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Tutorial

A tutorial on plastic consumer optics

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Abstract

Consumer devices increasingly contain embedded optical systems. Many of these optical systems are based on molded plastic optical elements. This tutorial provides background on the design and manufacture of such systems. Consideration is given to the material issues, manufacturing concerns, and typical design trade-offs and constraints that often accompany plastic consumer optics.

Keywords: consumer optics; mold; plastic optics; polymer optics; tolerancing.

1. Introduction

Optical systems can be found in a growing number of consumer devices, including smart phones, laptops, PDAs, and entertainment devices such as gaming systems. The desire for light-weight, cost-effective performance has led many of these optical systems to rely on plastic optics, particularly injection molded plastic optics. The use of injection molded plastic optics brings with it a particular set of opportunities and challenges. Developers of consumer optic systems need to be aware of the manufacturing, design, prototyping and production considerations that utilization of plastic optics involves. Because the manufacturing method of plastic optics strongly influences design decisions, it is covered first. Following this, a discussion of typical design constraints and required analyses is provided. Finally, the prototyping and production of plastic consumer optics is reviewed.

2. Manufacturing

The use of injection molding to produce plastic components is commonplace, as can be seen in the many plastic items used in our daily lives. The use of injection molding to produce optical elements is less common, although still a well-developed industry. The main difference between non-optical and optical injection molding lies in the increased precision associated with optical elements. An understanding of the manufacturing process aids in the creation of a high-yield, producible plastic optic design.

2.1. Manufacturing process

The manufacture of injection molded plastic optics is based upon replication. That is, each optical element is created by forcing plastic to take the form of a set of high-quality masters. In the case of plastic optic injection molding, the precision masters are contained within the injection mold, which will be described in the next section. The use of a replication process allows for the production of repeatable, precision formed optical components. By utilizing several copies of a given mold, with each copy containing multiple masters, large numbers of components can be readily produced, as is often required for consumer optics.

From a process step viewpoint, injection molding is a straightforward procedure. For our discussion, we assume that an injection mold has been fabricated and placed in an injection molding machine. A schematic of an injection molding machine, with a mold in place, is shown in Figure 1. To begin the molding process the plastic, which usually comes in pellet form, is dried to remove any water it has absorbed during storage. The dried plastic pellets are transferred to the hopper of the injection molding machine, where they are fed as needed into the injection barrel. Inside the injection barrel is a large screw, which moves the plastic forward and will be used to inject it into the mold. As the plastic travels along the length of the barrel, friction from the screw motion and heat from heater bands around the barrel melt the plastic pellets, creating a quantity of molten plastic near the front end of the screw. The molten plastic will next be injected into the plastic mold. To prepare for injection the two halves of the mold are brought together by the clamp. The clamp, in addition to opening and closing the mold, provides a large force which will hold the halves together when the molten plastic is injected. The injection screw is next moved backward slightly, allowing molten plastic to pool in front of it. The screw is then driven forward, injecting the accumulated material at high pressure. The molten plastic flows into the mold, entering the cavities where the masters reside and the optic is formed. The screw is held forward to maintain pressure on the plastic in the mold, forcing it against the replication masters and preventing backflow, while the clamp pressure prevents the mold halves from separating. The mold is now held closed for a period of time, known as the 'hold time', while the molten plastic in the replication cavities is allowed to harden. When the plastic in the mold is sufficiently hardened, the mold halves are separated and the newly molded optical

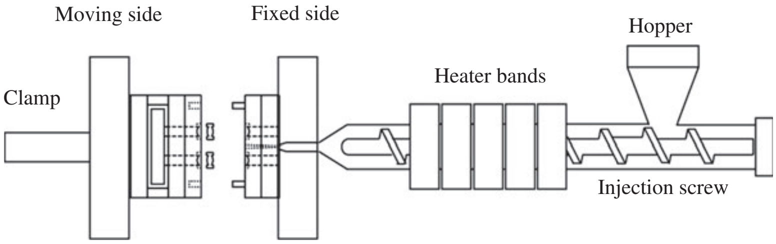

Figure 1 Schematic of an injection molding machine.

components removed from the mold. With the mold empty, the process can be repeated, producing another set of parts.

The total time taken from when the mold closes and plastic is injected until the parts are removed and the mold is again ready to close is called the 'cycle time'. The cycle time, of which the hold time is the main contributor, is the primary driver (along with optical coatings) in the cost of consumer plastic optic elements. As such, the cycle time is kept as short as possible. The length of the hold time is defined by how long it takes to cool/harden the optics. It is somewhat intuitive that the time to reach a particular hardness depends on the physical volume of the components being molded, as thinner, smaller parts tend to cool more quickly than thick, large parts. In addition, the amount of hardness will depend on the requirements placed on the optical elements. Parts that are removed too quickly from the mold may still be pliable, flexing or distorting their optical shapes during or after their removal.

2.2. Injection molds

An understanding of the basics of plastic injection molds can be crucial to the effective design of plastic consumer optics [1]. Although often unappreciated by those using the products created by them, precision optical injection molds are a testament to advances in design, materials and machining. Production molds are usually capable of producing millions of high-quality optical elements. A typical plastic injection mold comprises a series of plates, each plate serving one or several functions. The multiple plates allow the mold to be disassembled for internal access, as well as serving machining purposes. Plates are stacked together to build the mold halves, which in turn combine to create the final mold. A schematic of an injection mold is shown in Figure 2.

The two halves of the mold close and open, as described above, to allow the parts to be formed in and removed from the mold. In actuality, one of the mold halves is stationary in the molding machine, whereas the other moves back and forth. Because of this, the two halves are often referred to as the 'fixed' and 'moving' halves, respectively. In Figure 2, the fixed half of the mold is on the right and the moving half on the left. The fixed half is placed in the molding machine near the end of the injection screw. Through the center of the fixed half of the mold is a tunnel, known as the 'sprue', through which the molten plastic is injected. Upon passing through the sprue, the plastic runs through a series of channels, known as 'runners', up to the mold cavities. Between the runners and each cavity is a small opening, known as the 'gate', through which the plastic enters the cavity. The mold plate also contains a set of shallow grooves known as 'vents'. The vents allow the air in the cavities to escape when the molten plastic is injected.

The cavities, as mentioned above, contain the masters from which the plastics will replicate. For production of plastic consumer optics, the molds hold multiple masters (multiple cavities), to form multiple optical elements during each molding cycle. The molds are often referred to by the number of cavities they contain. For instance, a mold with eight cavities is called, not surprisingly, an 'eight cavity' mold, which should be able to produce twice as many components in a given time period as a 'four cavity' mold. In most optical molds, the masters consist of nickel plated steel pins ('optic pins'), into which the inverse of the optical surfaces of the components have been diamond turned. In reality, the exact inverse may not be diamond turned, as there will be some shrinkage of the plastic during the molding process. The optic pins, as well as dimensions such as the diameter of the hole that forms the periphery of the lens, are typically adjusted for this shrinkage. Normally, a mold contains sets of optic pins on each half of the mold. For a given cavity forming a standard lens, the optic pin on the fixed mold half forms one surface of the lens, whereas the optic pin on the moving half forms the other. Details around the optical surfaces, such as any flanges or mounting features, can be directly machined into the mold plates around the hole into which the optic pin has been inserted. Alternately, the flange features can be machined into a separate piece, which is itself inserted into

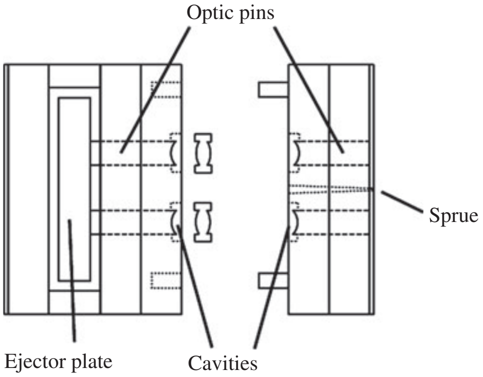

Figure 2 Schematic of an injection mold, with representative molded parts.

the mold plate. The combination of an optic pin inserted into a machined piece which creates the features around the optic surface is often referred to as a 'cavity set'.

Once the injected plastic has filled the mold cavities and the required hold time has passed, the parts are ready to be removed from the mold. The 'moving' mold half is pulled back from the 'fixed' half, taking the parts with it. That is, the molded components remain attached to the moving half of the mold. With an air space between the two halves, the parts are 'ejected' from the mold (the moving half), normally being pushed off the face of the mold plate by the optic pins themselves, or by a set of pins ('ejection pins') specifically put in the mold for this purpose. The optic or ejector pins on the moving mold half are connected to the ejector plate (see Figure 2), which when moved forward pushes the molded parts from the mold face. Because the parts for plastic consumer optics often have strict optical requirements, the parts are not actually ejected, or flung, from the mold. Instead, as the parts slide off the mold face they are typically grabbed by a set of vacuum heads or other devices that retain them. The vacuum heads can be attached to a robotic arm which places them onto a tray, conveyor belt, or other storage or transport means.

The construction of the mold sets many of the tolerances on the parts it produces. For instance, the centration of one optical surface to the diameter of the part depends on how well the optic pin is centered to the diameter feature machined into the mold cavity. As the optic pin is inserted into the cavity, there is some small clearance that must be allowed. The alignment of the two optical surfaces depends on the alignment of the two halves of the mold. The two halves are typically aligned using rods for coarse alignment and taper interlocks for precision alignment. Injection molds typically have few adjustments, as most dimensions are hard-machined into the mold plates or cavities. The exception for adjustment is the axial position of the optical surfaces (pins). These are adjusted by using hard shims beneath their back ends. This allows the adjustment of the surfaces relative to the flanges and to each other (center thickness).

3. Design

The design of plastic optical systems is a subset of the optical design field, which is in turn a subset of the larger optical engineering field. There are several excellent texts on the practice of general optical design [2–6], as well as a few on the more specific field of plastic optics [7–11]. For our discussion, we focus on the characteristics of plastic consumer optics that influence their design.

3.1. Cost/size/detectors

Consumer optics, generally being high volume items, receive heavy pressure to maintain low prices. This has resulted in many of them being produced using plastic optical elements, which typically cost less than comparable glass optics [12]. In addition to the use of plastic optics, the price pressure often limits the number of elements (lenses) that are allowed in a given design. The cost of the optic assembly, excluding the detector or electronics, tends to scale directly with the number of elements. In many devices, the number of allowed lenses will be one, two or three. Limiting the element count has a significant impact on the optical designer, as the imaging performance of an optical system generally improves with increasing element count. This is because the increased number of optical surfaces allows additional variables to control the aberrations that naturally exist in imaging systems. As an example of the number of elements in a well-known high-quality imaging system, consider that a standard, fixed focal length SLR camera lens typically contains between six and ten individual lenses within the 'lens' barrel. However, as will be described in Section 3.3, the use of aspheric surfaces can help improve optical performance while maintaining low element count.

Consumer optics often also have constraints on their overall size. For items such as cell phone cameras, there is a restriction on their total length, to keep the phones they are in thin. The overall length limit impacts the optical design, forcing the optical elements to be relatively close together. This can reduce the spread that the beams from different field angles achieve on the different lens elements. Separation of different field beams on some lens elements is a technique often used to correct aberrations in optical designs.

In addition to cost and size constraints, the design of consumer optics is often impacted by the detectors that are used with them. Many consumer devices utilize complementary metal oxide semiconductor (CMOS) image sensors, which may contain micro-lenses over their pixels. The micro-lenses serve to maximize the amount of light that is collected by each pixel. However, the micro-lenses only work well for a limited range of ray incidence angles. This maximum acceptance angle places an additional burden on the design, constraining the angles at which the beams can exit the optical system, potentially impacting the shape of the rear-most lens in the system.

3.2. Materials

Compared to optical glasses, there are relatively few plastic optical materials [13]. This limits the material options the designer has when developing the optical system. Table 1 lists the types and properties of the most common plastic optical materials. In general, optical plastics have relatively low refractive indices, from approximately 1.49–1.61. Their dispersions (or Abbe numbers), which describe their change in index with wavelength, take on values between 27 and 57. Lower Abbe number materials are more dispersive than higher Abbe number materials. It can be seen from the table that several of the plastic optical materials are similar in refractive index and dispersion, further reducing the optical variable choices. In fact, from a purely optical standpoint, polycarbonate and polystyrene can often be interchanged with no impact on the nominal optical performance. Note that this substitution may have other, non-optical consequences. In many cases, the choice of a particular optical plastic will depend more on

Table 1 Properties of common plastic optical materials.

Material	Acrylic	Polystyrene	Polycarbonate	SAN	NAS	COC	COP	Polyester
Glass code[a]	492.572	590.309	585.299	567.348	564.334	533.567	530.558	607.270
Specific gravity	1.18	1.05	1.25	1.07	1.09	1.02	1.01	1.22
Service temperature (°C)	85	75	120	80	80	130	130	–
CTE[b]	60	50	68	50	58	60	70	72
dn/*dt*[b]	-105	-140	-107	-110	-115	-101	-130	-130
Birefringence[c]	4	10	7	5	5	1	1	1
% Water absorption[d]	0.30	0.10	0.2	0.28	0.15	<0.01	<0.01	0.15

[a]ABC.XYZ=refractive index of 1.ABC and Abbe number of XY.Z. [b]$\times 10e^{-6}$. [c]Relative on a scale from 1 to 10, 10 being most birefringence. [d]For 24-h immersion.

their non-optical properties, such as service temperature, than on their optical ones. Consider that the service temperature, which describes the highest temperature at which the optical material should be used, of acrylic is lower than that of the cyclic olefin copolymers (COCs). Thus, higher temperature requirements, such as those seen in cell phone cameras, may drive the selection of COCs instead of acrylic. Spectral transmission (particularly near the UV end of the spectrum), water absorption, hardness and chemical resistance are all factors that may influence the choice of a particular material.

3.3. Surface forms

Conventionally fabricated glass optics are typically manufactured having spherical surfaces, based on the grinding and polishing processes used to create them. Random motion between a polishing tool and a glass optical material tends to produce a spherical surface. The radius of the optical surface can be controlled by adjusting the radius of the polishing tool. By contrast, plastic optical elements can easily be fabricated having non-spherical surfaces, because of the fact they are produced using a replication process. The replication (molding) process, as described above, is based on having suitable masters within the mold. Using nickel-plated diamond turned pins as replication masters allows considerable freedom in surface form, due to the extreme precision and programmability of the diamond turning machining process.

The most commonly used surface forms for plastic consumer optics are spherical, aspheric and diffractive surfaces. Spherical plastic surfaces are similar to those used in conventional optics. Because of the limited number of surfaces allowed and the relative ease of fabricating non-spherical plastic optics surfaces, aspheric surfaces are often used in place of spherical ones. Aspheric surfaces, as their name implies, are not spherical. Instead of having a single radius of curvature, as a sphere does, an aspheric surface can have a varying local radius of curvature. This allows the effect of different parts of the surface to be tailored for the specific beams passing through them [14]. We mentioned above that separating beams on a surface is used for aberration control. A brief, simplified explanation of this is to consider the radii of curvature (in two orthogonal directions) that an incident beam sees when striking a spherical surface. If the beam strikes the surface along the optical axis, the surface appears symmetric, with the same radii in both directions. As the beam moves off axis, the surface no longer appears symmetric. As the beam moves further off axis, the difference in orthogonal radii increases. If we consider astigmatism as the difference in focus created by the difference in the two orthogonal radii, we see that the amount of astigmatism will vary depending on where the beam strikes a surface. For our simplified explanation, we can consider that the further from the optical axis that a beam strikes the surface, the greater the astigmatism created. This is due to the increasing difference between the orthogonal radii as a function of increasing height. By adjusting the value of the radius of the spherical surface, we adjust how fast the astigmatism changes as a function of off-axis position, but do not alter the fact that it increases with height. Thus, we have one parameter (the radius) that controls the surface astigmatism impact (we are ignoring the ability to move the surface axially, which will affect where the various beams strike the surface).

Now consider replacing the spherical surface with an aspheric surface. Deferring for the moment how the surface is prescribed, by the very definition of an asphere we can vary the local radii of curvature of the surface as a function of off-axis position. Thus, we have more than one parameter that controls the astigmatism created. For the spherical surface above, the astigmatism increased monotonically with distance from the axis. For the aspheric surface, this does not have to be the case. If we want the maximum astigmatism at a normalized height of 0.5 (1 being the edge of the surface), we would define the asphere such that the orthogonal radii difference was a maximum half way out. Having multiple parameters to describe the surface (i.e., using an asphere) thus provides increased aberration control.

There are multiple ways of defining aspheric surfaces, among them polynomial expansions, splines and point-by-point data sets. The most commonly used aspheric surface for consumer plastic optics is the even ordered polynomial asphere, shown in Eq. (1).

$$z(r)=\frac{cr^2}{1+\sqrt{1-(1+k)(cr)^2}}+Ar^4+Br^6+Cr^8+\ldots \tag{1}$$

where c is the curvature of the surface (inverse of the radius of curvature), k is the conic constant, $r^2=x^2+y^2$ (radial distance from the optical axis), and *A*, *B*, *C* … are the even ordered polynomial aspheric coefficients. In this description, the depth of the surface, known as the sag *z*, at any height from the optical axis is defined as the sum of the depth from the base sphere or conic (the first term), plus the depth contributions from the even ordered polynomial terms. Although the even ordered power series in theory extends to infinity, it is common that powers less than or up to the 10th order are used. The coefficients on the power terms are varied during the optimization of the lens prescription. The use and theory of aspheric surfaces are described in several of the referenced texts as well as a short course [15].

Another non-spherical surface that is sometimes seen in plastic consumer optics is a diffractive surface. Diffractive surfaces are based on diffraction gratings, where a series of steps or rulings are used to disperse the light passing through them [16]. The gratings can be molded into a base spherical or aspheric lens surface. We mentioned above that there are a limited number of plastic optical materials and that several have similar dispersion properties. By adding a diffractive surface to the plastic material, we can tailor the dispersion of the combination, in effect creating a new material. The amount of dispersion of the combination is controlled by the relative powers of the refractive and diffractive surface, as well as their dispersions, similar to an achromatic doublet [17–20]. For the visible spectrum, diffractive gratings have an Abbe number of -3.45, implying a very large dispersion. The negative sign of the Abbe number indicates the dispersion is the opposite of that seen with conventional refractive surfaces. That is, a refractive surface bends blue light more than red light, whereas a diffractive surface bends red light more than blue. This is due to the fact that the surface relies upon the principle of diffraction, rather than refraction.

Although attractive for their ability to tailor the dispersion of plastic optic lenses, diffractive surfaces are not without their drawbacks. For one, the diffraction grating is only theoretically 100% efficient for a single wavelength (the design wavelength). That is, only for the design wavelength does all the light at that wavelength go in the desired direction. For all other wavelengths, some of their energy does not go in the desired direction. This undesired direction light can work its way through the remainder of the optical system and end up as stray light in the image [21–23]. In reality, the diffractive surface will not be 100% efficient for any wavelength, as this implies the diffraction grating features are perfectly manufactured. The heights of the diffractive features are typically on the order of a micron, which may be difficult for some molders to accurately reproduce in the injection molding process. For these reasons, the use of diffractive surfaces requires additional care, analysis and potentially an alternate/back-up design that does not include them.

3.4. Approach

Because of the issues and advantages discussed above, there is generally a certain design approach associated with consumer plastic optics. Of course, each designer has his or her own philosophy on how to approach a design, but the number of constraints that plastic consumer optics systems impose often leads multiple designers down the same path. The design of plastic consumer optics may be best described as a customer-driven balancing act. There are almost always several competing forces at work in these designs, many of which have been mentioned above. Often, it is impossible to meet all the customer's requests, at which point the designer may need to perform trade studies. The trades most usually take place between the performance, cost and size of the design [24].

The design process is best begun with a clear understanding of the system function and desired requirements. For instance, in the case of a web camera, it may be that the customer is most interested in performance in the center of the field of view of the system, where a person's face may be placed during teleconferencing. In this case, the design could be weighted to have better performance on axis than at the corners of the image. In other cases, uniform performance may be desired across the entire image.

Because of the cost limits on the number of elements, the limited material choices, and the general standardization of detector sizes, most, if not all, of the possible plastic consumer optic design forms have already been created. Consider that for a two element lens system there are four possible power combinations (positive/positive, positive/negative, negative/positive and negative/negative). Each of the lenses can be one of several materials and can have multiple shapes (biconvex, meniscus, biconcave), which adds to the complexity. Nevertheless, some forms will be excluded based on optical design knowledge, etc., so the total number of possible effective combinations is reasonable to understand.

3.5. Tips

There are several design tips that can be applied to most plastic consumer optics [25]. They are based on the characteristics of injection molded plastic optics and their manufacture.

1. Talk to molders – one of the first steps in creating a design should be to contact potential molders. They will be able to guide you in developing a design that will be producible. Waiting to talk with them until after a design has been developed may require a redesign, costing the project extra time and money.
2. Consider the starting point – as many similar designs have probably been produced, they may be used as a starting point for the design. Prior designs can often be found in conference proceedings or the patent literature. Care should be given not to infringe on the starting point patent or other patents.
3. Control edge thickness – we discussed above that injection molding requires molten plastic to flow into the cavities where the lenses are formed. If the edge thickness of the lens is too small, the plastic will not be able to flow properly, resulting in poor quality lenses. To determine the appropriate minimum thickness, see Tip 13, then Tip 1. Outside of this, 1 mm is a good reference point.

4. Control center thickness – we discussed above that the cycle time, mainly the hold time, drives the cost of the plastic optical elements. Thick lenses generally take longer to cool than thin lenses, increasing their cost. This is not to say that all lenses should be thin, but that lenses should not be unnecessarily thick. Given free rein, many optical design optimization features will maximize the thickness of all lenses. The performance impact of reducing the thickness of a lens should be evaluated. If a large increase in thickness provides minimal performance improvement, the lens should be constrained to a thinner value.
5. Keep away from plano surfaces – this is another result of the injection molding process. The molten plastic tends to take a more uniform shape for curved surfaces than for plano surfaces. Using a long radius surface instead of a plano surface may aid in the production of the lens.
6. Limit the number of diffractive surfaces – if diffractive surfaces are used, subject to the caveats above, they should be limited such that each imaging path sees only one. Novice designers sometimes make many or all of the surface diffractive, which produces a wonderful 'on paper' design, but does not perform well in reality due to diffraction efficiency issues.
7. Use more rays and fields – we discussed that aspheres are easily produced in plastic optics. When designing with them, more fields need to be defined and more rays used than is often done with spherical optics. The reason for this is that the optical design software only evaluates the performance where the fields are defined. If only a few fields are defined, the additional variables provided by the aspheric surfaces may result in excellent performance at the defined fields, but horrible performance in between them. Alternate or additional fields from those used to optimize the design should be used to evaluate its performance.
8. Limit aspheric orders – consider the impact that is gained by each additional aspheric order. If a system performs well with 6th order aspheres and changing to 8th order aspheres has minimal impact, stick with the 6th order surfaces.
9. Leave some space – we discussed that shrinkage of the plastic occurs during molding and that most molds are compensated for it. The shrinkage tends to be highest in regions of thickness change or discontinuity, particularly the edge of the optical surface. As a result, it is extremely difficult to control the optical surface all the way to the edge of the part (or up to the transition into the flange). To account for this, there should be room allocated around the clear aperture (the region the optical surface must meet its requirements). This room may be in direct conflict with the size constraints, cell phone cameras being an excellent example.
10. Aim for production performance, not nominal performance – the performance of an 'as built' design will usually be lower than that of the nominal (computer) design. This is due to the fact that the actual hardware will not be perfectly produced and assembled. The tolerance analysis, discussed below, will predict the expected performance of the real systems. It should be kept in mind that the best performing nominal design in the computer is not always the one that performs best when built. The optimization process should use the feedback from the tolerance analysis to produce the best producible design.
11. Think about testing – consideration of testing of the elements and assembled system should not be left as an afterthought to the design, but should be in the mind of the designer throughout the process. The old saying of 'if you can't test it, you can't build it' applies. Extremely steep or 'buried' surfaces can be difficult to test. Diffractive surfaces may require special equipment such as white light interferometers or diffraction efficiency test setups.
12. Know when to stop – because of the constraints on the number elements, length, etc., there may be no 'perfect' solution. At some point, no benefit is gained from continuing to 'beat on' the design.
13. Realize and accept that 'it depends' – developers of plastic optic systems quickly learn that there are no absolutes when it comes to their design and production. The most likely answer to a generic plastic optic question (e.g., how thick does the edge need to be?) is 'it depends'. This can be difficult for some designers to believe, but it is the truth. The shape, thickness, volume, material, requirements and other parameters can all play a factor into what is and what is not a producible optical element or system.

The list is certainly incomplete, but applying these ideas to the design process will help in going down a productive path.

3.6. Opto-mechanical

Plastic optics allow for some creativity in the opto-mechanical design of the system [26]. One of the benefits of using injection molded plastic optic elements is the ability to create integral opto-mechanical features on the lens elements. For instance, flanges can be molded on the element which can be used to set its axial position in the system. It is common for plastic consumer optical systems to rely on stacking the lenses and any baffles or apertures within a lens barrel. By designing appropriate flanges, the spacing between the lenses can be easily controlled. It is good practice, if possible, to have the flanges extend past the highest point on the optical surface. This way, the lenses can be placed down on the flange face, in a tray, for instance, without damaging the optical surface. In addition to flanges for axial spacing, orientation features, either visual (to indicate which side of a lens goes forward) or mechanical (e.g., to control the rotation of the lens) can be molded into the parts. Reference features or surfaces for metrology may also be included on the parts.

3.7. Analyses

There are several analyses that should be performed on any plastic consumer optics design. The list and discussion below represent the minimum effort that should occur.

3.8. Tolerancing

Tolerancing refers to defining the allowed deviation from perfection of manufactured hardware, along with determining the impact of the allowed deviations on system performance. Tolerances can be broken up into two types, those on the individual components and those on the assembly of the components. There are two general forms of tolerance analysis, sensitivity and Monte Carlo, with both forms usually performed on a given design.

A sensitivity analysis determines the impact of each tolerance, that is, each allowed departure of a particular characteristic from its design value. For instance, if the nominal design has a surface with a radius of 10 mm, the impact of having a shorter (e.g., 9.95 mm) and longer (e.g., 10.05 mm) radius will be determined. Similarly, every other characteristic of the system would be evaluated. This includes the component tolerances (lens thickness, refractive index, surface form, etc.) and the assembly tolerances (tilt, decentration, axial spacing, focus, etc.). Performing a sensitivity analysis allows the design to see which characteristics have the greatest impact on the performance of the system. This information can be fed back into the design cycle, potentially reducing the impact of a particular characteristic. The sensitivity evaluation also needs to be considered with regard to the capability of the molder and molding process. If the molder can only hold 0.5% variation on a radius and a 0.1% radius change destroys the system's performance, the design needs to be revisited.

A Monte Carlo analysis provides predictions on the distribution of performance that will result from building several systems. Monte Carlo analyses are performed by randomly assigning departure values (within the allowed tolerance ranges) to the nominal design. This process is repeated many times, effectively building multiple systems within the computer. Each system's performance is evaluated and a distribution developed. The advantage of this approach is that it accounts for interactions between the various tolerances, whereas the sensitivity analysis generally evaluates each tolerance individually. Monte Carlo calculations are also useful for predicting the performance of systems created from multi-cavity molds.

Because of the high quantities and price pressures on plastic consumer optics, tolerance analyses need to be carefully performed and evaluated [27]. Tolerance assumptions should be reviewed with potential molders before the final tolerance analysis is performed. The predictions of the Monte Carlo analysis will give the estimated yield of the hardware produced. If the Monte Carlo analysis overestimates the performance, there will be a yield hit and an associated increased cost. The results of the Monte Carlo analysis should be reviewed with the customer, with the knowledge that there may be a spread in performance among the systems produced.

3.9. Stray light

Plastic consumer optics can be particularly susceptible to stray light, where stray light is defined as unwanted image artifacts produced by sources within or outside the scene that is viewed. There are several reasons for this susceptibility. One reason is that the length constraints may not allow adequate baffling or sunshades. Secondly, the use of flanges around the lenses (which are transparent like the lens) may allow light to propagate around the lens surfaces and to the image plane. Third, if cost is kept low by not anti-reflection coating the optics, ghost images may be more visible.

Stray light analysis has developed significantly in the past decades. There are several commercially available software codes to perform the analysis. The codes work by tracing rays, including multiple bounces off or scattering from the optical and non-optical components, to determine the energy on the detector from a given source (such as the sun). Many times a strict stray light requirement has not been developed, so the results of the analysis may be subject to engineering judgment rather than comparison to a hard number. The use of sunshades, opaque spacers, mylar annular disks and ink printing are all methods that are used to control stray. The need for stray light control elements should be considered during the optical and opto-mechanical design [22].

3.10. Environmental

If the plastic optical system is expected to work over a range of environmental conditions (e.g., temperatures, humidity), an environmental analysis should be performed [28]. Plastic optics have a much larger coefficient of thermal expansion (CTE) and change in refractive index with temperature (dn/dt) than glass optics. A change in temperature, with the resulting change in physical dimensions and refractive index (where the latter usually has the largest impact), can produce a focus shift of the system. This focus shift may be large enough to degrade the image performance. If possible, a focus mechanism may allow recovery of the image performance. Alternately, the system may be designed to have minimal change over temperature, by balancing the impact to the various changing characteristics [29, 30]. The cost pressures may not allow for a focus mechanism or enough elements to balance the focus over temperature, in which case the image degradation may need to be accepted. Using a slow enough $F/\#$, which provides depth of focus, or controlling the thermal environment (for devices used most often in an office or home) can be enough to enable adequate performance.

4. Prototyping

Because of the cost associated with building injection molds, prototypes of plastic optical designs are typically built and tested before committing to a full set of production molds. The prototype systems can be produced in several ways, such as direct machining (diamond turning) [31, 32] or prototype molding, and in various degrees of representation to the final design configuration. The choice of which (or how many) prototyping methods to use depends on the available time and money. Diamond turning optical parts typically produces a low number of high-quality, fairly costly parts. The machining process allows for the parts to have many or most of the features of the elements, such as flanges. The material used for the machining blanks can be either cast or molded, depending on the material specified. Care should be taken when prototyping systems containing polycarbonate, as it does not diamond turn as well as other materials such as acrylic, cycloolefin coploymer (COC) and cycloolefin ploymer (COP). Polycarbonate tends to be 'gummier', resulting in a larger surface roughness for diamond turned parts compared to molded ones. Many vendors have molds specifically designed for molding blanks, which can be used for prototyping or for material analysis such as bonding or chemical resistance studies.

Prototype molding allows for more parts to be generated at a lower cost per part once the mold has been built and paid for. Depending on the effort put into the mold, the parts produced may be exact replications or simplified versions of the future production parts. If they are exact replicas and no changes are required, the prototype mold may be used for early, low rate production. Prototype molding also helps develop the molding process (the settings on temperature, injection pressure, etc.) that will be used in production and may catch molding issues earlier in the development cycle.

As a note of caution, prototypes should not be allowed to set too high a bar for the production systems. This is particularly true for the case of diamond turned prototypes, which can be expected to closely conform to the design characteristics. A prototype may not exhibit the performance loss associated with production molded parts, due to the care in building them and the low quantities produced. They also may not show potential stray light problems if they do not adequately represent the true optical and optomechanical features of the system. Unrealistic expectations can be set up by showing the performance of a 'near design' prototype.

5. Production

Once a design has been deemed ready for production, based on design and manufacturing considerations, decisions must be made in regard to numbers of molds and vendors. Many times, the quantities involved in plastic consumer optics require the production of several copies of each lens mold. The number of molds and the number of cavities per mold should be determined considering cost and risk. As a risk mitigation strategy, multiple vendors may be placed under contract for the production. Close interaction between the molder and designer should occur during the transition to production. In particular, test methods, test equipment and quality control procedures should all be reviewed. Statistical performance tracking should be used throughout the production run to determine if the various processes are remaining in control.

6. Conclusions

The success of plastic consumer optics can be seen in the large number of devices on the market with embedded plastic optical systems. As covered in the discussion above, there are many considerations to attend to during the development of such systems. There is a great deal of work that must occur beyond the creation of an optical prescription using the optimization function of an optical design code. Tolerancing, optomechanical design and analysis, manufacturing and assembly considerations, test strategy development and prototype evaluation are all necessary steps on the path to production. The designer should be involved in all of these steps, adjusting the design as necessary based on their various constraints and inputs. Bringing potential molders in early in the design process will help in avoiding a number of missteps [33] that can occur due to the characteristics of plastic optics.

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