Invited Paper

Do what I say and not what I did: Common polymer optics mistakes

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ABSTRACT

As the use of polymer optical systems increases, several common mistakes are seen in their design. These mistakes span the range of materials, design methods, and manufacturing and are often made due to a lack of familiarity with the special design considerations of polymer optics. In this paper we provide specific examples of some common polymer optics mistakes, how they happened, and how to avoid them.

Keywords: polymer optics

1. INTRODUCTION

The increasing use of polymer optics has created a situation where engineers of all disciplines are being asked to specify, design and utilize them. Often, these engineers have no experience with polymer optics and must learn about them while performing the design task. This lack of experience results in a number of common mistakes being repeated. While "learning from your mistakes" often provides the best education, we take the view that learning from the mistakes of others can be even more valuable. As such, we provide a series of examples of common mistakes that should be understood and avoided. These mistakes are broken down into four categories: material, design, prototyping and production.

2. COMMON MISTAKES

2.1 Materials

There are a fairly limited number of polymer optics materials to choose from. Nevertheless, it is still possible for a project to go badly due to the selection of an inappropriate polymer optical material. As an example, consider the case of the design of an early cell phone camera. The camera requirements called for a single polymer lens mated to a small detector. The selection of a crown (low-dispersion) material made sense, in order to limit the chromatic aberration of the system. The most common crown material, acrylic, was selected and the optical design performed. The lens and barrel were prototyped and found to provide adequate imaging in the laboratory setting. However, after exposure to real world environments, the image was found to be degraded. In particular, the heat of a car dashboard in Arizona was enough to deform the lens and ruin its performance. This resulted in the need for another round of design and prototyping using a different, higher temperature material. The best way to avoid material selection mistakes such as this is to fully define and understand the requirements and environments before the design is begun. It should be kept in mind that environments cover not only temperature (as well as temperature change rates), but shock/vibe, humidity, pressure and exposure to chemicals, airborne particles such as sand, and solar and/or laser radiation.

Another common polymer optics mistake is incorrectly or incompletely specifying the material. While there are a limited number of materials available, there are a large number of grades of these materials. Searching a polymer distributor site will show tens or hundreds of different varieties of acrylic. These various grades are usually differentiated by the additives in them, which include mold release or UV stabilizers. Additionally, there can be various color grades. As an example of an incomplete material specification mistake, consider a molded lens cell containing an opening meant to serve as the aperture stop of the system. As typically defined, the aperture stop of the system is the aperture that limits

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the size of the on axis light beam passing through the system. Thus, the aperture stop should pass light through its opening and block light elsewhere. At first thought, a molded lens cell should easily meet this requirement. That is, of course, if the material that it is molded out of is opaque. However, materials may come in several grades, one being "natural" which often has a whitish appearance, while other grades are completely opaque. In this case, the material color was not specified and the molder produced the lens cell/aperture stop prototypes out of natural color material. When inserted in the system, the aperture provided the correct size imaging beam through the system, while the remainder of the lens cell, being translucent, provided a high level of diffused stray light, completely washing out the image. After a few minutes of discussion on the foolishness of even constructing the system with such a part, the lens cell was blackened and an acceptable image obtained. Shortly after, the drawing was updated and the molder instructed to change to the opaque grade. The best way to get exactly the material you want is to specify it exactly, including not only the material name, but the grade and manufacturer.

A corollary to specifying the material is to ensure that only virgin material is used. In standard polymer molding, scrap material from the molding process is often ground up and rerun through the molding process. This scrap typically comes from the runners and sprues, which are the channels in the mold that bring the molten polymer to the area where the part is formed. Repeated melting and remolding of polymer materials can change their properties, which may alter the performance of the polymer optical system. Most molders of polymer optical components will automatically use virgin material, but it is worth specifying this on the part drawing. A statement similar to "Virgin material only, no remelt, regrind or recycled material allowed" should suffice.

Another common material mistake, which is related to the specification of the material, is the use of "equivalents". This is sometimes seen on part drawings in a note stating "Use of equivalent materials is allowed". The main problem with having this statement on the drawing is the definition of "equivalent". In some cases, the use of an equivalent material may have no impact on the system. For instance, if a molder has particular expertise with one brand of acrylic, allowing them to use this instead of the acrylic called out on the drawing may provide an improved molding process. Other times, the use of an "equivalent" material can have detrimental results. Consider the case of a two element web camera design, which contained one crown material (COC) lens and one flint material (polycarbonate) lens. When the molder found they were running low on polycarbonate, they decided that polystyrene would be an acceptable, "equivalent" substitute. From a purely optical standpoint, this was true. Replacing the polycarbonate in the design with polystyrene had a negligible impact on the MTF of the system, since polycarbonate and polystyrene have similar refractive index and dispersion. However, the material properties of the two polymers are different, in particular their thermal properties. The use of polystyrene limited the temperature exposure that the lens could handle, which was unacceptable to the camera manufacturer. The best way to avoid this type of inappropriate "equivalent" substitution is to require written approval from the engineer responsible for the parts before the substitution is made. A note such as "Substitution of the primary material called out, by an alternate or equivalent material, must be approved in writing by the customer prior to the substitution taking place" should be adequate. If not on the drawing, a similar statement can be placed in the purchase order.

2.2 Design

Understanding the requirements on a system, the environments it will be exposed to, and selecting the proper materials are great first steps towards designing a successful polymer optical system. The next step is to develop the system without making design based mistakes. Most polymer optic design mistakes are caused by either improper use of the optical design code or by not understanding the physical constraints on manufacturing polymer optics. We begin by considering mistakes associated with improper design techniques.

One of the advantages of polymer optics is the ease of creation and use of non-spherical surfaces such as aspheres and diffractives. However, many engineers who are being asked to design polymer systems do not have any background in their use. As a result, they often create unnecessary or unbuildable aspheric or diffractive surfaces. In order to take advantage of these surfaces, they need to be properly controlled in the design of the optical system. As an example, consider the two element web camera discussed earlier. Knowing that the design must be controlled over the desired field of performance, the engineer defines field angles at the 0, 0.7 and 1.0 normalized fields, as is shown in Figure 1. Also knowing that aspheres can readily be produced, all surfaces are defined as 10^{th} order aspheres, with their coefficients allowed to vary. After optimization, excellent imaging is predicted, the design is drawn up and a prototype produced. Upon arrival of the prototype, the image quality is found to be excellent, at least at on axis, at the full field and at seven-tenths the full field. However, the image quality is poor in a ring at about half the full field angle. This is a result of the fact that the merit function used in the design only required good image quality at three field angle and not in between. The use of several aspheres, along with relatively few fields, resulted in a system with astigmatic field correction at the defined field points and poor correction in between. Viewing the field curves shows the curves wiggling back and forth, coming together at the defined field angles and separating elsewhere. The way to prevent (or correct) this mistake is to increase the number of fields used in the optimization run, so that the entire field is adequately represented, as shown in Figure 2.

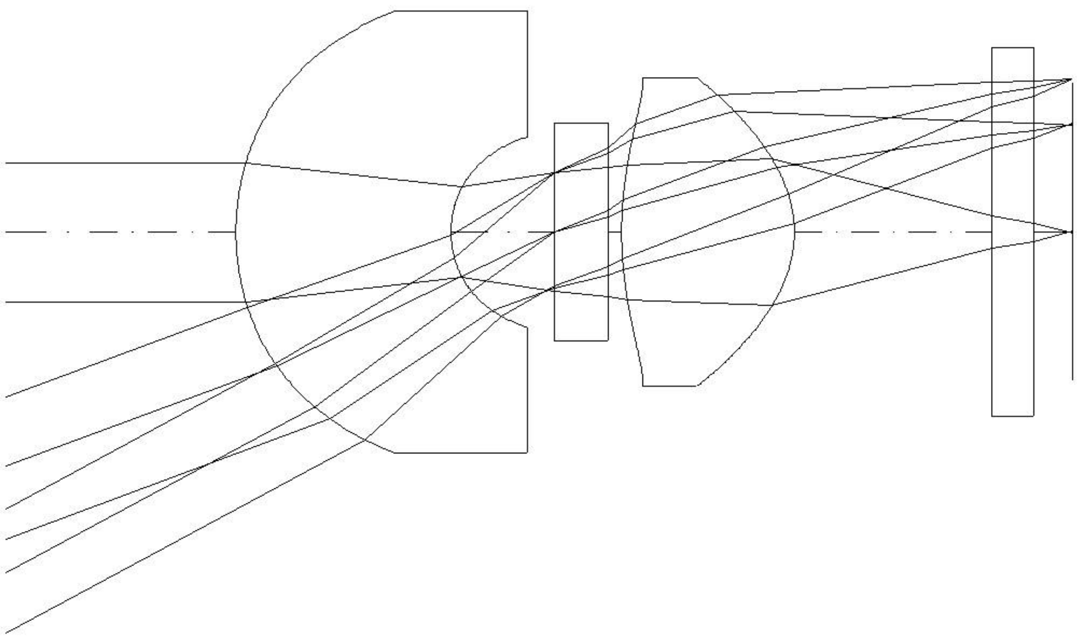

Figure 1. Inadequate number of fields defined for use with multiple aspheric surfaces.

The use of multiple aspheric surfaces can also enable the mistake of designing a “spherical aspheric” surface. That is, while the surface may be defined as an asphere, the actual departure of the surface from a base spherical surface is fractions of a micron. This is a product of allowing the aspheric coefficients of all the surfaces to vary. During the optimization process the design code will vary the coefficients, looking for an improvement in the merit function, and will change the surface from sphericity even if it provides only a small benefit to the merit function value. While the surface could just be called out as an asphere, there is no need to add unnecessary complexity to the manufacture of the system. This allows additional room for errors, such as in entering the coefficients of the surface during testing. The way to avoid this mistake is to either not allow all surfaces to vary as aspheres or to check the departure of each aspheric surface and convert those that have negligible departure back to spheres. A final optimization run will show whether or not the asphericity is needed.

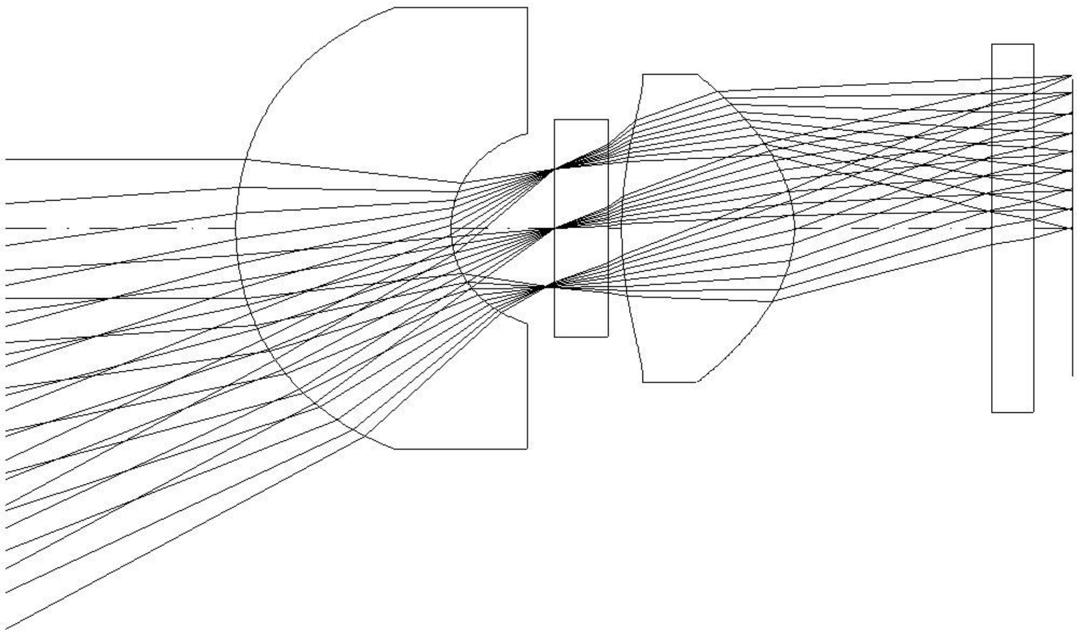

Figure 2. More appropriate number of fields for use with multiple aspheric surfaces.

The opposite of having too little surface impact can easily occur when diffractive surfaces are used. In this case, the optimization process drives the diffractive coefficients to values that create excellent predicted imagery but result in thousands of diffractive grooves, with an accordingly tiny spacing. It is extremely disheartening to think you have come up with a great design, only to check the minimum diffractive ring spacing and realize you have created a design that is not producible. The way to prevent this mistake is to constrain the minimum groove spacing allowed on the diffractive. Also, the often conceived idea of replacing a single diffractive surface having overly small groove spacings with multiple diffractive surfaces, each containing producible spacings, should be tempered by the consideration of diffraction efficiency. Each diffractive surface will have non-unity diffraction efficiency and the combined efficiency may not be adequate.

The other common design mistakes are based on not accounting for the actual process of polymer optic molding. In injection molding the polymer material is injected into the cavity which forms the part through a small opening known as the "gate". In order for the material to be injected properly, the gate needs a finite width. This width sets a lower limit on the edge thickness of the part. During the optical design, it is possible for the program to come up with a lens where the two surfaces cross over at the lens edge, leading to a non-physical part, as shown in Figure 3. While this example is physically impossible, increasing the center thickness of part until the two surfaces just meet, forming a knife edge, also shown in Figure 3, is not an acceptable solution. The center thickness must be further increased and/or the surface sags decreased in order to allow sufficient thickness for the polymer material to flow through. The edge thickness necessary for a particular part will depend on the part's form and material, but wider is generally better, with a mm or more desired. The thin edge mistake can be avoided by placing constraints on the edge thickness during the optimization process. Depending on the software used, there may be direct edge thickness constraints or constraints on the sags or sum of sags (relative to the center thickness) of the surfaces. As a note of caution, which leads into the next mistake, it is important to understand how the software defines the edge height and associated edge thickness. If it is defined as the actual height/thickness at which the rays strike, as opposed to further out, an additional buffer must be provided.

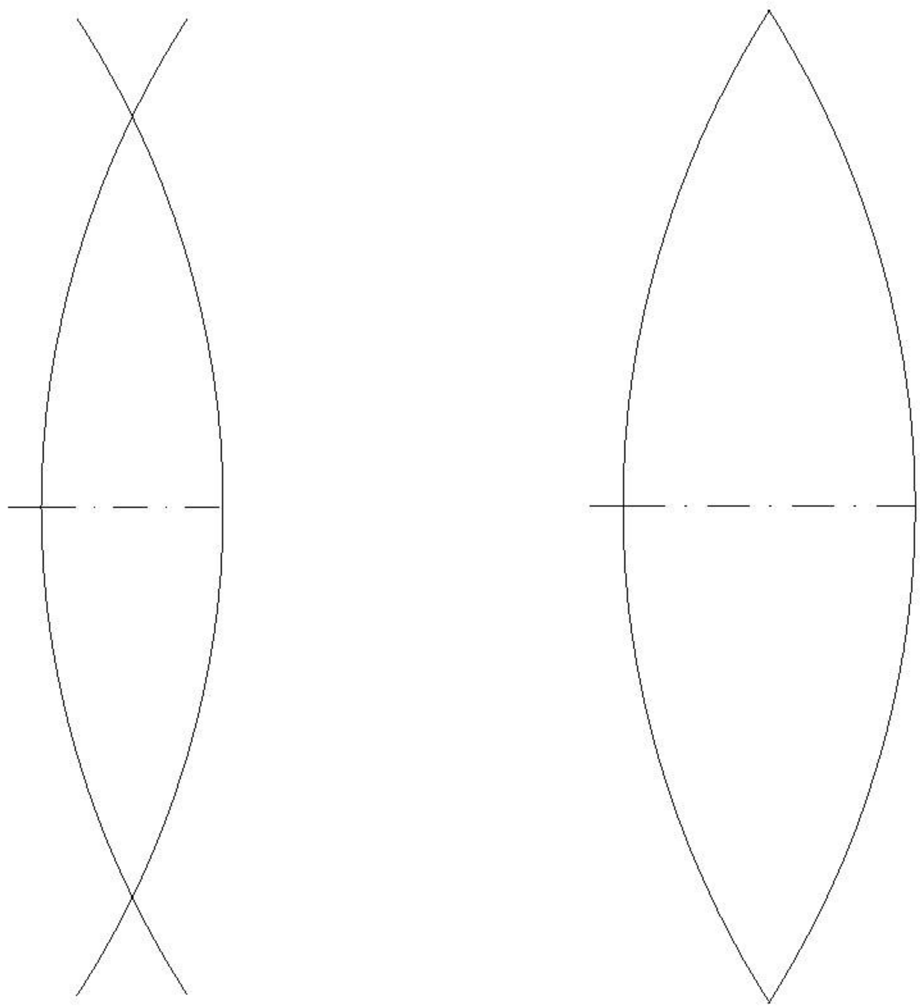

Figure 3. Physically unrealizable "crossed-over" and knife edge lenses.

Understanding the definition of edge thickness and edge height is important in avoiding the final design mistake we discuss, that of setting overly large clear apertures relative to the component diameter. In the molding process, there is a degradation of the surface form in the region where the optical surface transitions into the part diameter or flange. This degradation, known as "edge break" or "edge roll", is similar to what is often seen in polished glass optics. As a result the clear aperture of the optical surface, defined as the area where the surface specifications must be met, cannot cover the entire component diameter. In many polymer optic applications, such as cell phone cameras, space is a premium and using the optical surface as close to the edge of the component as possible is desired. However, this must be weighed against the performance of the surfaces at their outer boundary. Poor surface form at the edge of the optical surface can create a situation where the desired system F/# cannot be achieved, resulting in the need for a stopped-down system, as shown in Figure 4. The way to avoid this mistake is to intentionally allocate room for edge break in the design. This may require mechanical changes to the parts or may be controlled through optical means by limiting ray heights or allowing vignetting.

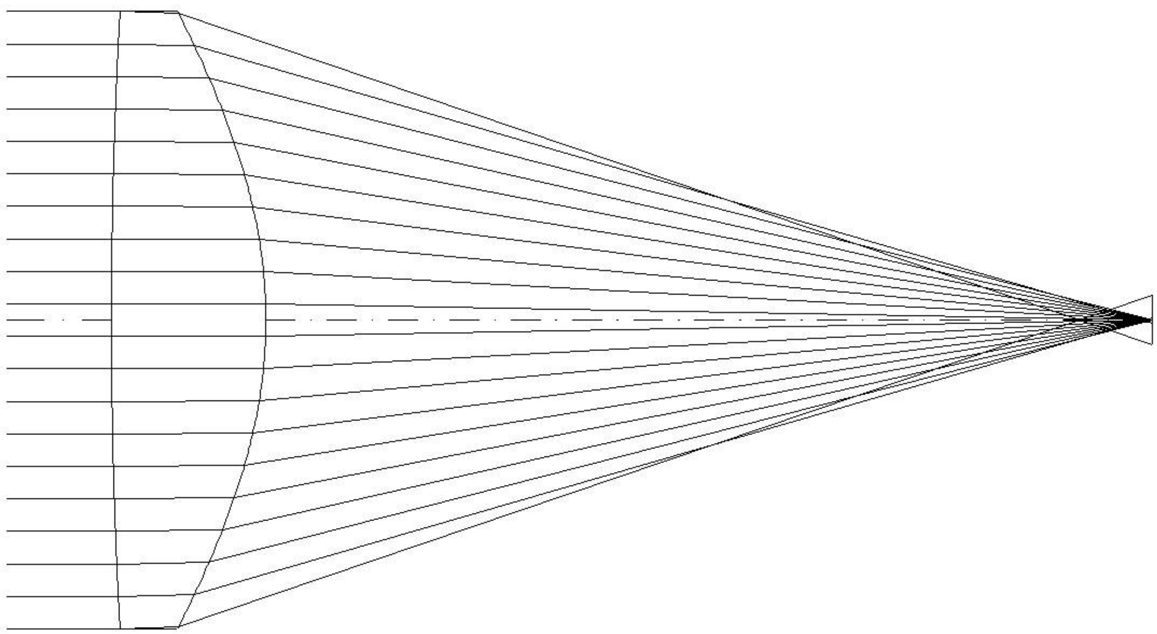

Figure 4. Edge break causing the need for a slower F/# system, due to specifying too large a clear aperture.

2.3 Prototyping

Mistakes made during the prototyping phase of a design can be of great benefit to the final product if they point out flaws in the design philosophy. However, most common polymer optic mistakes made during prototyping do not serve this purpose, but are simply annoying and wasteful. This is particularly true when only a small number of prototypes were made, they were expensive, took a significant amount of time to produce, and are completely ruined by the mistake. As an example, consider the prototyping of a three element camera module. Three sets of the lenses, each of which were acrylic, were diamond turned from cast acrylic material with representative flange structures. Barrels were machined from aluminum to house the lenses. The barrels were inspected to verify the inner diameters and axial spacings, while the lenses were inspected to verify their surface form, center thickness and centration. The lenses were installed in the barrels and were retained using a baffle staked in place with fast curing cyanoacrylate. The adhesive proceeded to fog all the lenses, destroying the prototypes. This type of mistake can be avoided by checking the appropriateness of materials before they are used with the polymer optics. Many standard optical cleaning fluids, such as acetone, can have a detrimental effect on polymers. If there is uncertainty about whether a material should be used on prototypes, it either shouldn't or testing should be performed before it is. In the case above, testing could have been performed on low quality machined or scrap pieces of acrylic to determine if there would be fogging issues.

Two other common prototyping mistakes occur because of a lack of adequate planning, preparation, and/or scheduling. The first of these is building up all of the prototypes at a single time. Consider the example above, once the fogging problem has been solved. After building up the units, it was found that a stray light problem existed, where light was passing between the connected flanges of the rear two elements. The solution to the stray light was to install a baffle between the two elements. However, in the rush to build up all the units, a plan to disassemble them had not been created. If only one unit had been built and tested, the baffle could have been inserted into the next unit built. As a result of all the units having been built simultaneously, disassembly was now necessary. The tight barrel fit and geometry of the parts did not allow for easy disassembly and resulted in a partial scrapping of the components. This type of mistake can be avoided by having an appropriate build plan and schedule, with some parts being held back, as well as having a disassembly plan.

Similar to building all the prototype units at once, another common mistake is testing them all at once. This is especially true for processes that may result, even inadvertently, in destructive testing. Again, consider the three element prototype units above as an example. With all units built, a series of tests were performed which included thermal cycling. While the thermal chamber was set to achieve a temperature less than the service temperature of the polymer optical material, loss of the controller led to a runaway condition where the chamber overshot the temperature bounds, passing the service temperature, and destroying the units. Once again, using all the prototypes at once led to a complete failure situation. This mistake can be avoided by simply segregating the prototypes into multiple sets, so that there is no possibility of risking them all at once.

The final common prototyping mistake that we discuss is having prototype units "set the bar too high". This is especially true in the case of diamond turned prototype optical components built using precision machined aluminum barrels. As an example, consider a two element cell phone camera lens with the stop between the lenses. In this design, the requirement on the centration of the two elements relative to each other was extremely tight. The proposed solution was to use tapers, conceived as full annular features on the lens flanges, to interlock the elements and maintain the required centration. The aperture stop between the lenses consisted of a stamped metal sheet, also tapered, and was intended to be part of the lens stack. The parts were fabricated, a number of units assembled, and the best two units sent to the customer for evaluation. The customer was extremely pleased with the prototypes, but from that point forward expected all units to perform equally as well or better. Given that the lenses were diamond turned, the barrels precision machined, and the units repeatedly assembled and disassembled to achieve the image quality obtained, it was completely unrealistic to believe that mass produced assemblies would meet the customer expectations, unless a 5% yield (and associated cost) was acceptable. In the end, the project was cancelled. This mistake could have been avoided by producing prototype lenses that gave a true representation of the image quality range that would be expected in production. In this case, simple showing the customer all ten prototype units would have sufficed. In other cases, it may be necessary to intentionally degrade the prototype performance. This can be achieved either by intentionally diamond turning the lenses with some centering error, machining the barrels with a defined error, or assembling the system imperfectly.

An alternate method is to use the image simulation capability of the optical design codes. Simulated pictures showing the range of predicted performance of the system can be generate in conjunction with the tolerance analysis. The pictures can be shown to the customer to provide an understanding of the expected performance versus yield and cost. If it is believed that the prototypes represent the high end of the performance range, actual images from the prototypes can be compared to the predicted high end range of simulated pictures to correlate the simulations.

2.4 Production

While mistakes made during the prototyping phase of a design can be highly annoying, they may also be beneficial to the final design. This is generally not the case during the transition to production or production phase, where such mistakes can have a serious impact on the ultimate success or failure of the program. The most common mistakes made during the production phase are related to money and schedule, with a shortage of both generally being the issue. In regard to molding, the most common production mistake is not spending the money and time necessary to develop a high quality, production level mold. Molds, also known as tools, are by no means cheap. Mold prices are typically measured in tens of thousands of dollars, as opposed to thousands of dollars. However, they usually provide a good example of getting what you pay for. Skimping on the cost of a tool, or trying to rush its delivery, often results in a tool that does not perform to the requirements of the design. This mistake can be avoided by being realistic during the planning of a project. This approach requires all parties to perform and pay as needed: the design must be completed by an appropriate deadline, the drawings must be ready, quotes must be obtained, and the purchase orders must be placed in a timely manner.

Along with not paying enough for a mold, a similar mistake is not to purchase enough molds. One of the advantages of molded polymer optics is the ability to produce multiple copies of the part in a single molding cycle. The number of copies made is directly related to the number of cavities the mold contains. It is most common for molds to have cavity numbers that are factors of two (two, four, eight, or sixteen). Increasing the number of cavities in a mold allows increased production, but also increases the risk to production stoppages. As an example, consider the case of a cell phone camera lens. The production volume demands that sixteen cavities produce components. The choice in this case is to build an expensive sixteen cavity mold, or to build two eight cavity molds. The two eight cavity molds will likely cost more than the sixteen cavity mold, and thus the sixteen cavity mold is often chosen. However, if the sixteen cavity mold goes down, the total production is at zero until the mold is fixed. In contrast, if one of the eight cavity molds goes down, production can still continue, with at least half the rate. If the molds are not being used twenty four hours a day, it may be possible to mold on an additional shift and maintain production rates using the single eight cavity mold.

Another production mistake, one which can affect the project schedule, is misunderstanding during the approval or acceptance of a tool. In general, a mold is considered ready for acceptance when it is shown to be capable of producing parts that meet the drawing requirements. In some cases, particularly when the molder is not the mold-maker, there can be a disagreement as to when a tool is delivered and ready. The mold-maker may deliver the mold by a certain date, but the molder will need additional time to test the mold, develop the molding process, and adjust and/or compensate the mold before production can begin. Depending on the complexity of the mold, this process may take weeks, which need to be factored into the schedule. Again, this mistake can be avoided simply by being realistic, as well as by maintaining clear communication between all parties.

3. CONCLUSIONS

Most common polymer optic mistakes result from a lack of familiarity with polymer optics, their special design requirements, and their manufacturing processes. The mistakes discussed in this paper, and others, can most easily be prevented by having early communication with producers of polymer optic components, ideally before the design work is even begun. They also can be avoided by learning from others who have previously made them and not doing what they did.