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**Research Article**

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# Aspherical plastic lens injection molding warpage and opto-mechanical analysis

**Abstract:** The aspherical plastic lens is commonly used in commercial optical products. The injection molding process introduces warpage and stress residue into the aspherical plastic lens. Mold flow software is generally used in injection molding simulation and successfully predicts molding warpage results. This paper attempts to link mold flow and optical design software by opto-mechanical analysis. The lens surface warpage can apply the Zernike polynomial and transform it to the optical aberration. Meanwhile, the injection molding process and the operation parameters also affect the plastic lens warpage value. Thus, according to optical software, the injection molding process parameters will affect lens optical performance. The plastic lens aberration results can evaluate the lens warpage effect and optimize the injection molding process parameters. Further, by reversing lens warpage aberration in the plastic lens model, it can preliminarily compensate for the warpage error in the lens design process.

**Keywords:** aberration; mold flow; plastic lens; warpage; Zernike polynomial.

**OCIS codes:** 220.4880; 220.1250; 220.1000; 220.4610.

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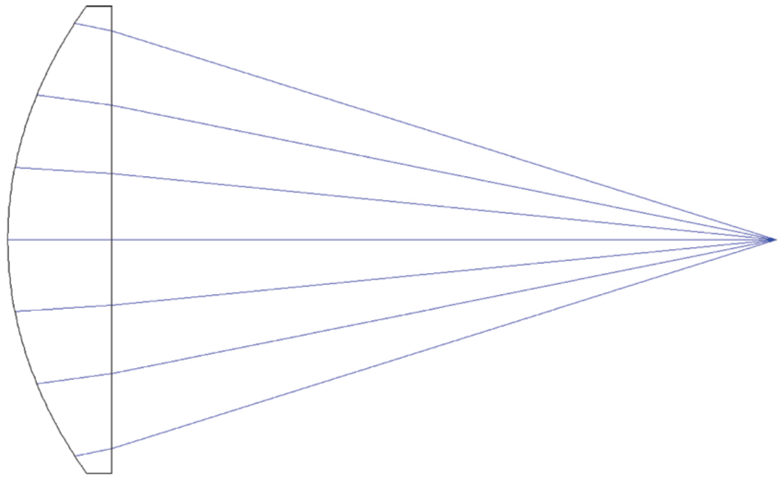
## 1 Introduction

The plastic lens is generally used in small diameter optical systems, such as in cell phone lenses or web cameras. The large plastic lens accuracy is lower than the grind glass lens. This study attempts to apply opto-mechanical analysis in the mold injection process to improve plastic lens accuracy. The injection molding process of the plastic lens will cause lens geometry warpage and introduce optical aberration to the lens surface. The aspherical plastic lens general design process occurs after injection molding, measuring the lens geometry by form Talysurf or interferometer, for correcting the lens warpage error. There are many articles [1–4] discussing aspherical plastic lens warpage error compensation. This study attempts to analyze the relationship between the injection molding process and optical aberration. Mold flow software is widely used in injection molding simulation because it provides an injection mold warpage prevision [1]. The plastic lens is needed for filling, pressure packing, and cooling in the injection molding process. The aspherical plastic lens optical design result is shown in Figure 1. The optical software can export the lens 3D model by STL file.

The 3D lens model is imported to the mold flow software and designs the lens melt flow channel, model base, and cooling channel, as shown in Figure 2. The injection molding operation parameters include: filling time, melt temperature, mold temperature, maximum injection pressure, packing time, maximum packing pressure, and cooling time. The mold flow simulation operation parameters are shown in Table 1. Melt temperature is one important parameter in the mold injection process. Melt temperature will affect plastic flowability in the mold chamber. Note, plastic flowability is a factor of lens warpage. This study discusses the melt temperature effect on lens warpage results at melt temperatures of 240°C, 245°C, and 250°C. The plastic material is Polymethylmethacrylate.

The mold operation parameters were inputted to the mold flow software and the lens warpage grids were exported. The lens warpage grids were needed to search the grids on the lens surface. The Zernike polynomials fitting results can be used by optical software to evaluate lens optical performances. Meanwhile, the Zernike polynomials fitting can compensate for lens warpage, as shown by the simulation flow chart in Chart 1. The aspherical plastic lens mold flow simulation combined



| | Surf:Type | Comment | Radius | Thickness | Glass | Semi-Diameter | Conic | Par 0 (unused) | Par 1 (unused) | Par 2 (unused) |
|---|---|---|---|---|---|---|---|---|---|---|
| OBJ | Standard | | Infinity | Infinity | | 0.000 | 0.000 | | | |
| * | Even Asph.. | 32971 | 39.827 V | 12.000 | PMMA | 27.000 U | -0.676 V | | -6.297E-004 V | 9.053E-008 V |
| 2* | Standard | | Infinity | 76.916 V | | 27.000 U | 0.000 | | | |
| IMA | Standard | | Infinity | - | | 5.344E-004 | 0.000 | | | |

**Figure 1** The aspherical plastic lens optical design.

with opto-mechanical analysis can predict lens warpage and compensate for it in the design process.

**Table 1** The mold flow simulation operation parameters.

| | |
|---|---|
| Filling time, s | 0.67 |
| Melt temperature, °C | 250, 245, 240 |
| Mold temperature, °C | 80 |
| Maximum injection pressure, <MPa | 221.8 |
| Packing time, s | 5 |
| Maximum packing pressure, MPa | 221.8 |
| Cooling time, s | 20 |

## 2 Numerical method

The mold flow simulation result grids are needed to find the lens surface grid point. Thus, if the lens grid position meets the aspheric equation, Eq. (1), the grid is on the lens surface.

$$z=\frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}}+\alpha_1r^2+\alpha_2r^4+\alpha_3r^6+\alpha_4r^8+\alpha_5r^{10} \quad (1)$$

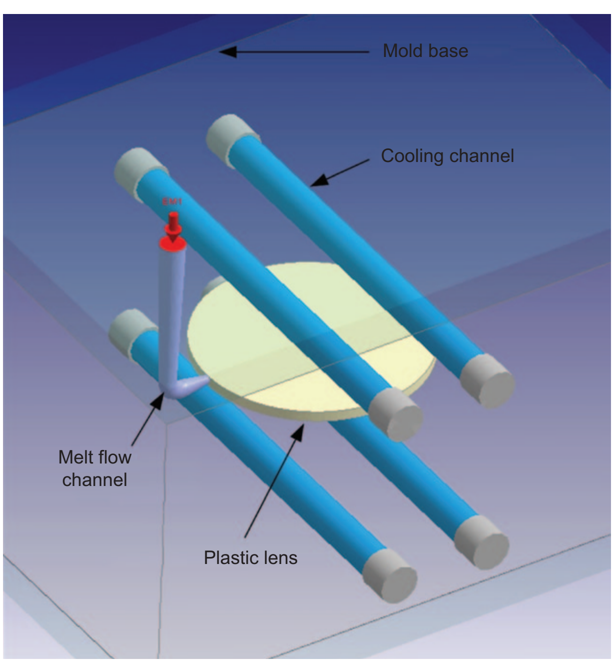



**Figure 2** The mold base, cooling channel, and melt flow channel design in mold flow simulation software.

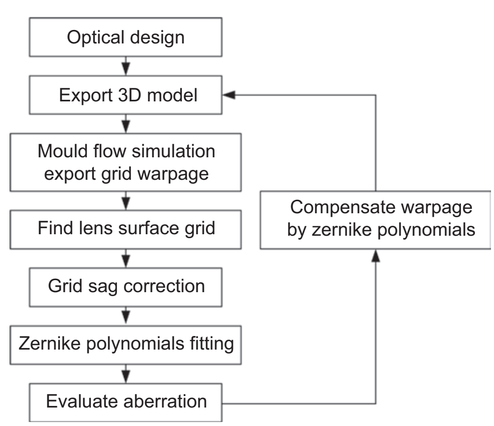



**Chart 1** The flow chart of plastic lens mold flow and opto-mechanical analysis.

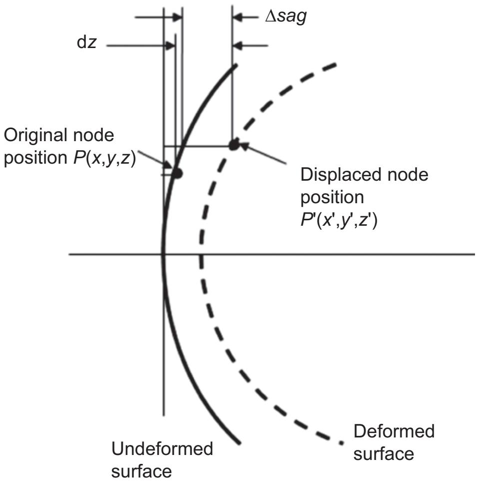



**Figure 3** The lens warpage grid node point requires correction to the optical sag distance.

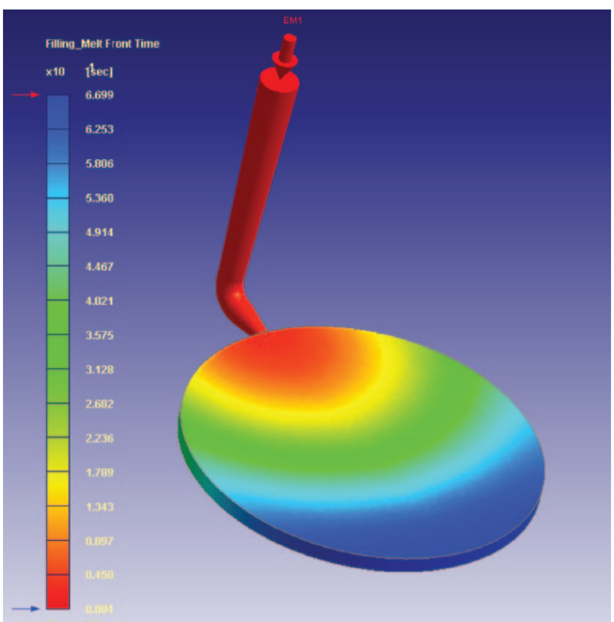



**Figure 4** The mold filling melt front time.

where $r$ is the lens radius, $c$ is lens curvature, $\alpha$ is the aspherical factor, and $k$ is the conic constant.

The warpage of the lens surface grid is needed to transfer to optical axial sag [5–11]. The fitting results are fed into the optical software to evaluate system aberrations. As shown in Figure 3, the original node point is $P(x,y,z)$, the lens warpage leads the node point to $P'(x',y',z')$. Therefore, the warpage on the optical axial sag is shown in Eq. (2).

$$\Delta sag = P'(x',y') - P(x',y') \tag{2}$$

The lens warpage result after correcting the sag can be used to find the Zernike polynomial coefficients shown in Eq. (3):

$$\Delta Z(r,\theta) = A_{00} + \sum_{n=2}^{\infty} A_{n0} R_n^0(r) + \sum_{n=1}^{\infty}\sum_{m=1}^{n} R_n^m [A_{nm}\cos(m\theta) + B_{nm}\sin(m\theta)] \tag{3}$$

where $\Delta Z(r,\theta)$ is the optical surface at the lens entrance side, $r$ is the radial on the reflection surface, θ is the azimuth angle, and $A_{nm}$ and $B_{nm}$ are Zernike coefficients. The $R_n^m(r)$ radial dependence of the Zernike polynomial is shown in Eq. (4). The Fringe Zernike fitting results are added to the incidence surface. The Fringe Zernike fitting results can be fed into optical software by Fringe Zernike sag terms.

$$R_n^m(r) = \sum_{s=0}^{\frac{n-m}{2}} (-1)^s \frac{(n-s)!}{s!\left(\frac{n+m}{2}-s\right)!\left(\frac{n-m}{2}-s\right)!} r^{(n-2s)} \tag{4}$$

## 3 Simulation result

The melt plastic flowed into the mold cavity and the plastic injection direction introduced tilt aberration. The

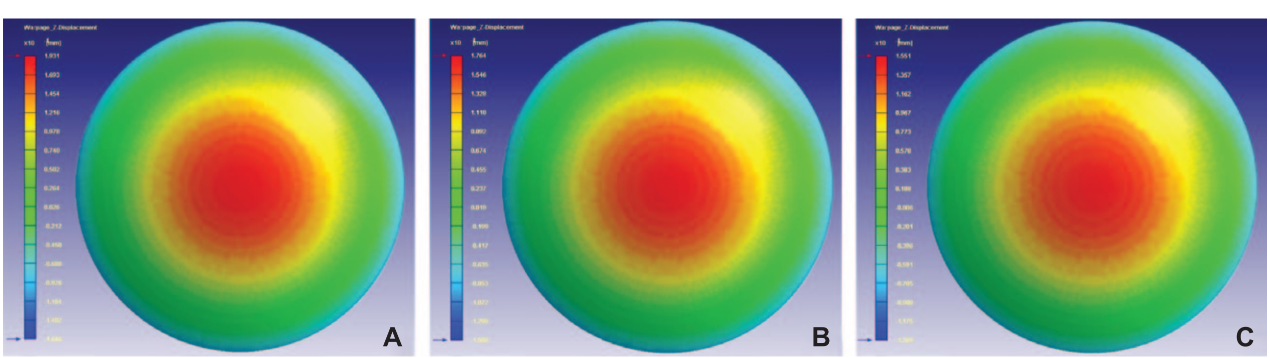



**Figure 5** The different melt temperatures of the lens surface 1 $Z$-direction displacement. (A) Melt temperature 250°C. (B) Melt temperature 245°C. (C) Melt temperature 240°C.

**Table 2** The different melt temperatures affect lens surface aberration (mm).

| | Melt temperature, 250°C | Melt temperature, 245°C | Melt temperature, 240°C |
|---|---|---|---|
| Lens surface 1 | | | |
| Piston | 2.7031193240E-01 | 2.6289639564E-01 | 2.5542261433E-01 |
| Focus | 4.7136202762E-02 | 4.59442D8592E-02 | 4.4678382350E-02 |
| Pri-spherical | -1.9677000788E-02 | -1.9013980S31E-02 | -1.8334497917E-02 |
| Lens surface 2 | | | |
| Piston | -1.3502S29796E-01 | -1.3136247809E-01 | -1.2763571S72E-01 |
| Focus | 2.1726259675E-02 | 2.08S5382S57E-02 | 2.00026IS503E-02 |
| Pri-spherical | 5.72341699S1E-03 | 5.4630861 D15E-03 | 5.2032594619E-03 |

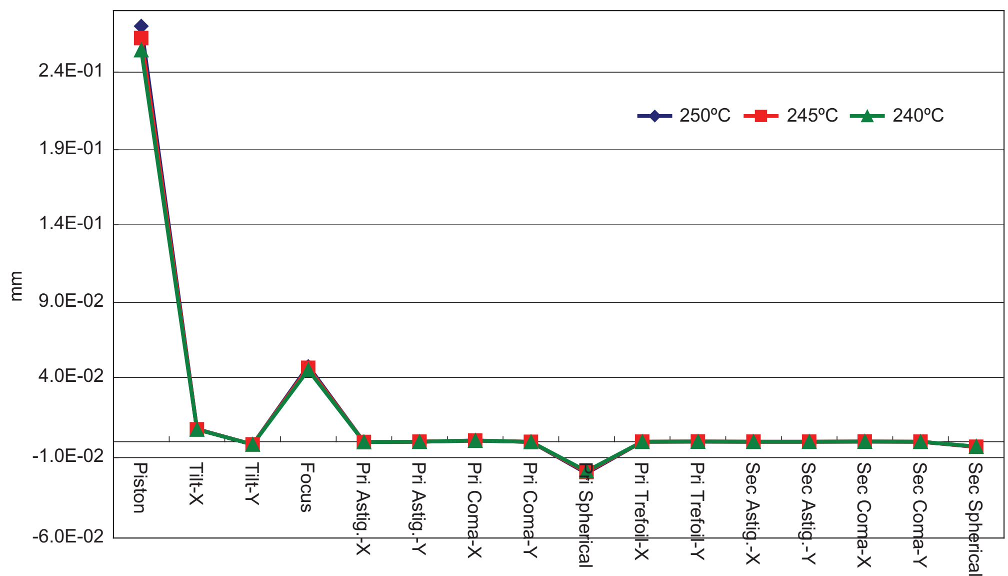



**Figure 6** The different melt temperatures of the lens surface 1 aberration.
The blue rhombus melt temperature is 250°C. The red square melt temperature is 245°C. The green triangle melt temperature is 240°C.

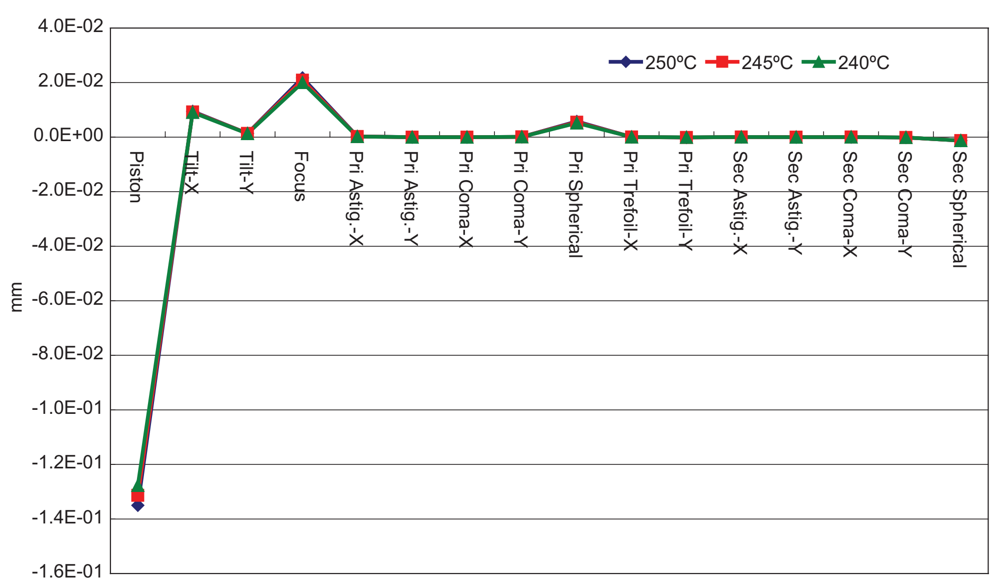



**Figure 7** The different melt temperatures of the lens surface 2 aberration.
The blue rhombus melt temperature is 250°C. The red square melt temperature is 245°C. The green triangle melt temperature is 240°C.

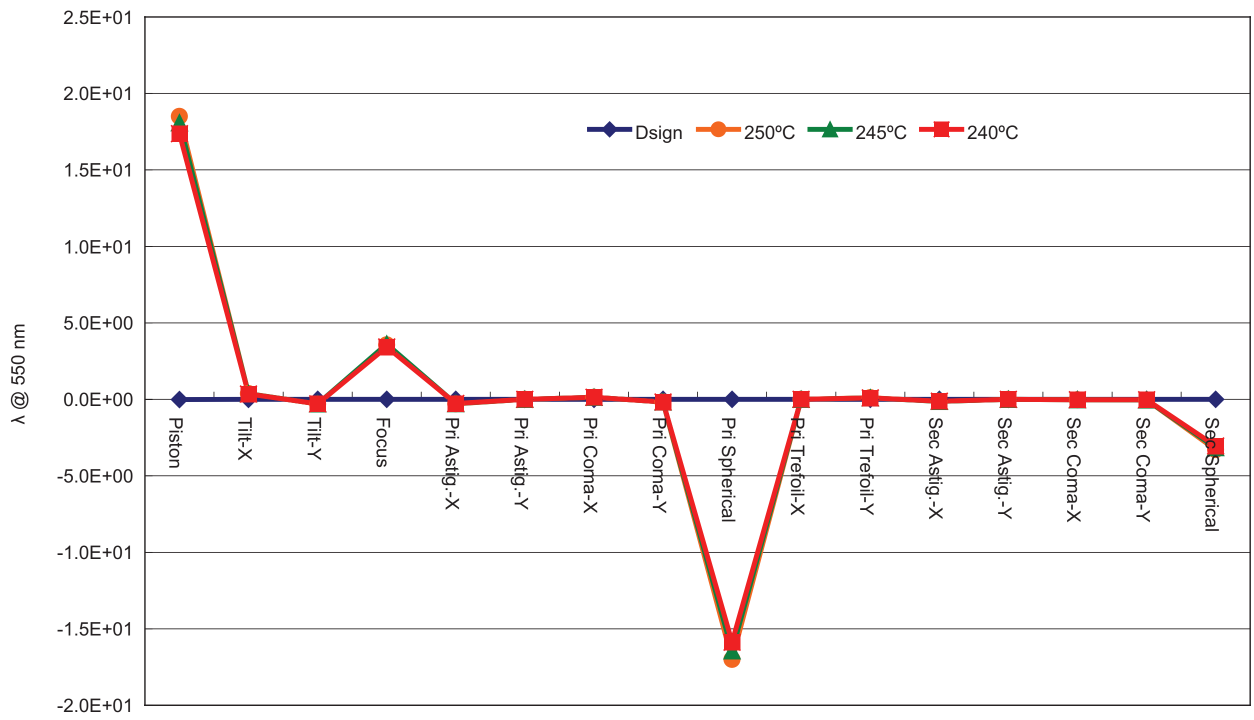



**Figure 8** The different melt temperatures of the lens system aberration.
The blue rhombus is the original design aberration. The orange circle melt temperature is 250°C. The green triangle melt temperature is 245°C. The red square melt temperature is 240°C.

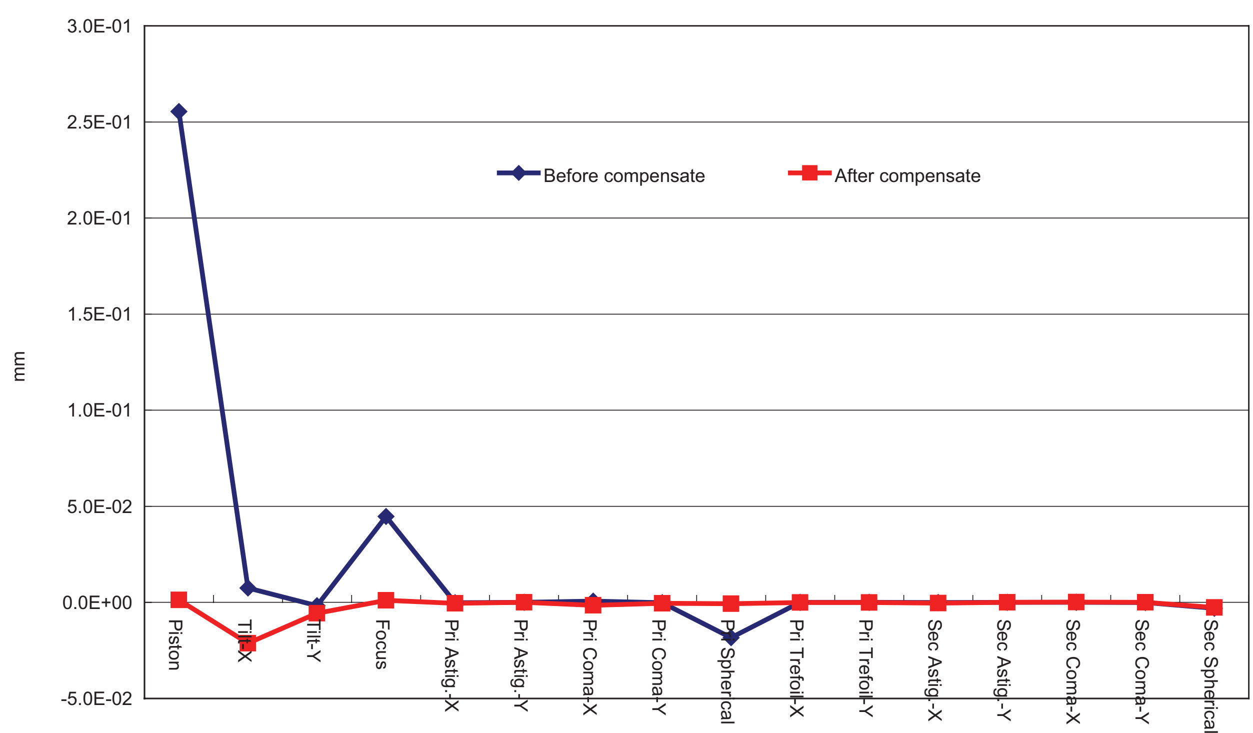



**Figure 9** The lens surface 1 aberration compensation before and after results.
The result before the aberration compensation is shown by the blue rhombus. The result before the aberration compensate is shown by the red square.

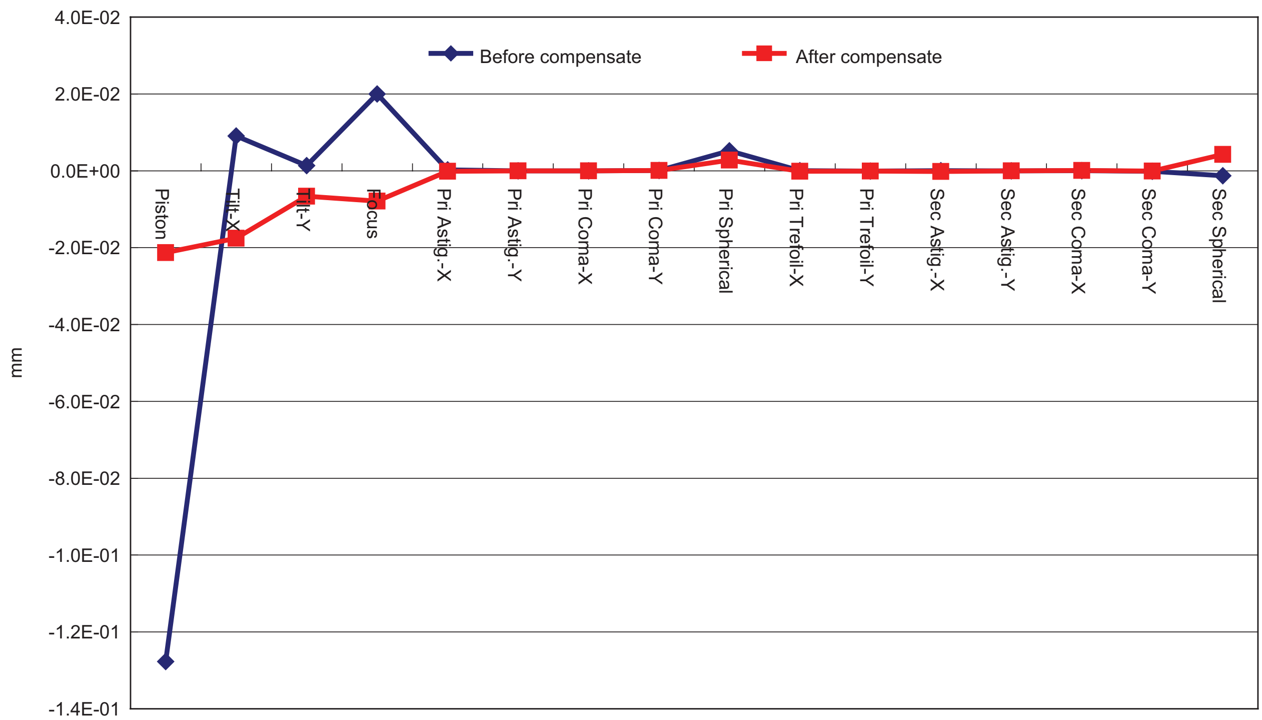



**Figure 10** The lens surface 2 aberration compensation before and after results.
The result before the aberration compensation is shown by the blue rhombus. The result before the aberration compensate is shown by the red square.

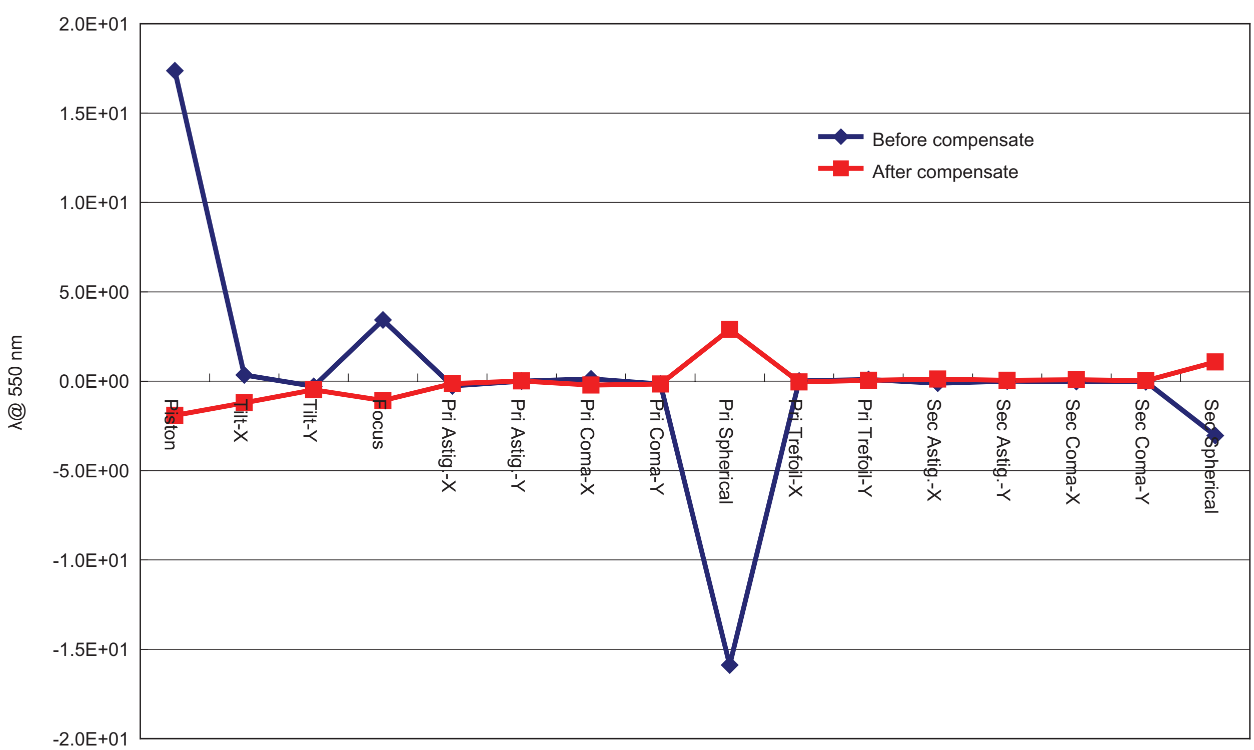



**Figure 11** The lens system wavefront error aberration compensation before and after results.
The result before the aberration compensation is shown by the blue rhombus. The result before the aberration compensation is shown by the red square.

plastic melt front time is shown in Figure 4. The different melt temperatures will cause different *Z*-direction displacement in the plastic lens. The melt temperature 250°C *Z*-direction maximum displacement is 1.934 mm. The melt temperature 245°C *Z*-direction maximum displacement is 1.764 mm, and the melt temperature 240°C *Z*-direction maximum displacement is 1.551 mm, as shown in Figure 5. Thus, different melt temperatures of the lens caused *Z*-direction displacement variance, as represented by the piston, focus, and spherical aberrations shown in Table 2. The plastic lens warpage significantly affecting the lens surface aberration are piston, tilt, focus, and spherical aberrations, as shown in Figures 6 and 7. Although different melt temperatures also affect the lens system warpage aberration, only the piston, focus, and spherical aberrations were more significant, as shown by the results in Figure 8. The lens warpage compensation can be achieved by reverse Zernike aberration. For instance, focus aberration of surface 1 at melt temperature 240°C is 4.4678E-2 mm, shown in Table 2. To compensate focus aberration of surface 1 -4.4678E-2 mm in Zernike focus term on surface 1 has been added for improvement. After lens warpage compensation, reverse warpage aberration on the lens surface meant the lens surface aberration significantly declined, as shown in Figures 9–11. The lens system aberration also reduced and the spherical type is the major aberration in the lens system. Therefore, reversing the lens surface warpage aberration can successfully reduce lens warpage error. Meanwhile, the lower melt temperature assists in lens warpage decline. Melt temperature too low will cause flowability decline and introduce defects in the lens.

## 4 Conclusion

This study employed mold flow software to investigate warpage aberration in a plastic aspherical lens. The simulation results provide the following insights:

- The melt temperature affected the lens surface warpage aberration; the lower the melt temperature the lower the aberration.
- The lens surface warpage that caused aberration are piston, tilt, focus, and spherical.
- The lens reverse warpage aberration on the surface can significantly compensate for warpage error.
- The major lens system aberration types are piston, focus, and spherical.

The other mold injection parameters, such as mold temperature and packing pressure, also influence plastic lens warpage. A further study will discuss the multi-molding injection parameter optimized effect of plastic lens optical aberration.

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