

# Material

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## SELECTION OF PLASTICS FOR OPTICAL APPLICATIONS

### Overview of Plastic Optics

The last century has seen a profound expansion of the science of optics applied to products enhancing quality of life and contributing to a strengthened defense posture. In many such products glass is a principal material constituent but it is being replaced by plastics. While not a universal replacement, due to certain physical deficiencies compared to glass, plastics possess other properties making them an attractive alternative and possibly the best choice for certain applications. Plastics having useful optical properties typically are far less dense than optical glasses, providing savings in weight, contributing to consumer product appeal, and development of military products not otherwise viable. The impact resistance of many plastics exceeds that of silica glass, enhancing the safety of military and consumer products. While these properties have contributed to the expanded use of plastic optics, likely the greatest motivation has been the development of fabrication and replication processes, creating opportunities for production of unique optical components and systems not achievable with glass. The expanded scope of variables and processing approaches endow engineers with tools to achieve significant reductions in cost for high volume production.

There are two types of optical plastics, referred to as thermoplastics and thermosets. Thermoplastics can be softened repeatedly without undergoing a change in chemical composition. While the word thermoplastic infers "heat flowable," some thermoplastics do not flow when heated and others flow without heat under mechanical pressure. While thermoset infers "heat-set," some thermosets can be set without heat. The confusion introduced by these commonly used terms may be alleviated by understanding the molecular differences between the two types of plastics. Thermoplastics are linear, i.e., the polymer chain remains linear and separate after molding and thus remolding can be achieved over and over. Thermosets are cross-linked, i.e., linear chains are joined irreversibly during molding into an interconnected molecular network, and cannot be remolded. Such cross-linking can be initiated by heat, chemical agents, radiation or a combination of these.

When employing thermoset resins, the polymerization takes place during the creation of the part, which may be produced by casting or by transfer replication. Further shaping of the part may be accomplished by post process machining. An example of a thermoset plastic product is ophthalmic lenses for eye wear. They are processed by introducing a liquid monomer stored at low temperature into a mold where it is polymerized into a part taking the shape of the mold. In other applications, epoxy based materials have been applied to form replicated reflective components using a transfer process and low cost aspheric surfaces have been created on spherical refractive and reflective surfaces.

Plastic optics other than eyewear are routinely fabricated from previously polymerized materials using small pellets as starting materials. The pellets are heated to form a melt that may be formed to the shape desired. Two molding techniques, compression and injection molding, are used in high volume production to achieve the desired shape. In compression molding, the melt is compressed and heated in a vertical flatbed press while undergoing a heating cycle. This process is capable of achieving details of less than a micron and is applied to the production of Fresnel lenses and lenticular lens arrays where detail rather than quality is important.

For high quality plastic optics, injection molding is employed. In this process, the liquid melt is injected into a temperature controlled mold under pressures up to 10,000 psi where it solidifies. The tooling mold design, being highly specialized, accounts for nearly the total cost of the plastic optics it produces. The injection molding process has the advantage of incorporating many components and features (mounting flanges, spaces, holes, staking tenons, etc.) into a single part. The very good surface-figure quality, having been demonstrated by injection molding, has made possible the creation of plastic optical components for a wide variety of applications. Included therein are medical disposables, intraocular lenses, many consumer products, military optics and a number of articles in which optical, mechanical, and electrical functions are combined in a single part.

### Selection Criteria

Selecting a plastic material for a specific optical application requires an evaluation of the environment in which it is anticipated to operate and the performance required. Success is dictated by selecting a plastic having physical properties compatible with enduring the environment in the intended application and having optical properties consistent with the desired level of performance. Physical properties worthy of consideration are density, hardness, rigidity, service temperature, thermal expansion, electrical and thermal conductivity, outgassing, affinity to absorb and retain water, additives and radiation resistance. Optical properties worthy of consideration are spectral transmission, refractive index (and its variation with temperature), purity, homogeneity, surface finish and strain.

### Physical Properties

Density determines the weight of the component. Plastics for optics vary in density from 0.83 g/cm<sup>3</sup> to 1.4 g/cm<sup>3</sup>. This may be contrasted to optical glasses ranging from 2.3 g/cm<sup>3</sup> to 6.3 g/cm<sup>3</sup>. The number of elements required in an optical design may often be reduced by the use of aspheric surfaces, easily achieved with plastics, and such consideration should be paramount in weight critical applications.

A drawback of plastic compared to glass is its relative softness,

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making it susceptible to surface damage (scratches, digs, etc.). The hardness of plastic optics is difficult to quantify (compared to glass) since it is dependent on not only the material, but the processing. The compressibility of thermoplastic polymers limits success in the use of harder surface coatings to protect against superficial abrasion. This disadvantage may be overcome by locating plastic elements internal to a device in such a way that they are inaccessible.

The rigidity of a polymer determines its impact or shatter resistance and is therefore a factor that impacts safety. Evaluation of rigidity is based on examination of the plastic's elastic modulus (Young's Modulus) and the elongation factor at yield. Since these properties are dependent on not only the specified polymer alloy and additives, but also on the processing history of the polymer, it is often difficult to precisely determine end product rigidity. In selecting a plastic for a desired degree of rigidity, consideration must also be given to the fact that properties which contribute to impact resistance may be liabilities if the optical part is subjected to some torsion or compressive stress. Attention must be given to thickness/diameter ratios and compression introduced by retaining rings in component and product design if unacceptable optical figure deformations are to be prevented.

Service temperature limits for plastic optics (60 °C to 250 °C) are substantially less than for optical glasses (400 °C to 700 °C). Furthermore, their thermal conductivity may be as much as an order of magnitude less than that of glasses and their thermal expansion coefficient may be as much as an order of magnitude higher than glasses. Therefore, applications in which thermal transients may be encountered require consideration of thermal gradients to assess if performance requirements (optical figure) can be maintained in the environment of application.

The thermal expansion of plastic is higher than that of glass. For example, the linear thermal expansion of acrylic is  $7 \times 10^{-5}/^{\circ}\text{C}$  while that for common crown glass is  $0.7 \times 10^{-5}/^{\circ}\text{C}$ .

Typically, optical plastics are unfilled polymers and are very effective electrical insulators. They are therefore susceptible to build up of electrical charge on their surface and subsequent attraction of oppositely charged contaminants. If these contaminants are harder than the plastic surface, superficial damage may result when attempting to clean the surface. Furthermore, the static charge may present a hazard to sensitive electronic components in the near proximity and potentially, for large optical surfaces such as a canopy in a high performance military aircraft, may represent a substantial hazard to a human being.

All environments are not tolerable to the use of plastic optics. These materials commonly contain lubricants, colorants, stabilizers, etc. and may continually outgas in a vacuum environment. This has been found to be a severe limitation in consideration of plastic optics in space related applications since the outgassed contaminants tend to deposit and accumulate on critical surfaces such as solar panels. However, some thermoset resins may be clean enough for such applications if their reaction stoichiometry is carefully controlled when creating the optical element.

Optical plastics, particularly thermoplastics, are inherently hygroscopic. A typical plastic optical surface may absorb from 0.003% to about 2% water by weight producing dimensional changes and minor alterations

in spectral transmission. Surfaces may be coated with less hygroscopic materials to reduce water absorption.

Additives to the basic optical polymer to alter viscosity, retard flammability and enhance release from the mold are not uncommon. Also colorants are sometimes added to create an artificially clear appearance, effectively reducing spectral transmission. The advantages and disadvantages of such additives for an optical application must be carefully considered.

Optical plastics are susceptible to radiation. Intense ultra-violet and ionizing radiation will induce polymer chain cross-linking, the degree of which depends on the particular polymer chemistry. This results in discoloration and nonuniform energy absorption. Inhibitors may be added to the polymer to inhibit such crosslinking. Typically, polymers most susceptible to UV induced discoloration are more tolerant to ionizing radiation and vice-versa. Optical plastics also have a tendency to fluoresce under sufficiently intense high-energy radiation, a phenomenon that could degrade their utility in certain applications.

### Optical Properties

Optical plastics are inherently limited to visible light applications. Most optical plastics begin to absorb in the blue portion of the visible spectrum and have absorption bands at about 900 nm, 1150 nm, 1350 nm, and become totally opaque at about 2100 nm. The similarity in the absorption spectra of most optical plastics can be attributed to the similarity in their molecular structures. Exceptions occur in the blue and UV portion of the spectrum with some specially formulated variants of poly-methylmethacrylate having useful transmission down to 300 nm. A few plastic materials, if made sufficiently thin, have been used in IR filter applications due to a narrow band of transmission leakage in the far infrared.

In general, optical plastics have lower refractive indices than optical glasses. When designing a lens, it is desirable to use a high refractive index from the standpoint that the optical power required to form an image is a combination of the refractive index and the curvature of the optical surface. Commonly, these two variables are traded off in the lens design process. However, curvature contributes more to aberration than refractive index and it is thus desirable to achieve optical power from a low curvature high refractive index material leaving plastics at a disadvantage.

The variation of refractive index with temperature ( $dn/dt$ ), can range from 6 to 50 times greater than that of glass depending on the specific materials being compared. For acrylic, the change of refraction with temperature is approximately  $-8.5 \times 10^{-5}/^{\circ}\text{C}$  and for BK-7 glass, the value is  $+0.3 \times 10^{-5}/^{\circ}\text{C}$ .

The Abbe number of optical plastics varies from about 100 to a little less than 20. This is a commonly used parameter to describe the ratio of refractivity to dispersion. A high value indicates more nearly equal refraction at all wavelengths and thus less chromatic aberration in a lens made of that material. Chromatic and astigmatic aberrations may be effectively compensated through hybrid combinations of plastic and glass optics. The materials employed should possess similar ratios of Abbe number to central refractive index and should be well separated in their Abbe number. Such hybrid combinations may actually be superior to all-glass optics.

The plastic optic molding process may alter the material's refractive

index and introduce refractive index inhomogeneity. Tests with acrylic lenses have revealed refractive index variations of  $1.7 \times 10^{-4}$  and inhomogeneities in the long dimension on the order of  $3 \times 10^{-5}$  cm. Stresses develop when a plastic part is injection molded as a result of the temperature cycle involved. These stresses create two indices of refraction, one across the direction of flow and a different one in the direction of flow, a condition called birefringence. Furthermore, some plastics such as styrene and butyrate resin are somewhat crystalline and inherently birefringent. Birefringence and inhomogeneities in the refractive index affect the elements ability to form an image.

Bulk plastics, not unlike bulk glasses, retain residual stresses even after annealing. Machining a plastic part to shape introduces additional stresses. The attainment of high performance in an imaging system requires reducing stress induced index changes to a minimum through application of special annealing methods.

Haze is the amount of stray light scattered within an element due to impurities (embedded particles) and surface imperfections. Typically, optical plastics must be free of bubbles and foreign particles larger than 0.002 in. and only one imbedded particle larger than 0.008 in. is permitted per 20 cm<sup>2</sup> of material. In regard to surface finish, only one surface imperfection between 0.004 and 0.010 in. is permitted per square foot. The bulk scattering properties of a molded optical element are dependent on the inherent properties of the material but are also strongly related to the cleanliness of the processing and the heat history of the finished part.

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Two principal types of optical glass have been routinely used in optical applications, i.e. crown and flint. Crown glass is harder than flint glass, has a lower index of refraction and lower dispersion. Both types are used in the production of compound lenses. Their plastic counterparts are acrylic (polymethyl methacrylate) and polystyrene respectively.

### Acrylic

Acrylic is readily moldable, has good stability and is easy to machine and polish. Since its low thermal conductivity reduces heat dissipation, a lubricant such as water must be applied when it is machined. Since it is hygroscopic, the machining operation affects its optical properties.

The coefficient of linear expansion of acrylic is 8 to 10 times that of glass ( $7.0 \times 10^{-5} / ^\circ\text{C}$ ). Consider an  $f/2$  plastic lens of 1.0 in. diameter. The lens diameter will change 0.003 in. and the focal length will increase 0.008 in. as the temperature changes from 27 °C to 65 °C. However, the return of acrylic to its original dimension upon cooling (optical memory) exceeds that of glass.

The luminous transmission of acrylic is about 92%. Some acrylics have extended transmission into the IR. Due to its low internal scatter, it is a clear haze free material holding up well without perceptible aging.

### Polystyrene

Polystyrene has a luminous transmission of 88%. It is easily injection-molded. While it is stable in molding, its stability is impaired by exposure to ultra-violet light.

Achromatic lenses are made by combining acrylic and polystyrene optical elements, and if properly designed, can outperform all-glass achromats.

### Copolymers

Copolymers formulated from mixtures of styrene and other polymers provide diversification of optical properties. NAS is a blend of 70% acrylic and 30% styrene.

The index of refraction can be adjusted over a range ( $n_d = 1.533$  to  $1.567$ ) by varying the blend. The distortion temperature is comparable to acrylic.

Another copolymer styrene acrylonitrile (SAN) has index  $n_d = 1.567$  and a low thermal expansion coefficient. It can be used in place of styrene, molds well and is stable. However, it tends to yellow.

### Polycarbonate

Polycarbonate, exhibiting high impact strength, has found application as street light lenses, construction-warning lights, automobile tail lights and other applications requiring high durability and ruggedness. Ultraviolet degradation from sunlight has been inhibited by use of stabilizers with only 5% loss in transmission. Polycarbonate performs well over a broad range of temperature (-137 °C to 121 °C). It has a tolerable coefficient of thermal expansion, heating to 104 °C resulting in an increase in linear dimensions of only 0.07%.

### TPX

Methylpentene (TPX) is a tough light weight plastic having superb electrical properties. It is unaffected by many chemicals at temperatures up to 160 °C. Its major disadvantage is that it shrinks from 0.15 to 0.30 cm/cm during molding.

### Terpolymers

Terpolymers of acrylonitrile, butadiene and styrene have lower transmission than acrylic (80% for thickness of 6.35 mm), but are tougher than most plastics and are cheaper than polycarbonate.

### CR 39

Allyl diglycol carbonate (ADC), commonly known as CR39, is widely used to fabricate cast plastic eyeglass lenses. It offers excellent clarity and in addition, it is resistant to abrasion, impact and chemicals. While it can withstand continuous temperatures up to 100 °C and short-term temperatures up to 150 °C, its shrinkage (up to 14% during casting) limits its use. Applications are further limited by material and processing costs.

### Add-Ons

Epoxies, silicones, urethanes and cross-linked acrylics are other thero-most materials available in optical grades. While these are seldom used to fabricate optical elements themselves, they are utilized as add-ons to form aspheric surfaces.

## Coatings

Four types of coatings are applied to plastic optics: reflective coatings, antireflection coatings, antiabrasion coatings and antistatic coatings.

### Reflective Coatings

Reflective coatings have been applied to plastic optics by solution plating and vacuum deposition. These are commonly metal coatings; aluminum is often used in vacuum deposition and chromium is often used in plating. A dielectric protective coating can be applied over the metal coating to enhance durability and reduce oxidation. In the vacuum deposition process this may be done after depositing the metal without breaking the vacuum. In the plating process, the coating may be applied by spraying or dipping, however resulting degradation in optical quality may limit applications.

### Antireflection Coatings

Losses in transmission occur in transparent materials due to surface reflections at the air/material interface. Of the 8% transmission loss in acrylic, 7.5% is due to surface reflection; in polystyrene, reflection causes a 10.6% loss. Surface reflectance may also introduce veiling glare. The

penalty associated with surface reflectance is obviously compounded in a multi-element optical system containing many surfaces. A single quarter wave coat of MgF on each surface is commonly used on acrylic and polystyrene, reducing reflectance losses to about 3%. As with glass optics, broad band and "V" coats are available for plastic optics. Their durability and quality vary depending on the specific plastic and deposition process. These compromises arise from the high vacuum environment necessary to deposit the coating and the high temperature required to achieve good adhesion and abrasion resistance. Ion beam deposition processes reduce the vacuum chamber temperatures required and have demonstrated improved coating durability.

#### Antibrasion Coatings

Both inorganic materials (vacuum deposited) and organic materials are used to reduce susceptibility to scratching. The same inorganic materials used for antireflection may be applied in thicker films to provide a harder more scratch resistant surface. The ultimate thickness is limited by internal stress and the internal expansion between the coating and the substrate. The utility of the coating can be compromised by external pressure collapsing the underlying substrate and fracturing the coating.

The effectiveness of organic coatings is derived from employing materials with low coefficients of friction thus reducing the grasp of hard contaminants on the surface that create scratches. As they are applied by dipping, spraying or spinning, they degrade the smoothness and quality of the optic.

#### Antistatic Coatings

Both vacuum deposited and chemical coatings are available to increase surface conductivity. The residue left by chemical treatments

is sufficiently thin as to not introduce interference. Judicious choice of materials used for antireflection and/or antiabrasion coatings may provide sufficient conductivity to also achieve reduced accumulation and dissipation of static charge.

Some of the more important optical and thermal properties of thermoplastics and thermosets are listed in Table 1.

#### References

The following list of references may be found helpful in the selection of materials for optical applications.

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		Acrylic PMMA (Lucite) (Plexiglass)	Styrene Polystyrene (Dylene) (Styron) (Lustrex)	NAS Methyl Methacrylate Styrene Copolymer	SAN Styrene Acrylonitrile (Lustran) (Tyrl)	Poly- carbonate (Lexan) (Merion)	TPX Methylpentene (TPX)	ABS	ADC Allyl Diglycol Carbonate (CR39)	Glass BK 7
Units										
Refractive index, n		1.491	1.590	1.533-1.567	1.567-1.571	1.586	1.467	1.538	1.504	1.517
n <sub>D</sub> (589.3)		1.488	1.585	1.558	1.563	1.581	1.464		1.501	1.514
n <sub>D</sub> (656.3nm)		1.496	1.604	1.575	1.578	1.598	1.473		1.510	1.522
n <sub>D</sub> (486.1nm)		61.4	31.1	35	37.8	34.5	51.9		56.0	64.6
Abbe Value, V <sub>d</sub>										
Rate of Change in index with Temperature	dn/df x 10 <sup>5</sup> /°C	-8.5	-12.0	-14.0		-11.8 to -14.3			-14.3	+0.3
Coefficient of Linear Expansion	10 <sup>5</sup> /°C	6.74@70°C	6.0-8.0		6.5-6.7	6.6-7.0		0.83	11.4 25 to 75°C 14.4 75 to 125°C	0.71
Deflection Temperature										
3.6°F/min. 264 psi	°C	92	82		99-104	142		90		
3.6°F/min. 60 psi	°C	101	110		100	146		84		
Recommended Max. Cont. Service Temp.	°C	92	82	93	79-88	124			100	
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	0.266
Haze	%	2	3	3	3	3	5	12	3	
Luminous Transmittance	%, Thickness 3.175mm	92	88	90	88	89	90	79-90.6*	93	99.9
Water Absorption	%, Immersed 24 hr @ 23°C	0.3	0.2	0.15	0.20-35	0.15			0.2	
Mold Shrinkage	%	0.2-0.6	0.2-0.6	0.2	0.2-0.6	0.5-0.7	1.5-3.0			

\*Luminous Transmittance 79%, thickness 6.35mm, 90.6%, thickness 0.381mm

Table 1. Properties of Principal Optical Plastics Ref. [2]



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