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.

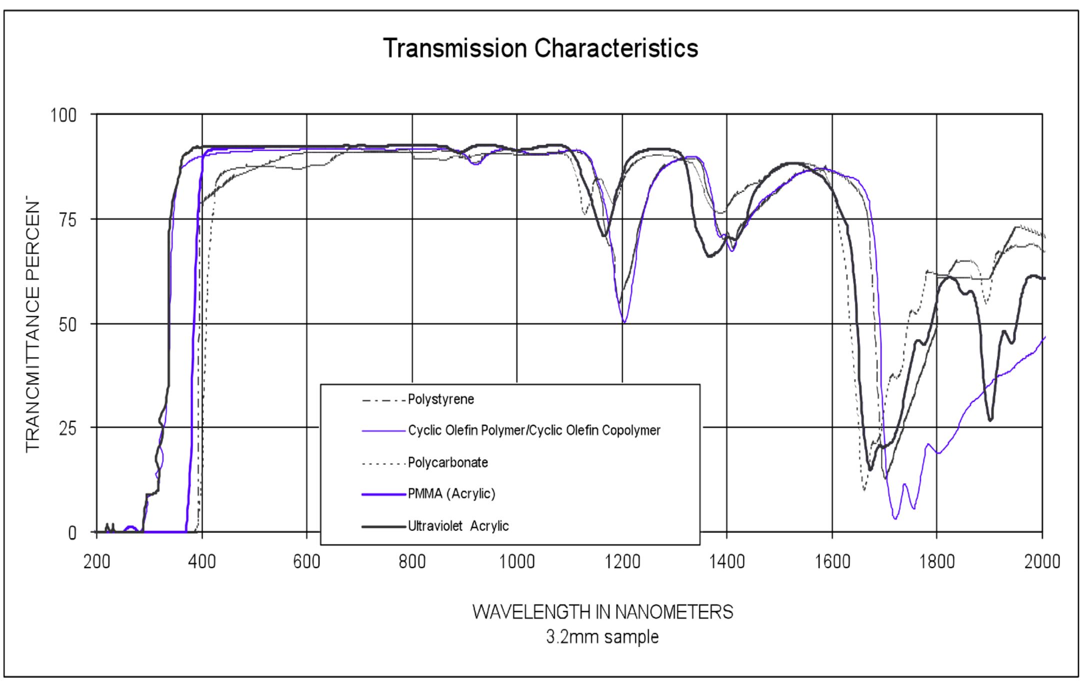
SPECIFICATIONS OF OPTICAL GRADE PLASTICS

Properties	Acrylic (PMMA)	Polycarbonate (PC)	Polystyrene (PS)	Cyclic Olefin Copolymer	Cyclic Olefin Polymer	Ultem 1010 (PEI)
Refractive Index N_F (486.1nm) 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. 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.

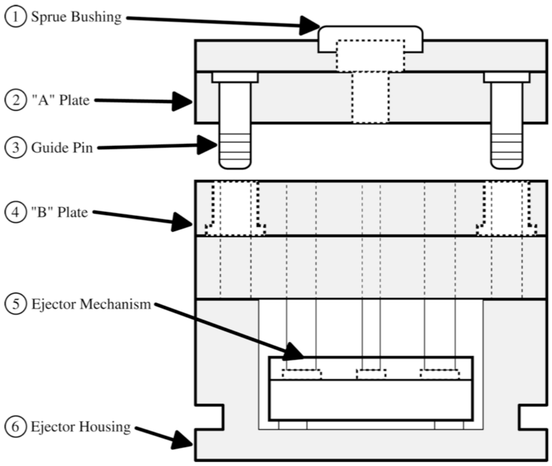


Figure 1. Mold Cross Section

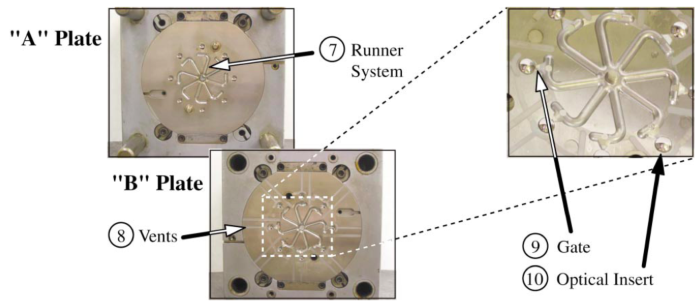


Figure 2. Mold-parting line photos

The following is a brief list of some of the key features generally found in molds along with a brief description of their intended function[2].

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 of the molding press.
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. Structures 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 (sometimes referred to as nubbins). Pins within the mold that have been deterministically ground and polished against which the optical surface forms during the molding process. These surfaces can be steel or a non-ferrous alloy.

2.2.3 Molding Machines

Molding machines are used to hold the mold and to melt and inject the plastic into the mold. The figure below shows the basic features of a molding machine.

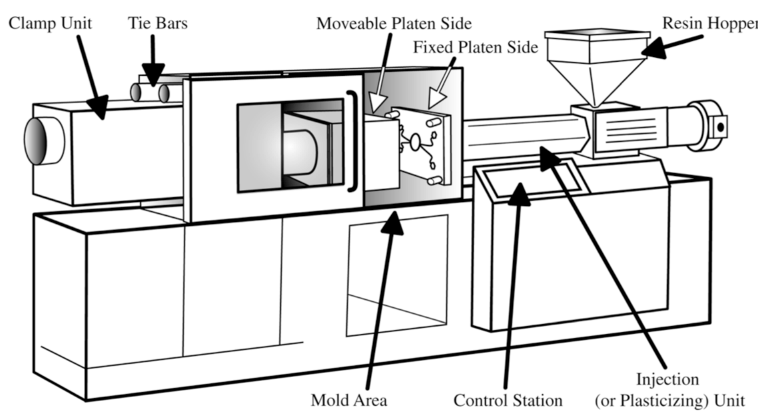


Figure 3. Schematic of a molding press.

The molding press has a clamp unit on one end and the injection unit on the other. The mold is hung in the middle region as shown. The clamp unit is used to keep the two mold halves together as the molten resin is being injected. The molding cycle begins. The moveable platen closes against the fixed platen (closing the mold). An appropriate amount of force is used to hold the mold closed during the injection cycle. The injection unit, consisting of a feed hopper, reciprocating screw, and barrel, picks up an amount of pelletized resin from the hopper. It is the job of the injection unit to melt the resin and to push it into the mold through the sprue bushing. The reciprocating screw turns within the barrel. It is fluted allowing it to trap the material between the heated chamber wall and the screw. The chamber wall is the bearing surface where sheer is applied to the resin as it is being advanced towards the mold. Once the molten material accumulates at the end of the screw it is injected at an appropriate speed and pressure into the mold. This causes the material to flow into the mold to fill the cavities. The molding machine provides complete control over this process, governing the size of the shot, injection speed, injection pressure, backpressure, cushion, and other critical variables that will determine the final outcome of the optic. After an appropriate cooling time, the moveable platen moves away from the fixed platen, and the mold opens. This allows the optics (still attached to the runner system) to be removed. After the shot is removed, the cycle starts over again.

Other equipment is often found along side the molding machine. For parts that require a large amount of material, auto loading hoppers are used to feed material into the machine. Also, the thermoplastics must be dried before being fed into the injection unit. It is common to see desiccating equipment located near the press for this purpose. Once the molding cycle is completed it is desirable to promptly remove the shot so that the entire molding process may be repeated with regularity. To aide in this, a robotic arm is frequently used to ensure that the removal is done on time. This enables the entire process to go into a steady state. Depending on the nature of the program, additional automation or end of arm tooling may be required to remove of the parts from the press, degate them from the runner, and package them into trays for final shipment. Degating is the process whereby the optical elements themselves are removed from the runner system.

3. TYING IT ALL TOGETHER

As noted above, it is important that the designer has a basic understanding of the manufacturing process and of the limits of size and tolerances that might be expected of the finished optics. In general terms, overall shape and tolerances of the optic will drive cost and manufacturability. There are some general guidelines: thicker parts take longer to mold than thinner parts. Optics with extremely thick centers and thin edges are very challenging to mold. Negative optics (thin centers with heavy edges) are difficult to mold. Optics with very tight tolerances may not be manufacturable at all in a one cavity mold, much less in a mold with more than one cavity. There are some other general tolerances that can describe the limits of fabrication in an ideally designed optic.

Attribute	**Rules of Thumb Tolerances**
Radius of Curvature	± 0.50%
EFL	± 1.0%
Center Thickness	± 0.020mm
Diameter	± 0.020mm
Wedge (TIR) in the Element	< 0.010mm
S1 to S2 Displacement (across the parting line)	< 0.020mm
Surface Figure Error	≤ 2 fringes per 25.4mm (2 fringes = 1 wave @ 632nm)
Surface Irregularity	≤ 1 fringes per 25.4mm (2 fringes = 1 wave @ 632nm)
Scratch-Dig Specification	40-20
Surface Roughness (RMS)	≤ 100 Å
Diameter to Center Thickness Ratio	< 4:1
Center Thickness to Edge Thickness Ratio	< 3:1
Part to Part Repeatability (in a one cavity mold)	< 0.50%

Table 2. Rules of thumb.

Two things should be observed here. (1) Even with the rules of thumb, it is very difficult for the experienced optical molder to communicate all of the things that the designer should look out for. There are simply too many variables to consider without expert guidance. In this regard we might say it is not unlike consulting with a doctor on a medical issue or with a lawyer on a legal matter. One might have a general idea of the issues from one's own reading or researching on the internet; however, expert assistance is needed to answer deeper questions. And (2), what is not discussed here is how the rules of thumb interact with one another or how a change in one area will impact another. Rules of thumb are quick generalizations. They are useful for initial discussions, but the rules can quickly break down as the limits of size, shape, thickness, materials, and tolerances are encountered. It is impossible to publish an exhaustive list of possible interactions between all of these variables. The main reason for consulting with the optical molder is that a good optical molder will bring years of experience to the table.

What is the best way for the designer to work with an optical molder? Perhaps the best way is to proceed from a systems design perspective. Instead of communicating with the optical molder at arms length with a drawing and tolerances hoping for the right solution, instead, why not communicate the big picture to the molder so that they can help address questions that may not even be in view at the component drawing level. Perhaps the best way to grasp this is to consider an example.

3.1 Example 1. The effect of design on cycle time and total cost of acquisition

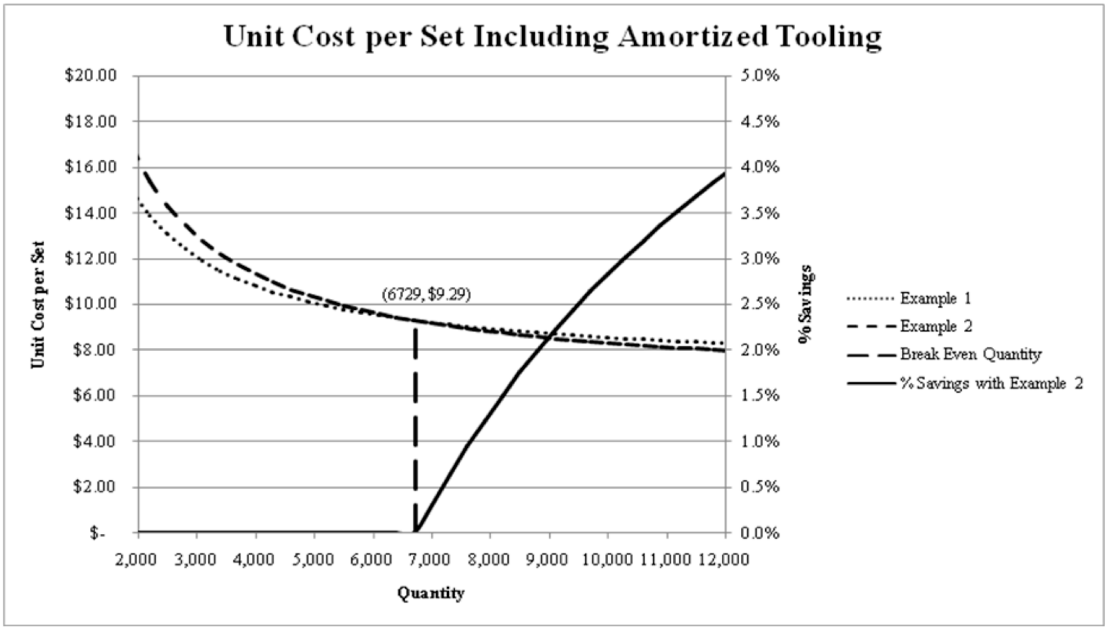
The optical molder received the following request for quotation. The element is acrylic, bi-convex, aspheric on both surfaces, 75mm in diameter ± 0.050mm, with a 12mm center thickness and a 2mm edge thickness, both toleranced at ± 0.020mm. The clear aperture extends to within 2 mm of the edge. Power and irregularity are specified at 5 fringes and 10 fringes respectively. The lens has a S1 to S2 displacement tolerance of ± 0.020mm. The drawing has no provisions for a gate location. Volumes are 10,000 pieces per year. Please quote.

A lens with this description is going to be very expensive. If we use an overhead rate of \$120/hr[3], and an estimated cycle time of 6 minutes, we would have a lens that costs about \$12.00. The tight tolerances would likely increase scrap, so accounting for yield loss would push the price higher to around \$14.00. To mitigate this increase, a typical tactic would be to build a higher cavitation tool, but because of the tight tolerances, this lens could never be run in a multi-cavity mold. Cavity to cavity variation would increase the power and irregularity errors to a point where not every cavity would meet the specification. There is no way to achieve the economies of scale that can be realized by going to higher cavitation. If we say that the mold for this lens would cost about \$15,000, the total cost of acquisition for the first year production would be about \$15.50/lens.

3.2 Example 2. How a manufacturable design can reduce the total cost of acquisition

An alternative approach to example 1 is to look at the system design with guidance from an optical molder, who may ask the question: can this thick optic be split into two thinner optics? If the system design were flexible enough to allow a two lens solution, then we might see an alternative scenario where two lenses with 3 minute cycle times can reduce the total cost of ownership through yield improvements (assuming the two separate lenses have more achievable tolerances, which is very likely).

The tooling cost for the two-lens solution, which would involve building one mold with two cavities that can be run independently, would be about \$20,000 – a \$5,000 increase over example 1. The graph below, which plots the unit cost of examples 1 and 2 (a set of two parts) including amortized tooling, shows that the improvement in yield gained through a more manufacturable design results in a breakeven point of around 6,700 pieces. From a cost perspective, if more than 6,700 pieces are required, it becomes cheaper to have a two lens solution. This savings could increase if the cycle time for either lens is less than 3 minutes (which is likely).



Graph 2. Unit cost per set with tooling amortized.

The economics work out, but the hidden cost of the risk between examples 1 and 2 is not captured. On paper example 1 is more challenging to manufacture and may lead to unexpected manufacturability issues. A competent optical molder would identify those issues as potential red flags so that contingencies can be determined upfront. For example, the power and irregularity tolerances are very difficult, and the parts may only barely meet the specification. What is the impact to the system if these values exceed the spec? Will it degrade performance? What if the tolerance analysis is incorrect and the specs need to be tighter, but that is only discovered after parts have been molded and tested? These are a few of the questions an optical molder must consider. Example 2 is expected to have looser tolerances, so many of the above concerns are inherently less risky.

The inquiry in example one called for an annual volume of 10,000 pieces. If the company has success selling the product, the volumes may go up and create a capacity constraint or lower cost requirement. A mold can only produce a certain number of pieces per year (around 35,000 pieces for one shift in example 1), and the cost is primarily cycle time driven. Since multi-cavity tools help to address both concerns, it is important to consider at the beginning if the lens can be made in a mold that has more than one-cavity. In example one above, the answer is no. The tolerances are too tight. In contrast example two has the benefit of looser tolerances and thinner optics, both of which bode well for the ability to expand to multiple cavities. The need to act on higher cavitation tooling may be delayed due to the higher production capacity of the 1-cavity molds (due to shorter cycle times), but having flexibility in the decision making process is often beneficial.

In much the same way that future expectations of multi-cavity molds must be considered upfront, the need for and method of prototyping must be mindful of future production methods and requirements. Prototypes are often used to provide functional devices to evaluate customer demand and market opportunities, but sometimes they are produced to prove that the system will work. Diamond turning is the most direct way of producing prototypes, and the achieved tolerances are typically much less than the specification limits. This is both a blessing and a curse, since the end result of the prototyping process may verify that a design is functional without testing the tolerance limits. Understanding the differences between what is achievable with prototypes (via diamond turning or prototype molding) versus volume production is crucial to making sure a design is production capable. The experienced optical molder can help a designer navigate through these potential pitfalls.

Other system design factors come into play as well. The temptation is to consider these as mundane non-optical issues, however, if not addressed correctly these issues can add considerably to the total cost of acquisition. For example, where will the lens be gated? Can the mating part be adjusted so that a longer gate vestige can be accommodated? How will the part be packaged? How will the part be handled? Does the optic need some kind of keying feature to help with down the road assembly? The answers to these questions can add additional and sometimes significant cost to the final component.

There are other things to consider: As the design deviates from a conventional on-axis rotationally symmetric optic, measuring the part to verify conformance can become a limiting factor. Interferometers are typically used to measure flat and spherical surfaces, and contact profilometers are proficient at measuring aspheres. For bi-conic, freeform, or off-axis surfaces, a combination of profilometry and CMM (contour measuring machine) inspection can answer many inspection questions. There are instances, though, where the design requires an optic be inspected to a level beyond which these tools are capable. Functional testers and customized inspection setups can often close the gap, but identifying that a gap exists early on in the design process is critical for finding a solution.

The point here is that the lens designer may not be thinking of these things when presenting a drawing for bid. He may not even be aware that there are larger issues like this to consider. He is probably concentrating on how the lens needs to perform in the system and rightly so. But the lens does not exist in isolation. The rest of the system, along with the commercial aspects of future production needs, should be addressed up front so that the appropriate tooling set can be accounted for. These are the things that the layman may not know that he doesn't know.

Finally, similar to how it is impossible for a designer to work from an exhaustive list of optical molding rules, there are other critical to success aspects of the manufacturing process that the molder does not know either. This is where the molder's supplier network comes into play. The tooling supplier identifies risks and makes suggestions about the mold in a back and forth process similar to how the molder works with the designer/customer. The same is true about coating, diamond turning, or other processes that are needed to make or support the production of the part. As an extension of this, it is beneficial for the molder to know many of these things first hand so that as many requirements can be determined in the one-on-one discussions with the customer. Finding a molder that has internal capability for diamond turning, coating, automation, fixturing, and so forth, will help to streamline the process, manage cost, and improve quality.

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