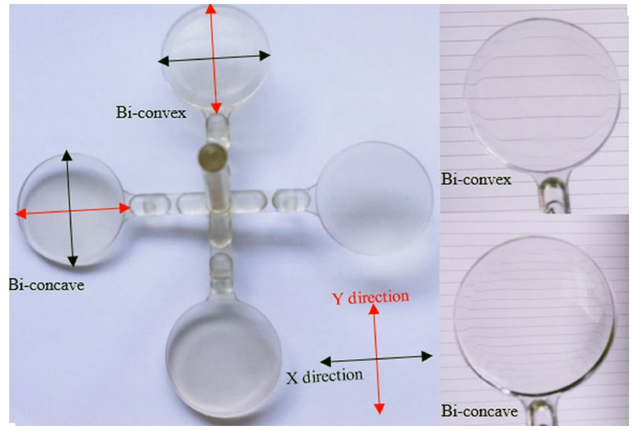


Fig. 5 Injected lenses designed by the 4-cavity mold

directional deviation, while the experiment no. 5 showed the lowest one. The difference between the minimum and maximum dimensional deviation was 26 and 33 microns, respectively, in the bi-convex lens. The difference was between 27 and 30 microns for the bi-concave lens too. This difference in the lens layout in an optical system created the optical aberrations. Comparing the results of the experiment no. 5, with a mold temperature of 80 °C and a packing pressure of 100 MPa over a period of 8 s, with the experiment no. 2, with a mold temperature of 90 °C and a packing pressure of 90 MPa for 12 s, indicated that an increase in packing time could not necessarily trigger the reduced warpage. Also, the high mold temperature could not help this procedure. Instead, the temperature of the mold should be determined according to the polymer conditions and its properties. It could also be observed that in the case of the least deviations, the values of both directional warpages were close together and the lens had a better fit in line with direction. The difference in this value was 8 microns in the bi-convex lens and 2 microns in the bi-concave one.

Due to the fact that the minimum warpage value is specified in bi-convex and bi-concave lenses, and the test conditions creating it are also specified, tracing the trend of pressure variations in the mold cavity could greatly help the production process [17–19]. Therefore, by placing the piezoelectric pressure sensor (the shape and method of installation can be seen in the experiments section) in the mold cavity, the output values could be recorded. Figures 6 and 7 show two trends in the pressure variations in the mold cavity from the start to the end of injection in both simulation and experimental states. Further, the range of injection phases included filling, packing and cooling stages, as shown in the pressure graphs.

The path that had the circle mark in both simulation and experimental modes represented the minimum warpage. As previously noted, longer packing times could not reduce warpage. In other words, it could be determined that if the pressure in each injection follows the trend of the above diagrams, the lenses may have the least directional warpage. A difference of 5 and 7 s could be seen in the experimental and simulation trend, depending on the sensor conditions. However, the methods of slope reduction and the maximum pressure

Table 4 Number and conditions of experiments

	Melt temperature	Packing pressure	Packing time	Mold temperature	Injection pressure	Injection time	Cooling time
Exp. No-1	230	90	8	80	90	6.5	100
Exp. No-2	230	90	12	80	90	6.5	100
Exp. No-3	230	90	8	90	90	6.5	100
Exp. No-4	230	90	12	90	90	6.5	100
Exp. No-5	230	100	8	80	90	6.5	100
Exp. No-6	230	100	12	80	90	6.5	100
Exp. No-7	230	100	8	90	90	6.5	100
Exp. No-8	230	100	12	90	90	6.5	100

Table 5 The results of the dimension measurement of lenses

	Bi-convex		Bi-concave	
	Dimensional variation in the perpendicular material flow (X)	Dimensional variation in the material flow (Y)	Dimensional variation in the material flow (X)	Dimensional variation in the perpendicular material flow (Y)
1	182	195	198	192
2	198	213	230	225
3	174	198	217	220
4	175	205	224	200
5	172	180	200	198
6	172	208	221	195
7	182	195	218	216
8	162	195	221	215

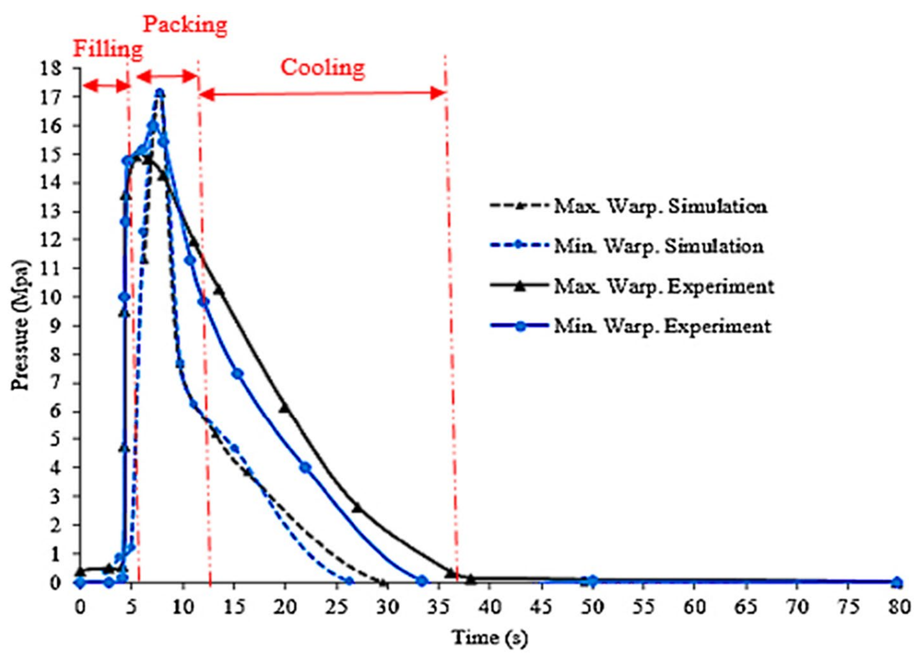


Fig. 6 The trend of pressure variations from the beginning to the end of the injection process in both simulation and experimental conditions for the bi-convex lens

points were consistent with each other. Table 6 shows the important numerical values in tracing the mold cavity pressure.

According to the data in Table 6, the amount of pressure in the mold cavity with the least directional warpage for both lenses was close to each other and is approximately 16 MPa. For the bi-convex lens, this pressure was 33 s until closing the gate and 30 s for the bi-concave lens.

In this research, the focus was to study the pressure conditions inside the mold cavity and its role in warpage. The simulations also showed the pressure drop in the runner system and the mold cavity. For example, Figs. 8 and 9 show the pressure variations in the bi-concave lens from the runners to the mold cavity. According to the Figs. 8 and 9, the amount of pressure drop from the first runner to the final gate was such that in the mold cavity, the 65–70% pressure drop occurred. Changes in packing conditions also cause changes in the pressure diagrams. In other words, changes in the low range during packing pressure will have a huge impact on the directional warpage.

4 Simulations

Simulation of the injection molding process was performed using the Moldflow Insight 2016 software. The simulation considered runners, gates, and sprues with a total of 1602279 meshes and a size of 0.75 mm, as shown in Fig. 10.

The directional warpage varied, as depicted in Figs. 11 and 12, which are related to the test no. 2,with the highest deviation for bi-convex and bi-concave lenses, thereby showing the contour of warpage along the melt flow of

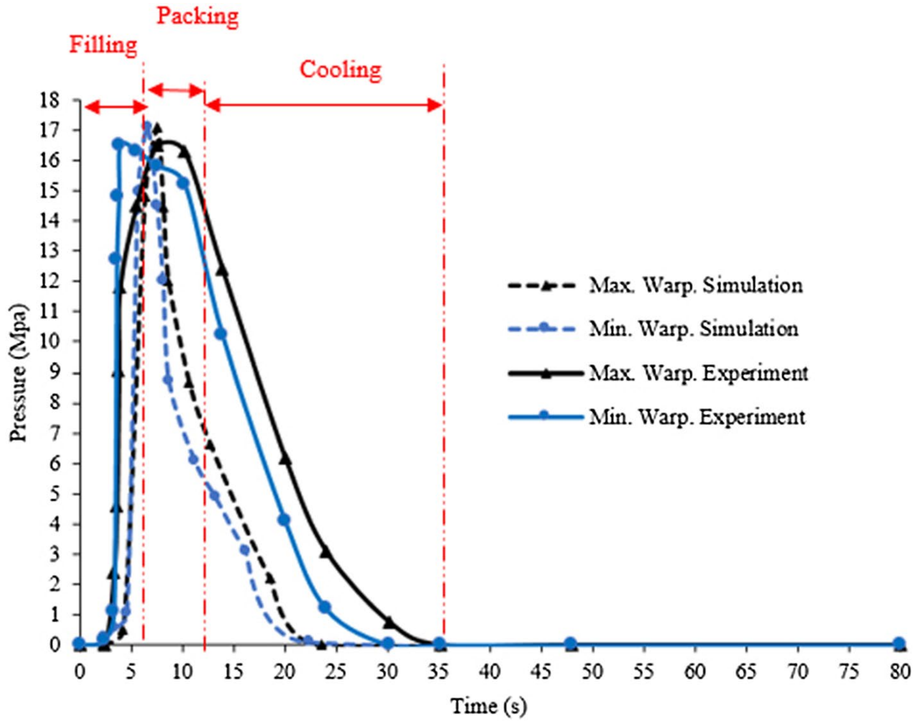


Fig. 7 The trend of pressure variations from the beginning to the end of the injection process in both simulation and experimental conditions for the bi-concave lens

Table 6 The table of maximum pressure and time pressure reaching zero in the experiments

	Maximum pressure in the least warpage condition	Pressure zeroing time in the least warpage condition	Maximum pressure in the maximum warpage condition	Pressure zeroing time in the maximum warpage condition
Bi-convex lens	16.1	33.2	15.2	37
Bi-concave lens	16.4	30.1	17.3	35.1

the polymer. Also, Figs. 13 and 14 show warpage in the direction of the flow perpendicular to both lenses.

According to Figs. 11 and 12, it is clear that in line with the mold gate and the end of it, the amount of this warpage was at its maximum and minimum in the center of the lenses. This could be related to the amount of the shrinkage of the polymer. According to the simulations in Fig. 15, the greatest amount of shrinkage occurred in the thick areas of the lens, and the polymer melt volume and temperature gradient changes in these regions could result in more shrinkage. Also, the value of the deviation from the nominal size was larger in the direction of the current flow, as compared to the vertical direction. The reason for this was the sudden change in temperature from the gate into the mold cavity. The rheology properties and the PVT graph of the assigned PMMA polymer are shown in Figs. 16 and 17, respectively. These graphs display important information about the polymer's behavior when encountering different temperatures and pressures. Behaviors such as polymer shrinkage play a major role in the directional warpage [20, 21]. Therefore, it is necessary to add these properties to the software before the simulation runs. Table 7 shows the values obtained from the simulation of the directional warpage of the lens.

As already mentioned, the amount of warpage in a direction perpendicular to the lens plane (Z axis) is somewhat negligible and almost constant in comparison with other directions. Therefore, it has been ignored in this study. Columns 4 and 7 in Table 7 show the simulated values in the direction of the Z axis.

5 Discussion

Figures 18 and 19 are the two charts derived from the output of Tables 5 and 7. Figure 18 shows the directional warpage simulation values for both bi-convex and bi-concave lenses. In Fig. 19, the same parameter has been investigated in the experiments.

In this figure, the warpage values aligned perpendicular to the lens plane (Z axis) show a significant difference from other values, and they are specified and relatively constant. Also, the minimum value of the warpage was specified to show the experiment no. 5. Also, in the experiment no. 2, the maximum warpage points could be observed.

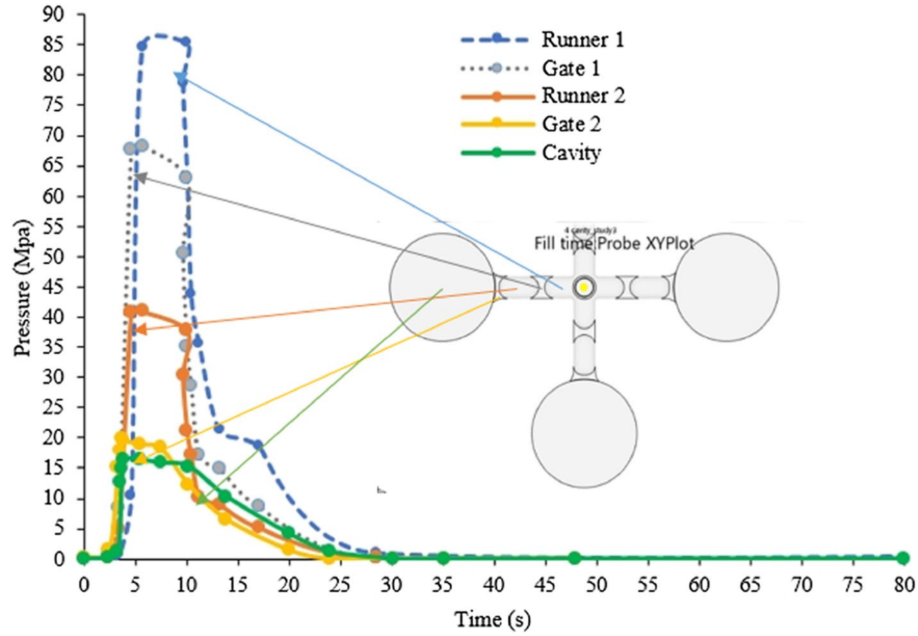


Fig. 8 The trend of pressure in the feeding system and mold cavity for bi-concave lenses at maximum warpage

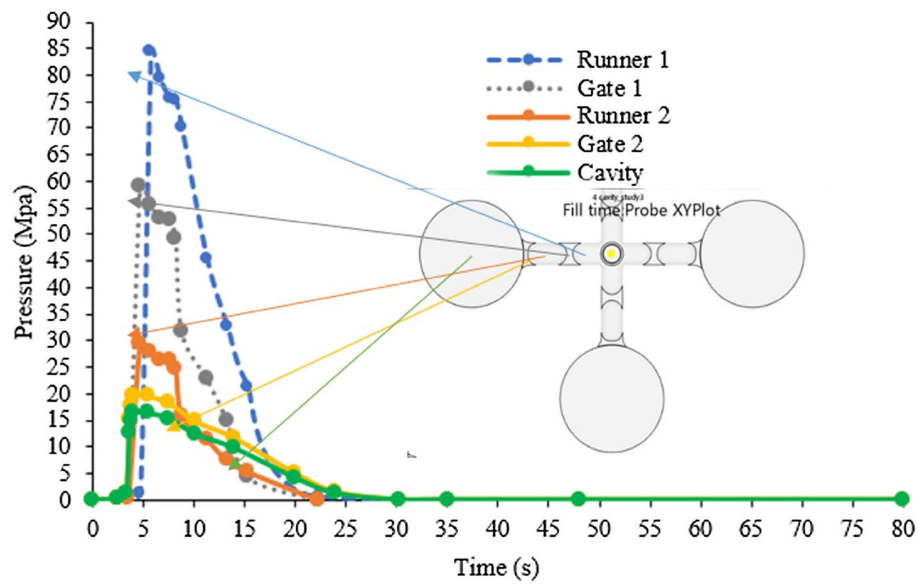


Fig. 9 Investigating the trend of pressure in the feeding system and mold cavity for bi-concave lenses at minimum warpage

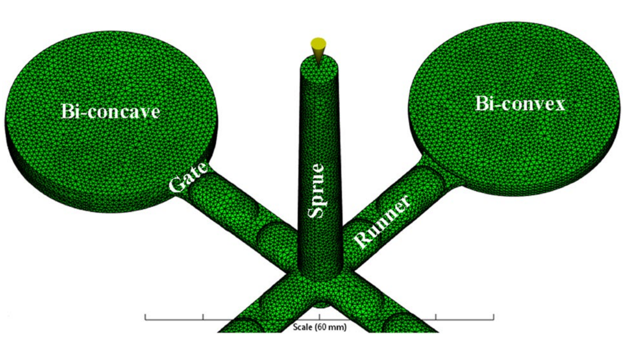


Fig. 10 Meshing the mold cavity and the 4-cavity-mold feeding system

Comparing the 2 charts of Figs. 18 and 19 reveals that the trends of the experiments and simulations diagrams were the same, both confirming each other. This means that experiment no. 5 conditions led to the minimum warpage. It is also clear that the warpage values did not fluctuate in the vertical direction of the flow in the bi-concave lens, because the rate of temperature variation in the vertical direction of the flow in the bi-concave lens was not high. Also, the numerical values in the experiment no. 5 conditions for both lenses, in both directions, were close to each other and close to the simulation.

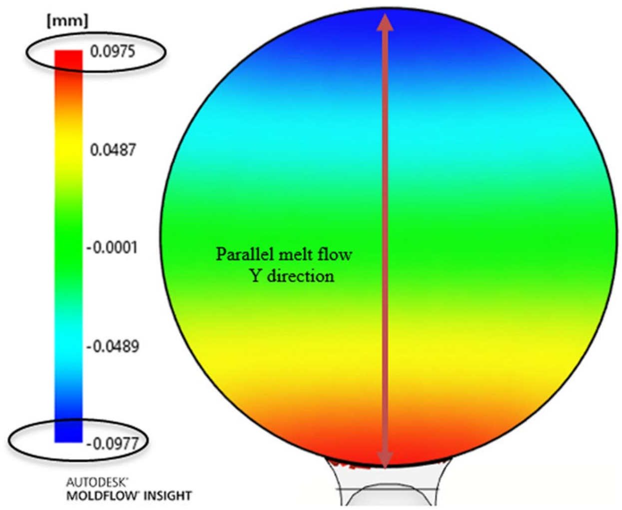


Fig. 11 Warpage of the bi-convex lens in the direction of melt flow—the total deviation of 194 microns

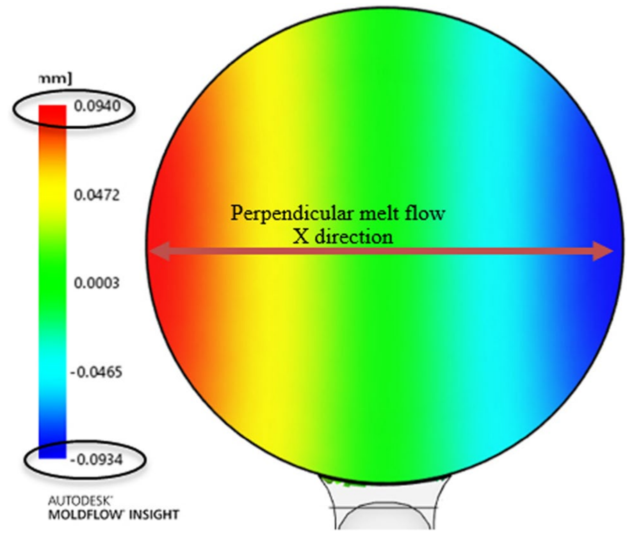


Fig. 13 Warpage of the bi-convex lens perpendicular to the melt flow-the total deviation of 187 microns

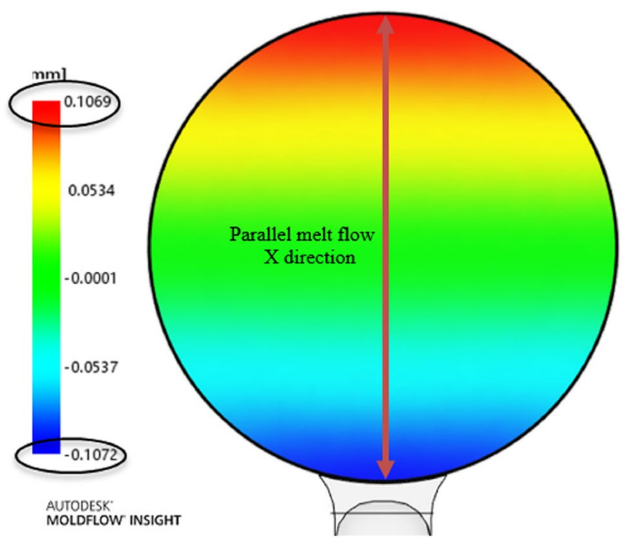


Fig. 12 Warpage of the bi-concave lens in the direction of the melt flow—the total deviation of 213 microns

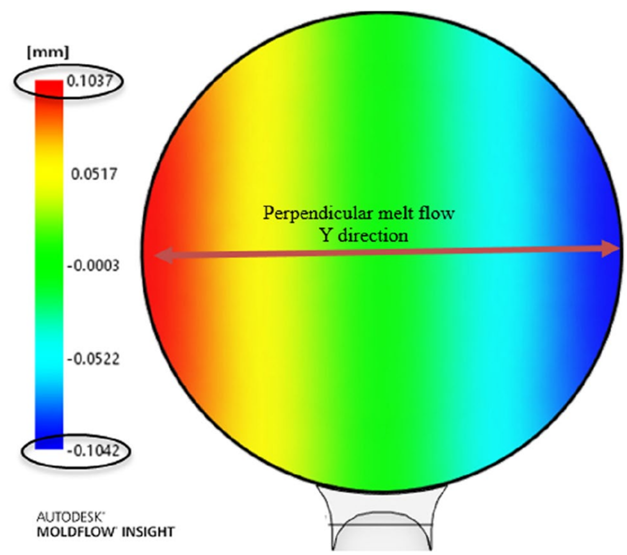


Fig. 14 Warpage of the bi-concave lens perpendicular to the melt flow—the total deviation of 207 microns

6 Conclusions

1. The conditions in which the lenses exhibited the least warpage, according to the results, consisted of a melting temperature of 230 °C, a mold temperature of 80 °C, and a 90 MPa injection pressure in 6.5 s, with a packing pressure of 100 MPa in 8 s. These data were, therefore, in a good agreement with the simulation results, proving that this methodology could be a good tool to predict the lens warpage. The high temperature of the mold and the increase in the packing time may not reduce the directional warpage and the minimum level could be limited. In the mentioned conditions, the directional warpage of the lens was minimum and in both directions, parallel to the flow direction and perpendicular to it, the values were close to each other. The directional warpage difference was 8 μm for the bi-convex lens and 2 μm for the bi-concave lens. Due to the important role of the directional warpage in the installation of the continuous optic systems, the pressure has been traced within the mold cavity.

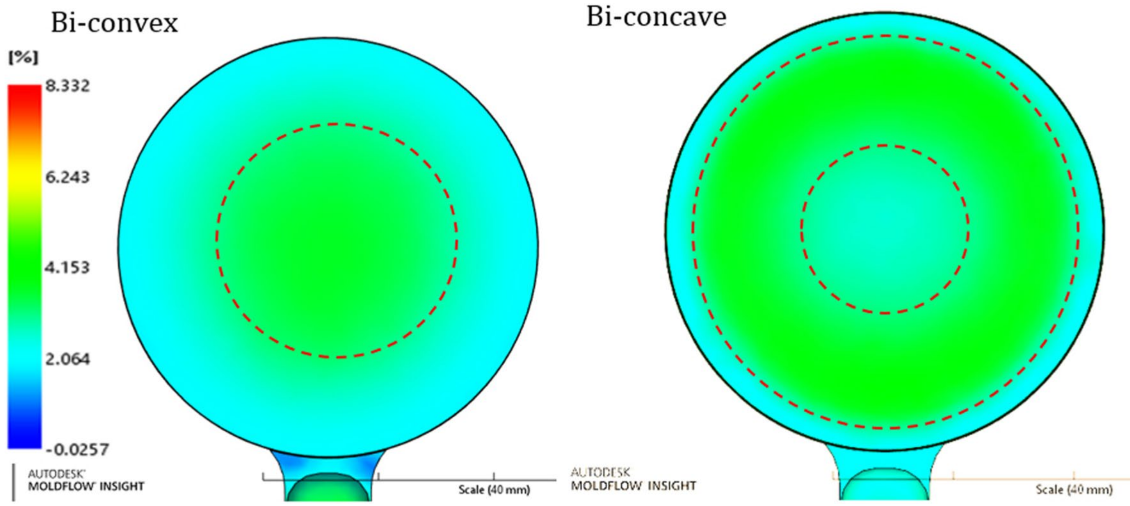


Fig. 15 Lens shrinkage volume after the end of the cooling phase

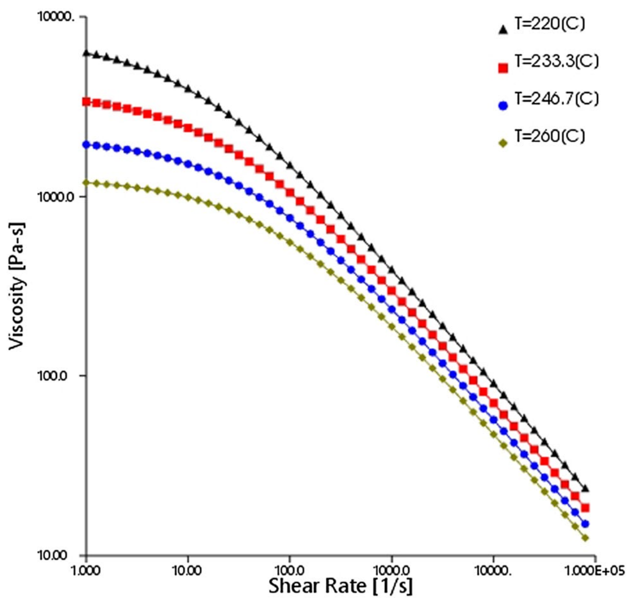


Fig. 16 Viscosity graph versus shear rate at different temperatures

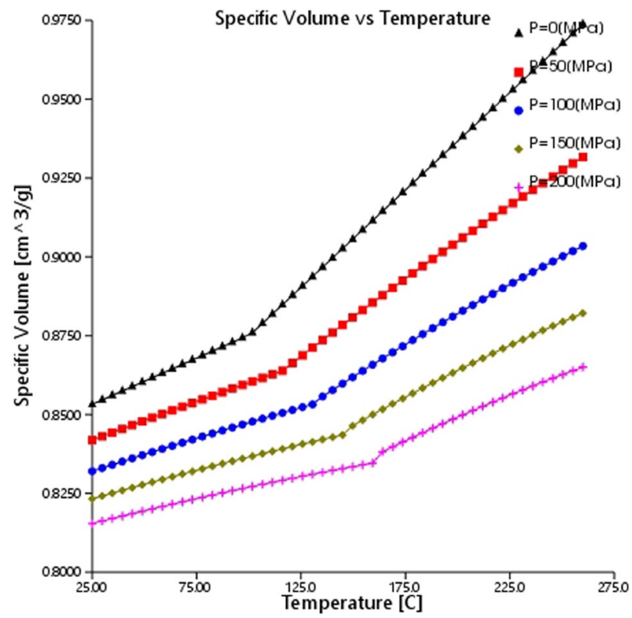


Fig. 17 Polymer behavior properties at different pressures of PVT

2. The trend diagram of the pressure showed that the increase in the time required to make the pressure caused by packing time reach zero was directly related to the directional warpage. In other words, the direction of diagram in the X axis (the time axis) could be important, such that in the experiments, this difference for the maximum and minimum warpage in the bi-convex lens was 4 s, while for the bi-concave lens, this was 5 s (lower values could result in the minimal directional warpage).
3. The packing condition, despite the low 10 MPa range, had an intensive effect on the reduction of directional warpage, so that with a 10% change in these conditions, the warpage improved approximately 30% in the experiments along the X and Y directions for the bi-convex and bi-concave lenses.
4. Injection pressure was different from the mold cavity pressure. The difference between the maximum mold cavity pressure for the most and least amounts of directional warpage in both lenses was about 1 MPa. However, for the bi-convex lens, the minimum warpage was 1.1 MPa greater than its maximum, and for the bi-concave lens, it was opposite. So, the minimum amount of warpage was 0.9 MPa less than its maxi-

Table 7 The warpage values obtained from the simulation of the lenses

	Convex			Concave		
	Dimensional variation in the perpendicular material flow (X)	Dimensional variation in the material flow (Y)	Dimensional variation in the Z direction	Dimensional variation in the material flow (X)	Dimensional variation in the perpendicular material flow (Y)	Dimensional variation in the Z direction
	X	Y	Z	X	Y	Z
1	170	177	24	198	198	26
2	187	194	24	213	207	31
3	169	176	24	197	193	28
4	163	175	22	203	198	29
5	143	149	20	186	180	26
6	145	150	21	196	192	28
7	168	165	22	205	199	30
8	145	150	20	190	185	26

Fig. 18 Simulated directional warpage values

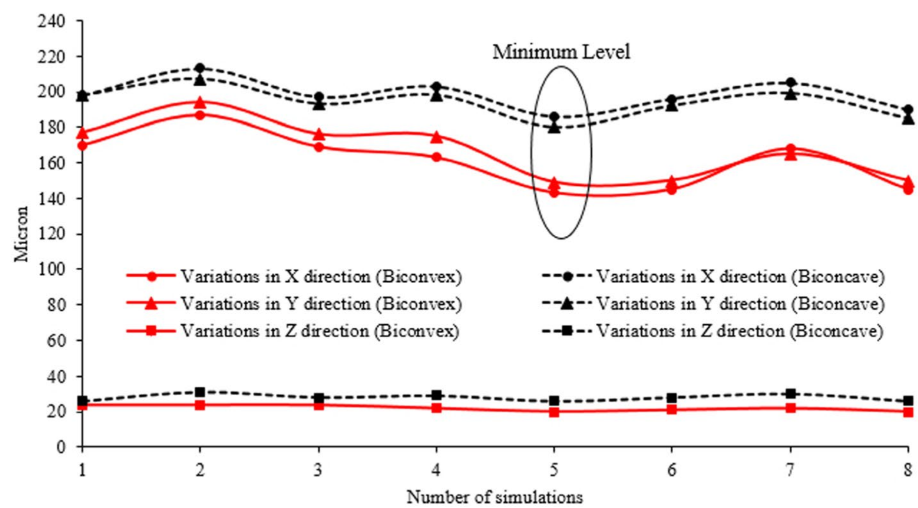
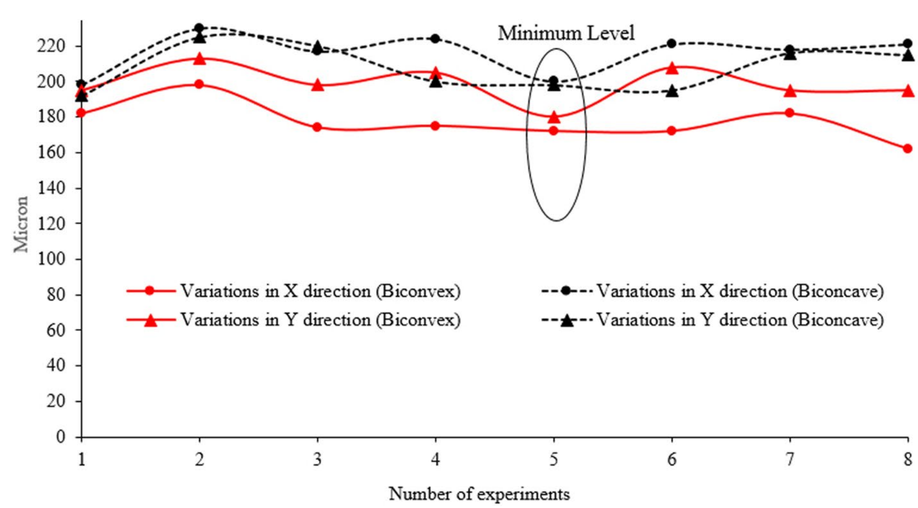


Fig. 19 Measured warpage values in the experiments



mum. This difference was related to the geometry of the lenses, as the surface curvature was changed in the position of the sensor.

5. The optimum level with the minimum directional warpage consisted of a melting temperature of 230 °C, a mold temperature of 80 °C, and a 90 MPa injection pressure in 6.5 s, with a packing pressure of 100 MPa in 8 s.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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