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-know 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 chose 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 un-economical 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.

Volume	Plastic Optics	Glass Optics
Low-volume 1 - 10^3	Tooling cost: $7.5K Process NRE: $1K	Available from catalog optics companies: Melles Griot, Newport, Edmund Scientific $10/each - $100 /each
Medium Volume 10^3-10^4	Tooling cost: $10-15K Process NRE: $2K Piece price: $1-10/each	OEM glass lens supplier Unit price: $3-$10
High Volume >10,000	Tooling cost:$25K to $50K Process NRE:$2k Piece price:$0.25 to $3	OEM glass lens supplier Unit price: $0.50 to $5

Summary

Material:

- <u>"Crown" materials</u>: Acrylic (PMMA), Polyolefin, Arton, Optores (see attached material table for details).
- <u>"Flint" materials</u>: 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 MgF_2 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

Properties of Optical Plastic Materials

Material	Characteristics	Acrylic (PMMA)	Polystyrene	Polycarbonate (Optical Grade)	NAS	Polyolefin (Zeonex)	Arton F	Optores (OZ1000 -1100)	Optores (OZ1310-1330)
Optical	Spectral Passing Band(nm)	390-1600	400-1600	360-1600	395-1600	300-1600	390-?	390-?	410-?
	Refractive Index @ 589nm @25^{0}C	1.491	1.590	1.587	1.563	1.525	1.51	1.4995-1.5025	1.5059-1.5096
	Abbe Value	57.4	30.9	29.9	33.5	56.3	57	57-56	54-52
	Transmittance (%) Thickness 3.2mm	92	92	90	90	91	92	92	92
	Haze(%) Thickness 3.2mm	1.3	1.5(?)	1.7(?)	1.5(?)	1.5(?)	1.5	1(?)	1(?)
Physical	Specific Gravity	1.19	1.06	1.20	1.09	1.01	1.08	1.16	1.19
	Max. Service Temperature (C)	90	80	120	85	123	171	95-100(?)	80-100(?)
	Linear CTE	$6.8x10^{-5}$	$7x10^{-5}$	$6.6x10^{-5}$	$7x10^{-5}$	$7x10^{-5}$	6.1	7	7
	Abrasion Resistance (0-10)	10	4	2	6	>10	?	?	?
	Izod Impact Strength 1/4” notched	1	1(?)	12	1.6(?)	3.2(?)	2	?	?
Environmental	dN/dT($x10^{-6}$)	-105	-140	-107	-110	-130	-35 (?)	-100	-100
	Sensitivity to Humidity Water absorption (%) 23C, 1 week	High 2.0	Low	Low 0.4	Mid	Low	Low 0.4	Low 1	Low 1
Manufacturability	Process-ability	Excellent	Good	Poor	Excellent	Good	TBD	TBD	TBD
	Birefringence	Very Good	Fair	Poor	Good	Good	Good	20% better than PMMA	Excellent
Chemical	Resistance to Methanol	limited	?	limited	?	?	Good	?	?
Cost	Material Cost	$1.3/lb	$1.1/lb	$2-3/lb	$1.3/lb	$20-30/lb	$16-20/lb	TBD	TBD

List of References

1 Lee R. Estelle """Third-order theory of thermally controlled plastic and glass triplets"", SPIE Proceedings, Vol. 237, pp. 392 - 401, 1980." Paraxial thin lens study of first and third order aberration corrected triplet starting points with thermal compensation. Uses combinations of glass and plastic solutions to achieve simultaneous aberration targets and thermal control.

2 Shigeo Kubota """A Lens Design for Optical Disk Systems"", SPIE Proceedings, Vol. 554, pp. 282 - 289, 1985." "Bi-aspheric plastic acrylic design for compact disk player; explores sources, effects, and compensation of spherical (generated by disk surface refraction) and coma (caused by disk surface tilt and lens decenter). Good discussion of CD lens reqts/tols."

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/correctors for space guidance systems and HUDs."

4 "Roy M. Waxler, Deane Horowitz, Albert Feldman" """Optical and physical parameters of Plexiglass 55 and Lexan"", Applied Optics, Vol. 18(1), pp. 101 - 104, 1979." "Details the optical, thermo-mechanical, electro-optical, and thermo-optical properties of acrylic and polycarbonate"

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."

6 John D. Lytle """Status and Future of Polymeric Materials in Imaging Systems"", SPIE Proceedings, Vol. 1354, pp. 388 - 394, 1990." "A semi-retrospective paper delivered from the perspective of 2005 AD and looking back, but with enough technical plausibility to be believable. Discusses how to create zero Petzval sum achromats by careful glass/plastic index/dispersion matching."

7 Atsuo Osawa, Kyohei Fukuda, Kouji Hirata" """Optical Design of High Aperture Aspherical Projection Lens"", SPIE Proceedings, Vol. 1354, pp. 337 - 343, 1990." "Design / analysis of a molded aspheric plastic lens for projection TV. Includes rules of thumb for designing plastic lenses, such as constant thickness to reduce temperature, humidity, and tolerance effects. Discusses zonal asphere/ray interactions."

8 "Masahiko Yatsu, Masaharu Deguchi, Takesuke Maruyama" """Zoom lens with aspherical lens for camcorder"", SPIE Proceedings, Vol. 1354, pp. 663 - 668, 1990." "Hitachi paper detailing aspheric design of a zoom lens with plastic optics for size/weight reduction. They generically discussed how to compensate for temperature and humidity changes, but no numbers/details."

9 "Yuki Tanaka, Hiroshi Miyamae" """Analysis on image performance of a moisture absorbed plastic singlet for an optical disk"", SPIE Proceedings, Vol. 1354, pp. 395 - 401, 1990." An analysis/simulation that models the effect of moisture diffusion into an acrylic CD singlet lens and its effect on specific aberration coefficients. Contains a time-dependent image quality analysis vs. diffusion time.

10 "J. M. Elson, H. E. Bennett" """Image degradation caused by tooling marks in diamond-turned optics"", SPIE Proceedings, Vol. 525, pp. 22 - 28, 1985." Analytical paper that takes a Fourier optic / power spectral density approach to modeling effect of tooling marks on image quality. Has numerical examples / results for a 10 cm diameter mirror.

11 "H. Koehler, F. Straehle" """Design of Athermal Lens Systems"", Space Optics: Proc. Ninth International Congress of the International Commission for Optics, National Academy of Sciences, Washington, DC, 1974." "Theoretical paper that examines the use of glass choice to achieve athermalized (or reduced thermal effect) of achromatic doublets,
both for homogeneous temperature changes, and for radial gradient conditions."

12 Thomas H. Jamieson """Thermal effects in optical systems"", originally SPIE Proceedings, Vol. 193, 1979 (later revised and presented in this refereed version at SPIE Seminar on Optical Systems Engineering, Aug. 27 - 28, 1979)" "Nice tutorial paper on characterizing thermal effects on glass & plastic lenses, and discusses the feasibility and limitations of material choice and mount material in reducing thermal impacts. Covers homogeneous and radial gradients."

13 "Paul Benham, Michael Kidger" """Optimization of athermal systems"", SPIE Proceedings, Vol. 1354, pp. 120 - 125, 1990." "A barely disguised ad for Kidger's lens design software. However, it does cover some points of athermalization via mechanical mount/compensator design"14 Mete Bayar """Lens barrel opto-mechanical design principles"", originally SPIE Proceedings, Vol. 193, 1979 (later revised and presented in this refereed version at SPIE Seminar on Optical Systems Engineering, Aug. 27 - 28, 1979)" "General paper on mounting lenses in barrels, including barrel materials, centration measurement, cementing, elastomeric mounting with minimum radial strain, and leak rate analysis."
15 Michael H. Krim """Design of Highly Stable Optical Support Structure"", Optical Engineering, Vol. 14(6), pp. 552 - 558, Nov/Dec 1975." An analysis for the Hubble Space Telescope that uses the graphite truss geometry in a novel way so as to maintain the telescope focus within specs during heating and cooling.16 "J. E. Stumm, G. E. Pynchon, G. C Krumweide" """Graphite/epoxy material characteristics and design techniques for airborne instrument application"", SPIE Proceedings, Vol. 309, pp. 188 - 198, 1981." "Covers the opto-mechanical details necessary to use graphite/epoxy materials for high precision aerospace optics, such as large lightweight mirrors, reflectors, telescopes, satellite sensors, etc."
17 "Juan. L. Rayces, Lan Lebich" """Thermal compensation of infrared achromatic objectives with three optical materials"", SPIE Proceedings, Vol. 1354, pp. 752 - 759, 1990." Paraxial thin lens analysis to find sets of three infrared materials to athermalize the focal plane location for IR triplet lenses.
18 Philip J. Rogers """Athermalized FLIR Optics"", SPIE Proceedings, Vol. 1354, pp. 742 - 751, 1990." Classic Phil Rogers paper (with humor and cartoons) discusses mechanical and optical athermalization techniques for FLIR systems.
19 Eugene K. Thorburn """Tolerances and techniques in high precision optical assembly"", SPIE Proceedings, Vol. 406, pp. 113 - 118, 1983." An autobiographical Thorburn paper on his experiences in optical design and fabrication during his career. Shares his philosophies of tolerancing and compensation.
20 Eugene K. Thorburn """Concepts and misconceptions in the design and fabrication of optical assemblies"", SPIE Proceedings, Vol. 250, pp. 2 - 7, 1980." "Another quasi-autobiographical Thorburn paper discussing optical tolerancing methods, while demolishing some fallacies and myths in the field."
21 "Donald E. Oinen, Nicholas W. Billow" """A New Approach to the Simulation of Optical Manufacturing Processes"", SPIE Proceedings, Vol. 1354, pp. 487 - 493, 1990." Seminal paper on the use of computer-intensive Monte Carlo techniques to predict as-manufactured tolerances. Discussion followed by concrete example for a star tracker telescope.
22 Berge Tatian """Testing an unusual optical surface"", SPIE Proceedings, Vol. 554, pp. 139 - 147, 1985." "One in a series of Tatian papers on unusual surfaces, which are plane symmetric general aspheric surfaces used in WALRUS-type systems. Explores describing these shapes and best fits to conics to minimize the wavefront departure for null testing
purposes"
23 William T. Plummer """Unusual optics of the Polaroid SX-70 camera"", Applied Optics, Vol. 21, No. 2, pp. 196 -202, 15 January 1982." "Describes the design and some optical manufacturing aspects of the SX70 camera, including the novel decentered aspheric viewfinder optics."
24 David S. Grey """Athermalization of Optical Systems"", JOSA, Vol. 38, No. 6, pp. 542 - 546, June 1948." "Thin lens analysis with examples for glass/plastic and plastic/plastic lens combinations. Published in 1948, it is still a good reference for simple calculations."
25 "Tetsuro Izumitani, Shinichiro Hirota, Isao Ishibai, Ryuji Kobayashi" """Precision molded aspheric lenses for a camera and for a compact disk system"", SPIE Proceedings, Vol. 554, pp. 290 -294, 1985." Discusses the measured performance of two precision molded GLASS lenses for CD player and camera.
26 D. Keyes (?) """Outline for CRC Handbook of Laser Science and Technology, Section on fundamental properties of optical plastics"" (Draft), source/citation unknown, marked ""4/92""." "Generic handbook type data on common optical plastics. Discusses haze, laser effects, has table of common optical plastic materials with manufacturers addresses, including optical and physical properties"
27 "Pierre J. Brosens, Vladimir Vudler" """Stability of lightweight replicated mirrors"", Optical Engineering, Vol. 28 No. 1, pp. 61 - 65, January 1989." Compares performance of solid and replicated (epoxy plus reflective coating) scanner mirrors over temperature. Points made discussing epoxy vs. temperature are applicable to other optical plastics.

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."
29 "Jay H. Lowry, Joseph S. Mendlowitz, N. S. Subramanian" """Optical characteristics of Teflon AF fluoroplastic materials"", Optical Engineering, Vol. 31 No. 9, pp. 1982 - 1985, September 1992." Tabulates optical and transmissive properties of a new Teflon formulation and compares them to other common optical plastics in a short table.
30 "Masayuki Muranaka, Masao Takagi, Terunori Maruyama" """Precision molding of aspherical plastic lens for cam-corder and projection TV"", SPIE Proceedings, Vol. 896, pp. 123 - 131, 1988." Hitachi paper that refines precision of molding aspheric plastics by doing a finite element analysis to model the non-uniform shrinkage that occurs due to temp. variation in the mold while curing. Good discussion of precision optical molding ideas.
31 "Pneumo Precision, Inc. Keene, NH" """A Designer's Guide to Diamond Machined Optics"", Pneumo Precision, Inc., April 1983." "An excellent tutorial/introduction to the mechanical aspects of diamond turning, including the diamond itself, specifications, callouts, and predicted scatter."

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."
3 H. D. Wolpert """A Close Look at Optical Plastics (Part 1)"", Photonics Spectra, February 1983, pp. 68 - 71." "Good trade magazine summary of optical plastics, issues, and trends within the industry."
4 H. D. Wolpert """A Close Look at Optical Plastics (Part 2)"", Photonics Spectra, March 1983, pp. 63 - 65."
5 "Claude Tribastone, Chuck Teyssier" """Designing Plastic Optics for Manufacturing"", Photonics Spectra, May 1991, pp. 120 - 128."
6 "Chuck Teyssier, Claude Tribastone" """Plastic Optics: Challenging the High Volume Myth"", Lasers & Optronics, December 1990, pp. 50 - 53."
7 "Harvey Pollicove, Thomas Aquilina" """Injection Mounting: A Lens Assembly Innovation"", Photonics Spectra, December 1987, pp. 109 -114."