Synopsis of "Study of Process Parameters on Optical Qualities for Injection-Molded Plastic Lenses"

By Eric Sauther
Department of Optical Sciences, University of Arizona Opto-Mechanical Engineering; OPTI 521 Opto-mechanical Enginering Fall 2013; Meinel Optical Science building 1630 E University Blvd Tucson, AZ 85721AZ USA

ABSTRACT

This synopsis summarizes and explains the technical report by Huai En Lai and Jen Wang entitled "Study of process parameters on optical qualities for injection molded plastic lenses" Posted 10 March 2008.

The focus of the paper is to study injection molded plastic lenses through numerical simulations and supporting experimental verifications. Investigations of Optical Qualities, Residual Birefringence induced stresses, and form accuracy resulting from various Mold Flow process conditions.

The paper is intended for the use of opto-mechanical designers dealing with Optical plastics, and an interest in effects of the plastic molding process in how it impacts individual piece/part optical performance. In the paper this summary encompasses will constrain the analysis to one material type; That being ZEONEX, a Cyclo Olefin Polymer (COP) attractive for its low moisture absorption, high temp resistance, low birefringence, and moldability: http://www.zeonex.com/.

Keywords: Plastic, Mold, Injection, ZEONEX 480R, COP polymers

1. INTRODUCTION

The paper itself is broken into several parts in discussions of injection molding, and effects on optical parts:

- Quantifying process influences on the aforementioned characteristics using the Taguchi methods for Robust Design Of Experiments (DOE).
- Three dimensional mold flow analysis to simulate how molten plastics will react inside of an mold cavity, and what stresses are induced due to cooling (hence shrinkage) inside the mold cavity itself
- Flow induced and thermal induced birefringence in relation to photoelesticity of the annealed lenses
- Birefringence, form accuracy, and volumetric deviations on Seidel Aberrations

1.1 Taguchi method for Robust Design

While not covered in the paper it is important to understand the concept of the Taguchi method of Signal to Noise ("the smaller the better" technique) as applied in the paper. Conceptually, this method without any reference or nominal test point to start from will allow you to deduce the key factors and best test settings to result in consistently good performance. For the characteristic run sheets (numbers of experimental runs) in the paper there are Control Factors and Noise Factors (Environmental Conditions, Unit to Unit variation). Noise factors are test conditions that cannot be changed, or are very difficult to change. While the Control Factors are the variables purposely changed under test that are going to be analyzed .

Because the form accuracy is interpreted in peak-to-valley (P-V) values, it should be minimized with an index with smaller-the-better (STB) characteristics as

$$\mathrm{SNR_{STB}} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$$

where n is the total number of measured values at each run process and yi is the P-V value for each run Process. More information can be found in " Taguchi Methods A Hands on Approach to Quality Engineering" by Glen Stuart Peace.

2. MANUFACTURING PROCESS ANALYSIS

2.1 Plastic lens manufacturing

Adoption of optics into consumer productions over the decades has gone on the rise, putting pressure on manufacturers to be able to produce large quantities to be integrated into consumer systems both quickly and cheaply. Because of this the injection molding process has been widely adopted due to its ability to meet stringent production requirements. However, Plastic lenses require thermal annealing for dimensional stability under real world environmental conditions. This annealing process leads to poor production yields because optical quality is affected by residual birefringence, and changing mechanical dimensions. Residual Birefringence has become a major design and production problem for high density storage media and high resolution optical systems. A good analytical study of a flat plate with birefringence due to residual stress and strain can be found here: "A study of birefringence, residual stress and final shrinkage for precision injection molded parts" by Sang Sik Yang1 and Tai Hun Kwon2*

2.2 Modeling a Lens as a Solid Structure

The paper treats the three dimensional stress-strain deformation as a simple linear elastic structure. Hence, the sum of the forces for the equilibrium condition will be:

$$\nabla \sigma + F = 0$$

This also leads to a some what familiar stress/strain relationship as related to the temperature change of a solid structure:

$$\sigma_{ij} = C_{ijkl}(\varepsilon_{kl} - \varepsilon^{0}_{kl} - \alpha_{kl}\,\Delta T) + \sigma^{F}_{ij}$$

$$\varepsilon_{ij} = 1/2(u_{ij} + u_{j,i})$$

Where σij is the stress component, and σFij is the stress induced by flow, εij is the infinitesimal elastic strain component, ε^{0}_{kl} is the initial strain from pressure volume-temperature effects, C_{ijkl} is the elastic material stiffness, α_{kl} is the coefficient of linear thermal expansion, and ΔT is the temperature difference.

After a geometric model is created in the RHINO application and then exported into the MOLDEX3D for flow analysis they show the highest amount of percentage shrinkage happens at the central portion of the molded lens. Shrinkage is defined as:

S= Vc-V= 1-V/Vc

where Vc is the specific volume at room temperature and V is the specific volume after ejection. As shown in Figure 2 a higher rate of shrinkage happens in the center due to the higher melt temperature that exits there. Non uniform cooling is also shown as warping after the part is ejected.

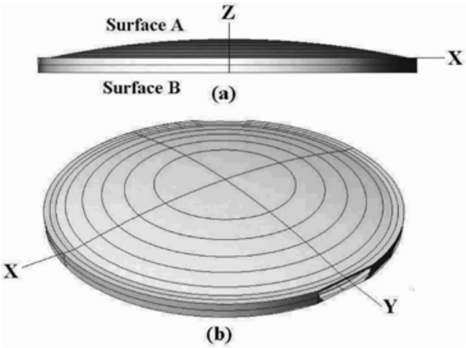
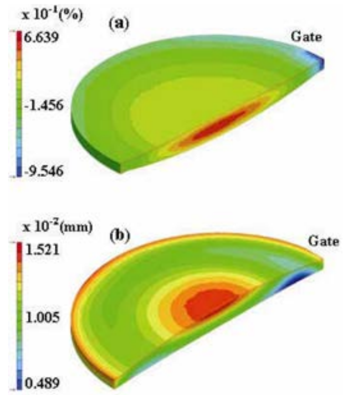
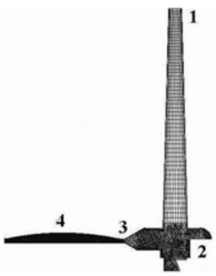


Figure 1 Plano-Convex Solid Mesh done in RHINO



Top Picture: volume shrinkage
Bottom Picture: is warping after ejection from the mold

Figure 2 Plano-Convex MOLDEX3D flow analysis



NOTE: The position labeled "Gate" is the actual area where the molten plastic is injected into the mold. See mesh structure of the tool where labeled 3 is the injection part, and 4 is considered the lens. This shows in the flow analysis and will be relevant later, but can be seen now as non-uniform shrinkage.

The total Stress tensor of molded lenses at the end of the filling stage is expressed as

$$\sigma = \begin{bmatrix} -P+\sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & -P+\sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & -P+\sigma_{33} \end{bmatrix}$$

Where the stress component in the Z direction is considered to be small in comparison to X, and Y and so is simplified to

$$\sigma = \begin{bmatrix} -P+\sigma_{11} & \sigma_{12} \\ \sigma_{21} & -P+\sigma_{22} \end{bmatrix}$$

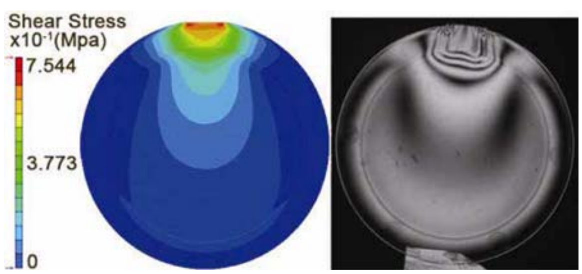


Figure 3 Comparison of modeled Shear Stress to Birefringence measurements

2.3 Post Annealing, Photoelasticity testing

The paper continues on to de-couple the two components of Birefringence in the molding process. That being flow induced and thermal induced quantities. Measurements will be taken with what is referred to in this paper as a Polarscope. A similar type of Polarscope used to test birefringent media is covered here: "Measurements of elliptically birefringent media parameters in optical vortex birefringence compensator" by Władysław A. Woźniak* and Marcelina Banac

2.4 Post Annealing testing Results

To test for relaxation due to thermal induced effects, molded lenses were checked after ejection, and then after an annealing process of of 12 hours at 125 degrees C (heat deflection for the ZEONEX material used is about 123 degrees C). Observations (representative of what is seen below) convey that thermal effects contribute noticeably little to the overall birefringent effect. Before and after annealing show a about 6.5 fringes. So it seams as if the Birefringence effects are dominated by the flow induced effects as determined in how it comes from the Gate in this initial trial run.

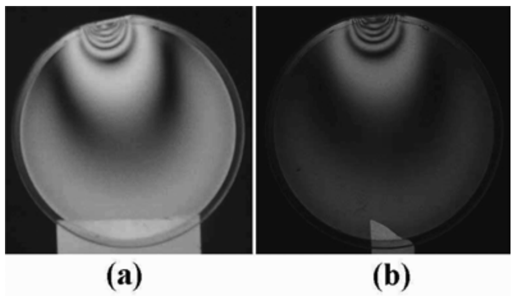


Figure 4 12 hour time elapse in annealing at 125 °C

However, while analyzing the flow effects test plates were again annealed at a temperature 15 degrees higher than before and analyzed over an 8 hour time period, showing more positive results.

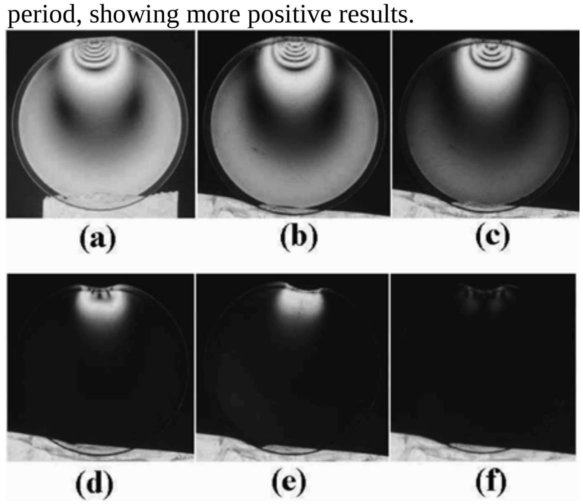
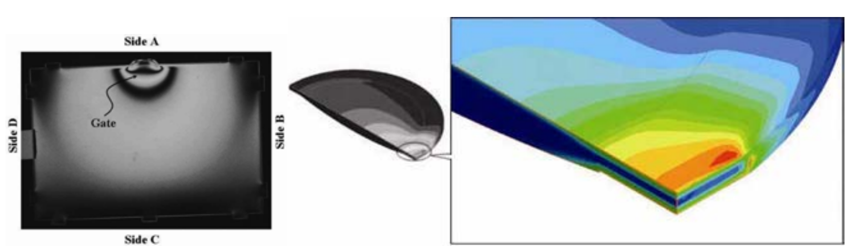


Figure 5 Annealing at 153°C over 8 hours

2.5 Flow induced effects

It is seen that the highest stress is at the point source of material flow, that being at the Gate. It was also modeled that high residual stress would occur near the lenses surface. Like before (in Figure 3), Blue are the lower stress areas and red are the highest.



To prove this experimentally they used a diamond machining tool in order to remove thin layers and test the residual stress left by the material flow at each layer. Layers were removed in 0.1mm increments up to 0.4mm. It was found to be a significant difference once the first 0.1mm layer was removed.

Layer removed	Percent of fringe removal (%)	Amount of Birefringence (approx) X10^{-3}
0.1	28	1.10
0.2	32	1.33
0.3	45	1.77
0.4	48	2.00

The rationale for this surface is stress is induced due to the Hot Melt coming in contact with a cooler mold. Considering their test conditions showed a Melt temp of 275 degrees C and a mold temp of 124 degrees C this would make sense.

2.6 Holding Form

Four interactions are stated that cause the optic to deviate from perfect mold form: Melt Temperature, Mold Temperature, Injection Speed, Holding Pressure, and Cooling Time. All four of these were used as control factors in testing. Through 8 different test runs all control factors were varied and then testing in front of an interferometer for residual Seidel Aberrations.

Qualities	High Birefringence	High Form Accuracy	High Volumetric Deviations
Process Conditions	Low melt temperature High injection speed	High mold temperature	High holding pressure

Full-scale Factorial Design of Experiments for Studying Effects of Qualities on Seidel Aberrations

	A. Birefringence		B. Form Accuracy	C. Volumetric Deviations
	Melt temperature	Injection speed	Mold temperature	Holding Pressure
Run	(°C) −(247.5) +(280.0)	(mm/ sec) −(19.8) +(22.4)	(°C) −(111.6) +(136.4)	(Mpa −(88.29) +(107.91)
1	−	+	−	−
2	−	+	−	+
3	+	−	+	−
4	+	−	+	+
5	−	+	+	−
6	−	+	+	+
7	+	−	−	−
8	+	−	−	++

Table 1 Siedel Aberrations contributions from variation of control factors

Astigmatism		Coma		Spherical Aberration	
Main factors	Contribution	Vital factors	Contribution	Vital factors	Contribution
A	41%	AB	24%	A	56%
B	40%	BC	22%	B	24%
others	19%	AC	14%	others	20%
		others	40%		

Birefringence, and Form Accuracy (labeled as A and B respectively) were found to be the biggest contributors to an aberrated wavefront. This proves that aberrations can never fully be removed, but can be optimized by making adjustments to the injection molding process.

3. CONCLUSIONS

This paper does a good job in conveying the stress induced sources of error in the fabrication of ZEONEX 480R material for a plano-convex lens type. They were able to isolate the major stress factors in fabrication, and correlate to first order the impact of optical performance through Seidel aberrations.

While they isolated manufacturing errors sources, they only hinted at avenues to pursue to minimize the impacts. Annealing, and flow processes are probably handled in another paper. Also, to give context another molded optical material should've been introduced (PMMA type) to fully appreciate the differences in performance, and manufacturability. More development should've been given to the volumetric flow rate of the molding process as this seems to be a significant impact to the layered magnitude of stresses as seen while traversing the volume. Also, it is not obvious during the diamond machining process if the stress induced was a combination of the thermal and diamond turning process. Qualitatively, this was a pretty interesting paper to see how far engineered thermo-plastics for optical products have come.

Reading a few related papers, relief of Birefringence in lens fabrication is an important topic for manufacturability. I would say any commercial industry from DVD players to cell phone cameras are interested in this topic to improve Optical Quality and Yields.

<u>Additional Reading Material</u>

"A Study of Birefringence Residual Stress and Final Shrinkage for Precision Molded Parts" by Sang Sik Yang and Tai Hun Kwon

"Application of Three Dimensional Optical Optical Components formed by Lithography, Electroforming, and Plastic Molding" by K. H. Brenner, M. Kufner, S. Kufner, J. Moisel, A. Mueller S. Sinzinger. M. Testorf, J. Gottert, J. Mohr