Precision Glass Molding Technical Brief

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Abstract

This technical brief provides an introduction to the Precision Glass Molding (PGM) technology that formerly existed at Kodak Optical Imaging Systems (KOIS), and now resides at Rochester Precision Optics (RPO) in W.Henrietta, NY. The presentation includes the design considerations that an optical engineer/lens designer must understand to be successful when designing RPO molded glass elements into an optical system. It will highlight the preferred optical glasses used by RPO, preform size and shape, lens geometry, tooling requirements, and post-molding processes. Preform and lens geometry will be detailed in depth so that optical engineers and lens designers can better understand these mechanical constraints when they are creating molded glass optics. RPO's glass molding technology will be compared to and contrasted with both traditional asphere manufacturing methods and other glass molding technologies that are currently being used to produce precision aspheres

Introduction

This technical brief provides information to help an optical designer to optimize lens performance and manufacturability when using the glass molding process at Rochester Precision Optics (RPO). These recommendations will help reduce the design time normally spent in customizing a lens for manufacturing. It is a guide and is not intended to be a definitive statement of capabilities or cost. Please consult with the Engineering Staff at RPO as needed during the design phase of a project.

The document is divided into the following sections: Benefits of Aspheric lenses, Traditional vs. Molding Aspheres, Molding overview, Moldable Glass Types, Preform Shapes, Lens Form, Tooling Requirements, and Post-Molding Processes. The engineering and manufacturing communities at RPO will update this document as improvements in process and technology advancements are made. Comments and questions are always welcome.

Benefits of Aspheric Lenses

It is widely known that Aspheric Lenses can be used to reduce the size and weight of optical assemblies and help eliminate spherical aberration problems (see figure 1-1). Historically, however, lens designers and optical engineers have preferred to continue to use spherical optics due to the high cost of manufacturing these elements. An aspheric element can easily cost between $1000 to $2000 dollars in prototype quantities, whereas spherical elements are usually available for less than $200 in the same quantity.

With the introduction of new CNC grinding and polishing equipment and sophisticated metrology over the last 20 years, manufacturing methods for producing Aspheres have rapidly been improving. Traditional Optics manufacturing companies have been expanding their operations to include aspheres and new companies are emerging each year basing their entire business strategy on selling aspheres. This increased competition has been driving down the cost and making aspheres more and more affordable and practical for low to mid volume production assemblies.

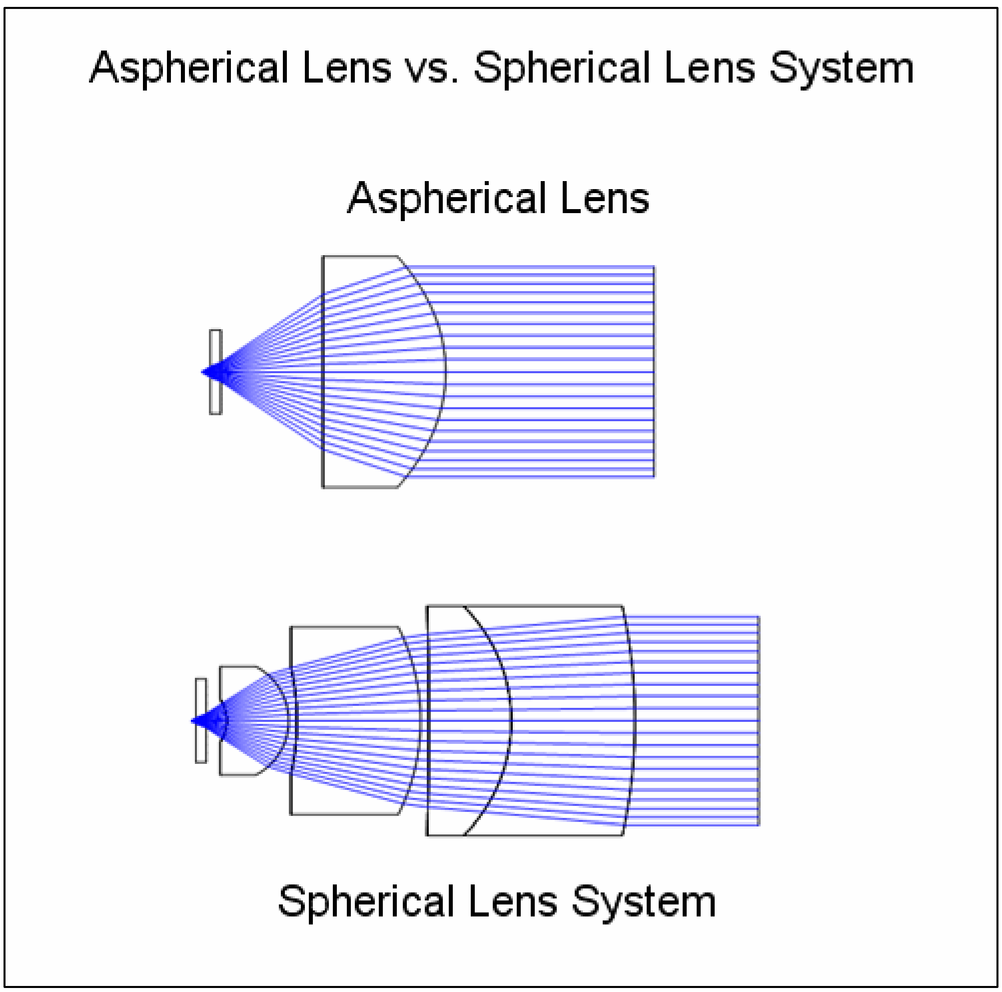


Figure 1-1

In the early 70's, Eastman Kodak developed the Precision Glass Molding (PGM) technology for rapidly producing aspheric lenses be to assembled in the Disc Camera projects. The development of the molding process was driven by the lens systems that were being designed at the time, which included small (3 to 10 mm diameter) aspheric glass elements. The PGM process enabled Kodak to manufacture a lens system that would be an appropriate size for the package constraints of the Disc cameras' distinct film format. This gave Kodak a clear advantage in the Disc camera market during the 1980's.

While the PGM process was predominately developed for the disk camera, additional work was put in to the development of molded aspheric collimator lenses. These types of molded optics are primary used with laser diodes for various electro-optical applications. The major benefits are the reduction of the total number of lenses and total weight. These types of collimators and a host of new generation of molded aspheres are being produced today by RPO who acquired the technology from KOIS in the fall of 2005.

In the early 1990's, the PGM process was adapted to mass produce aspheric lenses in support of larger lens systems (10 to 20 mm diameter). This adaptation was beneficial to the optical designers for they were able to obtain high volume molded aspheric lenses for their multi-aspheric element lens designs. This also allowed PGM to develop the molding process and offer glass molded aspheres to external customers.

Traditional Aspheric Manufacturing vs. Molded Aspheric Manufacturing

Traditional methods of manufacturing aspheric lenses utilize a variety of techniques, such as single point grinding, diamond turning, hand polishing, small pad zonal polishing, and MRF polishing. These processes require continuous surface evaluation and correction. This is often a time consuming iterative process even with advances in modern CNC deterministic grinders and polishers. It is not uncommon to have grinding and polishing runtimes of 2-3 hours per surface. Furthermore, traditional methods can produce varying degrees of surface deviations that would affect the overall performance of the lens.

While these methods have been successful, molded lenses are a superior method for obtaining large volumes of lenses with minimal surface deviations. Molded lenses give an excellent tool replication and a minimal part-to-part variation.

Standard production times for aspheric molded lenses are in the range of 8 to 15 minutes, these shorter cycle times allow for the high volume manufacturing process of molded aspheres being a distinct advantage over the increased time to manufacture a single traditional asphere. Additionally, with the ability to produce multiple elements per molding cycle, this manufacturing technique can quickly overcome production volumes of any tradition aspheric manufacturing process.

Glass Molding Overview

Glass-molded lenses are used in a variety of applications, such as imaging, laser pointing and aiming, medical devices, laser diode to fiber coupling, and micro optics to name a few. These elements are a proven alternative to traditional grinding and polishing manufacturing of rotationally symmetrical single or bi-aspherical, and strong radius spherical lenses.

As mentioned above, RPO molded lenses are produced using the former Eastman Kodak proprietary glass molding process, which enables high volume manufacturing of extremely precise lenses. The highly repeatable process is accomplished by heating and press forming of optical grade glass blanks (preforms) using ultra precision tooling and molds. RPO is vertically integrated allowing the in house manufacturing of all tooling, molds, preform fabrication, centering and AR coating, providing a faster response and lower cost than most competitors. Standard and precision quality lenses are available depending on specific design requirements. (See Table 1-5).

The molding process produces an optic that has a free form edge; when necessary, a secondary operation of centering defines the finished diameter. These molded lenses can have spherical or aspherical surface designs or a combination of both.

In addition to customer specific lenses, the following molded aspheric catalog lenses (Table 1-1) are available off the shelf in low or high volumes with minimal lead times.

LENS CODE	EFL (mm)	NA	Design λ (nm)	BFL (mm)	CT (mm)	CA (mm)	OD (mm)
A220	11.00	0.26	633.00	7.97	5.00	5.50	7.200
A170	6.16	0.30	780.00	4.27	3.48	3.70	4.700
A375	7.50	0.30	810.00	5.90	2.75	4.50	6.510
A397	11.00	0.30	670.00	9.64	2.20	6.59	7.200
A110	6.24	0.42	780.00	3.39	5.36	5.00	7.200
A150	2.00	0.50	780.00	1.09	1.87	2.00	3.000
A240	8.00	0.50	780.00	5.92	3.69	8.00	9.940
A390	4.60	0.53	655.00	2.89	3.10	4.89	6.000
A230	4.51	0.54	780.00	2.91	2.94	4.95	6.325
A435	5.30	0.55	635.00	3.50	2.93	5.83	7.330
Injection Mounted Assemblies							
A414	3.30	0.47	670.00	1.94	3.95	3.52	7.370
A365	4.59	0.53	780.00	3.28	2.27	4.87	7.190
Short Wavelength Visible Lenses							
A610	4.00	0.60	408.00	2.73	3.04	4.80	6.325
A671	4.02	0.60	408.00	2.39	3.00	4.85	6.325

Table 1-1 Current RPO molded aspheres

Moldable Glass Types:

With the exception of a few glass types, many varieties of glass can be used to manufacture glass-molded optics at RPO. Molding can be accomplished with a large range of glasses, and unlike many molders, RPO is not restricted to using only low transformation temperature (T_g) glasses. The T_g is expressed as the temperature above which a glass changes from a solid state to a plastic state.

Figure 1-2 shows the preferred glass types from the major glass manufacturers. Note that many other glass types are available and can be evaluated as needed.

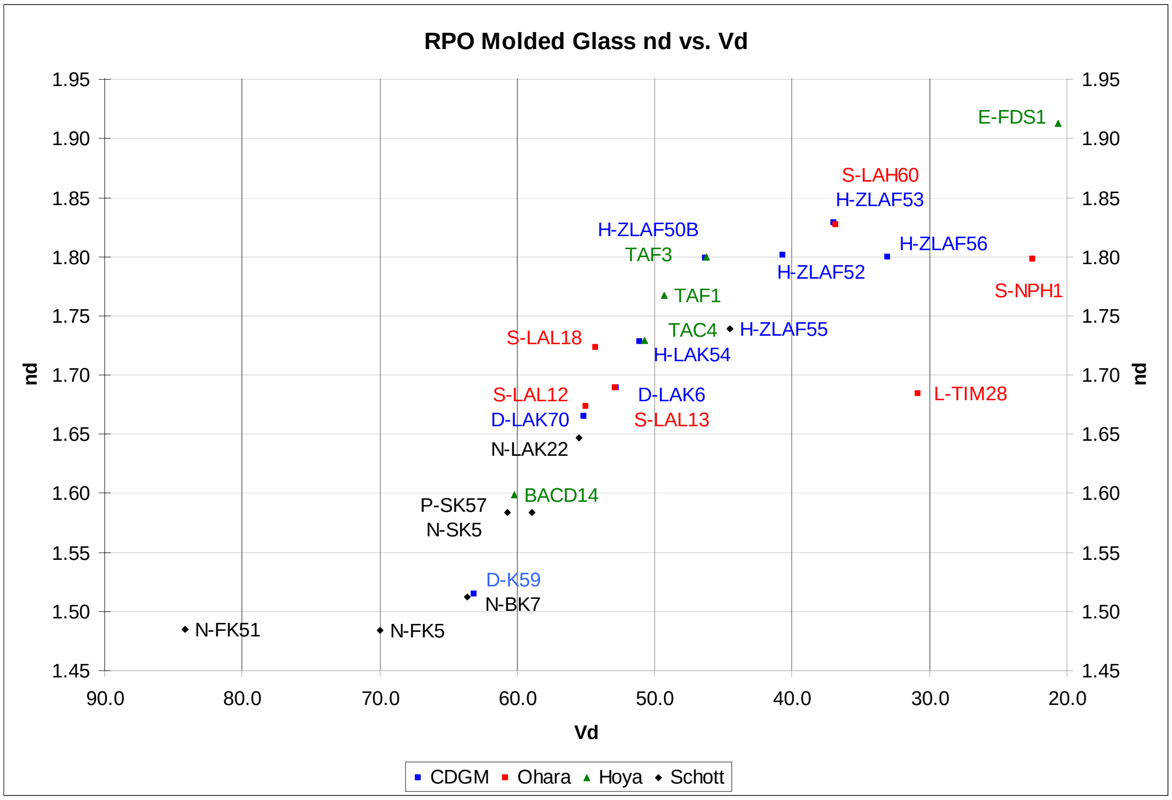


Fig. 1-2 Moldable Glasses

The Chinese CDGM glass types are readily available and are usually less costly than other alternatives, for high volume manufacturing.

Molding Index Drop

The RPO glass molding process uses a relatively rapid cooling rate after pressing the lens. This is important in reducing process cycle time and increasing efficiency. Since the glass is molded above the T_g and cooled rapidly (compared to a fine anneal cooling rate), the resulting optic retains a small amount of residual stress. As a result, the glass exhibits a small index change when compared to its fine anneal state. The index drop is small (usually .002-.006), but the optical design needs to be optimized to compensate for this change. Re-annealing the lens is usually not cost efficient, as the index-change requires only a small adjustment to one of the lens curves. Index Drop information is available for all the RPO moldable glasses, and can be quickly determined for glasses not previously molded. For designers using the ZEMAX® optical design package, as-molded index data for all glasses in the above Abbe diagram (Figure 1-1) are available in the "RPO_Mold" Glass catalog distributed with the January 22, 2007 update to the program.

Table 1-2 shows a listing of current optical grade glass types that have been demonstrated in the RPO molding process. The glasses have gone through a molding verification for their reaction to the temperature cycling and the effects on the tooling surfaces. The data of the dispersion (Vd) and index (Nd) shows the after molding values for these specific glasses. RPO is verifying new glasses regularly to expand its glass molding capabilities, and a updated listing can also be found on our website at http://www.rpoptics.com/glass_index.html If there is a specific glass type that you are interested in and do not see listed, please contact the engineering group at RPO.

Our current measurement technique for measuring glass index drop is performed with a Hilger Chance Refractometer, which uses index-matching fluid that has indices ranging from 1.30 to 2.00 and wavelengths that range from 365nm to 1014nm. This test requires that the samples have a ground and polished 90-degree segment with a maximum side thickness of 0.5". This process can be expedited quickly for measuring new glass types as needed.

RPO Molded Glasses Index and Dispersion

Glass Type	Manufacturer	V_d	N_d
N-FK5_MOLD	Schott	70.0	1.4844
N-FK51_MOLD	Schott	84.1	1.4847
N-BK7_MOLD	Schott	63.6	1.5126
D-K59_MOLD	CDGM	63.1	1.5148
N-SK5_MOLD	Schott	60.7	1.5839
P-SK57_MOLD	Schott	59.0	1.5840
BACD14_MOLD	Hoya	60.2	1.5985
N-LAK22_MOLD	Schott	55.5	1.6467
D-LAK70_MOLD	CDGM	55.1	1.6653
S-LAL12_MOLD	Ohara	55.0	1.6733
L-TIM28_MOLD	Ohara	30.9	1.6840
S-LAL13_MOLD	Ohara	52.9	1.6889
D-LAK6_MOLD	CDGM	52.8	1.6894
S-LAL18_MOLD	Ohara	54.3	1.7238
H-LAK54_MOLD	CDGM	51.1	1.7285
TAC4_MOLD	Hoya	50.7	1.7290
N-LAF2_MOLD	Schott	44.5	1.7388
TAF1_MOLD	Hoya	49.3	1.7670
S-NPH1_MOLD	Ohara	22.5	1.7979
H-ZLAF50B_MOLD	CDGM	46.3	1.7987
TAF3_MOLD	Hoya	46.2	1.7998
H-ZLAF56_MOLD	CDGM	33.0	1.8000
H-ZLAF52_MOLD	CDGM	40.7	1.8013
S-LAH60_MOLD	Ohara	36.8	1.8273
H-ZLAF53_MOLD	CDGM	37.0	1.8292
H-ZLAF55_MOLD	CDGM	42.7	1.8300
E-FDS1_MOLD	Hoya	20.6	1.9127

*This data represents the refractive index after molding

Table 1-2 Current moldable glasses

Preform Requirements

As mentioned previously, the PGM process requires a molding blank, or preform, which is subsequently pressed into a lens. The internal and external quality of the blank must be the same or better than the requirements of the finished lens, since the molding process will not heal any imperfection on or in the blank. Blank dimensions must also be tightly maintained. Depending on the lens geometry, several preform shapes are used. The shapes include spherical (ball), near spherical gob, plano-plano, plano-convex, and biconvex blanks. With the exceptions of the ball and gob preforms, the other shapes must be manufactured using conventional grinding and polishing techniques. Ball preforms can be ground and polished or formed from molten glass, while gobs are only extruded from molten glass. As one might expect, a low cost preform is most desirable in keeping manufacturing costs low.

The following sections describe the types of preform geometries that can be molded with the RPO molding process. These descriptions have general guidelines for diameter ranges, shapes, and current manufacturing methods of preforms, and where an optical designer can evaluate their individual elements in their lens design for manufacturability and cost considerations.

Formed Ball Preform

This is the lowest cost, highest volume, preform option for manufacturability. RPO can produce tens of thousands of formed ball preforms per week. This unique technology allows for a virtually endless supply of preforms for lens manufacturing into the RPO molding machines.

The forming process at RPO is a proprietary technology for manufacturing glass balls in the range of 3.5 mm to 6.0 mm in diameter. This relatively low cost preform is an alternative to a traditional ground and polished ball preform. Used specifically for lenses with positive power: biconvex, plano-convex, and meniscus where the convex side is stronger than the concave side, this only works for a relatively small volume of material. In general, the lens diameter needs to be less than 7.0mm in diameter. Not all glasses on the RPO moldable glass list have been evaluated for this process. The forming process cannot manufacture preforms of low-dispersion crown glasses such as the Schott® N-FK5 and N-FK51.

Ground and Polished Plano-Plano Preform

As a lens changes to negative in power biconcave, plano-concave, and meniscus where the concave side is stronger, an alternative preform shape, plano-plano, is required for the molding process.

This type of preform is produced by the traditional grinding and polishing methods. All moldable glass types where the part diameter does not exceed 50.0 mm can be manufactured and used by the RPO molding process. Relative to a formed preform an increase in cost is observed for the manufacturing of this type of preform.

Ground and Polished Ball Preform

When the geometry of a lens extends beyond the volume range of a formed ball preform, a ground and polished ball preform is required. Used for lenses with positive power: biconvex, plano-convex, and meniscus: where the convex side is stronger, this geometry allows for molding of lenses with larger total volume.

The manufacturing of this type of preform is done with traditional grinding and polishing methods. All moldable glass types where the part diameter does not exceed 30.0 mm can be manufactured and utilized in the molding process. Relative to a formed preform and a plano-plano preform, an increase in cost is observed for the manufacturing of this type of preform.

Ground and Polished Lenslet Preform

The Lenslet preform is primarily for lenses with positive power, biconvex, plano-convex, and meniscus: where the convex side is the strongest surface. The use of this type of preform allows for molding of the largest volume of glass at any given time in the molding machines.

The Lenslet is traditionally ground and polished to a near net shape of the final lens, and then pressed. It can be made from any moldable glass type with a diameter not to exceed 50.0 mm. The cost associated with the manufacturing of the Lenslet preform is the highest of all preform types.

Gob Preform

Gob preforms, while historically difficult to obtain in the U.S. market, are becoming increasingly available. They can be a viable, low cost alternative to ground and polished preforms, although available glass types are limited and minimum order quantities often exist.

Particular Glass Concerns

- Many lead oxide flint glasses are moldable in the RPO process; however, they are not ROHS compliant.
- High dispersion fluoride glasses have been shown to reduce molding tool life; however, they are usually moldable.
- Most titanium containing flint glasses greater than 5% are not moldable due to the occurrence of surface reactions during the molding process that impacts overall cosmetic quality.

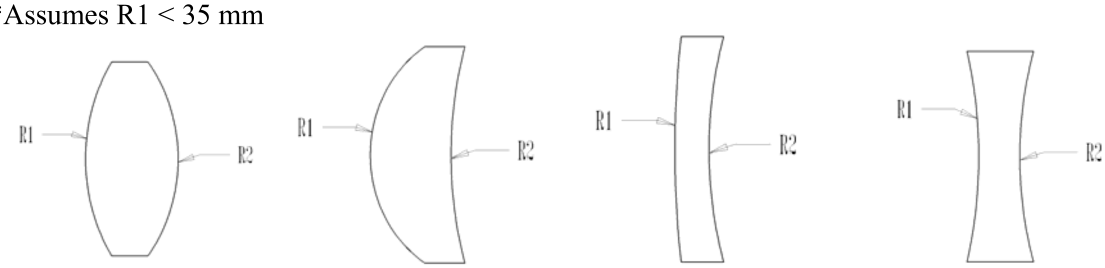
Preform Predictor

Table 1-3 is a reference tool for Optical designers to assist in evaluating lens shape vs. required preform geometry in relation to preform cost. This will help in keeping costs to a minimum, providing that the designer has the flexibility to choose from a variety of lens geometries.

Additionally, this spreadsheet will assist designers to see early in the design phase what effect selecting a particular lens shape will have on the required preform for precision molding. The “Preform Option” range from the Formed Ball to the Lenslet option, where the price and level of manufacturing difficulty increases accordingly. The “Lens Shape” column details the current molding capabilities for a particular lens shape. The recommended preform option is detailed for a given lens shape.

Lens Shape	Preform Options				
	RPO Formed Ball	G&P Ball	G&P (Plano-Plano)	Lenslet (Plano-Convex)	Lenslet (Bi-Convex)
Bi-Convex					
R1 , R2 strong					
∅ to 7mm	√	√			
∅ > 7mm		√			
R1 strong, R2 weak					
∅ to 10mm	√				
∅10mm to 20mm		√			
∅>20mm					√
R1, R2 weak					
∅ <10mm	√*				√
∅10mm to 15mm		√*			√
∅ >15mm					√
Equal Meniscus					
R1 = R2					
∅ <10mm	√*			√	
∅10mm to 20mm		√*		√	
∅ >20mm				√	
Positive Meniscus					
R1 stronger than R2					
∅ <10mm	√*			√	
∅10mm to 20mm		√			
∅ >20mm		√		√	
Negative Meniscus					
R1 weaker than R2					
∅ <10mm	√*		√		
∅ >10mm			√		
Bi-Concave					
R1 > R2			√		
R1 = R2			√		
R1 < R2			√		

Table 1-3 Preform Predictor
*Assumes R1 < 35 mm

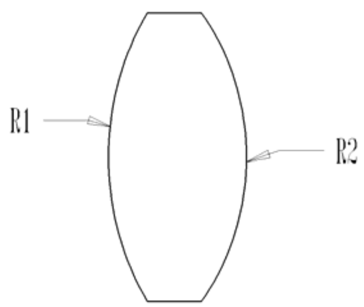


Bi-Convex Positive Meniscus Negative Meniscus Bi-Concave

Lens Shape

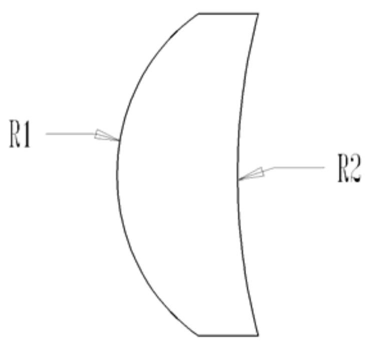
The following lens geometries are for the use of particular glass types and the required preform shapes. Recommendations on size constraints are to minimize the cost of the required preform for a given lens shape.

Bi-Convex or Plano-Convex



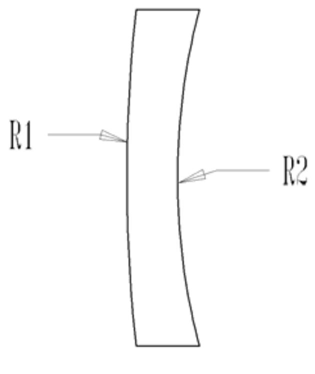
Bi-Convex or Plano-Convex lenses require either a formed or a ground and polished ball preform. The formed ball preform is very inexpensive, but generally requires a part diameter less than 6 mm. The ground and polished ball preform is relatively expensive compared to a formed preform, but still less expensive than the lenslet preform. Keeping the part small enough to form a ball will lower costs significantly; however, some glass types are unsuitable for the RPO ball forming process.

Positive Meniscus (Convex side stronger than Concave side)



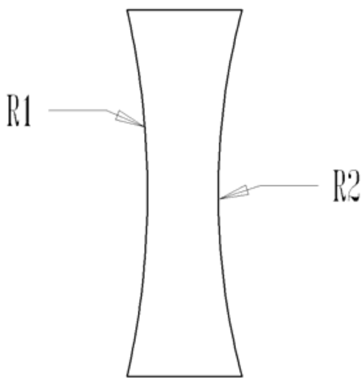
Positive meniscus lens shapes are relatively inexpensive if they can use the formed ball preform shape. This means they must have a diameter less than 7 mm and use a glass that can be formed. Otherwise, this lens form needs either a ground and polished ball or lenslet preform; which are relatively expensive. Diameters up to 30 mm can be manufactured.

Negative Meniscus (Concave side stronger than Convex side)



Negative Meniscus lenses use a ground and polished plano-plano preform, which are relatively inexpensive. The curvature restriction is that the concave side should have a stronger radius than the convex side, if this is not possible for the required lens, than a lenslet-preform is required for molding.

Bi-Concave or Plano-Concave



Bi-concave or Plano-Concave lenses use a moldable glass that can be processed from a manufacturer's ground and polished plano-plano preform. These preforms are relatively inexpensive compared to lenslet preform; however, they can be more expensive than a ball style preform, depending on the required total volume.

Edge Thickness and Clear Aperture (all elements)

Edge thicknesses of molded elements of no less than 1.0 mm are preferred. Clear apertures should be at least 1.0 mm (per side) less than the finished lens diameter to accommodate centering and coating processes. If less than 1.0 mm beyond clear aperture is required, it may be necessary to cup center the lens within the clear aperture during the centering operation. This may result in scratches inside the clear aperture.

Lens Size

Table 1-4, is divided into four size categories; Small, Medium, Large, and Extra Large for showing the current lens diameter ranges of manufacturability, general cycle time for pressing lenses, and the preform availability. The medium category or "Catalog Size" is the range for the best cost and highest preform availability, where inception of high volume manufacturing of this size can be achieved in a relatively short time. Efforts are under way to expand our high volume molding process over each of these size ranges.

Size	Lens Diameter	Cycle Time	Preform Availability
Small	< 4.0 mm	Shortest	High
Medium "Catalog Size"	4.0 mm <15 mm	Medium	High
Large	15 mm < 30 mm	Long	Medium – Low
Extra Large	30 mm > 60 mm	Longest	Low

Table 1-4 Moldable Lens Sizes

Optical Surface Characteristics

When designing a rotationally symmetric surface, utilizing the following equation is necessary for modeling in the RPO molding process and tooling manufacturing. Taking Z as the axis of revolution:

$$Z = \frac{cS^2}{1+\left[1-(K+1)c^2S^2\right]^{1/2}} + A_1S^4 + A_2S^6 + A_3S^8 + A_4S^{10} + ... + A_{12}S^{26} \quad \text{(Eq.1)}^1$$

where $S^2 = x^2 + y^2$ and $c = 1/r = 1/radiusofcurvature$. The aspheric deformation constants are $A_1, A_2, A_3, A_4, ...A_{12}$, and K is the conic constant that is the eccentricity of a conic surface $(K = -e^2)$. When the aspheric deformation constants are all zero the surface is a conic surface of revolution, which in table 1-5 has the following conic values:

Hyperboloid	$K < -1$
Paraboloid	$K = -1$
Ellipsoid rotated about its major axis	$-1 < K < 0$
Sphere	$K = 0$
Ellipsoid rotated about its minor axis	$K > 0$

Table 1-5[1]

Optical Surface Specifications and Tolerances

Lens and tool optical surface specifications (spherical or aspherical), are typically given in terms of "fringes" of surface departure from an ideal surface, which also includes irregularity of the surface in "fringes". The use of a profilometer allows for measurement of rotationally symmetric surfaces, and interference tests are utilized for spherical evaluation.

Table 1-6 shows the current standard and precision manufacturing tolerances of the lens molding process. As new technology and process-improvements are added to the manufacturing capabilities, RPO will update this table accordingly. At RPO, the continuous improvement of processes and equipment is an ongoing effort for supplying customers with the highest quality molded optics

[1] Daniel Malacara, Optical Shop Testing, John Wiley and Sons, 1978, pg.479

Manufacturing Tolerances		
Feature	Standard Quality	Precision Quality
Center Thickness	+/- 0.025 mm	+/- 0.012 mm
Diameter	+0 / -0.030 mm	+0 / -0.010 mm
Surface Deviation Power – Irregularity (Fringes)	5 – 2	3 – 1/2
ETD (Wedge)	0.05 mm	0.01 mm
Axis Alignment	5 Minutes	2.5 Minutes
Scratch-Dig	60 – 40	20 – 10
AR Coating	Single Layer R < 1.5% per side*	Multi Layer R < 0.5% per side*
Index of Refraction (N_d)	+/- 0.001	+/- 0.0003
Abbe Number (V_d)	+/- .8%	+/- .5%
Sag	+/- 0.015 mm	+/- 0.010 mm
*Minimum value for design wavelength		

Table 1-6 Lens Manufacturing Tolerances

Tooling Requirements

The material used for tooling in the Precision Glass Molding process is low porosity Silicon Carbide (SiC). The manufacturing of the required geometry of the tooling is performed by a precision grinding and polishing process. This method allows for minimal deviation of the optical surface with respect to the outside diameter of the tool. Tolerancing of the tool geometry and the graphite molds ensure a precision fit of the two components, and minimize the tilt/decenter/wedge of the lens surfaces. Table 1-7 shows our current capabilities and tolerances for our tooling manufacturing.

Surface Roughness	5-20 Å RMS
Surface Accuracies	1/10 λ

Table 1-7 Molding Tool Tolerances

Lens designs require that the optical surfaces have a base radius to be no less than 3.0 mm and sags no greater than 8 mm on both concave and convex surfaces. Additionally, the transition from the optical surface to the lens outside diameter requires a minimum radius value of 3.0 mm.

Post Centering of Molded Elements

Due to the free-form edge produced on all precision molded optics manufactured in the RPO process, a post centering process is required to obtain a finished element diameter. This can accomplished with the use of variety of manual, semi-automatic and fully automatic lens centering machines. Optical centering machines at RPO can produce a centered lens element from 1.0 mm to 300 mm in diameter (see Table 1-6). High volume centering can be accomplished with the use of six Nakamura-Tome® automated centering machines. Low and medium volumes can be performed on the laser centering LOH® CM2 and C2 brand centering machines. Beveled, radius, or segmented edge features can be applied to the elements, during the centering process or as a secondary operation.

Post Coating of Molded Elements

Precision molded lenses can be coated with a host of materials that range from single layer Magnesium Fluoride (MgF_2) to a multilayer antireflective coating. Optimized for a specific wavelength or a general range of wavelengths, coatings are applied after the molding process and prior to the centering operation.

Collimator Lens Specification

All lenses designed for collimation, are best specified for transmitted wavefront error deviation in waves, Root Mean Square (RMS). All RPO collimators are designed to exceed diffraction-limited performance.

These lenses are used typically in a “single-pass” method. That is the light travels through the lens once in the system. Most interferometric measurements are in a “double-pass” configuration. The conversion from a double-pass measurement to a single performance is in the scale factor within the interferometer software. This can be set for proper evaluation of this type of lens within the evaluating software.

Chalcogenide Materials

RPO has performed many molding trial runs on different types of Chalcogenide materials that include Vitron®: IG2, IG4, IG5, and IG6. Lens surface figures obtained on these elements are similar to comparable optical grade glasses, used in the visible region. The lens design must allow the use of a plano-plano, plano-convex, or biconvex preform, as ball preform shapes are not easily manufactured from these materials (see Table 1-3).

Summary

The RPO molding process is a proven technology to produce precision molded optics. This paper will assist optical designers with understanding the design envelope of the molding process and show the benefits of tailoring certain elements in their lens design for the molding application at RPO. Optical engineers will find that this paper can be useful for assistance in selecting an existing RPO catalog lens for their applications. The overall benefits can be seen when the collaboration of design and manufacturing comes together, early in the design phase of a project.

Acknowledgement

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