Polymer Optics: A manufacturer's perspective on the factors that contribute to successful programs

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ABSTRACT

Precision polymer optics is a key enabling technology allowing the deployment of sophisticated devices with increasingly complex optics on a cost competitive basis. This is possible because of the incredible versatility that polymer optics offers the designer. The unique nature of injection molding demands a very disciplined approach during the component design and development phase. All too often this process is poorly understood. We will discuss best practices when working with a polymer optics manufacturer. This will be done through an examination of the process of creating state-of-the-art polymer optics and a review of the cost tradeoffs between design tolerances, production volumes, and mold cavitation.

Keywords: Optical fabrication, injection molding optics, polymer optics, plastic optics, optical systems design

1. INTRODUCTION

Polymer optics is a key optical technology enabling a wide array of sophisticated devices. Because these types of optics are made of plastic and through the process of injection molding many options exists for providing customized solutions to unique engineering and product problems. However, the tremendous flexibility available to the designer is at once a bonus and a burden. It's a bonus because of the potential for creative problem solving. The burden comes from not understanding how the optics are made, how they're toleranced, and how alternative solutions may accomplish the goal-albeit with a different design.

While many options are available the challenge for designers is to understand the manufacturing process behind these solutions so that they can design their programs to leverage the technology. Without this level of understanding the designer may not achieve an optimal solution. Or, as is sometimes the case, the design team may go away thinking that a polymer optic is not an appropriate solution after all. We call this not knowing what you don't know. From a manufacturer's perspective many times we have encountered programs where we were given a small glimpse of what the engineering team was trying to achieve. This is often presented as a set of disembodied specifications for a particular optic. Frequently this comes in the form of a request to substitute the existing expensive glass substrate for a 'cheaper' plastic one. It's not unusual to hear something like, "the specs are on the drawing, just substitute the word acrylic for the word BK-7."

While this approach sometimes works, more often than not the challenges in making polymer optics a commercial success are completely ignored. The glass-appropriate specifications, which are completely wrong for plastic, result in either a no bid or an optic that works but could have been customized for plastic to work even better.

It is our belief that given the challenges and opportunities, designers are well served by getting the manufacturer involved early on in program discussions, since it is the optimal time to insert manufacturability expertise. To that end we will discuss the polymer optics manufacturing process and examine the best practices to use when working with a polymer optics manufacturer.

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2. WHAT ARE POLYMER OPTICS

Polymer optics are precision optics that are made of thermoplastics. Materials such as acrylic, styrene, Topas, Zeonex, and Ultem are examples of thermoplastics. In most instances they are made by a process called injection molding.

There are some exceptions to this. For example, some large area plastic optics, such as Fresnel lenses, are often made using compression molding. We will confine our discussion to optics made using the injection molding process. The technology was pioneered by companies such as Eastman Kodak, Polaroid, and U.S Precision Lens.

Today, in addition to being manufactured in the United States, polymer optics are made in Europe and in Asia, by companies such as Jenoptik in Germany and Nalux in Japan.

2.1 Where are they used, why would you want to use them

The number of devices and instruments that use these types of optics continues to grow. In short, any application that calls for an optical component, be it for imaging, scanning, detection, or illumination is a candidate for using a polymer optic. Some limitations on use will be discussed below.

A partial listing of devices that are in the market place today employing polymer optics would include: barcode scanners (both linear-1D laser scanners and matrix- 2D bar code imagers), biometric security systems, medical devices, document scanners, printers, light curtains, light guides, cameras and mobile imaging, smoke detector optics, automated sanitary valve systems, and laboratory equipment such as spectrometers and particle counters. All of these and more have benefited from using precision polymer optics. Polymer optics are also found in certain telecommunication products and commonly used to replicate micro structured surfaces such as microlens arrays, Fresnel lenses, refractive-diffractive optics, and some types of gratings. They are increasingly being used in LED illumination applications.

2.2 How are they made: the manufacturing technology

Polymer optics are manufactured by injection molding thermoplastics into optical forms. The key ingredients for production are molding resins, the molds, and injection molding machines.

2.2.1 Thermoplastics

As noted above, the principle molding thermoplastics are acrylic, styrene, polycarbonate, cyclic-olefins polymers (such as Zeonex and Zeonor, manufactured by Zeon Chemicals), Cyclic-olefin co-polymers (Topas, manufactured by Topas Advanced Polymers), and other specialty resins such as Ultem., Radel, and Udel. All of these materials are thermoplastics, which means they are plastics that can be heated and cooled repeatedly. This category of polymer is different from the optical grade thermoset plastics, which, once cured, are not able to become molten again. The manufacturers of these materials publish data related to their mechanical, thermal, and optical properties. Optical designers need to understand how these materials behave so that they can arrive at appropriate solutions.

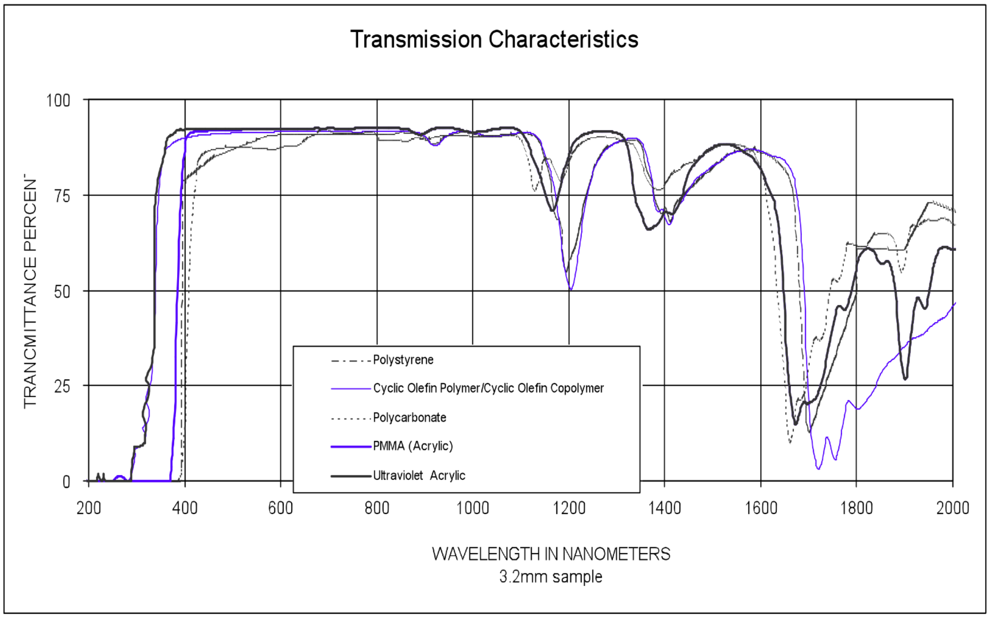
SPECIFICATIONS OF OPTICAL GRADE PLASTICS

Properties	Acrylic (PMMA)	Polycarbonate (PC)	Polystyrene (PS)	Cyclic Olefin Copolymer	Cyclic Olefin Polymer	Ultem 1010 (PEI)
Refractive Index						
N_F (486.1nm)	1.497	1.599	1.604	1.540	1.537	1.689
N_D (589.3nm)	1.491	1.585	1.590	1.530	1.530	1.682
N_C (656.3nm)	1.489	1.579	1.584	1.526	1.527	1.653
Abbe Value	57.2	34.0	30.8	58.0	55.8	18.94
Transmission % Visible Spectrum 3.174mm thickness	92	85-91	87-92	92	92	36-82
Deflection Temp						
3.6°F/min @ 66psi	214°F/101°C	295°F/146°C	230°F/110°C	266°F/130°C	266°F/130°C	410°F/210°C
3.6°F/min @ 264psi	198°F/92°C	288°F/142°C	180°F/82°C	253°F/123°C	263°F/123°C	394°F/201°C
Max Continuous Service Temperature	198°F 92°C	255°F 124°C	180°F 82°C	266°F 130°C	266°F 130°C	338°F 170°C
Water Absorption % (in water, 73°F for 24 hrs)	0.3	0.15	0.2	<0.01	<0.01	0.25
Specific Gravity	1.19	1.20	1.06	1.03	1.01	1.27
Hardness	M97	M70	M90	M89	M89	M109
Haze (%)	1 to 2	1 to 2	2 to 3	1 to 2	1 to 2	-
Coeff of Linear Exp cm X 10-5/cm/°C	6.74	6.6-7.0	6.0-8.0	6.0-7.0	6.0-7.0	4.7-5.6
dN/dT X 10-5/°C	-8.5	-11.8 to -14.3	-12.0	-10.1	-8.0	-
Impact Strength (ft-lb/in) (Izod notch)	0.3-0.5	12-17	0.35	0.5	0.5	0.60
Key Advantages	Scratch Resistance Chemical Resistance High Abbe Low Dispersion	Impact Strength Temperature Resistance	Clarity Lowest Cost	High moisture barrier High Modulus Good Electrical Properties	Low Birefringence Chemical Resistance Completely Amorphous	Impact Resistance Thermal & Chemical Resistance High Index

Table 1. A brief summary of some of the key characteristics of the most important optical thermoplastics.

2.2.1.1 Light Transmission

Most optical plastics have high clarity in the broad band visible portion of the spectrum. For example, acrylic and some grades of Zeonex have transmission properties of about 92%. Materials such as polycarbonate have lower transmission, but higher impact resistance. The table below summarizes the transmission characteristics of the most commonly used optical polymers.



Graph 1. Transmission characteristics of optical polymers.

2.2.1.2 Index of Refraction and abbe value

The range of available indices of refraction is quite narrow when compared to that available for glass. Acrylics and COP materials behave more like crown glass types (having abbe values in the mid 50s) with an index of refraction of about 1.49 and 1.53 respectively. On the other hand styrene and polycarbonate behave more like flints (with abbe values in the low to mid-30s) and having an index of refraction of about 1.59.

2.2.1.3 Transition Temperature, Coefficient of Thermal Expansion, H2O uptake, and dn/dt

When compared to glass, plastics have a much lower transition temperature (it's not unusual to see maximum continuous service temperatures of under 130-degrees C.) They also have a much higher coefficient of linear expansion (about an order of magnitude higher). Plastics will exhibit a change in index of refraction relative to temperature; the thermoplastic dn/dt is fairly large (about 20 times that of glass) and negative[1]. Most thermoplastics (with the exception of COP and COC materials) will absorb water, which will cause the lens shape to change dimensionally. For example, acrylic will absorb approximately 0.3% water over a 24-hr period. During the same period, a COP or COC material may absorb only 0.01%.

Plastic generally is lighter in weight than glass, so depending on the glass type alternative, using a polymer optic can significantly reduce the weight in a system. Finally, it should be noted that polymers are not nearly as hard as glass. Many different scales are used to measure hardness. One scale that is readily grasped is Moh's ordinal scale of mineral hardness. With talc at the softest (1) and diamond at the top of the scale (10), most plastics come in at around 2 (absolute hardness of about 3), equal to gypsum. It is clear that polymer optics must be protected in whatever system they are used.

2.2.2 Molds

The mold used to manufacture polymer optics can be thought of as a sophisticated three dimensional steel puzzle that has two main features: (1) the cavity details along with the core pins (also known as optical inserts or nubbins), and (2) the frame (sometimes called the base) that houses the cavities and inserts. The figures below illustrate the basic concept of the mold. The complexity of the mold is a function of the complexity of the element being molded. One of the key advantages of using polymer optics is the ability to combine optical and mechanical features into one platform. So, depending upon the nature of the mechanical features being considered the mold itself can take on additional complexity.

The mold is mounted into the molding press. One side of the mold is mounted to the fixed side of the press; the other side is mounted onto the moveable platen within the press. During the molding process, the two mold halves are clamped together under high pressure. The molten resin is injected into the mold by the press and the melt moves through the channels in the tool to the cavities. The cavities fill with the resin and take on the shape of the cavity detail. Once the plastic has cooled to an appropriate temperature, the mold opens and the optics are removed.

The mold is built to the negative of the final part. Thus if the final optic has a convex surface the optical insert will be concave. The mechanical features of the part have to be drafted (tapered) so that they will not be trapped in the mold after the resin has solidified.

All thermoplastics shrink as they cool. In general, the shrinkage is approximately 0.5% to 0.6%. It is important that the shrinkage be taken into consideration when determining the final dimensions of the mold. If the mold is made to the final drawing specifications the part will be too small. One needs to make the mold wrong, if you will, to make the part right. Usually molds are built steel-safe, which allows mold adjustments to be done by removing steel.

With the advent of sophisticated CNC lathes most optical inserts are diamond turned from nickel-plated steel. This method makes it possible to create on and off axis aspheric surfaces and allows the optical molder the flexibility of adjusting the inserts for shrinkage after initial molding trials have be done.

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