

# An Introduction to the Design, Manufacture and Application of Plastic Optics

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A variety of industries are incorporating plastic optics in their optical systems to achieve lower unit costs, to employ complex geometry and uniquely shaped components, and to take advantage of the inherent quality and consistency of plastic molding. The integration of design, tooling, fabrication and coating have been critical to the success of these systems.

No single material solves all optical design problems. The features in such a comparison include optical characteristics, volume and packaging considerations, manufacturing precision levels, and environmental concerns. Some systems strongly favor the use of only glass optics, some benefit more heavily from the inclusion of only plastic optics, and others can draw advantages from each group. The evolution of polymer optical systems continues to expand in many industries and fields. As examples, plastic optics are widely used in medical diagnostic systems such as laparoscopes, arthroscopes, cytosopes, and blood analyzers; visual systems and information displays such as night vision goggles, surgical head-mounted video displays, and entertainment displays; and personal computer related products such as videoconferencing cameras,

LCD projectors, handheld laser barcode scanning units, and security-identification systems. This article presents design and manufacturing information regarding polymer optics in optical systems that demonstrate the benefits and limitations of this technology.

## Component Manufacturing Process

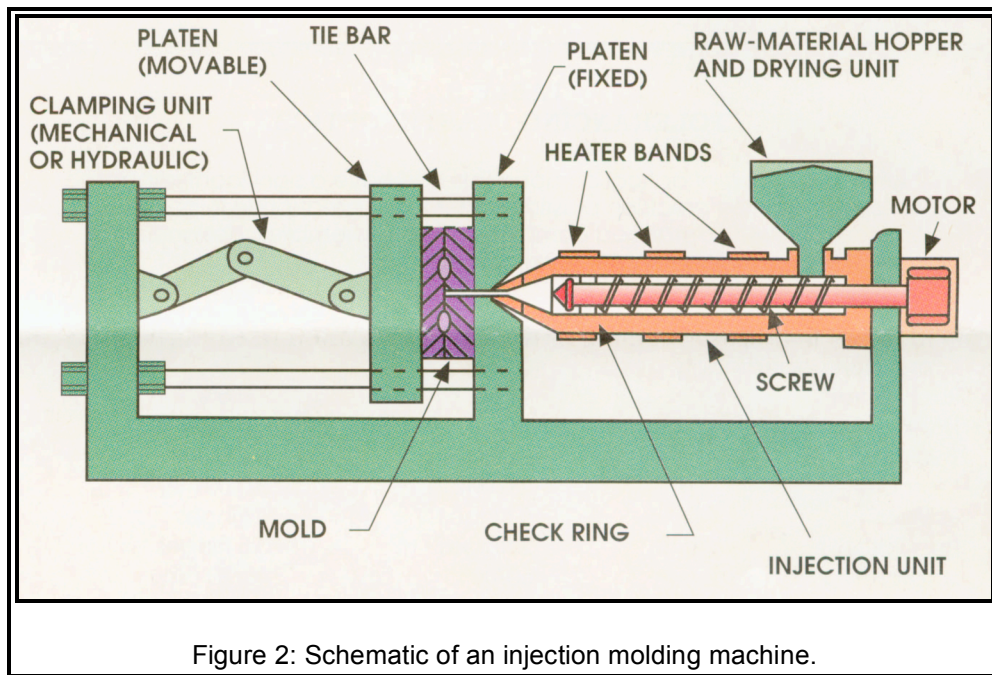
Precision plastic optics are fabricated with molding processes that yield high-volume production capability as compared to glass optics. Typical molding methods for optics are injection molding, compression molding, and a hybrid method: injection-compression molding.

### *Injection Molding*

Injection molding is capable of running single- and multi-cavity molds. Multi-cavity molds produce several parts per individual shot or cycle. Injection molding allows the manufacturer to optimize part cost, tooling complexity, and precision level to produce the right solution for all situations. This method yields consistent components with minimum unit costs.

An optical, plastic injection molding machine consists of a fixed platen, a moving platen, a clamping unit, and an injection unit (Fig. 2). Plastic pellets are placed in the hopper (raw material is either pre-dried or dried in the hopper via a desiccant drying system). The movable platen moves forward and closes the mold. The high pressure behind the clamp keeps the mold closed during the injection cycle.

The material, in pellet form, is gravity fed into the injection barrel, which contains the screw. The material is heated to a molten state and a predetermined amount of material is injected into the mold. Heat, injection pressure, and injection velocity at various stages in the molding cycle are adjusted to optimize and stabilize the process and yield the desired optical component. As the material cools and solidifies, it takes on the shape of the insert and cavity shapes; following a cooling phase, the mold opens. At the end of the cycle, an ejection mechanism separates the optic from the mold.



### *Compression Molding*

Optical compression molding is primarily used in the manufacture of fresnel lenses and lenticular arrays, where surface structure detail is extremely important.

In compression molding, material can be introduced into the machine in pellet or sheet form. The material is pressed between heated fixed and movable platens, which are temperature-cycled during normal pressing. This temperature cycling extends the mold time as compared to injection molding.

Detailed fresnel and lenticular mold inserts used in compression molding are generally nickel electroforms that are replicated from a brass or aluminum master insert. Extremely fine-depth grooves and tight angular tolerances can be achieved with this process.

### *Injection-compression Molding*

This process is a hybrid form of the two previously discussed methods; this method is sometimes referred to as coining. A molten resin is injected into a temperature-controlled mold, which is loosely clamped to prevent the escape of material through the mold parting line. Following the injection portion of the cycle, a secondary clamping operation fully closes the mold during the curing portion of the cycle. The results are a higher level of feature replication and tighter part tolerances. Because the cycle times are shorter for this process than in compression molding, this process is well suited to large or thick components.

Optical molding via any of the aforementioned methods should be performed in a clean environment. Standard optics handling issues apply in such a manufacturing operation. In addition to the use of positive air flow to maintain part cleanliness, a flow of ionized air can help reduce the attraction of dust to molded components.

**TABLE 1.  
PROPERTIES OF PRINCIPAL OPTICAL PLASTICS**

Units	Acrylic	Styrene	NAS	SAN	Poly-carbonate	TPX	ABS	Nylon	
	Polymethyl Methacrylate (Lucite) (Plexiglass)	Polystyrene (Dylene) (Styron) (Lustrex)	Methyl Methacrylate Styrene Copolymer	Styrene Acrylonitrile (Lustran) (Tyrl)	(Lexan) (Merlon)	Methylpentene (TPX)			
Refractive index, n									
n <sub>a</sub> (587.6 nm)	1.492	1.590	1.533-1.567	1.567-1.571	1.585	1.467	1.538	1.535	
n <sub>c</sub> (656.3 nm)	1.489	1.585	1.558	1.563	1.580	1.464			
n <sub>f</sub> (486.1 nm)	1.498	1.604	1.575	1.578	1.599	1.473			
Abbe Value, V <sub>d</sub>	57.4	31.1	35	37.8	29.9	51.9			
Rate of change in index with temperature	dn/dt x 10 <sup>-5</sup> /°C	-8.5	-12.0	-14.0		-11.8 to -14.3			
Coefficient of linear expansion	cm/cm x 10 <sup>-5</sup> /°C	6.74@70°C	6.0-8.0		6.5-6.7	6.6-7.0	0.83	6.8	
Deflection temperature									
3.6°F/min 264 psi	°C	92	82		99-104	142	90	124	
3.6°F/min 66 psi	°C	101	110		100	146	84	140	
Recommended max. cont. service temp.	°C	92	82	93	79-88	124		82	
Thermal conductivity	cal/sec-cm °C x 10 <sup>-4</sup>	4.96	2.4-3.3	4.5	2.9	4.65	4.0	5.0	
Haze	%	2	3	3	3	3	5	12	7
Uncoated transmittance	%,thickness 3.175 mm	92	88	90	88	89	90	79-90.6°	88
Water absorption	%,immersed 24h@23°C	0.3	0.2	0.15	0.2-0.35	0.15			3.3
Advantages		Transmission	High index	Good index range	Stable	Impact strength	Chemical resistance	Durable	Chemical resistance

Uncoated luminous transmittance 79%, thickness 6.35 mm; 90.6%, thickness 0.381 mm.

### Optical Molding Materials

The variety of available optical grade polymers is limited compared to that of glass, but the number of optical polymers is growing. The high volumes of optical plastics that have been used in CD-ROM disks have aided the industry in significant improvements in existing materials, particularly in transmission and haze reduction.

Table 1 lists several physical characteristics of the most commonly used optical plastics. Various plastic manufacturers specify refractive index to the third or fourth decimal place. Coefficients for a Laurent series expansion of index interpolation (often called the Schott formula) are shown in Table 2. Figure 3 is a glass map showing the refractive index and Abbe dispersion number of seven optical plastics. Prior to choosing an optical material, the engineer is well-advised to consult with the molding company to learn of the relative cost, quality, experience, and availability issues for the particular material. The following paragraphs provide supplementary information to Tables 1 and 2 for several of the most common optical polymers and copolymers.

**TABLE 2**  
**INDEX INTERPOLATION COEFFICIENTS FOR SOME OPTICAL PLASTICS**

COEF	ACRYLIC	POLYSTYRENE	POLYCARBONATE	SAN	POLYOLEFIN
$A_0$	2.185936	2.445984	2.428386	2.38687	2.212154
$A_1$	$8.0 \cdot 10^{-6}$	$2.2 \cdot 10^{-5}$	$-3.9 \cdot 10^{-5}$	$-1.231 \cdot 10^{-3}$	$4.8611 \cdot 10^{-2}$
$A_2$	$1.45315 \cdot 10^{-2}$	$2.72989 \cdot 10^{-2}$	$2.87574 \cdot 10^{-2}$	$2.29468 \cdot 10^{-2}$	$5.187444 \cdot 10^{-2}$
$A_3$	$-5.6315 \cdot 10^{-4}$	$3.0121 \cdot 10^{-4}$	$-1.979 \cdot 10^{-4}$	$3.6981 \cdot 10^{-4}$	$-8.0382 \cdot 10^{-3}$
$A_4$	$9.4903 \cdot 10^{-5}$	$8.8893 \cdot 10^{-5}$	$1.48359 \cdot 10^{-4}$	$2.6758 \cdot 10^{-5}$	$6.100 \cdot 10^{-4}$
$A_5$	$-3.9023 \cdot 10^{-6}$	$-1.7571 \cdot 10^{-6}$	$1.3865 \cdot 10^{-6}$	$2.848 \cdot 10^{-6}$	$2.9862 \cdot 10^{-6}$

$$n^2(\lambda) = A_0 + A_1\lambda^2 + A_2\lambda^{-2} + A_3\lambda^4 + A_4\lambda^{-6} + A_5\lambda^{-8} \quad (\lambda \text{ in microns})$$

(365 nm <  $\lambda$  < 1014 nm except for Polyolefin)  
(435 <  $\lambda$  < 830 nm for Polyolefin)

DATA COURTESY OF RICHARD M. ALTMAN AND ZEON CHEMICALS, INC.

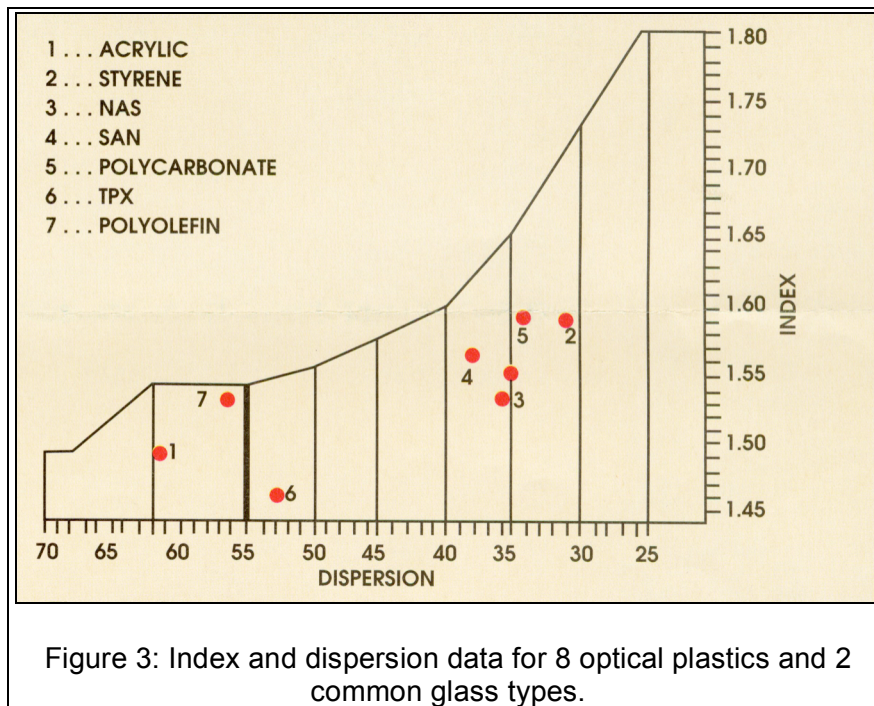


Figure 3: Index and dispersion data for 8 optical plastics and 2 common glass types.

### *PMMA*

Acrylic is the most commonly used optical plastic. Because of the similar refractive index and dispersion values (Fig. 3) of acrylic to common crown glasses (particularly BK-7), acrylic is referred to as the “crown” of the optical plastics. Acrylic is moderately priced, is easily molded, has a relatively high transmission, is very scratch resistant, and is not very water absorptive. Additives to acrylic (as well as to several other plastics) considerably improve its UV transmittance and stability.

### *Styrene*

Due to styrene’s index and dispersion values (high index, high dispersion) compared to other plastics (Fig. 3), styrene is often used as the “flint” element in color-corrected plastic optical systems. Polystyrene is a low-cost material with excellent molding properties. Compared to acrylic, styrene has lower transmission in the ultraviolet portion of the spectrum and is a softer material. Due to its lower surface durability, styrene is more typically used in non-exposed areas of a lens system.

### *Methyl Methacrylate Styrene – NAS® (Nova Chemicals)*

This copolymer material consists of seventy percent acrylic and thirty percent styrene. The specific blend ratio effects the actual refractive index of the material; the index of refraction range is 1.533 to 1.567.

### *Polycarbonate*

Polycarbonate is very similar to styrene in terms of several optical properties : transmission, refractive index, and dispersion. Polycarbonate, however, has a much broader operating temperature band of -137°C to 120°C. For this reason, polycarbonate is the “flint” material of choice for systems that are required to withstand severe thermal conditions. Additionally, the high impact-resistance of polycarbonate is the material’s strongest advantage. For that reason, safety glasses and systems requiring durability often employ polycarbonate.

### *Cyclic Olefin Copolymer - COC*

Cyclic olefin copolymer provides a high-temperature alternative to acrylic. The refractive index and Abbe number of COC is 1.530 and 56, respectively. The material’s heat distortion temperature (at 264 PSI) is rated at 123°C (about 30°C higher than acrylic). The material has a similar transmittance (92% through a 3 mm sample) and a similar differential coefficient of index with temperature  $-13 \times 10^{-5}/^{\circ}\text{C}$  to that of acrylic.

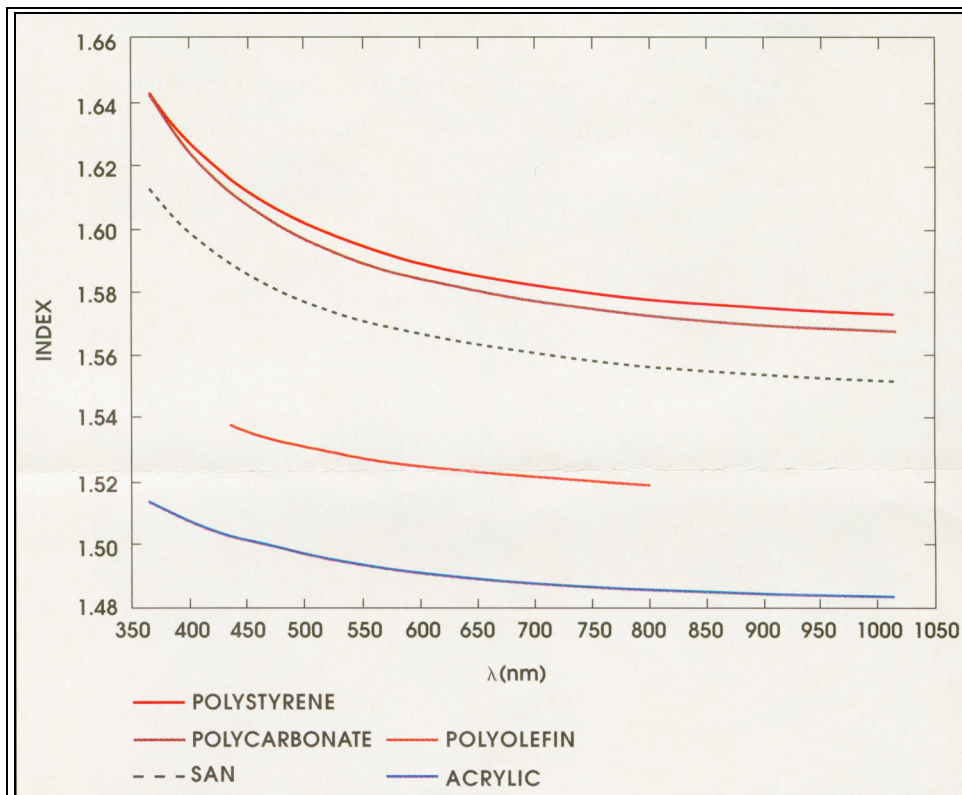


Figure 4: Index of refraction vs. wavelength. (Courtesy of Richard M. Altman and Zeon Chemicals Inc.)

### **Tooling**

An injection mold consists of three parts : the upper mold half, which is affixed to the injection-side platen; the lower mold half, which is affixed to the ejector-side platen; and the mold-ejection mechanism. Mold mechanisms, such as guide pins and taper locks, ensure proper alignment of the mold halves. While mold designers will add other features to satisfy a variety of molding needs, all molds have these basic components.

Thermoplastic shrink rates of most optical polymers lie in the range of 0.001 to 0.006 in/in. It is important to compensate for material shrinkage in the tooling. It is often difficult to calculate exact shrink rates due to the effects of component geometry and specific process for a part. In such cases the molds are built with dimensions that are smaller than the nominal final part dimensions; this case is known as building a tool *steel safe*. In this method, a tool can be run, fabricated components can be measured, exact shrink rates can be calculated, and the tool can be modified.

A well-engineered mold enables the molder to achieve precise dimensional tolerances. For example, the component center thickness tolerance can be consistently maintained once the molding process has been established and appropriate mechanical adjustments are finalized. A more precise level of thickness tolerances may be achieved if additional mold work is performed and stricter mold process controls are maintained. After the tool has been initially sampled, the tool manufacturer makes mechanical modifications to adjust particular dimensions. As an example of this process, the mold is usually designed to allow individual cavities to be adjusted for thickness control. Good tooling is obviously essential in optical molding; the parts will be no better than the tools. Good tooling, however, does not guarantee good parts. A strong understanding of the optical manufacturing processes is the key to producing precision plastic components.

The mold features that create the optical surfaces are fabricated as separate optical inserts. The optical surfaces of the mold inserts are fabricated as negative shapes of the final component surfaces. These generally take the form of spherical, plano, or aspherical shapes; the fabrication of these inserts is discussed below. In addition to these forms, diffractive, conical, lenticular, and cylindrical surfaces are also generated as inserts.

#### *Spherical and Plano Inserts*

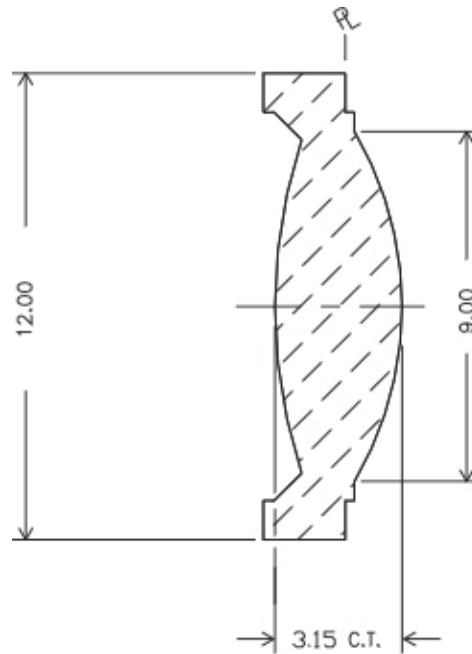
Spherical and plane inserts are generated and polished to the same accuracy as glass surfaces. The inserts are generally fabricated from chromium-alloy stainless steel. Steel is used because of its extremely fine and consistent microstructure. This characteristic is instrumental in providing the high surface finishes required in optical inserts. The steel inserts are hardened to a 50 to 54 Rockwell C-hardness rating range prior to polishing. This degree of hardness is required to maintain a surface finish that will not degrade under the heat and pressures of the molding cycle.

#### *Aspheric Inserts*

Mold fabricators use two distinct methods to manufacture aspheric inserts. The first method involves a process in which a best-fit curve is generated on a stainless steel substrate. The substrate is then subjected to a nickel plating process (electrolytic or electroless) that deposits a thin layer of nickel (up to 0.5 mm thick depending upon several fabrication conditions, such as the number of potential re-cuts). The final aspheric curve is produced in the nickel via numerically-controlled single-point diamond turning. The surface hardness of a nickel-plated insert is less than that of a steel, spherical insert. The inserts will therefore be more susceptible to scratches and cosmetic defects than steel spherical inserts. The diamond-turning process can produce inserts to very close surface deviation tolerances, although the process can leave residual grooving in the surface finish. Diamond turned inserts typically exhibit RMS surface roughness values less than 50 angstroms .

The second process used for generating aspheric inserts is numerically controlled diamond grinding. Unlike diamond-turning, this process can be used on ferrous metals such as stainless steel. This process typically yields inserts with surface accuracies close to, but typically not as good as diamond-turned inserts. Continuing development work is being conducted in the areas of finishing and polishing of steel aspheric inserts, and new developments in this area are likely to improve the state of the technology.

Conics, cylinders, and toroidal inserts can be manufactured using grinding methods similar to those that are used to produce these types of surfaces in glass. Surface quality and finish of these inserts typically fall short of that found in spherical, steel inserts.

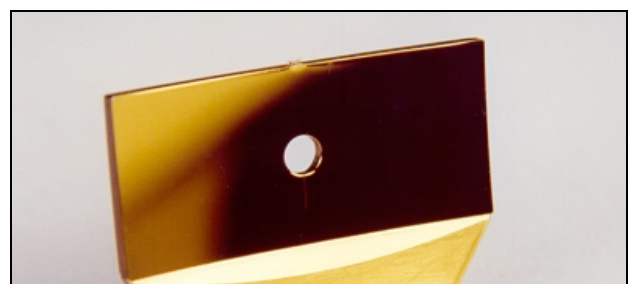


	Industry Standard	Precision Standard
<b>Thickness</b>	0.004 in.	0.002 in.
<b>Diameter</b>	0.004 in.	0.002 in.
<b>Power</b>	5 waves	2.5 waves
<b>Surface Figure</b>	2.5 waves	1 wave
<b>Scratch-Dig</b>	80-50	60-40
<b>Centration</b>	5 min.	2 min.

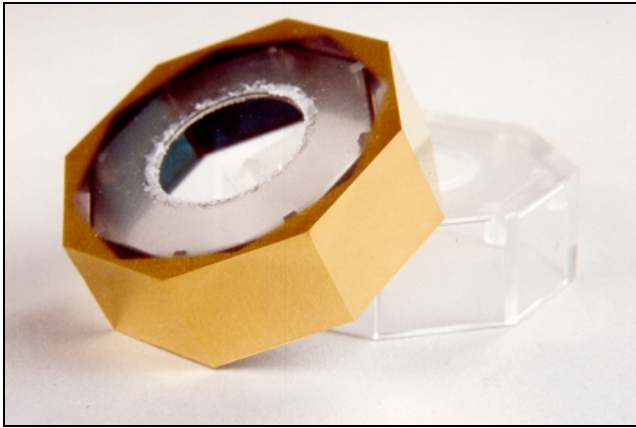
Figure 6: Example industry and precision tolerances for a bi-convex, acrylic optical component as molded per the drawing (drawing units: mm).

### Component Tolerances

Injection molding optical fabrication produces components with a high degree of repeatability. This is due to the nature of the process, the tolerances of the tooling, and the precision of the machinery. Components can be molded with little dimensional variability. The specific tolerances that can be held for an optical component depend strongly upon the part geometry and size, the component material, and the mold design and construction. For these reasons, general tolerances can not be presented as a rule of thumb; however, Figure 6 shows a molded lens component drawing and a list of tolerances for that component per industry and precision standards.



The mold is built to a set of tolerances that is much tighter than the component tolerances. Several component tolerances relate directly to their counterpart tolerances in the mold. For example, wedge or center of curvature displacement is one characteristic that molds very consistently and is most affected by the mold tolerances. During tool fabrication, the optical inserts are generated and polished with an oversized diameter dimension. The inserts are subsequently optically centered and externally ground. The wedge tolerance is held almost completely within the diameter clearances between the optical inserts and the tool.



**Figure 7:** An injection-molded octagon for a laser barcode scanning application (shown with and without reflective, gold coating.) Photo courtesy of ACCU-SORT SYSTEMS®, Inc.

## Coatings

The application of coatings to plastic optics is similar to the coating of glass substrates. A physical vapor deposition process is used to apply antireflective, conductive, mirror, and beamsplitter coatings on plastic optics. One key difference between the coating of the two types of substrates is that during the deposition of thin films onto plastic, the coating chamber temperature is significantly lower than that for coating glass optics.

### *Antireflection Coatings*

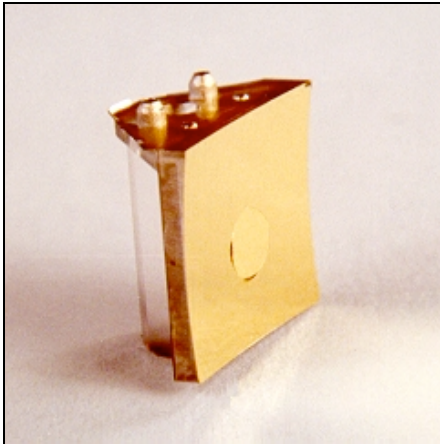
The most commonly used antireflective coating on plastic is a single layer (quarter-wave thickness) of magnesium fluoride. When applied to a plastic element surface, the average reflectance (450 nm to 650 nm) can be reduced from about 4% to about 1.5%.

Broadband, multi-layer antireflective coatings can provide average surface reflectances of less than 0.5% across the visible band; typical broadband coatings comprise three or four layers. Narrowband, multi-layer antireflection coatings can yield surface reflectances less than 0.2%.

### *Reflective Coatings*

A wide variety of front and back surface reflector coatings are available on plastic substrates. Typical coating metals include aluminum, silver, and gold. Aluminum coatings provide surface reflectances greater than 88% across the visible spectrum; gold coatings provide reflectances greater than 95% from 700 nm to 1000 nm.





**Figure 8:** An injection-molded ellipsoidal mirror (with aluminum mirror coating) that incorporates mounting tabs. Photo courtesy of ACCU-SORT SYSTEMS®, Inc.

## Design

### *Optical Design*

The optical design of all-plastic or hybrid glass-plastic lens systems is very different from that of all-glass lenses. The material selection for all-plastic design is quite limited in terms of optical parameters (see Fig. 3), and further, optical plastics have substantially lower refractive indices than their glass counterparts. Relatively few glass designs employ aspheric surfaces due to their prohibitively high-cost fabrication processes. Aspheric surfaces in plastic are quite common and offer the designer advantages in performance enhancement or sometimes as a means to overcome the plastic material's low refractive index. The prudent placement of an aspheric surface can reduce the element count in some designs or relax certain fabrication tolerances in others. While these can be the case, the tolerance situation can be worsened in some designs by the inclusion of an aspheric element. Therefore, the choice of location for an aspheric element can be a critical one.

Component shape design of polymer optics is very different than that of glass optics. Concentric elements are often avoided in glass lens designs due to the difficulty in achieving low component wedge values. The precise tooling nature of plastic optics eliminates this limitation in polymer optics systems. Ideal shapes for plastic optic components are those that maintain a nearly uniform wall-thickness. Strong meniscus, bi-convex, and bi-concave should be avoided in order to achieve high-quality, high-yield plastic optics.

### *Birefringence*

While continuing developments are being made in materials, tooling design, and processing to reduce birefringence in molded optics, birefringence still exists in polymer components. For systems in which polarization control is paramount, the optical designer must properly choose the location and component shape of plastic components. Recent studies indicate that various process parameters may be adjusted in combination with fairly low birefringent plastics to yield components that exhibit qualitatively high-extinction ratio components as viewed through crossed polarizers.

### *Thermal Effects*

The thermal differential index of refraction coefficient of optical polymers is approximately an order of magnitude greater than that of glass. For this reason, high-performance lens systems that require large temperature band operating conditions are more suited for hybrid glass-plastic designs. While the temperature band for all-plastic lenses may be quite limited (this characteristic depends strongly upon the resolution criteria for the lens), often a comparable design can be achieved with the introduction of a minimal amount of glass elements into the design.

### *Mechanical Design*

Often the mechanical design of both polymer optical systems and individual components is an iterative process coupled with the optical design. During the mechanical design of the components, the engineer often designs the mold, coating tools, and assembly tools concurrently. This is due to the fact that several features that are utilized in the fabrication, coating, and assembly are built into the individual components. Often information is learned during this process that affects the optical performance, and the process is iterated through again.

Most plastic optical components have a flange around the component circumference that performs several functions. The flange offers a buffer around the part to prevent potential cosmetic defects, offers additional mechanical rigidity to some components, provides a mechanical mounting surface, and sometimes incorporates an integrated spacer. While performing the mechanical design of the optical component, the mechanical engineer designs the flange and component gate size and structure. Because polymer components do incorporate spacers, airspace tolerances are often built into the components. Often this situation forces a compromise between airspace and center thickness tolerance. Due to tolerance effects like these, an optical and mechanical tolerance analysis is important in choosing the method for designing the mold.

### **Unique optical components especially suited for plastics**

Low component cost is the most significant benefit of polymer optical components and is often the impetus for the substitution of polymer materials for glass. However, there are many potential benefits that closely follow cost in terms of importance for employing polymers in place of glass. These benefits include complex apertures and component geometries, off-axis aspheres, surface aperture cut-aways, multiple-surface (>3) components, and various combinations of these. Examples of these include rectangular aperture magnifier assemblies for head-mounted displays; off-axis scanning parabolas; gold-coated, barcode scanning octagons; and medical arthroscope prisms, which comprise refracting, beam-deviating, and reflecting surfaces all within one component. Additionally, mounting surfaces are often incorporated into components to further reduce component and assembly cost. The components shown in Figs. 7 – 9 exhibit these beneficial features.

### *Diffractive Optical Elements*

The process, repeatability, and consistency of plastic molding offer a successful high-volume production method for diffractive elements. The design methodology and advantages of diffractive optics are beyond the scope of this paper (for design examples, see D. Buralli and G. M. Morris, “Design of diffractive singlets for monochromatic imaging,” *Appl. Opt.* **30**(16) 2151 – 2158 (1991) or M. Missig and G. M. Morris, “Diffractive optics applied to eyepiece design,” *Appl. Opt.* **34** (14) 2452 – 2461 (1995).); this section describes injection molding of diffractive elements.

The insert fabrication process (done primarily by single-point diamond turning) for diffractive elements has improved considerably since the early 1990s. This improvement of insert quality combined with advances in precision molding has yielded diffractive components with diffraction efficiencies greater than 95% at the desired wavelength and incident angle.

While injection molding is producing high-fidelity diffractive elements that perform close to the theoretical predictions, the diffraction efficiency versus incident wavelength and angle still detrimentally affect the contrast in visible broadband systems. These effects dictate proper optical system design and analysis for successful product implementation.

### **Summary**

The industry of plastic optics manufacturing has continued its progress in the past decade; this development has included advances in several enabling technologies: mold fabrication, machine design, materials, and coating. With proper design and implementation, plastic optics can offer several advantages in many optical systems. Examples of these advantages include lower-cost optical systems, aspherical surfaces, integrated components, and complex aperture or multi-surfaced elements. The successful implementation of plastic optics to an engineering problem comes from an integration of the opto-mechanical design process, the tooling construction, the component fabrication, and the surface coating deposition.