Affordable High Precision Injection Molded Progressive Addition Lenses

No. ：104
Institute：The Ohio State University
Contestant：Likai Li

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Moldex3D

Contestant Introduction

> Name: Likai Li

> Advisor: Prof. Allen Y. Yi

> Institute: The Ohio State University

> Department: Department of Integrated Systems Engineering

> Products in-charge: Affordable freeform optical components

> Specialties: Affordable manufacturing process design of freeform optics, modeling and optimization of injection molded freeform optics.

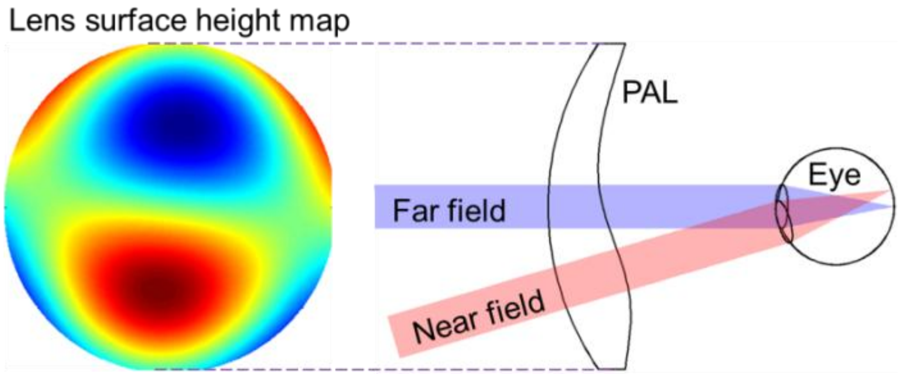
Research Lab Introduction

> The Precision Engineering Research Lab at The Ohio State University was established in 2002. Currently there are 5 Ph.D. students and some MS students. The Lab director, Prof Allen Yi was a staff scientist with Corning Precision Lens prior to joining the Ohio State. His research interests lie in Precision Engineering, in particular, Optical Fabrication and Micromachining. The PERL-OSU is recognized as one of leading centers focusing on affordable freeform optics worldwide.

> The goal of PERL-OSU is to seek fundamental and practical understanding of manufacturing freeform optics at extremely low cost. We realize the affordable devices with premium quality by using the combination of ultraprecision diamond machining and molding techniques. We are interested in microinjection molding, glass molding and hybrid glass-polymer compression molding.

> The PERL has published numerous papers in top journals, such as, Optics Letters, Applied Optics, Journal of Manufacturing Science and Engineering, etc.

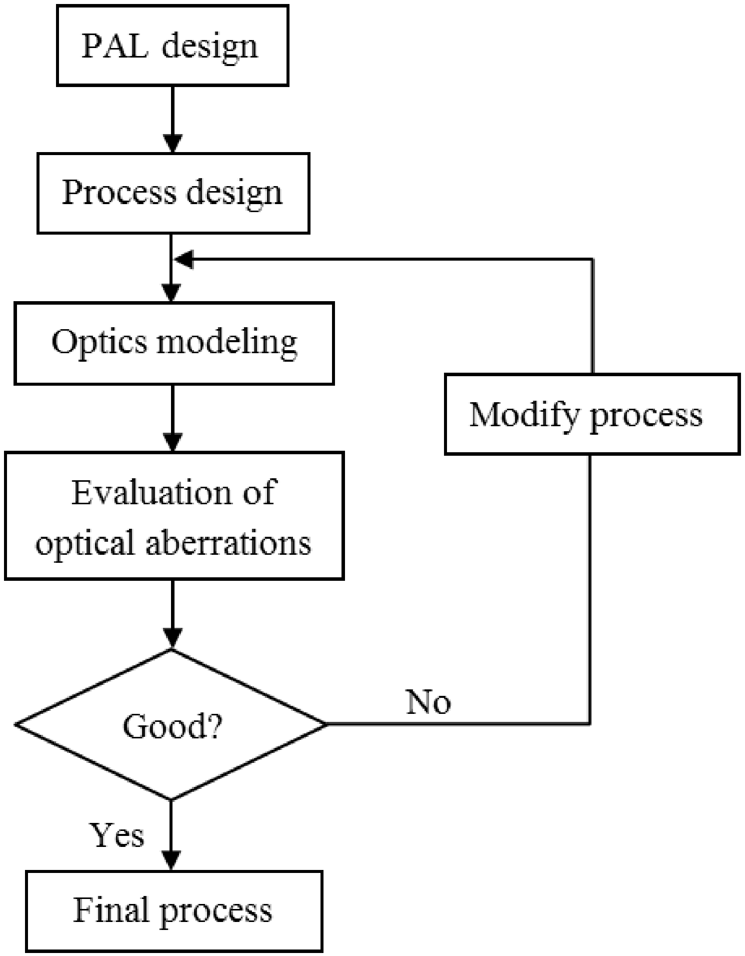
PAL Introduction



> Presbyopia is a common condition associated with the decline in ocular accommodation with age. Due to the poor self-adjusting capability of the aging lenses, seniors with myopia face even more difficulties when looking at objects up close and far away in the same setting.

> In order to compensate for both myopia and presbyopia, progressive addition lenses (PALs) have been widely used over the past few decades. Compared with conventional bifocal lenses where the lens area for near field objects is machined separately from the rest lens surface, a PAL provides users with a continuous change in optical power across different regions of the lens as shown in the above figure. This continuous, non-axisymmetric description of the freeform lens surface makes a PAL completely different from regular ophthalmic lenses for either myopia or presbyopia where optical surfaces are usually axisymmetric (hence much easier to manufacture).

Affordable High Precision PAL Development



- Bulk of the iterations in the optimization is performed using FEM simulation and wave optics theory. In this scenario, the parameters to be optimized are the spherical aberration and cylindrical aberration.
- This arrangement replaces time consuming and costly experiments with numerical modeling, plus the premium optical quality of freeform diamond machining and the low cost nature of injection molding.

Product Development Trend and Challenge

> Development Trend
  - Accurate optical correction
  - Customized medication

> Challenge
  - Modeling difficulty in combining freeform optics and injection molding
  - Difficulty of integrating high precision hybrid optical components
  - Evaluate optical performances influenced by injection molding
  - High cost and long cycle time for developing products

> Common Problems
  - Part warpage
  - Inhomogeneous refractive index distribution
  - Process design for thin plastic coating on hybrid PALs

Why CAE?

> Problems encountered

- Case 1: Part warpage and uneven refractive index distribution change the light propagation through the lens into the eyes
- Case 2: Unfilled hole occurs for plastic coating on hybrid glass-polymer PALs and high residual stress results in crack of part inserts

> Short-term solution implemented

- Case 1: Optimize the injection molding process parameters to achieve better quality. Compensate the optical aberration.
- Case 2: Optimize the part design and process parameters of the plastics coating

> Why utilize CAE Simulation Analysis

- Help engineer fundamentally understand the development of product defects
- Replace time consuming and costly experiments with numerical modeling
- Utilize CAE Simulation Analysis to identify potential problems

> Expected results and objects

- Case 1: Evaluate the optical performance of the injection molded PALs, and optimize manufacturing processes
- Case 2: Design appropriate manufacturing process parameters to achieve injection molded hybrid glass-polymer achromatic PALs

Moldex3D Successful Application
Case Study 1 – Freeform optics

Background

Problems

Injection molding → Part deformation
Uneven refractive index → Change light propagation

Solutions

Moldex3D FEM simulation
- Part deformation
- Refractive index distribution

Freeform optics calculation
- Wavefront error
- Optical aberrations

Wavefront optics measurement
- Shack-Hartmann sensor

Numerical modeling verification

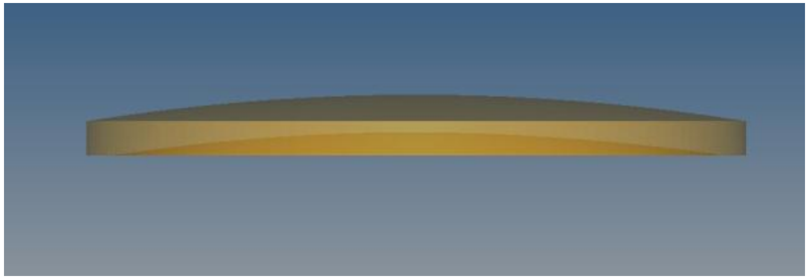
Process optimization and compensation

Background

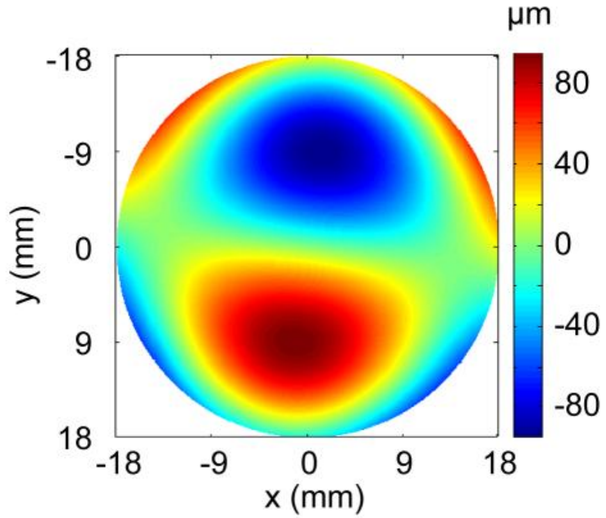
> **Product Size**
>
> – **Diameter： 40 mm**
>
> – **Thickness： 2.3 mm**

> **Material**
>
> – **PMMA**

> **Process Condition**
>
> – **Filling Time： 0.125 Sec**
>
> – **Melt Temperature： 250 ℃**
>
> – **Mold Temperature：75 ℃**



Top spherical surface



Bottom freeform surface

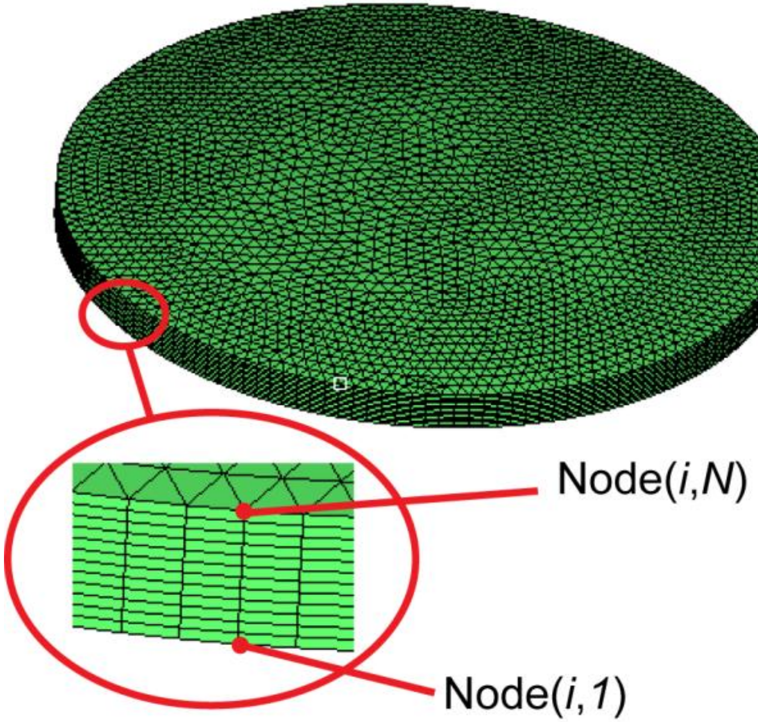
Mesh Model

> Mesh Type
  – **Prism element Solid Mesh**

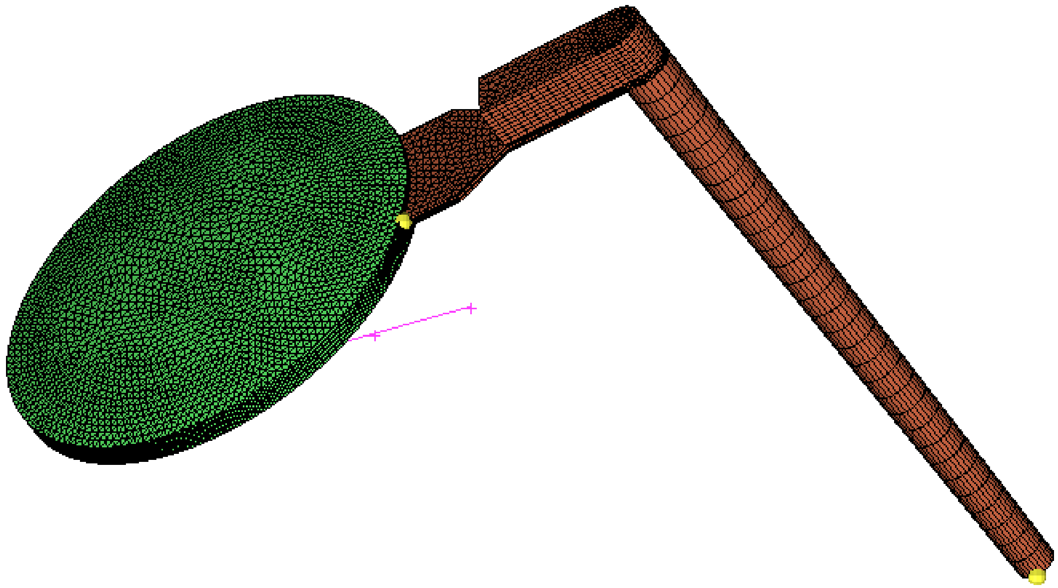
> Mesh Count
  – **Part Mesh: 50304**
  – **Runner Mesh: 11985**

> CPU CPU Time (23 mins)

> Computer Information
  – **CPU: Intel Core i7-3700K**
  – **RAM: 8G**



Runner Layout



Analysis Items and Contents

> Understand the part geometry shrinkage and uneven refractive index distribution resulted from injection molding process

> Utilize the information of part deformation and uneven refractive index to calculate the optical aberrations of the injection molded PALs

> Evaluate the optical performance using Shack-Hartmann wavefront system and further compare the measurements with the simulated results

> Optimize the injection molding process and compensate its optical deviation to achieve premium quality PALs

Process Parameter

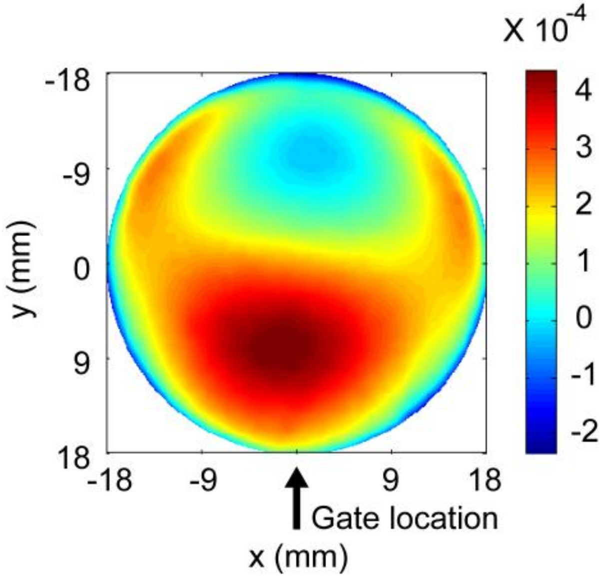
Injection molding condition parameters	
Molding parameters	Values
Melt temperature (ºC)	250
Mold temperature (ºC)	75
Injection velocity (mm/s)	200
Maximum injection pressure (MPa)	100
Velocity/pressure switch (vol %)	90
Packing pressure (MPa)	80
Packing time (s)	6
Cooling time (s)	25
Coolant temperature (ºC)	65

Process Influences [1]

Refractive index distribution

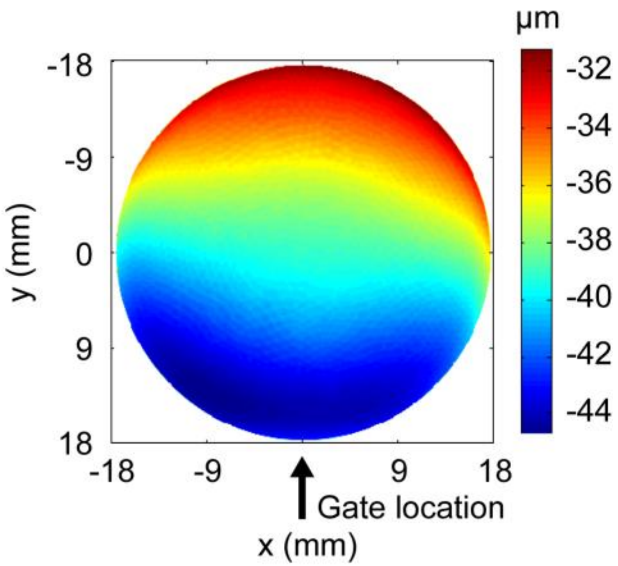
$$n_i = \left(\sum_{j=1}^{N} n(i,j)\right)/N$$

$$\Delta n_i = n_i - \sum_{j=1}^{N_A} n_j \Big/ N_A$$



Thickness deformation

$$d_i' = z'(i,N) - z'(i,1)$$

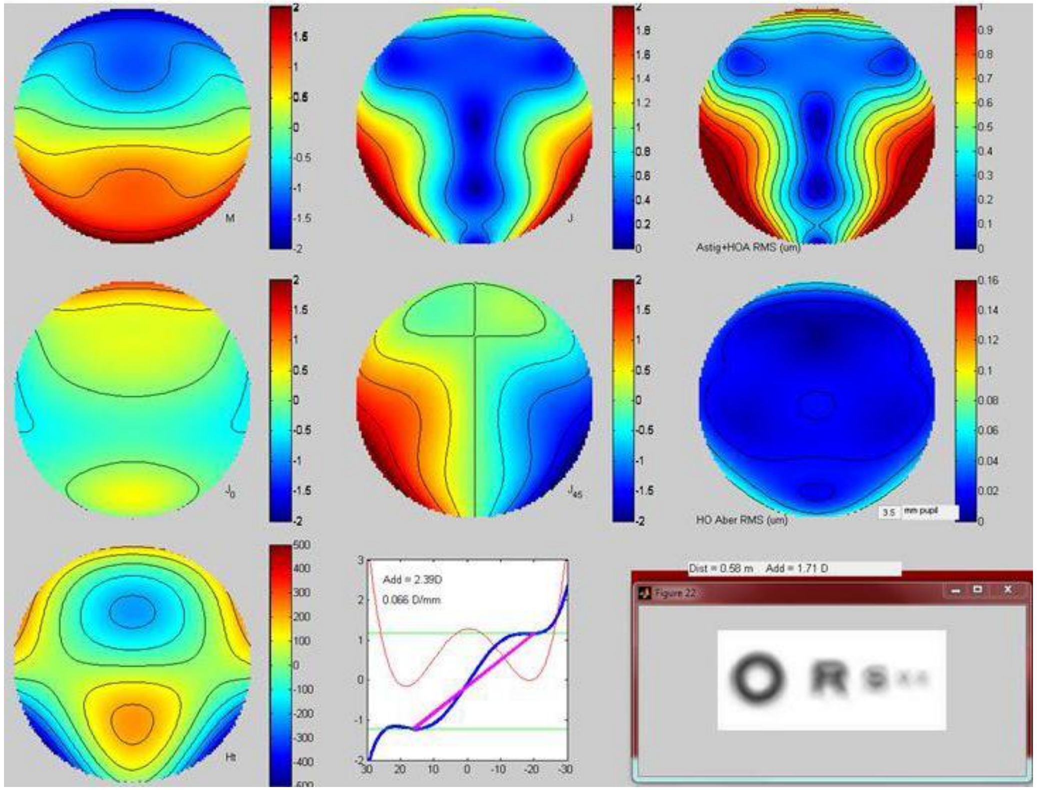


Process Influences

Wavefront deviation [2]

$$D = (\Delta n_i + n_0 - 1) \times (d_i^{'} - t_0)$$

$$cc^{'} = TZ \times ((ZT(x,y) \times cc).* rs_j)$$

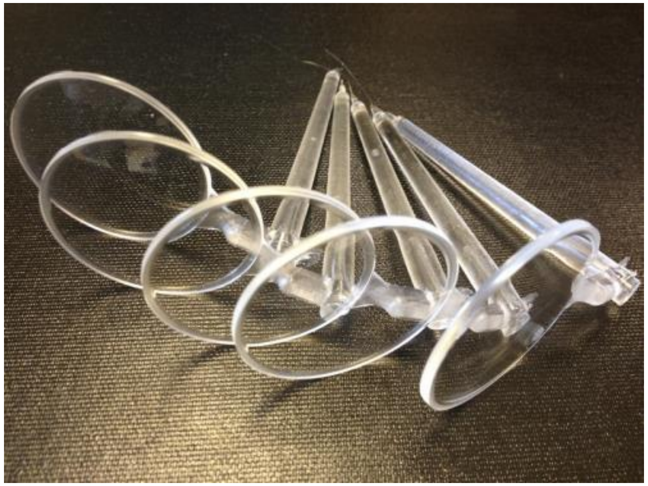


Moldex3D

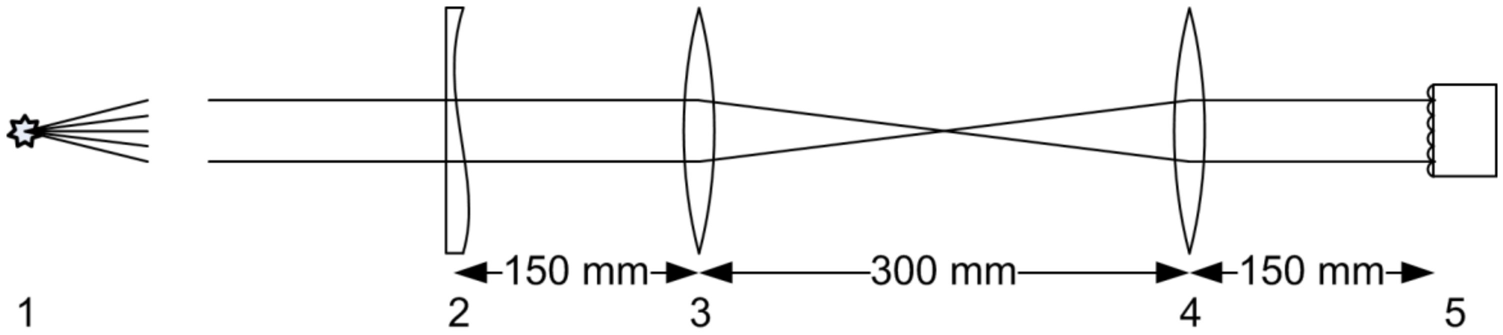
Experiments

Ultraprecision diamond machining

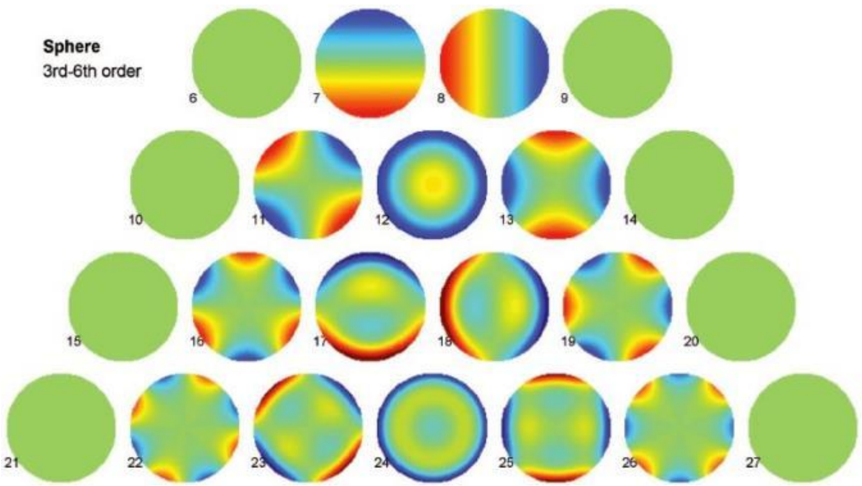
Microinjection molding



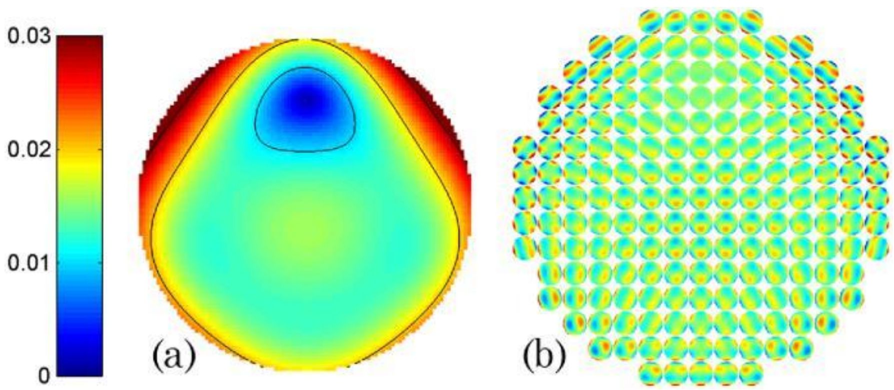
Optical Evaluation



Shack-Hartmann Wavefront sensing system

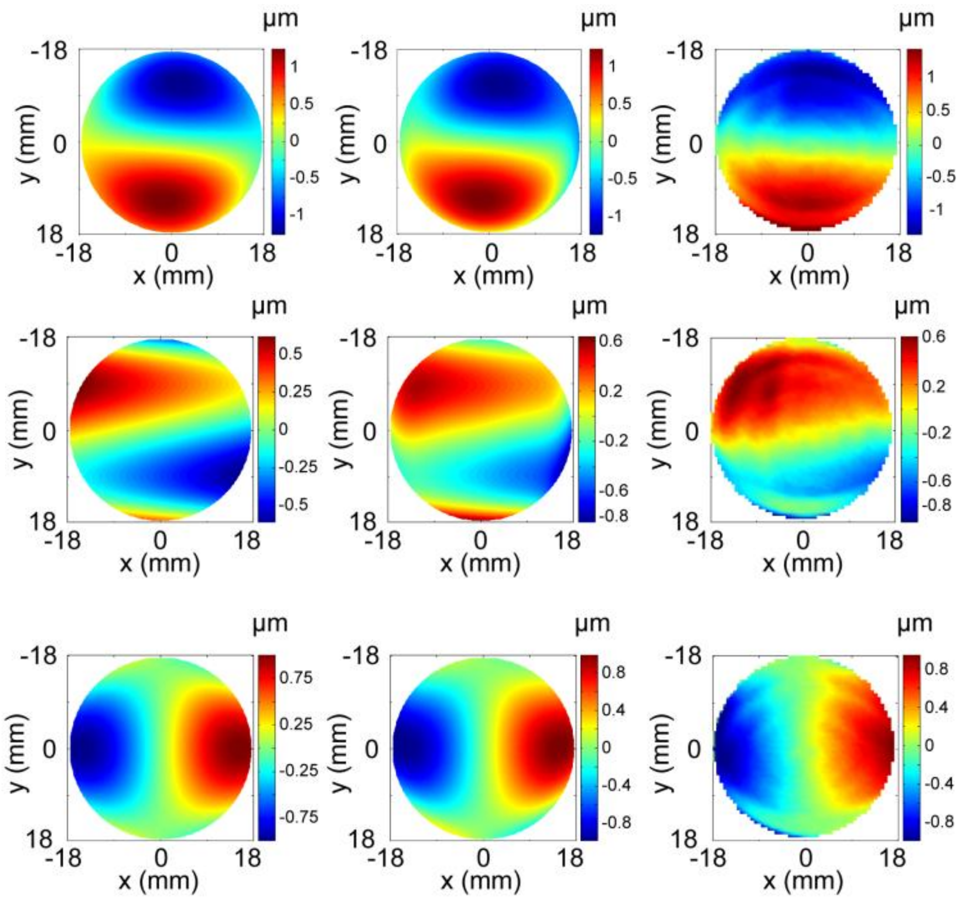


Zernike terms for spherical aberration



Assemble Zernike coefficients to map entire lens aperture

Simulation Verification



Design Simulation Measurement

$$M = \frac{-c_2^0 4\sqrt{3}}{r^2}$$

Spherical aberration

$$J_0 = \frac{-c_2^2 2\sqrt{6}}{r^2}$$

Cylindrical aberration
- Horizontal component

$$J_{45} = \frac{-c_2^{-2} 2\sqrt{6}}{r^2}$$

Cylindrical aberration
- Vertical component

It is demonstrated that the simulated results are in good agreements with the wavefront sensing measurements in terms of the accurate prediction of the difference between the design and measurement.

Process Optimization

Process number	Packing pressure (Kg/cm²)	Packing time (s)	Injection time (s)
1	800	3	0.125
2	1200	3	0.125
3	1200	6	0.125
4	800	6	0.125
5	800	3	0.1
6	800	6	0.1
7	1200	3	0.1
8	1200	6	0.1

Simulations of varied process parameters show:

1. Neither the packing time nor the injection time has considerable impacts on the optical properties of the PALs while other parameters are kept the same.

2. For the condition with the higher packing pressure, the refractive index variation is smaller as well as the thickness change (refractive index variation -1.5×10-4 ~ 3.5×10-4, thickness change -15.5 ~ -11 μm).

3. The patterns and the scales of the optical properties do not change dramatically though the injection molding process conditions are varied.

The 2nd process condition was adopted as the manufacturing process condition for future production of PALs because of its shorter cycle time, less power supply requirement, more uniform refractive index distribution and less geometric deformation.

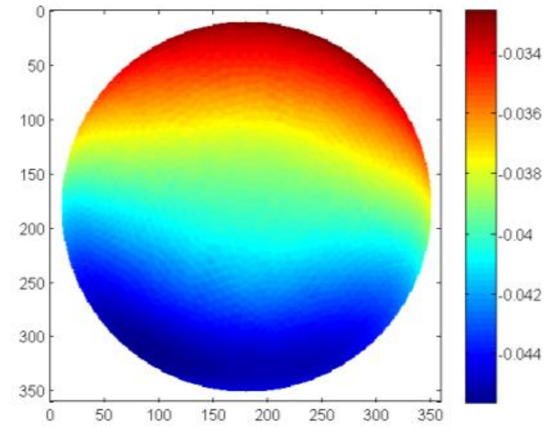
Design Compensation

Zernike Polynomials

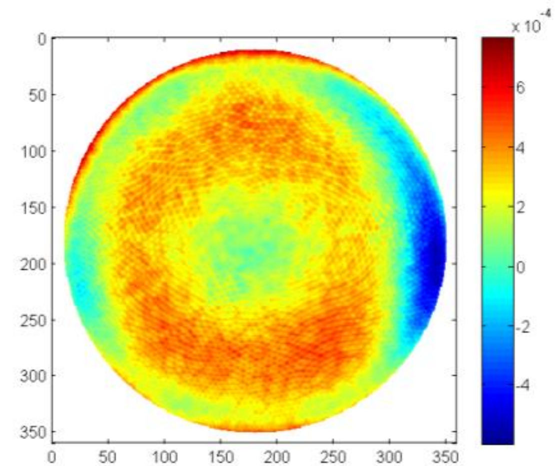
$z0 = 1;$
$z1 = \rho\,\mathrm{Cos}[\theta];$
$z2 = \rho\,\mathrm{Sin}[\theta];$
$z3 = -1 + 2\rho^2;$
$z4 = \rho^2\,\mathrm{Cos}[2\theta];$
$z5 = \rho^2\,\mathrm{Sin}[2\theta];$
$z6 = \rho\,(-2 + 3\rho^2)\,\mathrm{Cos}[\theta];$
$z7 = \rho\,(-2 + 3\rho^2)\,\mathrm{Sin}[\theta];$
$z8 = 1 - 6\rho^2 + 6\rho^4;$
$z9 = \rho^3\,\mathrm{Cos}[3\theta];$
$z10 = \rho^3\,\mathrm{Sin}[3\theta];$
$z11 = \rho^2\,(-3 + 4\rho^2)\,\mathrm{Cos}[2\theta];$
$z12 = \rho^2\,(-3 + 4\rho^2)\,\mathrm{Sin}[2\theta];$
$z13 = \rho\,(3 - 12\rho^2 + 10\rho^4)\,\mathrm{Cos}[\theta];$
$z14 = \rho\,(3 - 12\rho^2 + 10\rho^4)\,\mathrm{Sin}[\theta];$
$z15 = -1 + 12\rho^2 - 30\rho^4 + 20\rho^6;$
$z16 = \rho^4\,\mathrm{Cos}[4\theta];$
$z17 = \rho^4\,\mathrm{Sin}[4\theta];$
$z18 = \rho^3\,(-4 + 5\rho^2)\,\mathrm{Cos}[3\theta];$
$z19 = \rho^3\,(-4 + 5\rho^2)\,\mathrm{Sin}[3\theta];$
$z20 = \rho^2\,(6 - 20\rho^2 + 15\rho^4)\,\mathrm{Cos}[2\theta];$
$z21 = \rho^2\,(6 - 20\rho^2 + 15\rho^4)\,\mathrm{Sin}[2\theta];$
$z22 = \rho\,(-4 + 30\rho^2 - 60\rho^4 + 35\rho^6)\,\mathrm{Cos}[\theta];$
$z23 = \rho\,(-4 + 30\rho^2 - 60\rho^4 + 35\rho^6)\,\mathrm{Sin}[\theta];$
$z24 = 1 - 20\rho^2 + 90\rho^4 - 140\rho^6 + 70\rho^8;$
$z25 = \rho^5\,\mathrm{Cos}[5\theta];$

The simulation indicates that the wavefront error has been reduced significantly by the design compensation.

Original Coefficient	Compensated Coefficient
0	-0.007500512491978
0	-0.003633855959761
0	0.000783078822959
0	0.000035851604631
-0.462	-0.461312313629890
0	-0.000126308338920
0.015	0.014563904850738
0.046	0.046234086077506
-0.007	-0.006770010607658
-0.007	-0.006800039221270
0	0.000027139547490
0	0.000002154929423
0	0.000399977134218
0	0.000016859038963
0	0.000094886478329
0	0.000051419838979
0	0.000001935636014
-0.0064	-0.005997715871633
0	0.000054745659585
0	0.000024608566247
0	0.000018710372037



Simulated wavefront error for original design



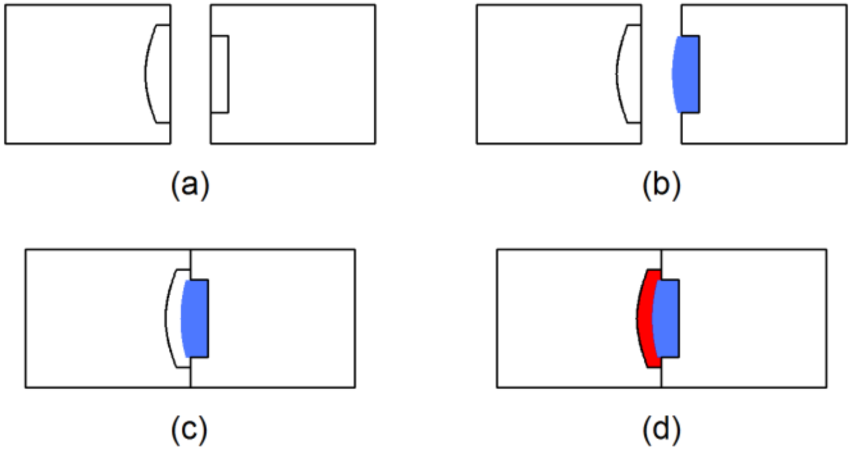
Simulated wavefront error for compensated design

Moldex3D Successful Application Case Study 2 – Hybrid PALs

The Ohio State University

Moldex3D

Background



> The combination of these two types of glass can lower the chromatic aberration by bringing focuses at red wavelength and blue wavelength closer.

> This motivates us to employ injection molding to coat one layer of plastic on PAL lens surface to achieve chromatic aberration free.

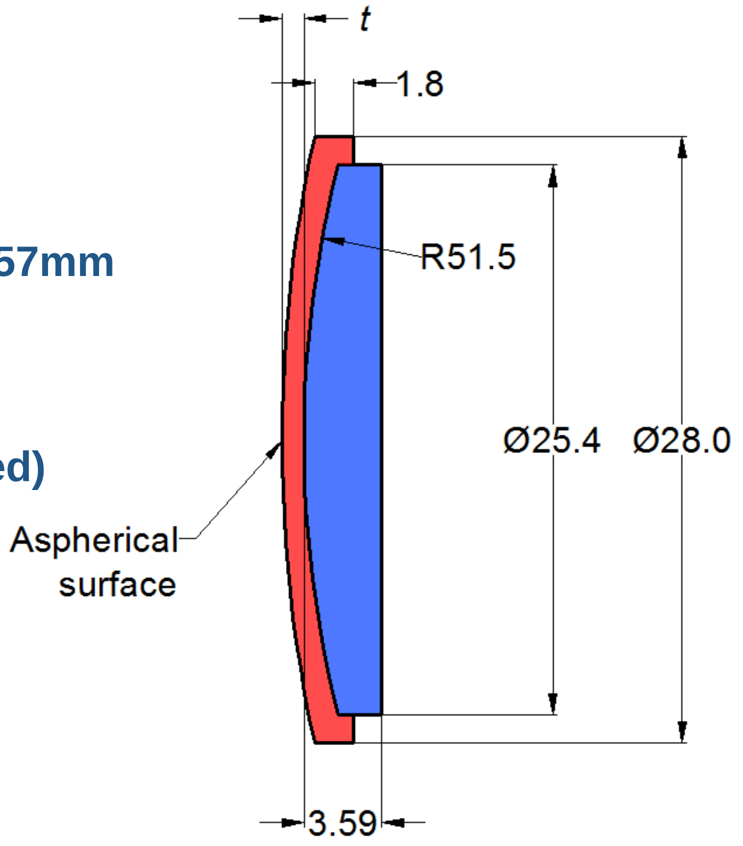
> The right mold insert is used to house the glass lens while the left side has the aspherical surface for the polymer lens. The blue area is the glass lens and the red is the injection molded polycarbonate polymer.

Background

> **Product Size**
- **Diameter： 28 mm**
- **Thickness： *t* 0.1257 mm or 0.7257mm**

> **Material**
- **Part: PC Sabic Lexan OQ1020 (Red)**
- **Part insert: BK-7 Glass (Blue)**

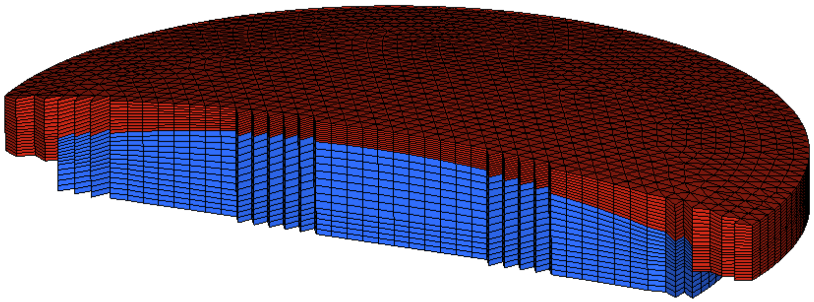
> **Process Condition**
- **Filling Time： 0.1 Sec**
- **Melt Temperature： 330 ℃**
- **Mold Temperature：82 ℃**



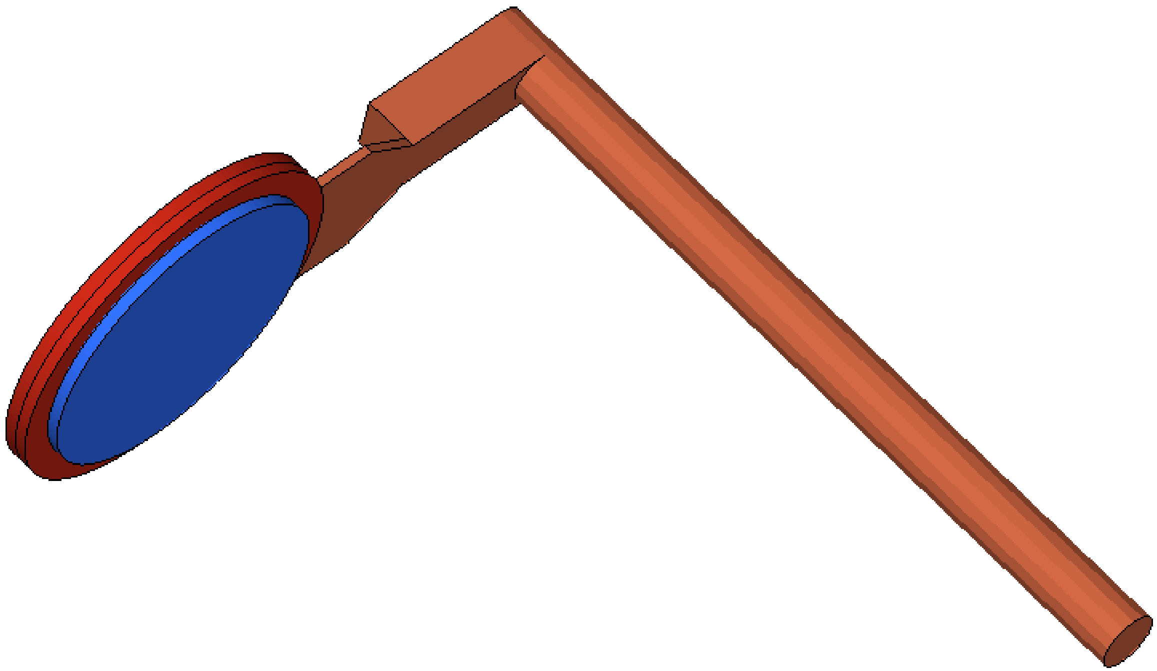
Moldex3D

Mesh Model

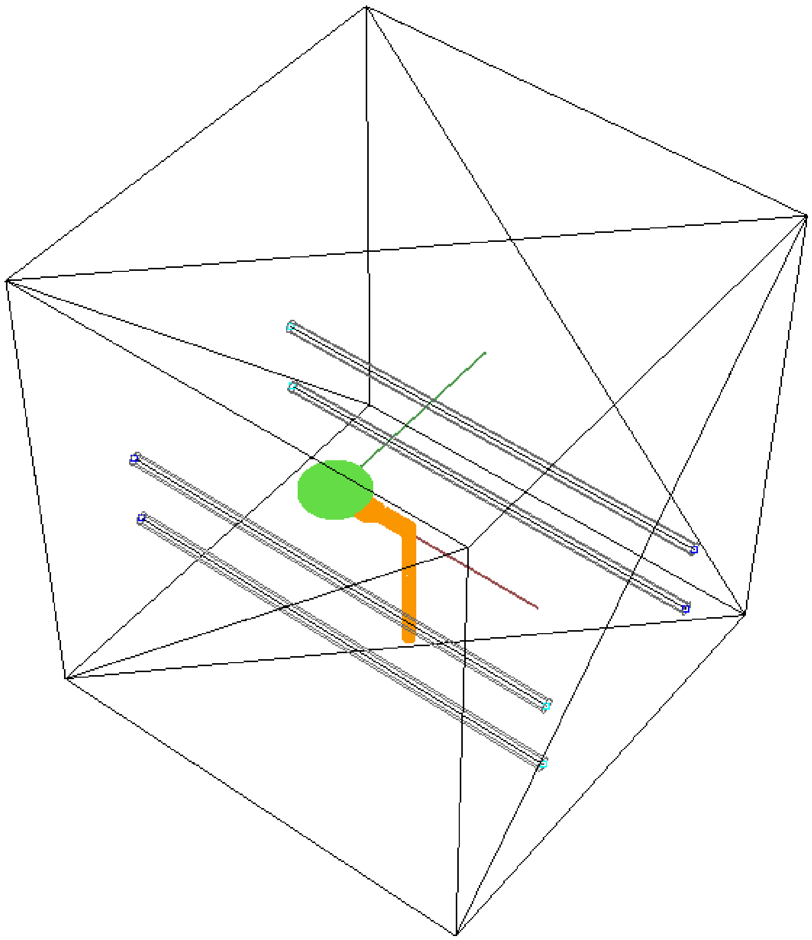
- Mesh Type
  - Prism element Solid Mesh
- Mesh Count
  - Part Mesh: 55037
  - Part Insert Mesh: 45318
  - Runner Mesh: 7157
- CPU CPU Time (20 mins)
- Computer Information
  - CPU: Intel Core i7-3700K
  - RAM: 8G



Runner Layout



Cooling Channel Design



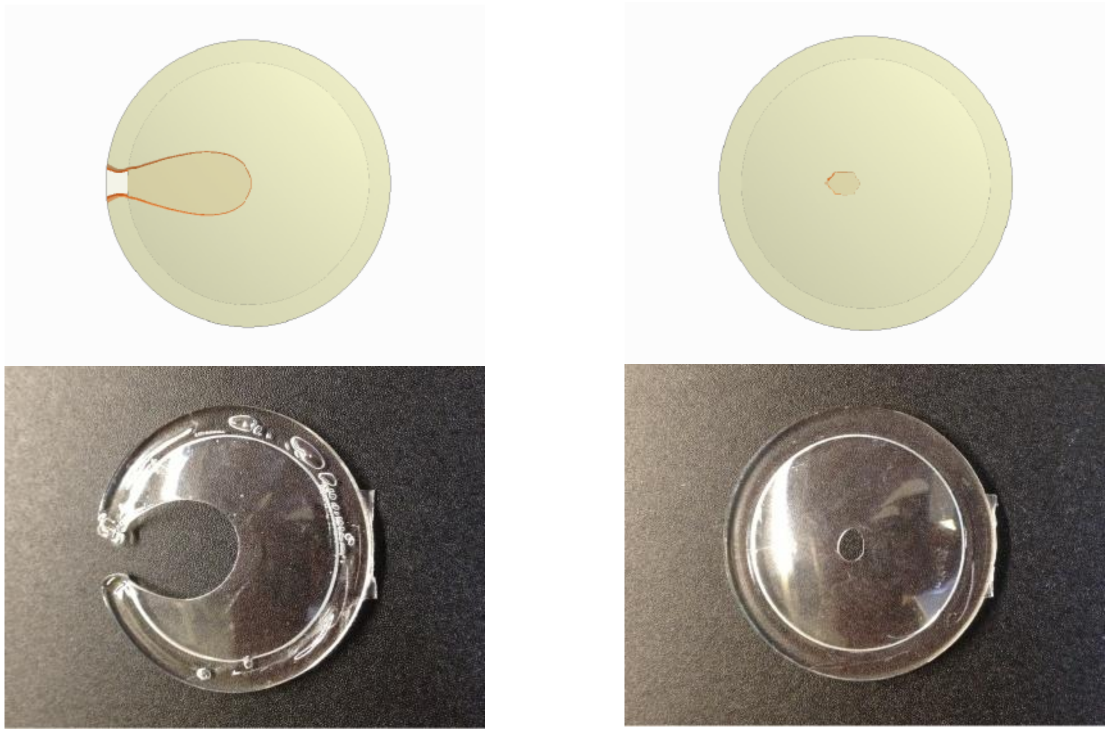
Analysis Items and Contents

- > Understand the melt front pattern resulted from injection molding process
- > Re-conduct optical design utilizing the Moldex3D simulation results to avoid unfilled holes of the injection molded thin plastic layer
- > Optimize the injection molding process to find proper assembly force between the polymer lens edge and glass lens edge
- > Evaluate the optical performance of the hybrid glass-polymer PAL using optical focal shift measurement setup

Process Parameter

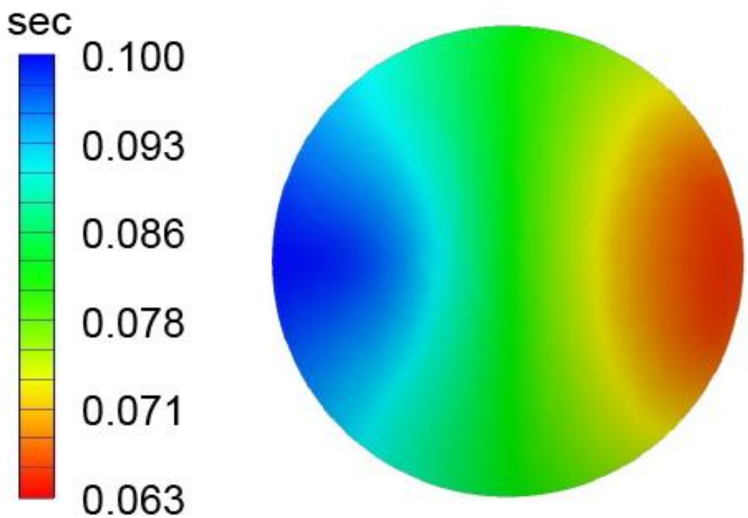
Injection molding condition parameters	
Molding parameters	Values
Melt temperature (°C)	330
Mold temperature (°C)	82
Injection time (mm/s)	0.1
Maximum injection pressure (MPa)	100
Velocity/pressure switch (vol %)	90
Packing pressure (MPa)	80
Packing time (s)	5
Cooling time (s)	35
Coolant temperature (°C)	82

Unfilled Holes



The simulation accurately predicts the unfilled holes formed at the center of the aperture of the injection molded polymer lens.

Optical Re-Design



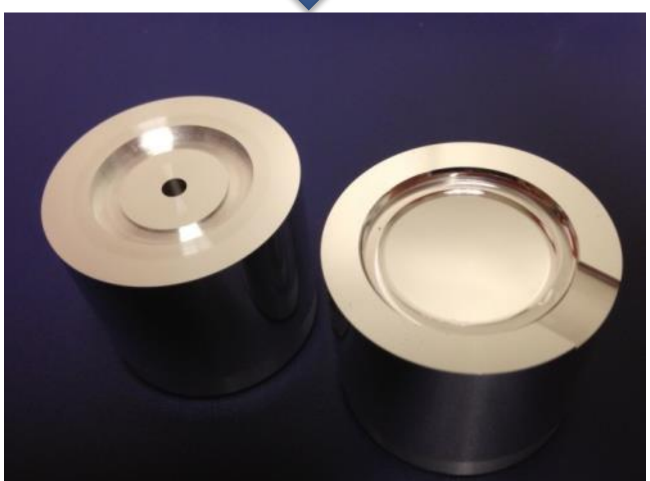
Melt front time

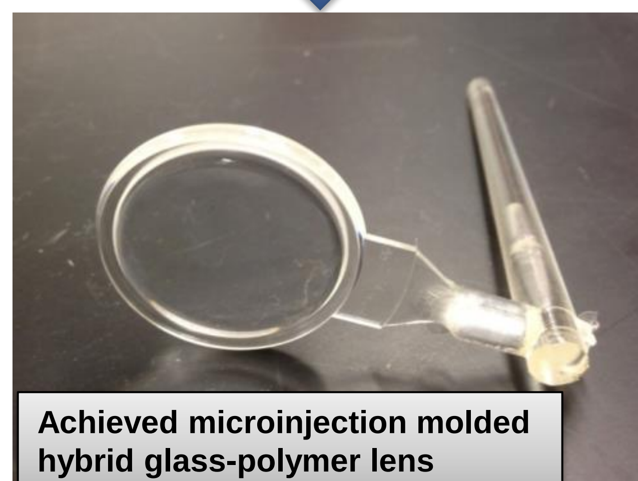
The optical setup is geometrically re-designed (increases the polymer lens thickness from 0.126 mm to 0.726 mm) to avoid unfilled holes. The melt front time of Moldex3D indicates the polymer melt should be able to pass the center of the aperture to fill the entire cavity.

Experiments

Ultraprecision diamond machining

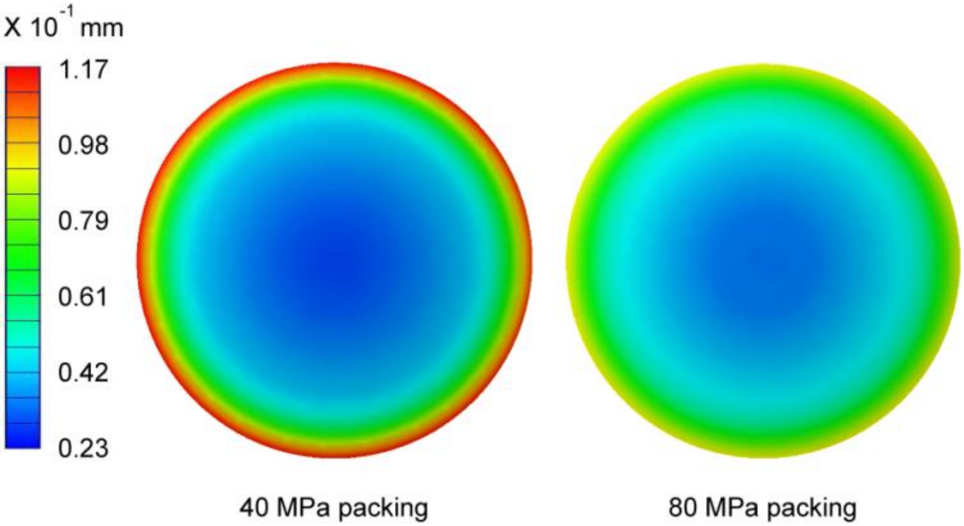
Microinjection molding





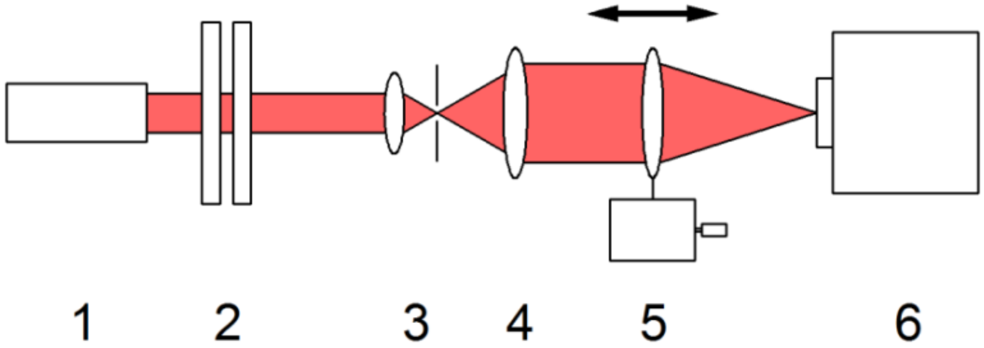
Achieved microinjection molded hybrid glass-polymer lens

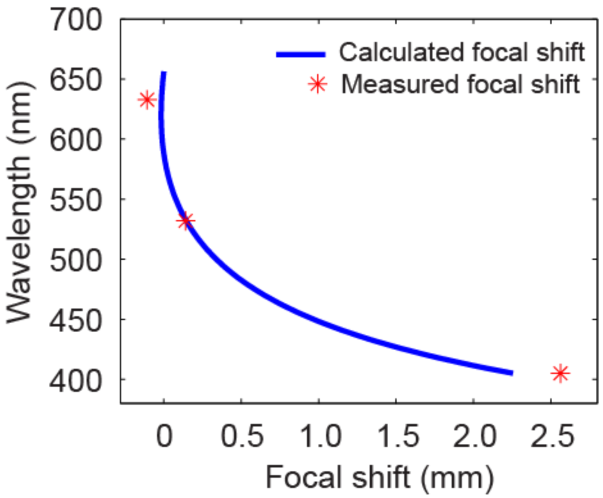
Packing Pressure Optimization



- The effect of the packing pressure to the deformation of the polymer lens edge was also studied in simulation because too much shrinkage may result in large deformations and high internal stresses.
- 40 MPa and 80 MPa were used as the two levels of the packing pressure in the process simulation
- The results show that the edge deformation on the condition with packing pressure 80 MPa is smaller than with the packing pressure 40 MPa, thus a higher packing pressure is adopted in all later experiments.

Optical Evaluation





> The experimental results show a good agreement with the theoretical values.

> The injection molded hybrid glass-polymer lens is demonstrated to be effectively correct chromatic aberrations in visible wavelength range.

Moldex3D Future Application

Future Application

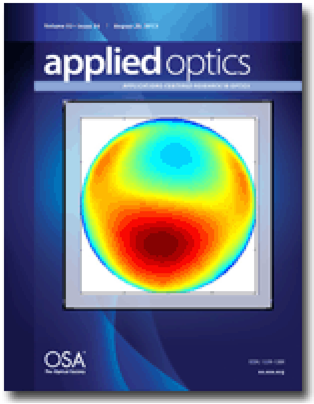
- > **Investigate residual stress before and after annealing and its influence to high precision freeform optics**
- > **Study large scale simulation combining injection molding and freeform optics**

References

1. Li, Likai, Thomas W. Raasch, and Allen Y. Yi. "Simulation and measurement of optical aberrations of injection molded progressive addition lenses." Applied optics 52, no. 24 (2013): 6022-6029. (**Cover Feature**)

2. Raasch, Thomas. "Aberrations and spherocylindrical powers within subapertures of freeform surfaces." JOSA A 28, no. 12 (2011): 2642-2646.

3. Li, Likai, and Allen Y. Yi. "An affordable injection-molded precision hybrid glass–polymer achromatic lens." *The International Journal of Advanced Manufacturing Technology* (2013): 1-7.



Thank you for your attention!