Injection Molded Polymer Optics In The 21st-Century

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1. Introduction

Precision polymer optics, manufactured by injection molding techniques, has been a key enabling technology for several decades now. The technology, which can be thought of as a subset of the wider field of precision optics manufacturing, was pioneered in the United States by companies such as Eastman Kodak, US Precision Lens, and Polaroid. In addition to suppliers in the U.S. there are several companies worldwide that design and manufacture precision polymer optics, for example Philips High Tech Plastics in Europe and Fujinon in Japan.

Designers who are considering using polymer optics need a fundamental understanding of exactly how the optics are created. This paper will survey the technology and processes that are employed in the successful implementation of a polymer optic solution from a manufacturer's perspective. Special emphasis will be paid to the unique relationship between the molds and the optics that they produce. We will discuss the key elements of production: molding resins, molds and molding equipment, and metrology. Finally we will offer a case study to illustrate just how the optics designer carries a design concept through to production. The underlying theme throughout the discussion of polymer optics is the need for the design team to work closely with an experienced polymer optics manufacturer with a solid track record of success in molded optics. As will be seen shortly, the complex interaction between thermoplastics, molds, and molding machines dictates the need for working closely with a supplier who has the critical knowledge needed to manage all aspects of the program.

2. Applications

Starting in the middle of the last century optics were molded for simple condenser lenses, toy objectives, ophthalmic applications, gauge windows and other low quality glass optic replacements[1]. At the dawn of the 21st Century polymer optics can be found in many more sophisticated applications. Examples can be offered to illustrate the widespread versatility of polymer optics and optical systems. The spectrum would range across medical, military and commercial applications.

2.1. Medical

Medical instruments such as laparoscopes and arthroscopes can be built using polymer singlets and doublets, sometimes in conjunction with traditional glass elements to correct optical aberrations. Polymer optics can be used for non-imaging applications in medical devices as well.

2.2. Military

Fig.1: *ITT Night Vision Goggles. The PVS-7 is designed and manufactured by ITT Industries Inc.*

Imaging systems such as those found in night-vision devices are a good example of how the properties of polymers can combine to address several key performance issues (see Figure 1). This example illustrates how a lightweight wearable night vision device containing as few optical elements as possible can be designed and manufactured because of the sophistication of the molded optics. Replacing a glass element with a plastic element can reduce weight in the system. A plastic element is approximately a factor of 2 to a factor of 5 lighter in weight than the glass element being replaced. Moreover, since polymer optics can be readily designed and manufactured with aspheric surfaces (resulting in a possible reduction in the total element count) the use of one or more polymer elements in the system is well advised.

2.3. Commercial

The use of polymer optics is found in a wide range of consumer applications such as digital cameras, PC peripherals, videoconferencing cameras, and mobile imaging. Laser based bar code scanners of various descriptions are good candidates for polymer optics (see Figure 2). More recently, lightweight image based scanners have been manufactured to read 2-D barcode images using a platform that contains multiple optics and a mechanical mount all in one shot (see Figure 3). Biometric security systems, smoke detector optics, automated flush valve systems, and laboratory equipment have all benefited from having precision polymer optics. Polymer optics are useful for certain telecom and datacom products and are commonly used to replicate micro structured surfaces such as Fresnel lenses, refractive-diffractive surfaces, and gratings.

***Fig.2**: Microscan Barcode scanner and polygon mirror. The MS-820 Scanner is designed and manufactured by Microscan Systems Inc., Renton, WA.*

3. Elements of Production

We will now turn our attention to the various elements that are required to manufacture precision polymer optics. They can be distilled into three major factors: thermoplastic resins, molding machines and molds, and metrology. Noticeably absent from this list is the optical design. A robust optical design is of course required but is beyond the scope of this discussion. What we will discuss is the importance of having the optic thoroughly designed for manufacturability given that the final product is a polymer optic. When considering polymer optics the need for a manufacturable design is vital. Manufacturability of design is important when considering glass designs to be sure. But when polymer designs are being considered, an optical design that works well in Zemax or Oslo will fail the designer if the manufacturing process itself is ignored. There is simply no way to gloss over this fact.

From a manufacturer's perspective this is often seen when glass designs are converted into the plastic analog (for example, that BK-7 element, n=1.5151, now becomes a PMMA element with n=1.49). The temptation is to plug in the new index numbers, alter the radii of curvature accordingly, and think that one is all set for production. In some instances, it is possible to simply change the index (or some other material related value) to accommodate the new material and let the design software make the necessary changes. In other instances the form of the optic is altered to the point where it is no longer manufacturable, for example if the radius of curvature becomes very steep or if the diameter to center thickness ratio becomes too extreme. With guidance from the manufacturer, it may be possible to design the optic so that it can be produced by the injection molding process. In this brief example converting the index to that of the new thermoplastic resin is a necessary but not sufficient step in converting an element from glass to plastic.

***Fig.3**: Code 2-D Scanner and integrated optic. The Code Reader 2.0 (CR2) is designed and manufactured by Code Corporation, Draper, UT.*

3.1. Polymers

In general two types of plastic materials are molded: thermoplastic resins, which can undergo repeated cycles of heating and cooling and thermoset resins, which become permanently insoluble after they have reached their final heating temperature[2]. This article will not discuss the thermoset resins. Thermoplastic resins are used for injection molding polymer optics.

The most commonly used optical thermoplastics are: Acrylic (Altuglas, Cyro), Polystyrene (DOW Corning) and Polycarbonate (GE Plastics, Bayer). More recently there are the Cyclic Olefins such as Topas (Ticona) and Zeonex (Zeon Chemicals) and specialty resins such as polyetherimide, with the trade name of Ultem (GE Plastics). All of these materials have properties and characteristics that need to be considered given the intended application. With the exception of Ultem most are suitable for broadband visible applications, with transmission falling off steeply below 350nm and above 1600nm. Acrylic and Zeonex have excellent external transmission properties in the visible (around 92%). Polycarbonate and Polystyrene have slightly more haze (with external transmissions of about 87% to 88% in the same region). The coefficient of thermal expansion of the polymers is approximately an order of magnitude higher than that of glass (7 or 8 X $10^{-5}/^{o}$ C). Most polymers have a fairly low maximum sustained operating temperature (MOT) (the temperature at which the element can survive for extended periods of time without deformation). This ranges from about 80° C in Polystyrene to about 185° C in Ultem. Ultem is a special case material, in optical molding. It is not suitable for broadband visible applications and represents the upper limit in terms of temperature survivability; most Polycarbonates and Olefins have a MOT of about 115° to 125° C. With the exception of the Cyclic Olefins, most polymers will absorb water and change dimensionally. Acrylic for example will absorb 0.3% H_2O (immersion at 23° C for 24 hours) while the COP Zeonex E-48R resin will absorb <0.01%. Moreover the change in index of refraction with temperature is fairly large (about 20 times that of glass) and negative[3]. Maintaining focus over a wide temperature range is a significant problem for plastic optics[3]. Another challenge for designers using the optical thermoplastics is that the range of index of refraction is fairly narrow. Acrylic is about 1.497, Polycarbonate about 1.599, Polystyrene about 1.604, the Cyclic Olefins around 1.53 and finally Ultem at 1.689. Table 1 below summarizes these and other important properties.

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) N_D (589.3nm) N_C (656.3nm)	 1.497 1.491 1.489	 1.599 1.585 1.579	 1.604 1.590 1.584	 1.540 1.530 1.526	 1.537 1.530 1.527	 1.689 1.682 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 3.6°F/min @ 264psi	 214°F/101°C 198°F/92°C	 295°F/146°C 288°F/142°C	 230°F/110°C 180°F/82°C	 266°F/130°C 253°F/123°C	 266°F/130°C 263°F/123°C	 410°F/210°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: *Important Properties of Selected Optical Grade Polymers*
Values may vary significantly depending upon manufacturer[4].

Optical injection molders have no control over the properties of the thermoplastic resins. Questions about the mechanical properties of the thermoplastic resins, the precision of the index of refraction, and questions about the consistency of material from lot to lot are best referred to the resin suppliers.

3.2. Injection Molding Machines

The injection molding machine consists of a clamp unit at one end, an injection or plasticizing unit at the other end and a mold area in the middle. The control station is usually located near the injection unit. Figure 4 illustrates the concept of a typical injection-molding machine. There are obviously many different types and configurations of molding machines. For the purposes of our discussion we will consider a machine in horizontal configuration, using an hydraulic clamping unit and single-stage plasticator.

Molding machines can range in size up to 10,000 tons of clamp force. As clamp tonnage is dictated to a large measure by projected area, for the optical molding world, machines tend to run from 20 to 300 tons of clamp force. Some micro molding applications call for machines with lower tonnage.

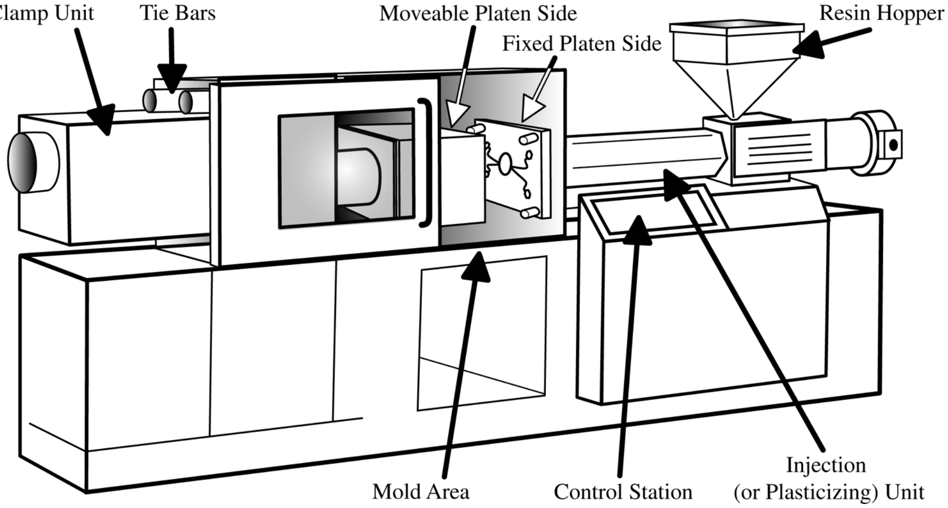

Fig.4: *Injection Molding Machine*

The mold is mounted on the platens which are part of the clamp unit. One of the platens is fixed in place, the other is moveable. There are typically four tie bars supporting this area of the press. During the molding cycle the clamp unit closes the moveable platen against the fixed platen. The mold itself is split into two halves (fixed and moveable). In effect the mold is separated across the parting line to allow for removal of parts. The clamping unit also exerts enough force on the mold halves to ensure that they are not forced apart during the injection phase. There are various types of clamping schemes: hydraulic, toggle, and hydromechanical.

The injection unit consists of a hopper located over the reciprocating screw and barrel. The reciprocating screw is located within the barrel. Heater bands surround the barrel. The thermoplastic resin is melted (a process known as plasticizing) using a combination of conductive heat from the heater bands and frictional heat from the rotating screw. Please note the unusual construction of the screw. See Figure 5. The screw begins to turn to collect material for the next shot. As the screw turns, resin from the hopper flows into the chamber and is collected in the feed section of the screw. The material is trapped between the chamber wall and the screw. The chamber wall is the bearing surface where shear is imparted to the melt as it is fed forward on the screw into the transition region of the screw. As the melt moves forward it accumulates at the tip the screw. As a result the screw is driven backwards. At a preset point the mold closes and the screw stops turning. The screw then moves forward, acting like a ram, injecting all the melt into the mold in a single stage.

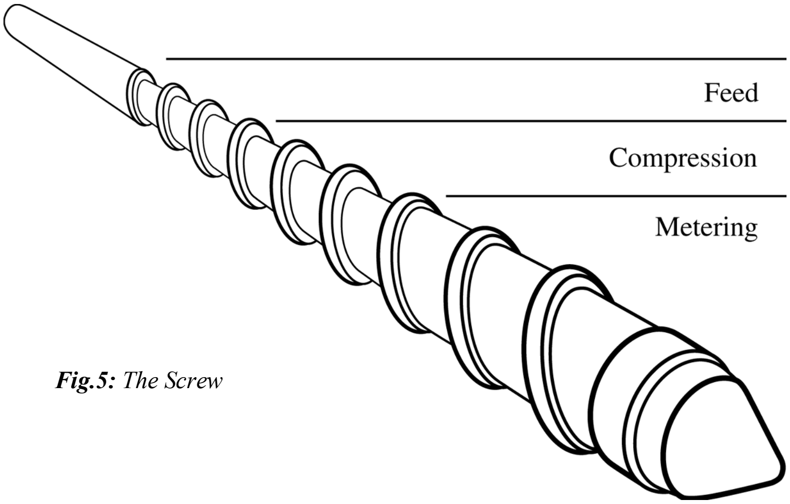

Fig.5: *The Screw*

The molding machine is designed to allow for complete control of the shot size, injection speed, injection pressure, backpressure, cushion and a matrix of other variables that ultimately determine the outcome of the molded element. Once the resin has been held in the mold for a sufficient time and has cooled, the screw starts rotating again to prepare for the next shot. The mold opens and optics are removed.

Other equipment is frequently added to the molding press as required to facilitate operations. For example the hopper on most machines can only hold a limited amount of material. Automated hopper feeds can be added to ensure a continuous feed of dried resin. Desiccators are used to remove moisture from the resin prior to molding. It is important to remove the shot from the press on cycle without fail. Robotic sprue pickers can be added to handle this task. It is possible to add other end of arm tooling to the robots to automate degating and placement of elements into appropriate packaging. Degating is the process whereby the elements themselves are removed from the runner system and placed in trays or holders. All of this tooling is driven by the program requirements.

3.3. Molds

The mold used to manufacture polymer optics can be thought of as a sophisticated three dimensional 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. Figure 6a and 6b illustrate the basic concept of the mold. The complexity of the mold is primarily driven by 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. Depending upon the nature of the mechanical features being considered the mold itself will take on additional complexity. The following table is a brief list of some of the key features generally found in molds along with a brief description of their intended function [2].

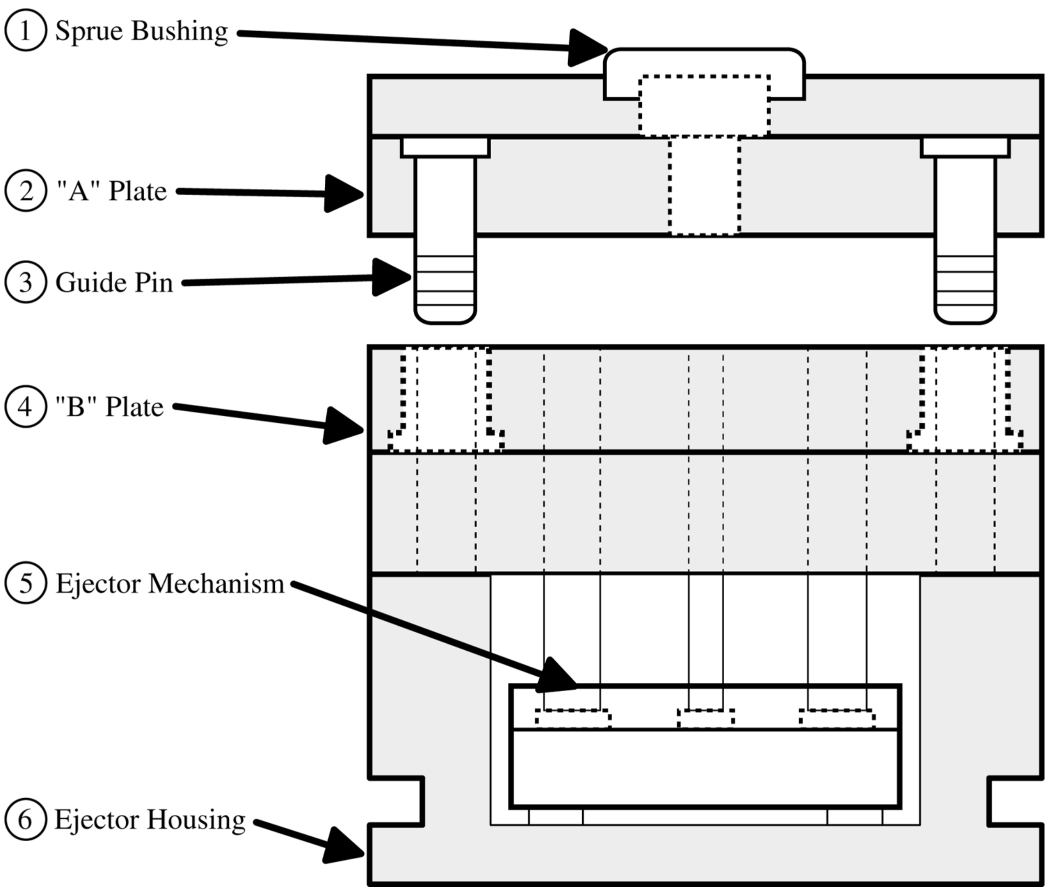

Fig.6a: *The Mold.*

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