Plastic vs. Glass Optics: Factors to Consider
(part of SPIE “Precision Plastic Optics” short course note)

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Why Plastic Optics?
Glass and plastic optics each has its own unique advantages. The properties of glass materials are very different from that of plastic materials. There are literally hundreds of different glass materials available from well-known suppliers such as Schott, Hoya and O’hara for making glass optics. The choice for plastic materials is limited only to about half dozen. The attached table lists the currently available plastic materials, and their key properties. Generally speaking, glass materials are harder and more durable than plastic materials. Glass materials are also more stable over a wider temperature range and humidity environment than plastic. Glass is much heavier than plastic (by a factor of 2.5x to 4x). The large selection of glass materials allows the designer to choose materials with desirable optical properties to gain better optical performance. This kind of freedom is limited with plastic materials. However, plastic optics offers other design freedoms that are not achievable or economical with glass optics (see below).

The manufacturing processes for glass and plastic optics are entirely different. Glass lenses are made by a grinding and polishing process whereas precision plastic lenses are made by injection-molding. The differences in manufacturing process provide plastic optics some unique advantages as follows:

High-volume production capability and low manufacturing cost: Injection molding process allows very high volume production, and the unit cost can be very low. Though it is possible to achieve moderately high volume production with glass optics also, it is virtually impossible to realize the same cost reduction because the grinding and polishing process is inherently time-consuming and labor-intensive.

Design sophistication: The grinding and polishing process makes difficult and very uneconomical to produce surface shapes other than sphere or flat in glass materials. However, the injection-molding process makes it feasible and economical to produce more sophisticated optical shapes such as asphere and diffractive surfaces in plastic provided a mold is properly made. From the design point of view, the more sophisticated surface shapes provide much better performance for many applications.

Unique designs possible: Many useful designs that cannot be realized with glass optics can be achieved with plastic optics such as lens arrays and Fresnel lenses those are useful for a range of light dispersion and collection applications.

Lightweight and shatter-resistant: The plastic materials are lighter weight and are more shatter-resistant. This feature is very important for head-worn optics such as head-mounted displays.
**Integral mounting**: For most optical applications, the individual optical components must be mounted in a system structure. With glass optics, it is done with separate mechanical mounting hardware. However, with plastic optics, it is possible to include the mounting features with the optical component. This not only reduces the overall system cost, but also the improves the reproducibility of the assembly.

**Consistent Quality**: Plastic optics can be made with very consistent quality since all the lenses are derived from the same mold cavity (ies). Modern statistical control techniques are also been used to monitor the molding process to ensure a good yield is achieved.

The major drawbacks of plastic optics are mostly material related. For example, plastic material is more sensitive to environment changes such as temperature and humidity. In addition, the material flow pattern and shrinkage during molding also limit the surface accuracy that is achievable with plastic optics. The index distribution within a molded component may be inhomogeneous and varying with the polarization (birefringence). The chemical properties of available plastic materials also limits the performance of the optical coatings that can be deposited on the plastic materials. It is important for the optical designer to understand the advantages as well as the limitations of plastic optics before a decision is made to use plastic optics. We strongly suggest that you discuss with us before finalizing your designs.

**Processes**

**Design**

Designing good plastic optics requires a solid understanding of the material properties and the manufacturing processes. The advantages of plastic optics can be realized only when the design is optimized for plastic manufacturing. The design rule for plastic optics is quite different from that of the glass optics because of the significant differences in the material and the manufacturing processes. Specific knowledge and design expertise are needed to take full advantages of what precision plastic optics can offer.

Many existing designs are being converted to plastic designs. Successful conversions must consider the performance and manufacturability of plastic optics. Merely substituting the indices of refraction and re-optimizing the design are rarely sufficient to ensure good manufacturability. Expert design assistance is to be sought at this stage.

**Prototype**

Once the design is completed, prototypes of plastic lenses can be made by diamond-turning. This is a ultra-precision machining process that cuts the optical surface profiles directly onto a solid block of plastic material. Experiences have shown that excellent surface finishes can be obtained with low-index plastic materials. Higher index materials such as polycarbonate do not yield very smooth surface finishes. This process is only recommended for making a limited number of prototypes to verify the fit, form and function of the design. The result of this process is not a validation of the
manufacturability of the design because injection molded lenses will usually have very different bulk index distribution and surface properties.

**Pre-Production Stage**
For most high volume products, a pre-production stage is required to validate the manufacturing process. This can be done by constructing a single-cavity prototype mold and developing a set of optimal molding conditions to process the part. Through this prototype molding process, one can verify that design performance can indeed be achieved with molded components. Design revisions if any should be implemented at this stage. In many cases, the prototype molds can also be used to start limited production since production tooling (multi-cavity) may take a significant amount of time to built and qualify. Preliminary process capability can also be gained through this stage.

**Production Stage**
The production stage usually require the construction of multi-cavity production molds. Depending on the product volume, throughput requirement and cost constraints, the production tooling can have 2, 4, 8, or 16 cavities. In truly high volume cases, 32 cavity molds can also be built to achieve the required throughput. The production molds are built with quality steel, and are designed to function for at least several hundred of thousands of injection cycles. Production tooling usually take significant amount of time to construct, and are costly. Therefore, it is critical that the product has been truly finalized before the production tooling is built.

Once the production molds are completed, it is necessary to qualify the molds. Process capabilities can be established by sampling the production molds. Any iteration or adjustment can then be made to achieve full potential of the production tooling. Molding parameters are also critical here. During the mold qualification process, the optimal molding conditions should be determined. These conditions must be maintained during production in order to achieve capability of the process. SPC techniques are used to monitor the production process to keep the process stable.

**Coating**
Unlike glass lenses, plastic lenses cannot be coated in an elevated temperature environment. The coating materials must be deposited in room temperature condition. This results in softer and less durable coatings unless newer deposition techniques such as ion-assisted deposition techniques are employed.

Multi-layer dielectric coatings are routinely deposited on plastic components. For example, a four layer anti-reflection coating can reduce the reflection to about 0.5% per surface across the entire visible spectrum.

**Assembly**
Plastic optical assembly are usually done in a clean room environment to minimize the dust and contamination. The components are designed to ensure ease of assembly. Snap-on
features are used whenever possible. UV-cementing, heat-staking and ultra-sonic welding can also be employed if appropriate.

Since most optical tolerances are additive, it is important to design in testing points along the manufacturing flow process to “kick” out non-conforming sub-assemblies before more valued add-work is done to that part. Automatic in-line optical performance monitoring such as MTF testing can be implemented to perform this function. SPC techniques should be used here to ensure the process is not drifting out of the controllable range.

For high volume assembly, it is also possible to use semi-automated or fully automated assembly machines to perform the optical assembly. These machines are built based on a generic “pick and place” machine. In-line optical testing functions can also be integrated with the assembly machine.

**Component Cost**

Even though plastic optics offers lowest cost in volume production, glass optics has cost-advantages for small volume requirements from an overall cost point of view. The following table compares the typical prices for glass and plastic optics at various volumes.

<table>
<thead>
<tr>
<th>Volume</th>
<th>Plastic Optics</th>
<th>Glass Optics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-volume 1 - 10³</td>
<td>Tooling cost: $7.5K</td>
<td>Available from catalog optics companies: Melles Griot, Newport, Edmund Scientific</td>
</tr>
<tr>
<td></td>
<td>Process NRE: $1K</td>
<td>$10/each - $100 /each</td>
</tr>
<tr>
<td>Medium Volume 10³-1⁰⁴</td>
<td>Tooling cost: $10-15K</td>
<td>OEM glass lens supplier</td>
</tr>
<tr>
<td></td>
<td>Process NRE: $2K</td>
<td>Unit price: $3-$10</td>
</tr>
<tr>
<td></td>
<td>Piece price: $1-10/each</td>
<td></td>
</tr>
<tr>
<td>High Volume &gt;10,000</td>
<td>Tooling cost:$25K to $50K</td>
<td>OEM glass lens supplier</td>
</tr>
<tr>
<td></td>
<td>Process NRE:$2k</td>
<td>Unit price: $0.50 to $5</td>
</tr>
<tr>
<td></td>
<td>Piece price:$0.25 to $3</td>
<td></td>
</tr>
</tbody>
</table>

**Summary**

**Material:**
- “Crown” materials: Acrylic (PMMA), Polyolefin, Arton, Optores (see attached material table for details).
- “Flint” materials: Polystyrene, Polycarbonate, NAS

**Geometry:**
- Precision lens shapes: Bi-Convex, Meniscus, Bi-Concave, Plano-convex, Plano-cave
- Diameter: 2mm-120mm.
• Thickness: 1mm-17mm.
• Flat, spherical, conic and high order aspheric surfaces
• Diffractive surfaces
• Curved mirror substrates including aspheric
• Low precision prisms (<10mm side)
• Integral mounting
• Flat surfaces have less accuracy

**Typical Tolerances:**
• Diameter: +/- 0.05mm
• Ctr. thickness: +/- 0.03mm
• Surface figures: better than 3 fringes /1 fringes for lenses < 8 mm dia. Rule of thumb: 5/3 fringes per 10mm for larger parts.
• Surface quality: 40-20
• Centration: 1-3 arc mins
• Max. clear aperture: 90% of the dia.
• Coatable with multi-layer coatings; no MgF2 on plastic
• Ideal production volume: 1000 to millions.
• Refractive index variations: the 3rd decimal place.

**Special Issues to Consider:**
• Plastic designs require special consideration for manufacturability and performance
• Quick prototyping possible by diamond-turning, expensive process (up to $500 per lens)
• Prototype tooling: 6-8 weeks lead time, can mold up to 10,000 lenses
  Production tooling: 12-14 weeks lead time, can mold up to several million parts
<table>
<thead>
<tr>
<th>Material</th>
<th>Characteristics</th>
<th>Acrylic (PMMA)</th>
<th>Polystyrene</th>
<th>Polycarbonate (Optical Grade)</th>
<th>NAS</th>
<th>Polyolefin (Zeonex)</th>
<th>Arton F</th>
<th>Optores (OZ1000-1100)</th>
<th>Optores (OZ1310-1330)</th>
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<tbody>
<tr>
<td>Optical</td>
<td>Spectral Passing Band (nm)</td>
<td>390-1600</td>
<td>400-1600</td>
<td>360-1600</td>
<td>395-1600</td>
<td>300-1600</td>
<td>390-?</td>
<td>390-?</td>
<td>410-?</td>
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<tr>
<td></td>
<td>Refractive Index @ 589nm @ 25°C</td>
<td>1.491</td>
<td>1.590</td>
<td>1.587</td>
<td>1.563</td>
<td>1.525</td>
<td>1.51</td>
<td>1.4995-1.5025</td>
<td>1.5059-1.5096</td>
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<td></td>
<td>Abbe Value</td>
<td>57.4</td>
<td>30.9</td>
<td>29.9</td>
<td>33.5</td>
<td>56.3</td>
<td>57</td>
<td>57-56</td>
<td>54-52</td>
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<tr>
<td></td>
<td>Transmittance (%)</td>
<td>92</td>
<td>92</td>
<td>90</td>
<td>90</td>
<td>91</td>
<td>92</td>
<td>92</td>
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</tr>
<tr>
<td></td>
<td>Thickness 3.2mm</td>
<td>1.3</td>
<td>1.5(?)</td>
<td>1.7(?)</td>
<td>1.5(?)</td>
<td>1.5(?)</td>
<td>1.5</td>
<td>1(?)</td>
<td>1(?)</td>
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<tr>
<td></td>
<td>Haze (%)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Thickness 3.2mm</td>
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<td></td>
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<tr>
<td>Physical</td>
<td>Specific Gravity</td>
<td>1.19</td>
<td>1.06</td>
<td>1.20</td>
<td>1.09</td>
<td>1.01</td>
<td>1.08</td>
<td>1.16</td>
<td>1.19</td>
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<td>Max. Service Temperature (C)</td>
<td>90</td>
<td>80</td>
<td>120</td>
<td>85</td>
<td>123</td>
<td>171</td>
<td>95-100 (?)</td>
<td>80-100 (?)</td>
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<tr>
<td></td>
<td>Linear CTE</td>
<td>6.8x10^{-5}</td>
<td>7x10^{-5}</td>
<td>6.6x10^{-5}</td>
<td>7x10^{-5}</td>
<td>7x10^{-5}</td>
<td>6.1</td>
<td>7</td>
<td>7</td>
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<tr>
<td></td>
<td>Abrasion Resistance (0-10)</td>
<td>10</td>
<td>4</td>
<td>2</td>
<td>6</td>
<td>&gt;10</td>
<td>?</td>
<td>?</td>
<td>?</td>
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<tr>
<td></td>
<td>Izod Impact Strength 1/4&quot; notched</td>
<td>1</td>
<td>1(?)</td>
<td>12</td>
<td>1.6(?)</td>
<td>3.2(?)</td>
<td>2</td>
<td>?</td>
<td>?</td>
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<tr>
<td>Environmental</td>
<td>dN/dT(x10^{-6})</td>
<td>-105</td>
<td>-140</td>
<td>-107</td>
<td>-110</td>
<td>-130</td>
<td>-35 (?)</td>
<td>-100</td>
<td>-100</td>
</tr>
<tr>
<td></td>
<td>Sensitivity to Humidity Water absorption (%) 23C 1 week</td>
<td>High 2.0</td>
<td>Low</td>
<td>Low</td>
<td>Mid</td>
<td>Low</td>
<td>Low</td>
<td>Low 0.4</td>
<td>Low 1</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>Process-ability</td>
<td>Excellent</td>
<td>Good</td>
<td>Poor</td>
<td>Excellent</td>
<td>Good</td>
<td>TBD</td>
<td>TBD</td>
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<tr>
<td></td>
<td>Birefringence</td>
<td>Very Good</td>
<td>Fair</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>20% better than PMMA</td>
<td>Excellent</td>
</tr>
</tbody>
</table>
List of References

3. ""I. K. Pasco, J. H. Everest" ""Plastics optics for opto-electronics"", Optics and Laser Technology, Vol. 10, pp. 71 - 76, 1978. ""General discussion of plastics and issues in molded/cast optics for various commercial & aerospace systems, such as cameras, fiber connector, pocket calculator LED lenslets, and high-precision mirrors/rectors for space guidance systems and HUDs."
5. John D. Lytle ""Specifying glass and plastic optics - what's the difference?", SPIE Proceedings, Vol. 181, pp. 93 - 102, 1979. ""Excellent lens designer/optical engineer tutorial on the design and specification of plastic optics, including highlights of the differences in calling out surface figure, quality, and cosmetics."
28 Taira Kouchiwa ""Designing of a plastic lens for copiers", SPIE Proceedings, Vol. 554, pp. 419 - 424, 1985." These investigators took plastic lenses and exposed them to various temperature and humidity conditions, then measured their optical parameters. Derived formulae for changes due to temperature and humidity for PMMA & polycarbonate. Partial compensation."

List of Trade Magazine Publications

1 "Chuck Teyssier, Chuck Devereese" ""What's Next for Plastic Optics?", Lasers & Optronics, pp. 23 -24, December 1995." A magazine-type summary of the state of the art in plastic optics - mentions the maturity of the technology due to diamond turning, diffractive lenses, and increasing use by designers and product developers. Includes material table with properties."
2 Charles N. Teyssier ""Molded Plastic Optics Enter the Mainstream", Photonics Spectra, pp. 105 - 110, March 1996." Similar in scope to Ref. 4 above - but includes some useful tips to the optical engineer working with this technology with regard to shrinkage, lens radii, gate location, temperature effects, etc."