# Deformation of Layered Polymeric Lenses and Glass Lenses under Thermal Loading

Alison N. Garbash
Mechanical Engineering Department, Ohio Northern University

Jed E. Marquart
Mechanical Engineering Department, Ohio Northern University

Hui Shen
Mechanical Engineering Department, Ohio Northern University

# Deformation of Layered Polymeric Lenses and Glass Lenses under Thermal Loading

## ABSTRACT

Glass has been widely used as the material for optical lenses. In recent years, with advancements in technology, polymers have become candidate materials to replace glass for optical lenses. Polymers are relatively light, cheap, and easy to manufacture. Layered polymeric optical lenses, produced using coextrusion technology, have been reported to have better optical properties than glass lenses. However, polymers have relatively high thermal expansion coefficients. In this paper, comparisons have been conducted on the deformation of layered polymeric lenses and glass lenses under thermal loading. Polymeric lenses are made by alternating layers of two polymers, poly(styrene-co- acrylonitrile) and polymethlymethacrylate. 2D and 3D finite element analysis methods were utilized to obtain responses of the lenses under thermal loading. The results show a significant difference between the two materials. Layered polymeric optical lenses have larger deformation than glass lenses, and the deformation varies with the layer thickness.

## 1. INTRODUCTION

Glass has been widely used for optical lenses. With today's advancements in material technology and the driving needs for light-weight and small-sized optical lenses, gradient refractive index (GRIN) materials become candidate materials to replace glass for optical lenses. The GRIN lenses are bio-inspired by the eyes of many species such as human beings. The GRIN crystalline lenses in biological eyes typically contain approximately 22,000 layers [1]. To mimic the structures of eyes in nature, lenses made of nanolayered polymer film with GRIN distributions have been developed in recent years [1,2]. The nanolayered polymer films are made by coextrusion technology combining thousand of alternating layers of different polymers. The optical properties of GRIN lenses, such as image quality and ability to collect light, can be improved [1]. The refractive index can be changed by varying the thickness of the transparent layers [1]. Layers can have a thickness of several microns to nanometers. However, polymers have relatively high thermal expansion coefficients. The shape could change under thermal loading. This would make the optical properties more difficult to keep consistent under heat flux or temperature change. Although glass itself is heavy, it has a low thermal expansion coefficient, which allows the glass to keep its optical properties consistent through varying thermal conditions.

In this paper, responses of glass and alternating layered polymeric optical lenses to various thermal loadings were compared. Thermal loadings include a constant heat flux and a constant change in temperature with boundary condition of constant rate of convection. Simulations of different lenses were completed using ANSYS Workbench 13.0 [3]. The results show a significant difference between the two types of optical lenses. Layered polymeric optical lenses have larger deformation than glass lenses, and the deformation varies with the layer thickness.

## 2. FINITE ELEMENT MODELING

To compare the deformation of glass and polymeric optical lenses under various thermal loading, 2D and 3D finite element (FE) models were created. In this section, the 2D and 3D FE models, the material properties, boundary conditions, and thermal loadings will be described.

## 2.1 2D and 3D FE models for glass and polymeric lenses

The glass lens was modeled as a half-sphere with a radius of 1 mm as shown in Figure 1. While the objective of this work is to compare the deformation of glass lens and polymeric lens, the size of the lens is constant for all the FE models for both glass and polymeric lenses.

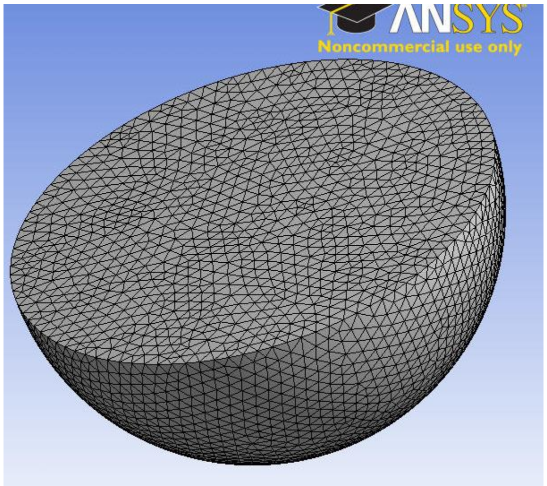


Figure 1: FE model for glass lens

The polymeric optical lens was modeled with 2, 4, 10 and 20 layers with 3D models. The 20 layer lens model is shown in Figure 2, with 50$\mu m$ thick layers. The layers were alternated with poly(styrene-co- acrylonitrile) (SAN) and polymethlymethacrylate (PMMA).

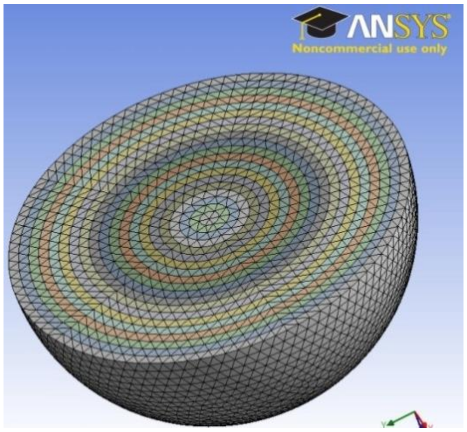


Figure 2: 3D alternating layered polymeric lens with 20 layers

Due to the axis symmetrical geometry of the lenses, the 3D lens model was converted to a 2D lens. The 20 layer 2D model is an axis symmetric FE model as shown in Figure 3. The 2D simulations allow for more layers, which would be difficult and time consuming to complete with the 3D model. The polymeric optical lens was modeled with 20 to 100 layers for 2D models. For the 100-layer model, the layer thickness is 10 $\mu m$.

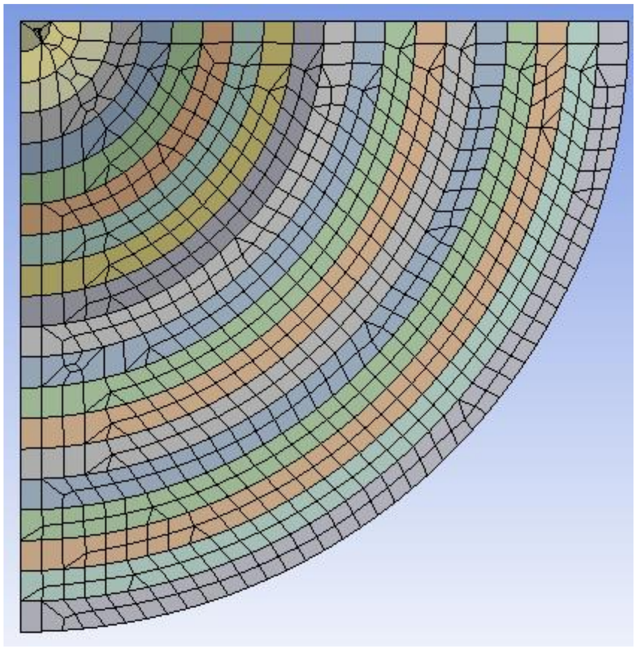


Figure 3: 2D alternating layered polymeric lens with 20 layers

All FE analyses were carried out using the ANSYS software using 2D or 3D skewness element for meshing[3]. Mesh convergence was verified based on local deformation values.

### 2.2 Material properties

Various polymers can be used to develop the lens. Which polymers are used in the lens determines the properties of the lens, including but not limited to the refractive index. Polymeric lenses are usually created by alternating layers of two or more polymers. Two polymers commonly used are SAN and PMMA [2]. With the layers set, the lens is molded into a plano-convex gradient refractive index optics lens [1]. Material properties for SAN [4- 6], PMMA [7- 9], and BK7 Glass [10] are shown in Table 1.

Table 1: Material Properties (Reference temperature: 20°C)

| Material | Density $10^3(\frac{kg}{m^3})$ | Young's Modulus $(GPa)$ | Poisson Ratio | Thermal Conductivity $(\frac{W}{mK})$ | Thermal Expansion Coefficient $10^{-6}\ (\frac{1}{°C})$ |
|---|---|---|---|---|---|
| SAN | 1.05 | 2.5 | .3 | .17 | 90 |
| PMMA | 1.2 | 3.1 | .4 | .25 | 60 |
| BK7 Glass | 2.51 | 82.0 | .206 | 1.114 | 8.3 |

### 2.3 Boundary Conditions

It was simulated that the lens was in a holder made of aluminum. It was held in place to allow polishing on the surface. Fixed support was chosen for the outer surface of the lens. In the polishing process, water was placed on the lens during polishing. To simulate the water sitting on the surface of the lens, the rate of convection was considered to be free convection heat transfer. The free convection rate for water is 20 $\frac{W}{m^2K}$ [11]. A transfer rate for convection was placed on all the models and was considered to be coming off the top face and outer surface of the lens.

## 2.4 Thermal loadings

Thermal loading added to the lens model was either a heat flux or constant temperature change through the lens. The heat flux was to simulate the thermal loading during polishing of the lens. The heat flux for the lens was calculated using the conservation of energy equation:

$$\dot{E} = \dot{Q} + \dot{W} \tag{1}$$

where $\dot{E}$ is the rate of energy transfer, $\dot{Q}$ is the rate of heat transfer, and $\dot{W}$ is the rate of work done.

Before using the conservation of energy, the power of the polisher needed to be determined. Using the equations below, the power of the polisher could be determined:

$$P = 2\pi\tau\omega \tag{2}$$

$$\tau = Fr \tag{3}$$

$$F = \mu N \tag{4}$$

where $P$ is power, $\tau$ is the torque, $\omega$ is the revolutions per minute, $F$ is the frictional force, $r$ is the radius of the polisher, $\mu$ is the coefficient of friction, *and* $N$ is the normal force of the polisher.

The coefficient of friction, $\mu$, was found to be .35 for SAN on steel with liquid [12]. During the polishing process, $N$ is the weight of the polisher which can be calculated from the mass of the polisher, 100grams. The $r$ of the polisher is 5mm and the $\omega$ is 120 $rpm$. The power of the polisher was equal to the rate of energy. Using the conservation of energy, since no work was being done the rate of energy is equal to the rate of heat transfer. The heat flux was then calculated:

$$\dot{q} = \frac{\dot{Q}}{A} \tag{5}$$

where $\dot{q}$ is the heat flux and A is the area of the polisher. The total heat flux was determined to be 216.5 $\frac{W}{m^2}$.

Another thermal loading was constant temperature change through the lens. The change in temperature value selected was 20°C. The change in temperature was constant through the entire lens. This thermal loading was to simulate the environmental temperature change. All lenses had an initial environmental temperature of 22°C.

## 3.RESULTS

In this section, the deformation for the models of glass lens and polymeric lens responding to different thermal loadings are compared.

### 3.1 Results for the Glass Lens Model

Figure 4 and Figure 5 show the total deformation of the glass lens under the heat flux and temperature change. It can be observed that the center of lens has the largest deformation, which is shown in Table 2. The maximum deformation value for each model will be used to compare with those of polymeric lens models in the following section.

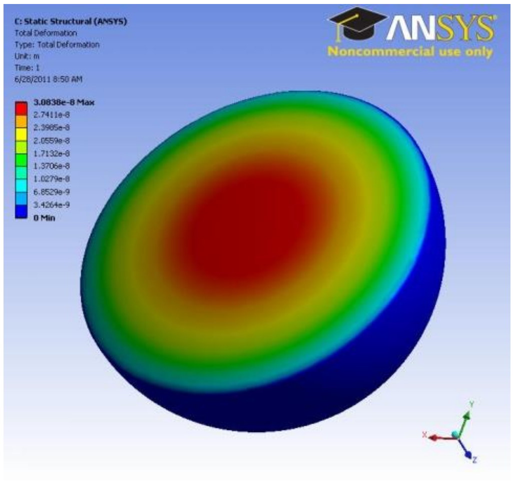


Figure 4: Total deformation of the glass lens with heat flux.

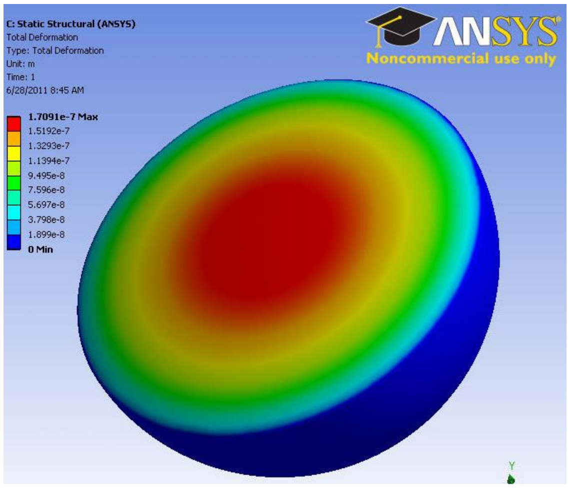
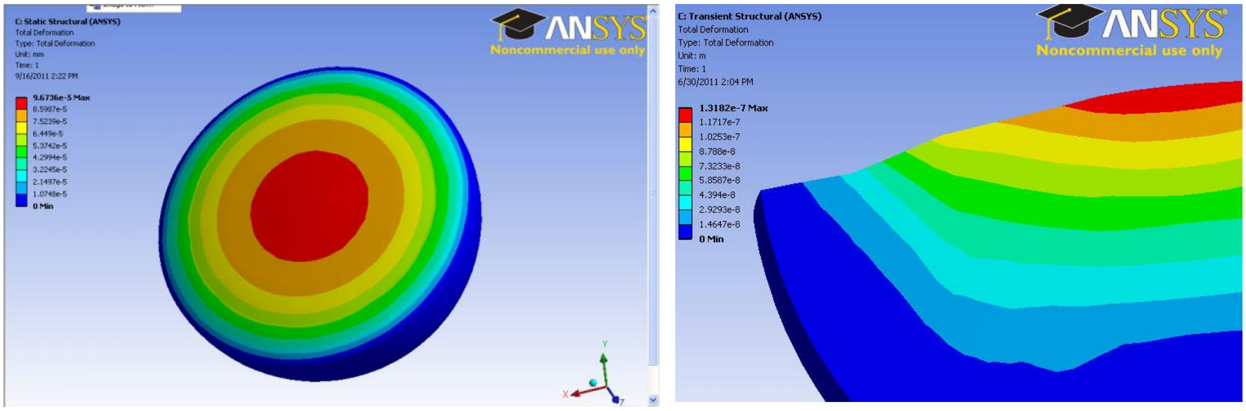


Figure 5: Total deformation of the glass lens with temperature change.

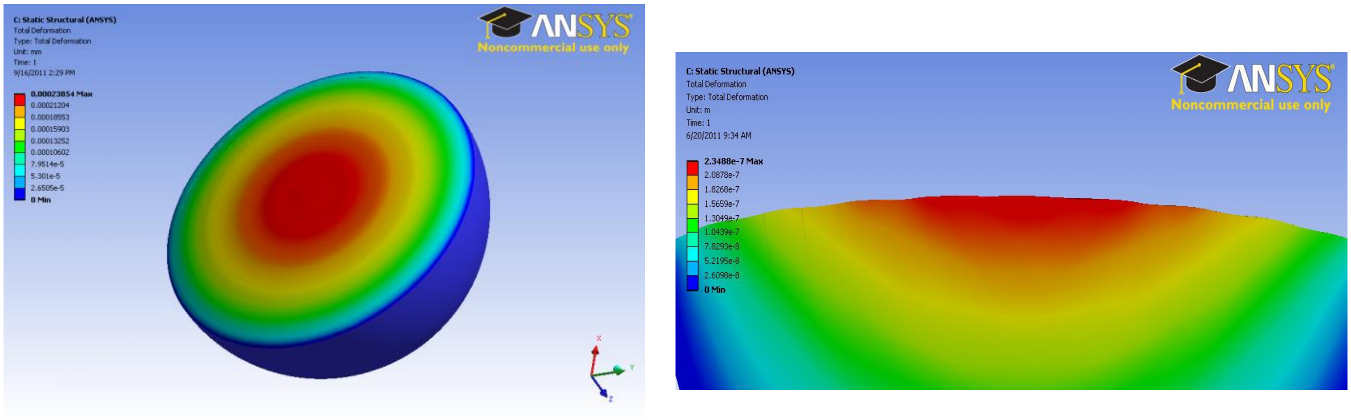
### 3.2 Results for the Polymeric Lens Model

The polymeric optical lens was modeled with 3D models for 4, 6, 10 and 20 layers, and 2D models for 20, 40, 60, 80, and 100 layers. The 3D 20 layer model and 2D 20 layer models were compared to verify that the two types of the models obtained similar results. The deformation of 4, 10, 20, and 100 layer polymeric lens models under heat flux with the fixed surface boundary condition are shown in Figures 6-9. It can be observed that for the layered polymeric lens the surface forms grooves when deformed. This is due to the different thermal expansion coefficients of the two polymers. Under the same thermal loading, the two different polymers expand differently. As the number of layers increase, the deformation becomes more evident. However, the grooves become shallower and the surface becomes smoother. The model was sectioned in order to see the different deformations that occurred between the alternating polymer layers.



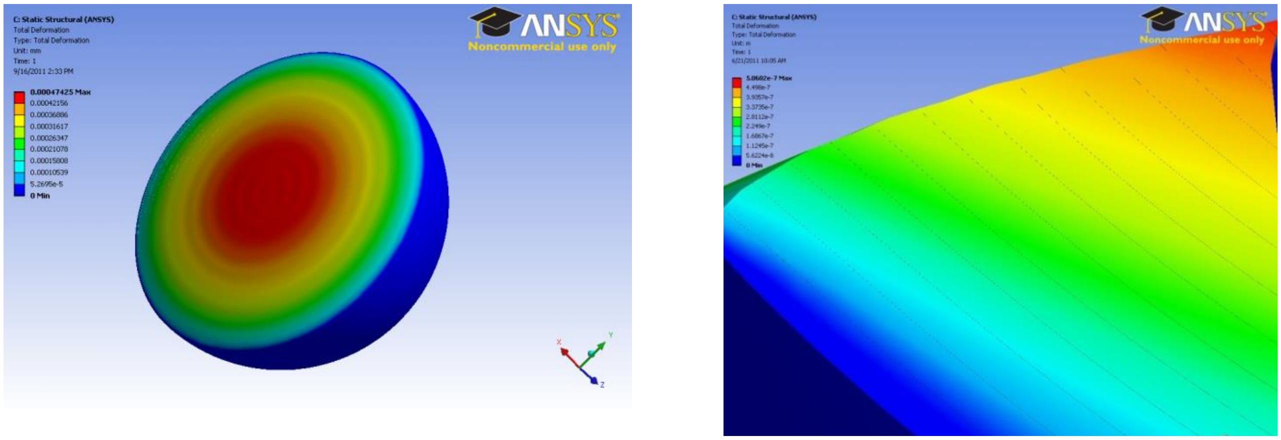
(a) (b)

Figure 6: 4 layer polymeric lens with heat flux. (a) overall deformation; (b) section view to show the local deformation.



(a) (b)

Figure 7: 10 layer polymeric lens with heat flux. (a) overall deformation; (b) section view to show the local deformation.



(a) (b)

Figure 8: 20 layer polymeric lens with heat flux. (a) overall deformation; (b) section view to show the local deformation.

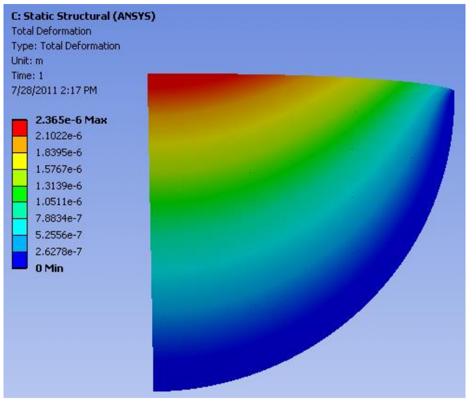
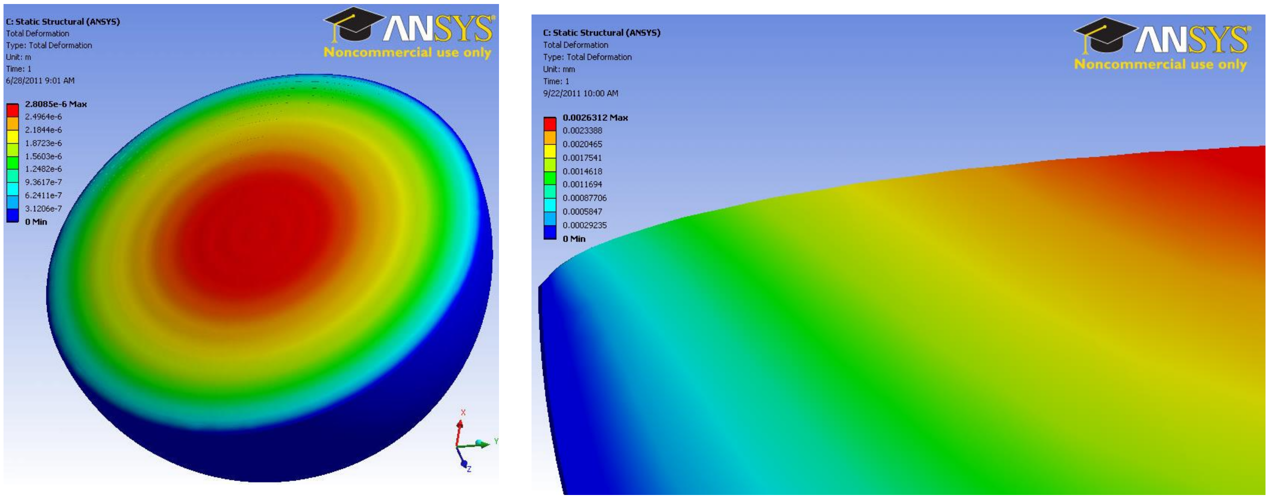


Figure 9: Overall deformation for 100 layer polymeric lens with heat flux (2D model).

The deformation of the 20 layer polymeric lens model under temperature change is shown in Figure 10. It can be observed that the temperature change still caused the wavelike deformation between the polymer layers to form.



(a) (b)

Figure 10: 20 layer polymeric lens with temperature change. (a) overall deformation; (b) section view to show the local deformation.

### 3.3 Comparison between glass lens and polymeric lens

The maximum deformation values of the glass lens model and polymeric lens models with various number of layers are listed in Table 2. It can be concluded that as the number of layers increase the deformation increases. As the layer number increases from 4 to 100, the deformation increases about 24.5 times under heat flux and temperature change. The relationship between the number of layers and deformation under thermal loading is approximately linear. The glass lens has lower deformation, which is about 1.3% of that of the 100 layer polymeric lens.

Table 2: Maximum deformation for glass and polymeric lens models

| Number of Layers (Polymeric) | Deformation under heat flux $10^{-5}$ (mm) | Deformation under temp change $10^{-5}$ (mm) |
|---|---|---|
| 4 | 9.67 | 53.7 |
| 6 | 14.4 | 79.9 |
| 10 | 23.9 | 132 |
| 20 | 47.4 | 263 |
| 40 | 94.6 | 525 |
| 60 | 142 | 787 |
| 80 | 189 | 1049 |
| 100 | 237 | 1311 |
| **Glass** | **3.08** | **17.1** |

## 4. Conclusions

The objective of this project is to compare glass and alternating polymeric optical lenses' responses to various thermal loadings. Two thermal loadings were applied on glass and alternating layer polymeric lenses to simulate the heat produced by polishing the surface and environmental temperature change. When comparing the deformations of the lenses, the polymeric lens had greater deformations than the glass lens. The maximum deformation of glass is only 1.3% of that of 100 layer polymeric lens. The relatively large deformation of the polymeric lens might have an effect on the optical properties. The two different lenses, glass and polymer, each have their pros and cons to being used. If thermal loading is not a major concern, the alternating lens would make a good choice. The glass lens would be a better choice if heat load is a concern. The material chosen to use would depend on what the lens would be needed for and the environment it would be placed in. Future work will be focused on the effect of different machining techniques, such as diamond turning, and material selection. The optical property changes due to the deformation under thermal loading will also be studied.

## ACKNOWLEDGMENTS

The authors acknowledge the financial support of the National Science Foundation through grant number DMR- 0423914.

## References

[1] G. Beadie, James S. Shirk, A. Rosenberg, Paul A. Lane, E. Fleet, A. R. Kamdar, Y. Jin, M. Ponting, T. Kazmierczak, Y. Yang, A. Hiltner, and E. Baer, 2008, "Optical properties of a bio-inspired gradient refractive index polymer lens," Opt. Express **16**, 11540-11547.
[2] Song, Hyunmin, Kenneth Singer, Yeheng Wu, Juefei Zhou, Joe Lott, James Andrews, Anne Hiltner, Eric Baer, Christoph Weder, Robert Bunch, Richard Lepkowicz, and Guy Beadie, 2009, "Layered Polymeric Optical Systems Using Continuous Coextrusion", Nanophotonics and Macrophotonics for Space Environments III, August 2009, San Diego, CA, USA.
[3] ANSYS, Inc., Canonsburg, PA
[4] Polimeri Europa. "Polimeri Europa Edistir RCL 600 Polystyrene." *MatWeb*. MatWeb, LLC. Web. 1 June 2011. <http://www.matweb.com/search/DataSheet.aspx?MatGUID=812327498deb4da28a99fa200dcc0524&ckck=1>.
[5] "Material Properties of PS (hips), Commodity Polymers | Polymers Data Sheets." *Mechanical and Physical Properties of Materials | Matbase - Material Properties Database*. Web. 08 June 2011. <http://www.matbase.com/material/polymers/commodity/ps-hips/properties>.
[6] "Poisson Ratio." *The Engineering ToolBox*. Web. 08 June 2011. <http://www.engineeringtoolbox.com/poissons-ratio-d_1224.html>.
[7] "LG Chemical EH910 PMMA, General Purpose Grade for Extrusion." *MatWeb*. MatWeb, LLC. Web. 08 June 2011. <http://www.matweb.com/search/DataSheet.aspx?MatGUID=ceba58327107472785344b105cde502c&ckck=1>.
[8] "Material Properties of PMMA, Commodity Polymers | Polymers Data Sheets." *Mechanical and Physical Properties of Materials | Matbase - Material Properties Database*.

Web. 08 June 2011.
<http://www.matbase.com/material/polymers/commodity/pmma/properties>.
[9] "PMMA." *MIT - Massachusetts Institute of Technology*. Web. 08 June 2011.
<http://www.mit.edu/~6.777/matprops/pmma.htm>.
[10] "Schott N-BK7 Glass." *MatWeb*. MatWeb, LLC. Web. 07 June 2011.
<http://www.matweb.com/search/DataSheet.aspx?MatGUID=a8c2d05c7a6244399bbc2e15c0438cb9&ckck=1>.
[11] "Convection Heat Transfer." *The Engineering ToolBox*. Web. 10 June 2011.
<http://www.engineeringtoolbox.com/convective-heat-transfer-d_430.html>.
[12] "Friction and Coefficients of Friction." *The Engineering ToolBox*. Web. 10 June 2011.
<http://www.engineeringtoolbox.com/friction-coefficients-d_778.html>.