Design for Manufacturability and Optical Performance Trade-offs using Precision Glass Molded Aspheric Lenses

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ABSTRACT

Precision glass molding (PGM) enables high-performance, low-cost lens designs through aspheric shapes and a broad array of moldable glass types. While these benefits bring a high potential value, the design of PGM lenses must be skillfully approached to balance manufacturability and cost considerations. Different types of mold tooling and processes used by PGM suppliers can also lead to confusion regarding the manufacturing parameters and design rules that should be considered. The authors discuss the various factors that can affect manufacturability and cost of lenses made to PGM standards, and present a case study to demonstrate the trade-offs in performance.

Keywords: Precision glass molding, asphere, optical lens, design rules, manufacturability

1. INTRODUCTION

Precision glass molding is a compression molding process (as opposed to the popularized injection molding of plastic) capable of transferring high-quality aspheric shapes from a precision mold set into the optical lens being formed. This technology has the distinct advantage of enabling low cost optical lenses for high volume applications, while maintaining the high quality of aspheric optical surface profiles and utilizing the inherent advantages of glass materials [1]. Modern PGM technology was pioneered in the late 1970's to early 1980's by companies such as Corning Glass Works and Eastman Kodak, who then transferred these complex capabilities to PGM manufacturers such as Geltech (acquired by LightPath Technologies in 2000) [2]. Over the past several decades, these PGM manufacturers have continued to improve and hone the processes, tooling and materials used to perfect the art of molding aspheric glass lenses for a growing variety of applications.

Despite advances in PGM capabilities, there remain some inherent limitations and trade-offs, as is the case with any technology, which can impact the cost and performance of lenses in manufacturing and production. It is therefore useful to define a set of design rules or guidelines for designing and implementing the manufacture of aspheric lenses which strike the right balance between ease of manufacture, cost and end-use performance. While each specific application will have a different emphasis and priority within the full trade-off space, there are typical boundaries within that space that define a "sweet spot" for manufacturability which can be a useful guide in the design process. These guidelines should be taken as recommendations and indications of risk levels, rather than hard limits. Pushing beyond these typical boundaries may be advantageous for certain cutting-edge applications with demanding requirements that can also tolerate the risk of moving outside of the

Polymer Optics and Molded Glass Optics: Design, Fabrication, and Materials 2016, edited by David H. Krevor,
William S. Beich, Michael P. Schaub, Alan Symmons, Proc. of SPIE Vol. 9949, 994909
 · doi: 10.1117/12.2238111

manufacturability “sweet spot”. Open communication of such risk, and candid negotiation between customer and supplier, are the keys to striking the right balance for a successful PGM product.

1.1 Overview of Precision Glass Molding

Precision glass molding, PGM, is a manufacturing process used to make high quality lenses and optical components. The general nature of the process is the compression molding of glass preforms at high temperature under highly controlled conditions. A more detailed overview of the process can be found in Schaub,et al [2] or Symmons, [3]. A brief summary of the PGM process follows. The PGM process starts with the manufacturing of tooling designed specifically for the product to be manufactured. This tooling typically consists of a top mold, a bottom mold and ancillary tooling to form the outside diameter or other features of the component. Additional tooling may be required to align the individual mold halves. The customized tooling is then inserted into the glass molding machine. A glass preform is then inserted into the tooling stack. The top mold is then introduced and the system is evacuated. The tooling stack and the glass preform are then heated at a controlled rate. A schematic of the process is given in Figure 1.

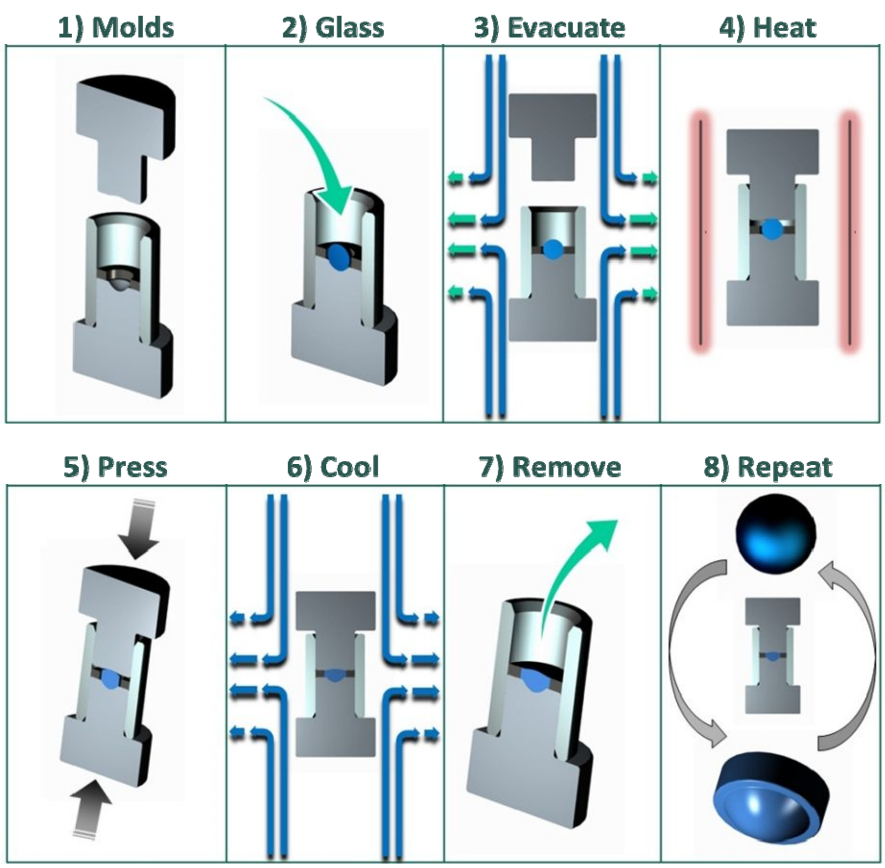

Figure 1 - *Precision Glass Molding Sequence*

The final processing temperature is dependent on the individual glass type. The preform is then put under compression in order to begin forming the glass. The amount of load applied to the glass is controlled throughout the molding cycle; the load is removed once the cycle is completed. The tooling stack is then cooled, typically by purging the system with an inert gas. In order to cost effectively manufacture the lens, this cooling cycle is optimized for the fastest possible cycle time. Once the final product is cool enough to handle, the component is removed and the process is repeated.

1.2 The Precision Glass Molded Aspheric Lens

Precision glass molding is used to make a variety of components including lens arrays, cylindrical lenses, spherical optics and even V-groove blocks used for fiber optic assemblies. Aspheric lenses are however by far the most prevalent component manufactured by PGM and are the focus of this paper.

A precision glass molded aspheric lens can have a number of standard lens shapes and sizes. PGM lenses can be bi-convex (BCX), plano-convex(PCX), meniscus (MEN), plano-concave (PCV) and even bi-concave (BCV) lenses. Outside diameters range from sub-millimeter to over 100mm, though the majority of lenses are in the 1-25mm range. Regardless of the shape or size of the lens there is a commonality between features. Figure 2 shows a detailed description of the physical features of a bi-convex lens including common industry nomenclature. A detailed description of each follows.

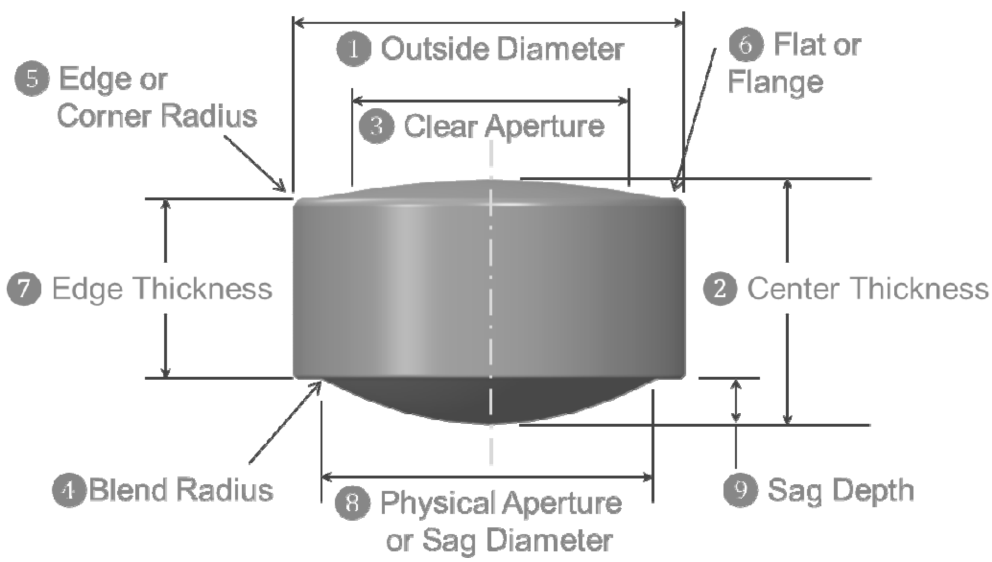

Figure 2 – *Description of a well-designed bi-convex precision glass molded aspheric lens*

❶ Outside Diameter, OD: The outside diameter, OD, sometimes referred to simply as the diameter of the lens is simply the outer cylindrical surface of the lens. The OD is almost always used in mounting and aligning a lens. OD is commonly toleranced with either a plus/minus tolerance. The outside dimeter is commonly formed during the molding process, (a volumetric process) but that is not always the case. The OD of larger diameter lenses are commonly manufactured using a secondary process.

❷ Center Thickness, CT: The thickness of the lens at its optical center. The center thickness, CT, of the lens is an optical parameter of the lenses and is explicitly defined by the optical design.

❸ Clear Aperture, CA, or effective diameter, ∅e: The optical or effective use diameter of the individual lens surface.

❹ Blend Radius, R_b: The radius transition between the optical surface and the flange of the lens.

❺ Edge Corner Radius, R_c: The radius on the outside edge of the lens at the intersection with the flange. An edge corner radius is an artifact necessary in volumetric precision glass molding. It is formed to account for preform tolerances to ensure the preform volume is always less than that of the finished lens. In non-volumetric molding, the lens is edged to its final diameter and chamfers are normally added.

❻ Flat or Flange: The section of the lens outside of the physical aperture leading up to the outside diameter. Typically used for mounting the lens.

❼ Edge Thickness, ET: The thickness of the lens along its edge.

❽ Physical Aperture, PA or Sag Diameter, ∅s: The physical or mechanical diameter of the individual optical surface.

❾ Sag Depth, d_s: The depth or height of the optical surfaces that corresponds to the physical aperture (sag diameter).

2. DESIGN FOR MANUFACTURE

2.1 Optical Design

The optical design process typically begins with performance specifications and a clean-slate approach to achieving those optical requirements. Design optimization that is constrained only by performance requirements, and not by mechanical or manufacturability limits, will often lead to unrealistic or costly lens shapes and form factors. Experienced optical designers will quickly identify practical limitations to begin the design search, thus leading to manufacturable results.

However, the typical "rule of thumb" limitations that designers use are often outdated or based on manufacturing techniques that differ greatly from PGM technology, such as injection molding or grind and polishing. Many designers begin their design process with some common outdated and erroneous assumptions, such as: 1) aspheres are more costly than spherical lenses, 2) departures from spherical shapes must be very mild, and 3) biconvex and meniscus lenses are more difficult than plano-convex lenses. While these guidelines have been historically true for some older lens manufacturing methods, the advancements of PGM technology has rendered these guidelines obsolete, and in some cases contradictory to actual modern PGM design rules. Aspheric shapes, for instance, are typically no more costly than spherical lenses, when using PGM technology. Similarly, plano surfaces may sometimes prolong mold life, but tighter control of form error can often be achieved by adding curvature to a surface, which in turn can lead to yield improvement. Meniscus lenses are also common lens forms for PGM and are well within design rules for achieving low cost and manufacturability (although other design rules may still limit the exact shapes). Finally, large departures from sphere are typically not a problem for PGM manufacturing, provided that the local curvature of the surface is smoothly varying and that the exact surface profile does not cause gas entrapment between the mold and the preform. These differences, relative to conventional design rules, can be frustratingly counter-intuitive for designers attempting to procure lenses from multiple suppliers. Therefore, optical designers would do well to stay abreast of the advancements in modern technology, and especially the differences in design rules that vary based on manufacturing techniques and materials.

The following sections describe many of the basic design rules and concepts that should be considered in the optical and optomechanical design of PGM lenses. These are followed by an example design case study in section 3, which illustrates many of the choices faced by designers and the associated impact on cost and manufacturability. However, it is worth repeating that the most important "design rule" is good communication between the customer and supplier to navigate these nuanced tradeoffs.

2.2 Material Selection

The most important step in almost any design for manufacturing effort is to select the correct material. This is no less important in precision glass molding. The proper selection of the right moldable optical glass can increase performance, decrease lead times and significantly improve cost.

There are over 200 moldable glass types [4] to choose from giving the optical designer extensive freedom in his design. However, consideration of manufacturability and cost can greatly reduce this freedom and limit the designer to a much reduced solution set.

Lower processing temperatures in PGM means shorter cycle teams due to shortened heating and cooling cycles. Shorter cycles improve processing speeds; increasing throughput. A lower temperature process results in less energy use and cheaper utility expenses. Lower processing temperatures also reduce the potential for oxidation of surfaces during the molding process. Oxidation leads to contamination, increasing the frequency of cleaning and maintenance.

Hence selecting a glass that can be molded at a lower temperature is typically advantageous. While the PGM process is not explicitly performed at the glass transition temperature, T_g, of the specific glass, it is an excellent indicator of the relative processing temperature. Therefore, T_g can be used as a quick indicator of potential moldability and relative processing cost. There are, however, many factors that impact the moldability of a lens and specific glass selection should also be reviewed with the manufacturer early in the design process. It is usually more cost effective to use a standard glass as recommended by a manufacturer.

There is a limit to the improvements in processing for low T_g glass types. As T_g decreases, glasses tend to become softer, which can add expense in manufacturing preforms, impact handling requirements, and limit cosmetic quality due to ease of scratching.

The best selection of a glass for PGM is usually achieved by taking these requirements into consideration and working closely with a manufacturer to select the optimum glass for the application.

2.3 Processing

The process of precision glass molding is optimized for throughput in order to keep costs to a minimum. This is achieved by minimizing the heating and cooling cycles while still maintaining good surface form of the lens.

The properties of glass are dependent on its thermal history, therefore, the optimization of processing cycles in PGM impact the final properties of the finished lens. While many properties are impacted by this change, the one of primary interest to the designer is the index of refraction. PGM results in a drop in index of refraction when compared to coarse or fine annealed glass. This “Index drop” is small, and is dependent on the individual material and processing conditions. The common range for index drop in oxide based glasses is between -0.0006 and -0.0100 while higher index Chalcogenide glasses exhibit greater index drops, on the order of -0.050 [5]-[8].

As-molded properties should always be used in the optical design of an aspheric PGM lens. These properties should be obtained from the individual molder as it is based on their process. Slight variations may be observed between molders due to variations in processing.

2.4 Opto-Mechanical Design

These recommendations are based on using a ball preform in a volumetric molding process using an in-line tooling configuration. PGM has many different configurations and this one in particular is best suited for low cost manufacturing. Some design for manufacturability recommendations may change due to changes in configuration. Ball preforms are the best option for designing low cost aspheres; they provide the best overall trade-off of cost, precision and surface quality. Volumetric molding is preferred as it eliminates the additional cost of post-processing and provides better centration.

Section 1.2 defined the opto-mechanical features of an aspheric PGM lens. Each of these features should be considered individually and in combination with one another in order to execute a well-designed lens that can be cost effectively manufactured.

❶ Outside Diameter, OD: PGM aspheric lenses typically range anywhere from less than a millimeter up to 50mm in diameter. The larger the size, the greater the cost. As size increases, material costs increase, and tooling costs increase due to increased manufacturing time. Tooling life is also normally decreased due to the increased statistical frequency of mold defects. Preform manufacturing costs also increase with size, especially for larger diameters when ball or gob preforms can no longer be efficiently used. Outside diameter should be kept to a minimum but should take into account the rules for flanges, blend radii and edge radii discussed below.

❷ Center Thickness, CT: As discussed in section 1.2, the center thickness, CT, of the lens is an optical parameter of the lens and is explicitly defined by the optical design. CT's down to 0.2mm can be manufactured but may require near-net shape preforms in order to reduce the molded-in stress within the lens. CT's larger than 4mm can lead to excessive thermal gradients within the molded lens. Large thermal gradients will result in inhomogeneity of the index of refraction across the lens, stress birefringence and even possible catastrophic failure due to thermal stress fractures. CT's should be kept between 0.5mm and 4mm but are largely dependent on the shape and the overall size and aspect ratios (see below) of the individual lens.

❼ Edge Thickness, ET: Very small edge thicknesses, (< 0.4mm) should be avoided, as they become very difficult to handle and can chip easily.

Aspect Ratios, AR: ❶ Outside Diameter, OD, ❷ Center Thickness, CT, & ❼ Edge Thickness, ET, these three parameters determine the relative aspect ratios of an aspheric PGM lens, where:

$$AR_{CT} = \frac{OD}{CT} \ , \qquad AR_{ET} = \frac{OD}{ET}$$

Aspect ratios are highly dependent on the lens shape, so general rules of thumb are difficult to provide. Aspect ratios, AR_{CT}, for plano-concave lenses can be very large while a typical bi-convex lens should be kept under 5.

❸ Clear Aperture, CA, or effective diameter $\varnothing_e$: The clear aperture must always be smaller than the physical aperture in order to allow for a blend radius between the optical surface and flange. The amount of relief between the CA and PA is dependent on the particular surface but a minimum of at least 0.1mm should be used. Transition zones can also be used if necessary (see slope).

❹ Blend Radius, R_b: Incorporation of a blend radius between the physical aperture and the flange of an aspheric PGM lens is essential for good design. A sharp transition at this intersection will lead to a stress concentration and results in poor tool design. The addition of a blend radius alleviates the stress concentration and provides relief for the cutting tool. Larger radii are better but the blend radius should never drive tool selection, ie. the minimum radius of the optical surface should not be driven by the blend radius. Large blend radii also require extending the physical aperture which may result in a larger outside diameter in order to meet requirements for ❻ flanges and ❺ edge radii. Therefore a compromise is normally reached that keeps the blend radius to a minimum while relieving a potential stress concentration and making the molds manufacturable. For the majority of lens designs the blend radius ends up in the 0.1mm to 0.3mm range.

❺ Edge or Corner Radius, R_c: A PGM aspheric lens manufactured using volumetric molding will have edge or corner radii. Edge radii are not explicitly designed for, rather an allowance for these features must be made by the designer. Edge radii are formed as the volumetric relief for the molding process; which compensates for the variations in the volume of the preform. Edge radii will vary slightly from part to part and are difficult to define with a dimension or a tolerance, though typically an estimated radius is used. The radius at the top corner relative to the molding process will have a smaller radius than the bottom corner, which may not be evident to the designer. Proper estimates on edge radii are based on the volumetric equivalent of the tolerances of the preform and are on the order of 0.1mm for most lenses.

❻ Flats or Flanges: Mounting features are common and good design practice for aspheric PGM lenses. Molded flanges allow for easy mounting in assemblies. Flange design must take into consideration both the ❹ blend radius and the ❺ edge radius. In order to have sufficient landing for assembly they may need to be extended to account for these radii. Flanges are always preferred because it is difficult or nearly impossible to extend the optical surface to the edge of the part. This situation creates a sharp tooling condition and also leaves no room for an edge radius.

❽ Physical Aperture, PA or Sag Diameter, $\varnothing_s$: The physical aperture of an optical surface should extend well beyond the clear aperture, in order to allow for ❹ blend radii. This means there are portions of the lens surface that are not intended to be optically active. Note the physical aperture cannot be measured explicitly due to the blend radii. Transition zones may extend the physical aperture, commonly to alleviate high slope surfaces.

❾ Sag Depth, d_s: The sag depth or sag height, d_s, is the height of optical surface from the flat plane of the physical aperture to the highest (convex) or lowest (concave) point of the surface. It is the equivalent depth of the ❽ physical aperture. Any change in the physical aperture results in a change in sag depth or height. Transition zones can extend the physical aperture and thereby impact the sag depth (see slope). The tolerance on physical aperture drives the tolerance on sag depth or vice versa. It is preferable to tolerance sag depth for lenses over physical aperture, as it is an easier measurement to make. The incorporation of ❹ blend radii makes measurement of the physical aperture difficult at best.

Slope : Optical surfaces with steep slopes should be avoided for aspheric PGM lenses. There are a number of issues with steep slopes: molds are more difficult to manufacture, testing of molds and finished lenses are more difficult, achieving high surface form and surface qualities is challenging, and steep slopes geometries can lead to gas entrapment. Good design practice is to keep the optical slope less than 55°, 50° if possible. High slope surfaces should incorporate large ❹ blend radii to reduce stress concentrations. Selection of the correct ❽ physical aperture is important in high slope designs, as in many of these designs there is severe aspheric departure outside of the ❸ clear aperture. One method to alleviate steep slopes is the use of transition zones. A tangent transition zone can be added at the end of the ❸ clear aperture where the angle is equivalent to the slope of the localized surface at the end of the optical surface. This limits the slope to the localized slope at the CA.

Preform Sizing: A common design flaw for aspheric PGM lenses is sizing a lens that can not be manufactured using a ball preform. If the volume of the lens requires a ball preform (of equivalent volume) whose diameter is greater than the ❶ outside diameter of the lens, then the ball can not be inserted into the tooling! An alternate preform is required, such as a cylindrical preform which increases cost and reduces precision. If a ball preform will not fit it is also unlikely that a gob preform could be used in its place.

Knowles Ratio: The Knowles ratio, κ, is named for Dennis Knowles, a long time PGM process engineer at Geltech and subsequently LightPath Technologies. The Knowles ratio is used to assist in the design of precision glass molded aspheric lenses manufactured using ball preforms. It is the ratio of the radius of the ball preform used to manufacture the specific lens to the radius of the mold (lens surface). For any lens there is a Knowles ratio for each surface. A Knowles ratio greater than 1.0 indicates the radius of the ball preform is larger than the base radius of the mold. This condition creates a cavity between the preform and the mold. Due to the excellent surface finishes of both the preform and mold, this will result in gas entrapment during the molding process. This can be overcome by incorporating a vacuum process during the molding cycle. However, vacuum molding extends cycle time and hampers heat transfer during the molding process and should be avoided if possible. Hence, it is preferable to keep the Knowles ratio under 1.0.

A Knowles ratio less than 0.4 will lead to difficulty in centering the ball preform in the tooling prior to molding without means of mechanical assistance. Poor preform centering can lead to lenses with greater wedge or decentration. For designs with a Knowles ratio greater than 0.4 the ball preform will essentially self-center.

Best design practice will keep the Knowles ratio between 0.4 and 1.0, Figure 3 shows the issues with both a low and high Knowles ratio.

$$\kappa = \frac{R_{ball}}{R_{mold}}$$

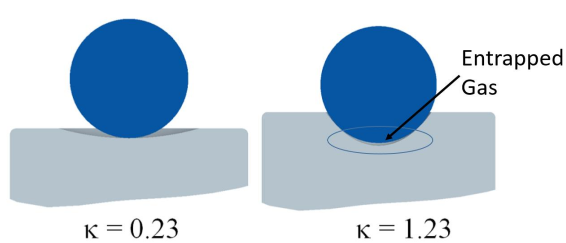

Figure 3 - *Low and High Knowles Ratios*

3 Optical Design Case Study

A case study was conducted for designing a lens to meet a specification that might be typical for a NIR coupling application, such as for optical communications, per Table 1. For simplicity, both the source and output are assumed to be symmetric, although this is most often not the case.

Table 1 - *Example optical specification for a high NA, finite conjugate lens*

Parameter	Specification
Source Wavelength	1310nm
Source NA	0.7
Front Working Distance	1.0mm
Output NA	0.12
RMS Wavefront Error	<0.07 waves

A preliminary design survey provided an array of design forms with a single material (D-ZK3M) for achieving the optical performance requirements alone, with minimal constraints on size, cost and manufacturability. Figure 4 shows several layouts for preliminary singlet lens designs, all of which meet the specifications of Table 1. The design forms span the range of plano-convex (PCX), bi-convex (BCX), and meniscus (MEN) lenses. Within the BCX category, two special cases are considered: the symmetric (BCX-Sym) and gullwing (BCX-Gull) designs. In the symmetric design, both surfaces have the same prescription, which can reduce tooling costs by making the tooling for both sides interchangeable. The gullwing design reverses curvature on the front surface (from convex in the center to concave at the edge) in order to correct aberrations from the high NA source.

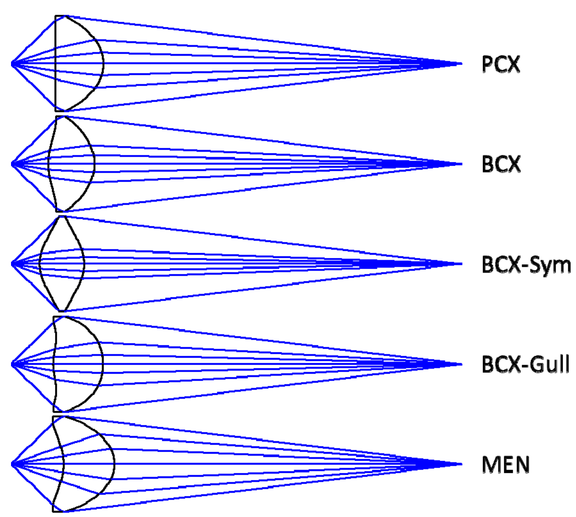

Figure 4 - *Singlet lens forms, unconstrained by manufacturing design rules*

These unconstrained designs were evaluated against the design rules for optimal manufacturability outlined in the previous sections, and the results are summarized in Table 2.

Table 2 - *Unconstrained preliminary designs evaluated against optimal manufacturing design rules*

Manufacturing Design Rules	Design A *PCX*	Design B *BCX*	Design C *BCX-Sym*	Design D *BCX-Gull*	Design E *MEN*
Outer Diameter	✓	✓	✓	✓	✓
Center Thickness	✓	✓	✓	✓	✓
Edge Thickness	✗	✗	✗	✗	✗
Flat Flange	✗	✗	✗	✗	✗
Blend Radius	✗	✗	✗	✗	✗
Edge Radius	✗	✗	✗	✗	✗
Max Slope	✗	✗	✓	✗	✗
Aspect Ratio (OD/CT)	✓	✓	✓	✓	✓
Aspect Ratio (OD/ET)	✓	✓	✓	✓	✓
Preform Fit	✓	✓	✓	✓	✓
Preform/Tooling Ratio (Knowles)	✗	✗	✓	✓	✗
Complex Curvature	✓	✓	✓	✗	✓

Adjustments were then made to the preliminary designs to bring them into conformance with optimal manufacturing design rules for PGM. Most lens forms required a material change from the low-index D-ZK3M (n_d = 1.586) to higher index materials in order to meet the manufacturability criteria, as outlined in Table 3 below.

Table 3 - *Adjusted designs optimized for manufacturing design rules*

Manufacturing Design Rules	Design A *PCX*	Design B *BCX*	Design C *BCX-Sym*	Design D *BCX-Gull*	Design E *MEN*
Outer Diameter	✓	✓	✓	✓	✓
Center Thickness	✓	✓	✓	✓	✓
Edge Thickness	✓	✓	✓	✓	✓
Flat Flange	✓	✓	✓	✓	✓
Blend Radius	✓	✓	✓	✓	✓
Edge Radius	✓	✓	✓	✓	✓
Max Slope	✓	✓	✓	✗	✓
Aspect Ratio (OD/CT)	✓	✓	✓	✓	✓
Aspect Ratio (OD/ET)	✓	✓	✓	✓	✓
Preform Fit	✓	✓	✓	✓	✓
Preform/Tooling Ratio (Knowles)	✗	✓	✓	✓	✗
Complex Curvature	✓	✓	✓	✗	✓

Even with a material change, not all design rules were met for each design form, due to the high source NA and finite conjugate system specifications. Nevertheless, a marked improvement was achieved in all designs while maintaining the performance requirements. In particular, designs B and C (BCX and BCX-Sym) converged to very similar final shapes, as seen in Figure 5 below, with both meeting all design rules.

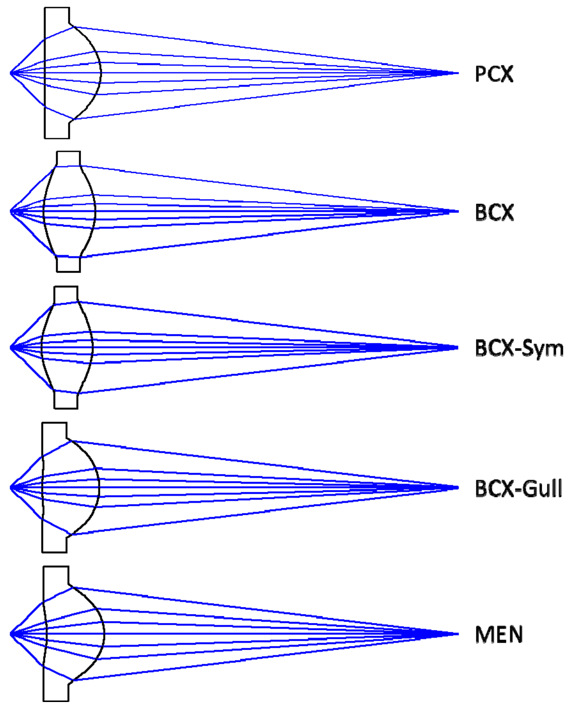

Figure 5 - *Adjusted lens forms for designs optimized to meet manufacturing design rules*

This case study shows that many preliminary design solutions can be found for a single application. However, those design choices may be greatly improved and down-selected when optimized for cost and manufacturability while still meeting the performance specifications. Certain design forms, such as the bi-convex lens, may offer the best balance of performance and manufacturability when properly designed.

4. CONCLUSIONS

Many preliminary aspheric PGM lens design options may be found for a single application. However, design choices may be greatly improved and down-selected when optimized for cost and ease of manufacturability. These fully optimized designs will often still meet performance specifications while incorporating best practices in design for manufacture. This will result in the best balance of performance and manufacturability when properly designed. However, there are always exceptions to any rule, and communication and understanding of the manufacturing technology are also important in optimizing designs. Selection of not only the right manufacturing technology but the right way of implementing that technology is the key to success.

ACKNOWLEDGEMENTS

The authors of this paper would like to thank the precision glass molding team at LightPath Technologies for their contributions to this paper. All figures courtesy of LightPath Technologies Inc.

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