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.

Tribute to Warren Smith: A Legacy in Lens Design and Optical Engineering, edited by Robert E. Fischer,
Proc. of SPIE Vol. 5865 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.626616

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^{o} C in Polystyrene to about 185^{o} 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^{o} to 125^{o} 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^{o} 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.

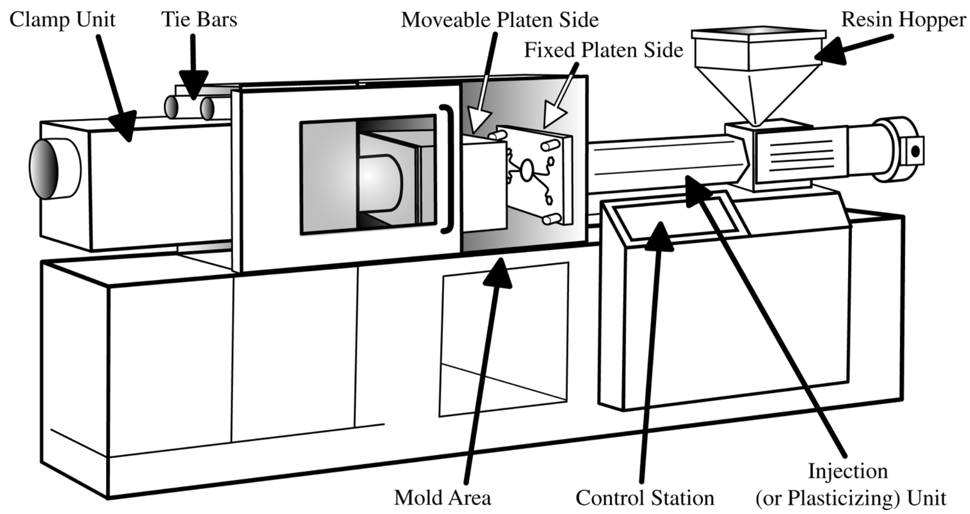

Fig.4: *Injection Molding Machine*

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.

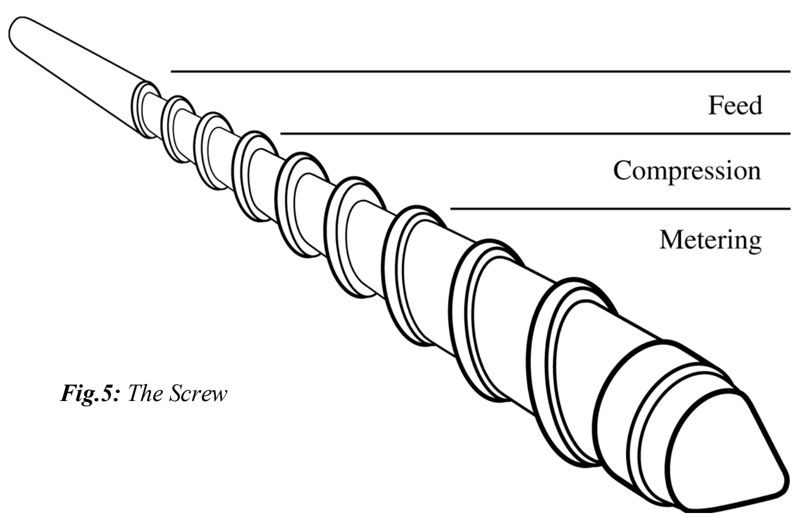

Fig.5: *The Screw*

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].

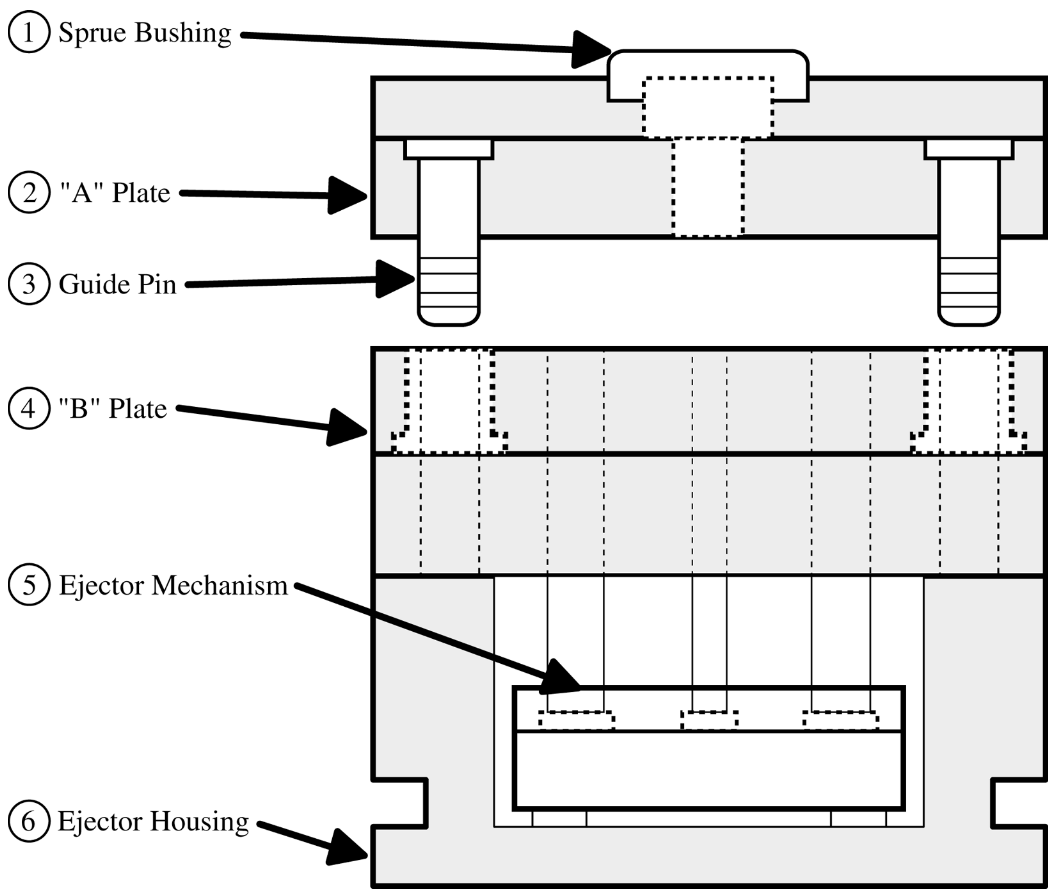

Fig.6a: *The Mold.*

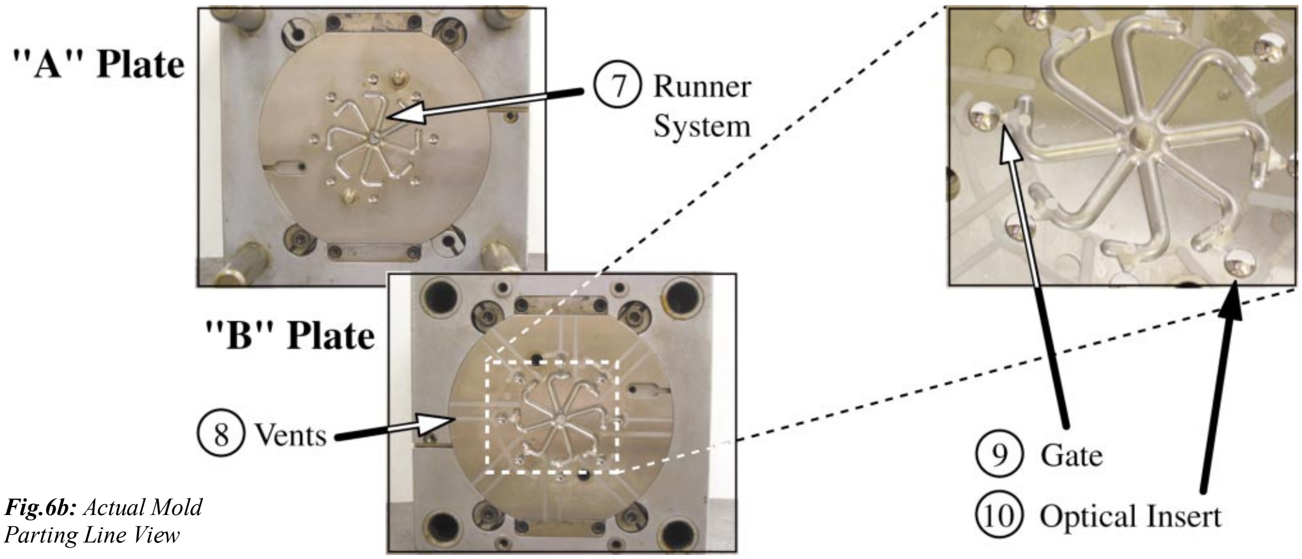

Fig.6b: *Actual Mold Parting Line View*

ITEM NO.	MOLD FEATURE	FUNCTION
1	Sprue Bushing	Provides means of entry into the mold interior.
2	Top (A-side) plate	Portion of the mold mounted on the stationary side of the press
3	Guide Pins	Maintains proper alignment of the two halves of the mold.
4	Bottom (B-side) plate	Side opposite the “A” side, sits on the moveable platen.
5	Ejector Mechanism	System used to eject rigid molded elements from the cavities.
6	Ejector Housing	Houses the ejector system.
7	Runner System	System of channels in the mold face used to convey molten plastic from the sprue to the cavities.
8	Vents	Structure that allows trapped gas to escape.
9	Gates	Region of the mold that controls the flow of molten material into the cavities.
10	Optical inserts (nubbins)	Deterministically ground and polished steel or steel/nickel pins against which the optical surface forms.

Table 2: *Mold Features*

The mold is mounted into the molding press. One side of the mold is locked into the stationary side of the press; the other side of the mold is mounted on to the moveable platen. During molding the two halves of the mold are closed and clamped under high pressure. The molten resin is injected into the mold from the molding press injection unit (also called the plasticator) located on the stationary side of the press. The melt flows through the passages within the mold (that is the sprue and the runner) and enters the cavity through the gate. The cavities fill with resin and take on the shape of the cavity detail and the form of the core pin. As the resin is held within the mold it is cooled to an appropriate temperature at which time the mold opens (the moveable platen on the molding press moves away from the fixed platen) and the ejector system is engaged to remove the elements from the mold. The elements are usually part of the runner system and this is set aside to allow further cooling and subsequent finishing.

When molding optics, much thought and effort is put into creating the cavity impression and the optical inserts in such a fashion that the final molded product will be at the proper dimensions at room temperature. All of the thermoplastic resins exhibit a measure of shrinkage as they cool in the cavity. A typical shrinkage would be 0.005 inch per inch of linear dimension. This shrinkage factor must be taken into consideration when laying out the cavity details. If not, the resultant elements will be too small. Note: if the element is very small, shrinkage factors become less of an issue.

Whenever the final part dimensions are very critical, an iterative process may be used to achieve the final dimensions. Initial shrinkage calculations are made and the mold will be built tool-safe. That is, the mold will be built slightly smaller than is required. After an initial molding trial has been completed, and the molded elements characterized, the actual shrinkage is better understood. Steel can then be removed from the mold cavity to increase the size of the element in a deterministic fashion. This process applies as well to the creation of the optical insert. Hence it may be necessary to rework the optical insert to correct for form error after an initial molding trial is undertaken and the molding process is understood.

The inserts can be made in several ways. One way is to grind and polish fine-grained steel in a fashion similar to the techniques employed in fabricating conventional glass optics. Another method used to make the insert is to fabricate a steel blank, plate it with an electroless nickel alloy and subsequently diamond machine the surface. Today single point diamond machining technology is capable of extremely accurate surfaces both in terms of surface error and RMS surface roughness. For example on a 1" diameter optical insert (steel base with nickel plating) a wavefront error on the order of $\lambda/2$ with a surface roughness of between 70Å to 50Å RMS is achievable. This can be achieved without post-polishing the surfaces.

3.4. Metrology

Having good metrology is an absolute requirement when molding optics. It is really no different than what is required for traditional glass fabrication. Without adequate metrology there is no reasonable way to assess performance. Molded optics can be tested on an interferometer. If the surface is aspheric, null correctors can be designed and employed. Another useful device is a contact profilometer. Many contact profilometers were originally designed for surface roughness measurements. However with the addition of solver programs it is possible to trace aspheric surfaces and measure form errors. Because of the common practice of integrating mechanical and optical features onto one platform, appropriate metrology is required to ensure these features are to print. Micrometers, calipers, optical comparators, and microscopes are appropriate for this. A coordinate measurement machine is also useful for this application. This is especially true if the molded optic has optics in multiple planes relative to a datum, such as is found in a rotating polygon.

Since injection molding is a volume related process, the use of some kind of functional test equipment is often required and can be tailored for the program needs. Functional testers allow for a go/no-go assessment of the process in a timely fashion. The downside to using this type of metrology is that when problems do arise the functional diagnostic will not necessarily allow the QC technician to uncover the root cause of the problem. The operator may be aware of a problem so lot containment can take place, but often other QC equipment will be required to push for the root cause problem. Additional equipment that can be used would include a lens bench for measuring flange focus, an MTF diagnostic, and resolution targets.

4. The Decision to Use Glass or Plastic

The question is often asked, "Why use plastic? Why not just stay with glass?" The answer is that some applications are simply better served by using a plastic element instead of a glass element. As noted earlier, the use of plastic optics today is found in a wide array of military, medical and commercial applications. There are some general guidelines that can be followed that will help determine when it is appropriate to consider a polymer optic solution.

4.1. How do the thermoplastic resins affect the decision

The factors that would argue against using polymer optics in an application are almost always centered on the limitations inherent in the thermoplastic resins themselves. For example: (1) spectral transmission (most polymers are suitable for the visible portion of the spectrum), (2) continuous service temperature (lower than glass, overall less than 120^{o} C), (3) dn/dt (close to a factor of 20 higher than glass and negative) [3], (3) coefficient of linear expansion (about an order of magnitude higher than glass) [3], (5) surface hardness (softer than glass), and (6) index of refraction (the index map is limited relative to glass). These properties do not preclude their use in optical systems, however the designer must be well aware of their performance limits when considering their use. It should be noted that not all of the properties of the thermoplastic resins are limiting. One prominent characteristic of thermoplastic resins that would be a desirable indicator for use in a system is the specific gravity of the material. Overall, polymers are lighter in weight than their glass counterparts, a positive factor when designing a weight-sensitive system.

4.2. How does the manufacturing process affect the decision

A key factor for considering polymer optics is the method of manufacturing itself, namely injection molding. Injection molding is a highly efficient method of reproducing optics with complex surface geometries. Moreover, such optics can employ integrated mounting features onto one platform and can be molded in varying volume requirements with a very high degree of part-to-part repeatability. The reason for this is the fact that the molds are built to a higher degree of precision than is required in the part.

When considering molds and the molding process the key thing to understand is that the tooling, while expensive, is usually done once and if done properly will last a very long time. It is not uncommon to get over 1,000,000 cycles on a fully hardened mold. Effort is put into building the best mold (base, cavity and optical inserts) to the highest tolerances with replication taking place off of the mold. So instead of each element being treated as a one-off component, replication is taking place within a highly precise master tool. This is where great economies of scale can be realized because it is possible to build multiple cavities into one mold base. If (1) the application involves a fairly high volume of components, or (2) if the optic has a combination of optical and mechanical features that are to be integrated onto one platform, or (3) if the optical surface is aspheric or if the optic is very complex, such that building a mold and running low production volumes is still more cost effective than competing options, then polymer optics would be a good consideration because of the method of manufacturing, injection molding.

4.3. How the shape of the element affects the decision

While the injection molding process is highly efficient, and the molds themselves are built to very high tolerances, the molding process is not without its own set of challenges. These challenges are often related to the shape of the optic and the fact that the optic may not be optimized for manufacturing. As noted earlier problems tend to arise when the optical design is done without considering the manufacturing process.

Some examples of difficult to mold optical forms would include: (1) a biconvex lens that has a very thick center and a very thin edge, (2) a bi-concave lens with a very thin center and a very thick edge, (3) a plano-convex lens, especially where the convex surface is quite strong, (4) an element with very stringent surface figure error or irregularity requirement, (5) an element whose clear aperture is equal to the geometric size of the optic, and (6) an optic with mounting feature requirements that are incompatible with molding a good optical surface (for example a mounting boss located directly behind a plano facet). Figure 7 shows some shapes that are very difficult to mold.

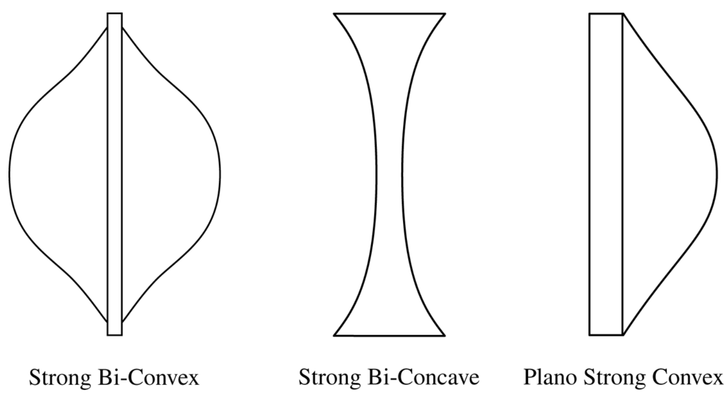

Fig.7: *Challenging shapes to mold*

4.4. Limits of Fabrication

Manufacturers are frequently asked the question, “How good can you make it?” The answer of course is, “It depends.” It depends on many factors. Several of these have been hinted at in the discussion above on when it is appropriate to consider using a polymer optic. When discussing the issue of the limits of fabrication closer attention needs to be paid to the form of the optic as the injection molding process will affect the final product. As noted above, elements that have extremes in wall thickness are more difficult to mold than elements of nearly uniform wall thickness. In terms of surface form error, square or rectangular shapes are more difficult to mold than round shapes. Figure 7 summarizes the discussion of optical forms that are challenging to mold.

One thing is clear. As the design of the optic progresses to the stage where the question of limits of fabrication are being asked, it is important for the designer to contract with an experienced optical molder for guidance through the fabrication process. As the design progresses, the molder will provide critical guidance to the designer on issues of manufacturability. As noted above this is often an iterative process as manufacturing features are traded off against the requirements of system performance. When discussing issues of manufacturing tolerances ultimately the question becomes one of what constitutes a manufacturable design. Again, it is very difficult to generalize beyond some basic rules of thumb; each design presents its own challenges and must be approached on a case-by-case basis. Other factors enter into the discussion at this point. For example, the choice of materials (when more than one is available), the best method for tool construction (the number of cavities in the mold, the type of mold base and the proper cooling configuration), and the way the part is gated (this is critical when stress birefringence is an issue).

Also, from a manufacturing perspective, this is the point in time when the optical molder needs to discuss such issues as degating and finishing the element, what quality metrics will be used to insure good consistent production and what kind of packaging needs will the program have. Table 3 provides a rule of thumb guide describing the state-of the art limits of fabrication. Each optic needs to be evaluated on an individual basis.

ATTRIBUTE	TOLERANCES (ROTATIONALLY SYMMETRICAL ELEMENTS LESS THAN 75MM IN DIAMETER)
Radius of Curvature	± 0.5%
EFL	± 1.0%
Center thickness	± 0.020mm
Diameter	± 0.020mm
Wedge (TIR) in element	< 0.010mm
S1 to S2 Displacement (across the mold parting line)	< 0.020mm
Surface Figure Error	≤ 2 fringes per inch (2 fringes = 1 λ)
Surface Irregularity	≤ 1 fringe per inch (2 fringes = 1 λ)
Scratch-Dig Specification	40-20
Surface Roughness Specification (RMS)	< 50 Å
Diameter to Thickness Ratio	< 4:1
Center Thickness to Edge Thickness Ratio	< 3:1
Part to Part Repeatability (one cavity)	< 0.50%

Table 3: *Limits of Fabrication*[4]

4.5. Polymer Optics and Coatings

Polymer optics can be coated using physical vapor deposition techniques, similar to glass. It is possible to apply dielectric coatings such as broadband AR, V-coatings, and special band pass coatings. Moreover, reflective coatings can be applied to polymer substrates. Coatings such as enhanced or protected gold, aluminum and silver are routinely applied. It should be noted that these coatings are applied at lower temperatures and are generally not as robust as coatings found on similar glass elements.

5. A Case Study: How to Work with an Optical Molder

The following case study will illustrate how the process of implementing a polymer optics solution works.

Irwin Industrial Tools first approached us about their requirement in January 2004. At this point there was no design only a concept: Irwin wanted to create a hand held consumer product that would project two orthogonal lines when held in position against a wall. The product would launch nationwide through major hardware store distribution channels the following Christmas season. We were given information about the laser sources and the overall package constraints and were asked if it was possible to develop a polymer optic design to satisfy this application. We thought that it would be possible.

Working with one of our design partners, we developed an optical design that would generate two orthogonal lines with a certain line characteristic over a certain length from the source. The goal for the program was to have the optical element molded as one piece. We were able to achieve the goal. The following process was followed to allow for careful implementation of the new design: (1) Develop initial optical design concepts. (2) Evaluate designs and choose one. (3) Take one design and optimize it for optical performance and manufacturability. (4) Hold a final design review. (5) Prototype the design using diamond machining. (6) Evaluate optical design performance and provide feedback to designer if last minute changes were necessary. (7) Build a prototype one-cavity mold that would serve as a test bed to develop the molding process. Metrology was put in place during this phase. (8) Build a multicavity production mold using what was learned from the one cavity mold experience. (9) Validate each element off of the production mold, release to production.

The design phase was fairly typical for this kind of project: an optical designer worked on the ray tracing aspects in optical design software such as Zemax. Three concept designs were presented. One was selected as the closest fit to the program goals and was carried through an optimization phase. As the design was nearing completion we got involved reviewing the mechanical and optical tolerances. Given the form of the element, we estimated what manufacturing tolerances might be achievable and provided detailed guidance to the product designer and the optical engineer on issues affecting manufacturability. This included gate location, tooling layout, choice of thermoplastic resin, draft angles and other details—all requirements critical to program success. While this was going on our manufacturing engineers began working on the automation required to handle and package the elements during volume production. Also during this time our mold processing engineers undertook a mold flow analysis to help visualize the fill pattern in the part.

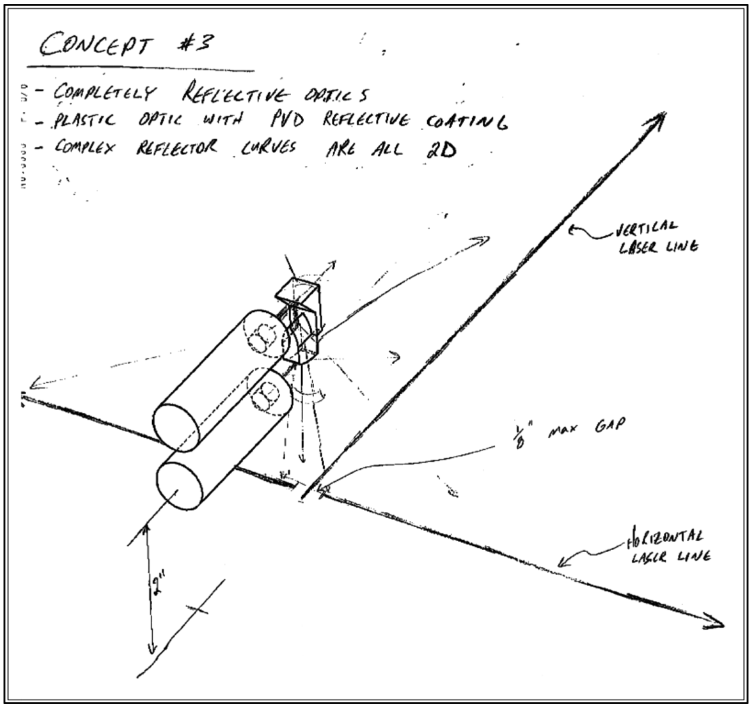

Fig.8: *Early Discussions: Initial Concepts.*

Prototypes were made using diamond machining techniques. The prototype phase was important since the people that made the prototypes would also make the optical inserts. Many things about the element performance were learned through this phase. Prototypes were delivered and were built into working models by the team at Irwin.

As the diamond machining was underway we started building the one-cavity mold. What was learned about the element during diamond machining the prototypes was transferred into the insert manufacturing. Upon completion the mold was set in the press and engineering samples were molded. At the same time the QC department began the process of qualifying the molded elements. This meant identifying all of the critical to function aspects of the element and preparing the appropriate metrology for measurements. In this case we used the Zeiss Profilometer (Surfcon 3000A) and the Mitutoyo coordinate measurement machine (CMM). Other mechanical aspects of the elements were measured using the OGP Smartscope.

In parallel with this we began building the production mold. The production mold benefited from what was learned in the pilot one-cavity mold. Refinements were made in our manufacturing processes both in terms of tool construction and mold processing. By the time the production tool was ready for installation in October we had a firm grasp of all of the unique challenges this particular element presented.

The automation component of the manufacturing along with the necessary shipping trays were designed and built in parallel with the production mold and timed so that everything would be installed and debugged in concert with the arrival of the production tool.

__Fig.9:__ Operational Concept

__Fig.10:__ Element Design and Finished Product. The Intersect Laser Level is designed and manufactured by Irwin Industrial Tools.

The following is a good guide to use when embarking on a program using polymer optics.

1. Develop an initial optical design concept
2. Contract with the polymer optics manufacturer
3. Optimize the design with guidance from the manufacturer
4. Finalize all optical and mechanical tolerances
5. Develop a mechanical drawing of the element suitable for injection molding
6. If prototyping using diamond machining develop a second mechanical drawing suitable for diamond turning
7. Develop QC metrics and identify specialized inspection requirements and functional test equipment
8. Discuss other manufacturing issues as early on as possible. These include:
    a. Volumes and ramp to production schedules
    b. Packaging requirements
    c. Shipping requirements
9. When practical, build prototypes
10. When practical, develop pilot tooling
11. Build production tooling. Build additional support tooling (degating fixtures, coating fixtures, functional test equipment, etc.)

6. Conclusion

We have discussed some of the ways polymer optics has been employed over the years. Today many optical challenges found in medical, military and commercial applications have been solved through the use of carefully designed polymer optics. We discussed the elements of production: thermoplastic resins, complex molds and molding equipment. We have discussed the level of metrology that should be employed when molding optics. We discussed the criteria for using polymer optics subject to the limitations of the thermoplastics and the favorable advantages conferred by the use of injection molding as a means to manufacture. We discussed some of the limits of fabrication, which are largely dictated by the size and form of the optic as well as the limitations of the molding processes. And finally we provided a case study to illustrate how an engineering problem, requiring the use of a polymer optic, was actually developed through a close cooperation between the client, the optical designer, and the optical molder.

Optical molding is nothing less than a very complex interaction between thermoplastic materials, good design and highly refined injection molding techniques. Because of the specialized knowledge required, a program in polymer optics calls for very careful preparation and should only be undertaken with the help of an experienced optical molder. Warren Smith has discovered this secret when he advises, "In considering a venture into the plastic optics arena, one is well advised to seek out a specialist in making plastic optics. Not only is the typical injection molder incapable of making good optics, but he or she also has no conception of what is required to do so[3]."

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