Invited Paper

Design Considerations and Manufacturing Limitations of Insert Precision Glass Molding (IPGM)

Alan Symmons, Bryan Auz
LightPath Technologies, Inc., 2603 Challenger Tech Ct, Ste 100, Orlando, FL, USA 32826

ABSTRACT

Precision glass molding (PGM) directly into metallic structures is a process similar to the plastic injection molding process of insert molding, however fundamental differences exist due to the processing temperatures, nature of materials and manufacturing requirements. Despite some limitations, insert precision glass molding (IPGM) extends many benefits to the product designer. IPGM occurs at the glass transition temperature of the glass therefore materials must be matched by their thermal properties so that undue stress is not exerted on the glass during processing or significant inherent stress left in the part after processing. Either of these conditions could lead to cracking, birefringence or failures due to thermal cycling during operation. This paper will discuss the techniques and specific design considerations that must be taken into account when designing for IPGM. Design aspects such as interface diameters, wall thicknesses, aspect ratios and material properties will be analyzed. The optical and mechanical performance and properties of the glass and holder assembly will also be reviewed, including strength of the assembly, quality of the sealing interface (hermeticity), optical to mechanical alignment and impact on optical quality. The review includes both chalcogenide and traditional oxide based moldable glasses.

Keywords: Precision glass molding, chalcogenide.

1. INTRODUCTION

1.1 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[1]. A brief summary of the PGM process follows. The process flow is documented in Figure 1 and the processing cycle is documented in Figure 2. Figure 1 depicts a single cavity, volumetric glass molding process in which the volume of the preform must be accurately controlled and only one lens is made at a time. This is a simplification of the process and many variations exist.

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, OD, 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, Figure 1-(1). A glass preform is then inserted into the tooling stack, Figure 1-(2). The top mold is then reintroduced and the system is evacuated, Figure 1-(3). The tooling stack and the glass preform are then heated at a controlled rate, Figure 1-(4). 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, Figure 1-(5). 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, Figure 1-(6). Once the final product is cool enough to handle the component is removed, Figure 1-(7), and the process is repeated, Figure 1-(8).

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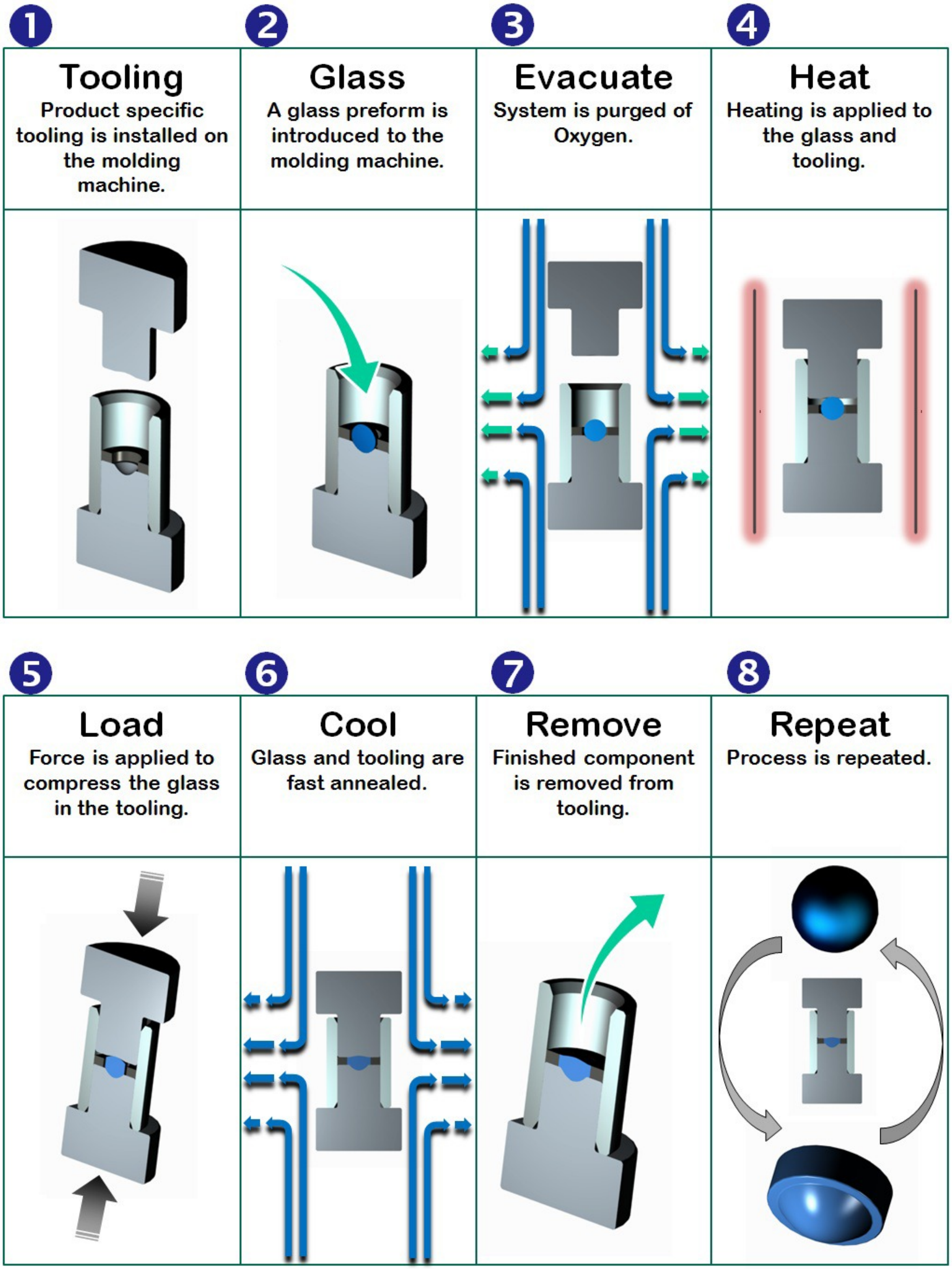

Figure 1. Precision Glass Molding Process Flow

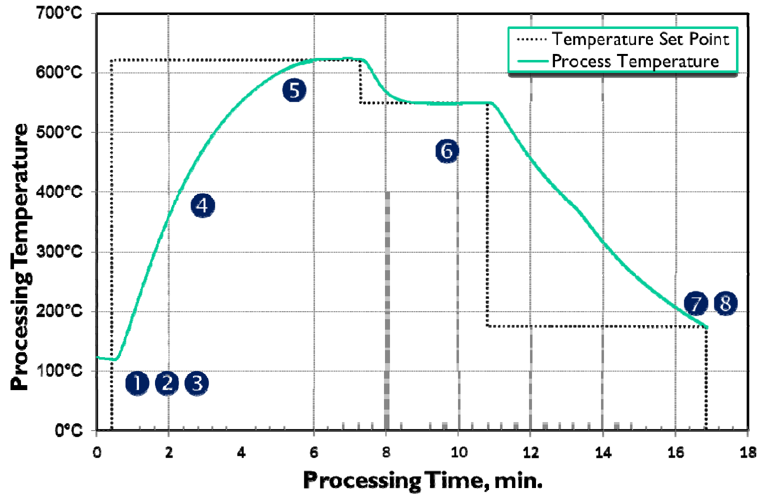

Figure 2. Typical Precision Glass Molding Processing Cycle

1.2 Insert Precision Glass Molding

Insert Precision Glass Molding (IPGM) occurs when a secondary component or insert is introduced to the molding process with the intent of manufacturing a finished product consisting of two independent parts in a single process. This additional component is usually a machined metal part used as a mounting device for the molded glass optic. A sampling of IPGM parts is shown in Figure 3.

Figure 3. Various IPGM lenses

The insert does not undergo any physical change during the molding process and must have a higher transition temperature than the glass. The material is normally selected for a number of mechanical properties with emphasis placed on the coefficient of thermal expansion, α, (CTE). The secondary component is introduced to the precision glass molding process prior to the first heating cycle, step 1a as shown in Figure 4. The tooling used in step 1 is modified to accommodate the additional component and therefore customized tooling is required. Otherwise the process is the same as documented in Figures 1 and 2.

Table 1. Coefficient of Thermal Expansion for Select Moldable Glasses

Glass	T_g (˚C)	Coefficient of Thermal Expansion, α, μm/m˚C	CTE Reference Temperature,˚C
Ge(28)Sb(12)Se(60)[2], LightPath BD2	285	14.30	0-200
Corning C0550[3]	330	15.0	20-300
LightPath ECO550[4]	375	15.60	340
Ohara PBH-71[5]	389	11.10	340
CDGM H-QK3L[6]	475	10.2	100-300
CDGM D-ZK3[6]	517	7.80	100-300
Sumita K-VC89[7]	528	8.30	100-300
CDGM D-ZLaF52LA[6]	546	8.30	100-300

The insert precision glass molding process has been in development for many years and was originally patented in 1993[8]. The emphasis of the early development work was for very small diameter optics used for the telecommunications industry. The early work was based on lead based glasses with lower glass transition temperatures, T_g, and higher CTE's, such as Ohara's PBH71 or Corning's C0550, Table 1. Environmental restrictions have driven the path towards obsolescence of these glasses and many other lead based glasses. These glasses have been replaced with higher T_g glasses such as CDGM's D-ZK3, CDGM's D-ZLaF52LA and Sumita's K-VC89. These glasses have lower CTE's than the lead-based glasses, as can be also noted from Table 1. These changes in materials and increased interest in insert molding for larger diameters, different shapes and insert materials requires looking at this process in a more detailed manner than the historical small diameter, one or two glass types with one insert material. The intent of this paper is to review IPGM with a much broader scope and more detail than has previously been documented.

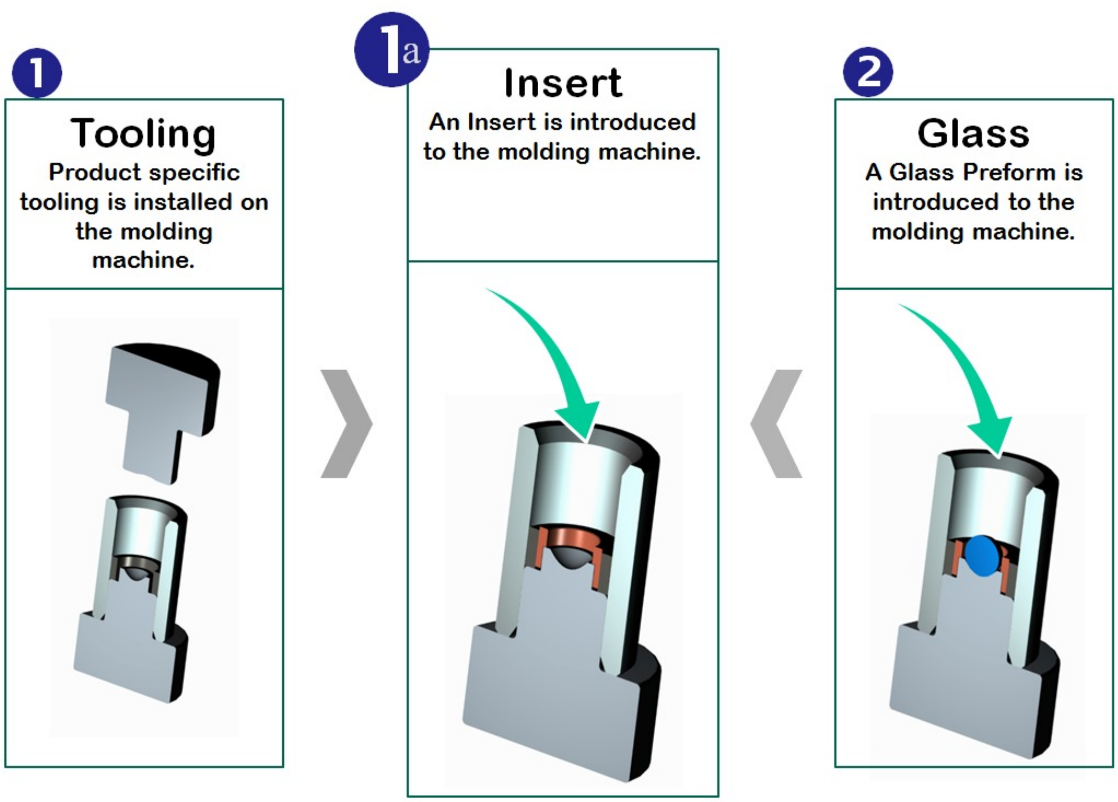

Figure 4. Changes to PGM Process Steps for Insert Molding

2. DESIGN CONSIDERATIONS

2.1 Material Selection

The first design consideration to be made when approaching an IPGM design is the material selections for both the optic and the insert. Typically the glass is chosen first because first and foremost the assembly must function optically. Once the glass is chosen and the optical design is completed, an insert material must be paired with the glass material. When choosing a metal to mold the optic into many factors come into play. All final assembly characteristics must be taken into account and the CTE mismatch must comply with generally accepted ranges for IPGM, to be discussed later. Table 2 lists a number of possible candidates for an insert material. A few common assembly characteristics that influence the insert material selection are cost, weight, material availability, magnetic properties, material weldability and possibly even sulfur content for high vacuum applications which require low outgassing of material. Once all of these factors have been taken into account, the material chosen must have a CTE that falls within an acceptable CTE range for the glass in use. There are two primary cases, the first where the CTE of the glass is greater than the insert and the second where the CTE of the insert is greater than the glass. A third case theoretically exists in which the CTEs of the glass and insert material are an exact match. This is an unlikely, if not impossible event, but would simply mean that the materials shrink and grow at the same rate creating a net zero force within the assembly.

Case 1: $CTE_g > CTE_i$ – Tensile Case

Case 2: $CTE_g < CTE_i$ – Compressive Case

where CTE_g – Coefficient of thermal expansion of the molded glass

CTE_i – Coefficient of thermal expansion of the insert material

In Case 1, after forming the lens at step 5 in Figure 2, the glass shrinks faster than the holder material. The glass will be attempting to pull away from the holder and either tensile stresses in the glass will develop if there is a material interaction between the glass and holder, or the glass and insert will not become a single unit. In case 2, after forming, the holder is shrinking faster than the glass, imparting a compressive stress on the glass and creating a monolithic unit or if the CTE mismatch is too great stress from the insert can cause the lens to crack. This CTE range varies slightly based on mechanical insert design which will be discussed later. At this point the insert material can be narrowed down and a final selection can be made. In general the ratio of insert inner diameter, which is the same as the lens outer diameter in the case of IPGM, to the outer diameter of the insert affects the feasibility of certain materials and their respective CTE values. Decreasing the ratio can help lower stress values allowing for combinations that would typically not be considered.

Table 2. Coefficient of Thermal Expansion for Select Insert Materials

Material	Coefficient of Thermal Expansion, α, μm/m˚C	CTE Reference Temperature, ˚C
Aluminum 6061-T6[9]	25.50	20-260
Brass UNS C36000[10]	20.50	20-300
Inconel 718[11]	13.00	20-100
Invar® 36[12]	4.18	260
Kovar®[13]	6.15	25-500
Stainless Steel 304L[14]	18.70	649
Stainless Steel 410[15]	11.50	0-540
Stainless Steel 416[16]	11.50	0-540
Stainless Steel SF20T[17]	10.40	0-100
Titanium 6Al-4V (Grade 5)[18]	9.70	20-650

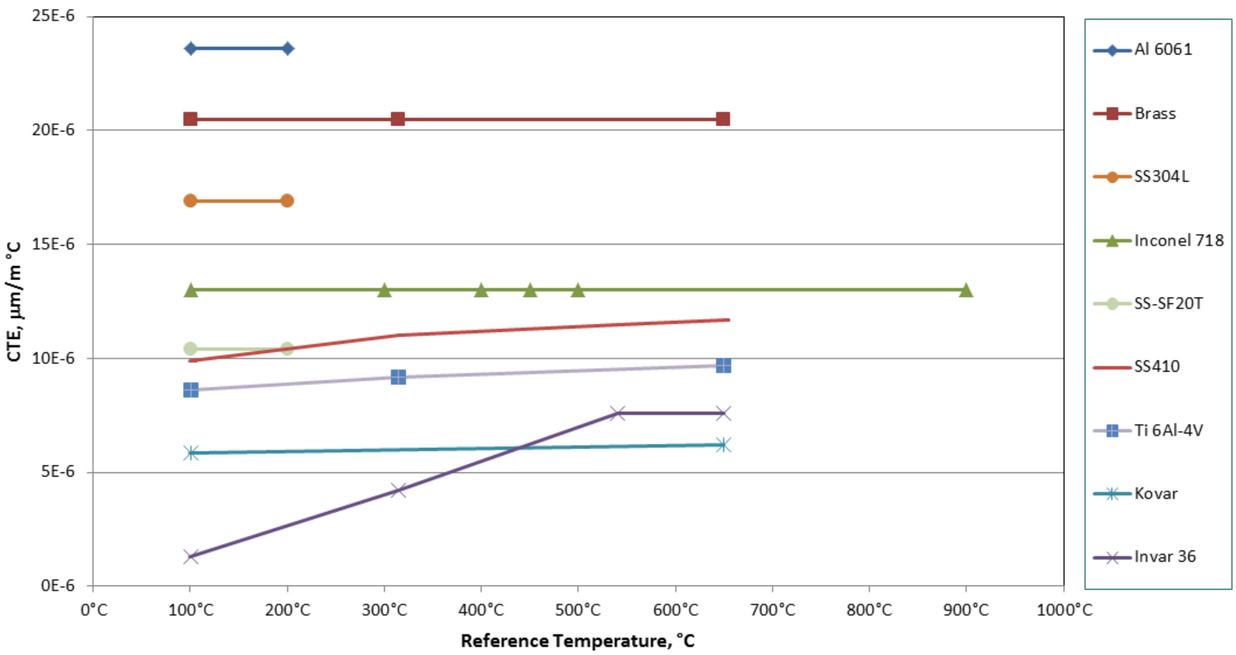

Figure 5. Coefficient of Thermal Expansion over Temperature for a Selection of Insert Materials

Once the materials have been chosen for the final assembly a calculation to estimate the pressure created on the lens from the thermal shrinkage of the insert can be used to determine the feasibility of the design. The interface pressure created between the glass outer diameter and the inner diameter of the insert is what can create problems that would not allow an assembly to be manufactured. If the pressure is too high the assembly has a tendency to squeeze on the glass and crack it when cooling. On the other hand, if the interface pressure is too low the optic has a possibility of falling out of the final assembly, or not meeting push out testing criteria.

The insert molded lens is analogous to the classical case of press fitting two cylinders, so calculation of the interface pressure between the glass lens and metal holder can be done using the same equations but with minor modifications. In the case of press fitting two cylinders together there is an interface pressure that is formed because of the interference fit and the shrinking material: equation (2.1) can be seen below[19]. The interface pressure, p, is related through equation 2.1 by the total material interference, δ_{int}, which can be solved for by equation 2.3 below. R is the transition radius, E_i is the elastic modulus, and ν_i is the Poisson's ratio of the material.

$$p = -\frac{\delta_{\text{int}} R}{E_i}(1 - \nu_i) \tag{2.1}$$

Equation 2.1 is used for similar materials. In the case of IPGM the interference is caused by differential thermal expansion of the dissimilar materials, specifically the contraction or expansion of the metal insert around the glass lens. When the molding operation takes place and the assembly pieces are heated the insert expands radially based on equation 2.2, where ΔD is the change in diameter of the insert, D_0 is the initial diameter of the insert, α is the CTE of the insert material, and ΔT the temperature difference between room temperature and maximum temperature.

$$\Delta D = D_0 \cdot \alpha \cdot \Delta T \tag{2.2}$$

The coefficient of thermal expansion determines how the diameter of the insert changes as the temperature changes. For the case of this approximation the coefficient of thermal expansion of the insert material is assumed to be linear across the temperature range determined by the maximum processing temperature from Figure 2-(5). The maximum processing temperature is used because the CTEs of most materials vary with temperature. CTE data for the metals used for this research can be seen in Figure 5. The equation is solved for the maximum nominal diameter of the insert at the glass annealing temperature and the glass preform viscosity is at a value which allows it to take the shape of the insert. After the molding process is complete and the assembly begins to cool, the insert contracts radially around the lens creating an interference pressure. This pressure is estimated by first solving for the interference between the glass and the insert. This is solved by equation 2.3 below where δ_{int} is the total interference between glass and insert, α_i is the CTE for the inner glass material, α_o is the CTE for the outer metal insert material, ΔT is the temperature differential between room temperature and maximum process temperature. Finally, R is the transition radius, or the radius at which the interface pressure is solved.

$$\delta_{\text{int}} = \Delta T(\alpha_i - \alpha_o)R \tag{2.3}$$

Equation 2.4 from Shigley[19] is simplified by having the inner radius set to zero, thus eliminating the inner radius or r_i term in the right half. The equation is then algebraically solved for the interface pressure, p. This solution is shown as equation 2.5. Once the total mechanical interference, Δ_r, is known from equation 2.4, Poisson's ratio, ν and the elastic modulus of the insert and glass materials, E, are then entered into equation 2.5, to estimate the interface pressure created by the insert shrinking around the glass.

$$\Delta_r = \frac{p \cdot R}{E_o}\left(\frac{r_o^2 + R^2}{r_o^2 - R^2} + \nu_o\right) + \frac{p \cdot R}{E_i}\left(1 - \nu_i\right) \tag{2.4}$$

$$p = \frac{\Delta_r}{R \cdot \left(-E_i \cdot r_o^2 - E_i \cdot R^2 - E_i \cdot \nu_o \cdot r_o^2 + E_i \cdot \nu_o \cdot R^2 - E_o \cdot r_o^2 + E_o \cdot R^2 + E_o \cdot \nu_i \cdot r_o^2 - E_o \cdot \nu_i \cdot R^2\right)} \cdot E_o \cdot \left(-r_o^2 + R^2\right) \cdot E_i \tag{2.5}$$

Once this interface pressure value is known it can be used to determine the manufacturing feasibility of the design, and if necessary the mechanical insert design can be optimized to increase the manufacturability. After solving for the interface pressure value, finite element analysis models can be created in a CAD software program to evaluate stress in the design. This is especially helpful for insert design with complex features, or when precise optical quality must be maintained. A stress calculation is not required to effectively design IPGM lenses, rather the interface pressure calculations described above are used as an empirical design tool to determine where a specific design falls in the range of manufacturability.

2.2 Mechanical Design

The mechanical design of the insert component should follow good machining practices. The simplest type of insert component is a simple ring, hereby referred to as a type I and shown in Figure 6 below. There are a number of advantages to a type I holder; it is very inexpensive, requires little or no custom modification of tooling, and the stress distribution is simple and predictable. A type II insert simply extends the holder beyond the edge of the lens as shown in Figure 6. This type of holder requires relief of the tooling in order to mold the lens and therefore increases tooling cost. The unsupported region of the holder (outside of the glass) shrinks at a faster rate than the supported region, as the temperature is reduced during processing; therefore a stress differential or stress concentration occurs at the interface of the lens and the extended holder. This concentration of stress may affect the performance or manufacturability of the design. A type III design is similar to a type II design in all aspects except the extension of the holder beyond the lens occurs on both sides creating further complexity and additional cost.

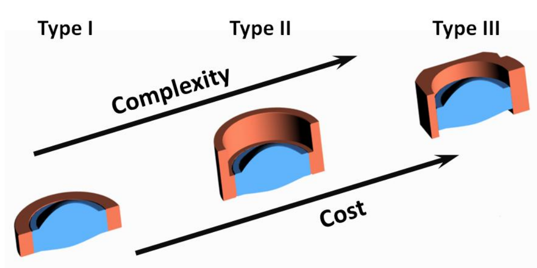

Figure 6. Types of IPGM lenses

It is important to note that one of the highest components of the manufacturing costs of the PGM and IPGM process is the tooling cost[1]. A reduction in tooling life results directly in an increase in component cost. Therefore it is important to evaluate the impact of designs on the tooling used to manufacture the product. Type II and type III inserts for IPGM increase the cost of tooling by increasing the machining steps and manufacturing cycle times on the carbide or ceramic tools. Designs in which the lens is deeply recessed in the holder can result in shortened tool life.

Figure 7 shows two concepts of the same design, on the left the design appears to be simple and straightforward. However this design generates a sharp edge condition in the mold. Sharp edge conditions limit mold life and can be difficult to manufacture. The design on the right is a much more robust design. By simply creating an expanded relief, the mold geometry becomes easier to manufacture and more durable.

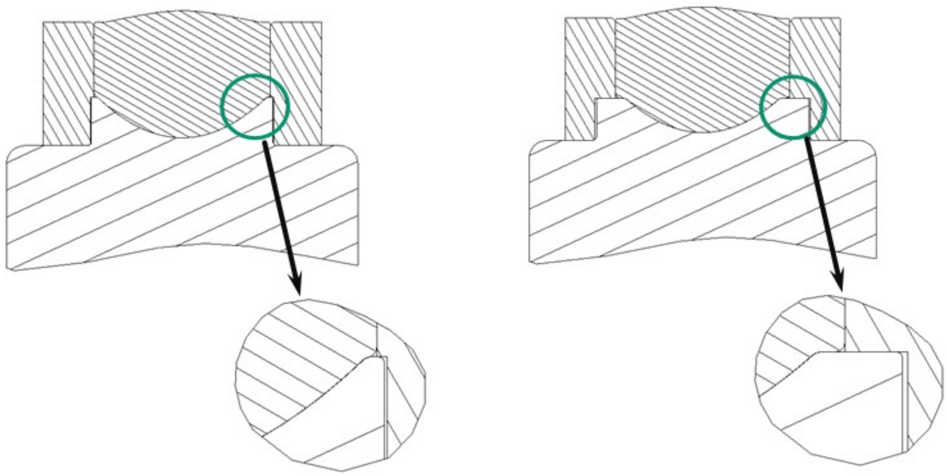

Figure 7. Design Impact on Tooling: Sharp Edge Condition (left) and Robust Tooling Design (right)

The IPGM process is a volumetric molding process. A volumetric molding process requires the volume of the preform match the volume of the finished product. The ball, or spherical, preform is the most prevalent preform geometry used in PGM and is used as an example in Figure 8 to show the proper volumetric fitting of a preform within an insert. As can be seen on the left side of Figure 8, the ball preform must not only match the volume of the finished lens but must also be able to be introduced into the insert during the manufacturing process in Figure 4-(2). This is obviously not the case on the right side of Figure 8, where the preform may be a volumetric fit, but the operator would be unable to place the preform into the insert. While this may seem to be an obvious issue, it is rather easy to overlook if one is not familiar with the volumetric nature of IPGM. Other preform shapes could be used to accommodate special designs but these are typically associated with increased costs or loss of precision.

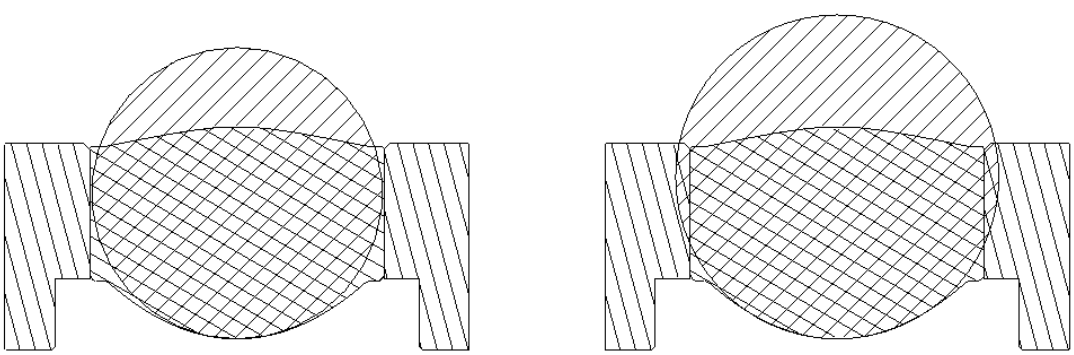

Figure 8. Preform fit: go (left) versus no go (right)

The wall thicknesses of the mechanical features of the insert also have limitations. These limitations are determined mostly by standard machining tolerances but sometimes the insert precision molding process can have an effect on the holder geometry. A typical thickness for any wall feature that is free standing, meaning not in contact with the optic, would have a minimum thickness of 0.250mm. A wall of that size should not extend in length past 1mm. Exceptions can be made however and would need to be reviewed on a case by case basis. The thickness of the wall that is in contact with the optic is limited through interface pressure calculations. When holding the optical design constant, and therefore the insert inner diameter constant, a ratio of the lens OD to insert OD can be formed and is directly related to the interface pressure by equation 2.5. As the ratio of insert ID or lens OD, which are the same in IPGM, to insert OD increases the interface pressure value decreases. The insert wall thickness must be large enough to create an interface pressure value that is within the known success range. If the insert OD is too large and the ratio grows smaller, the pressure rises and can result in a case in which the lens assembly is not able to be manufactured. Figure 9 below illustrates the typical relationship between the ratio of inner diameter to outer diameter and the interface pressure. The slope of the line changes slightly with different combinations of glass, molding temperatures, and insert materials. It is important to keep the design within the acceptable range of ratio to interface pressure, as well as maintain the mechanical intent of the design in the final assembly. The acceptable range of interface pressure has been determined empirically through trial and error. As research progresses and more data points become available, the range of acceptable interface pressure will become more defined.

Another unknown in insert molding is the effect of chemical interaction between glass and different metals during processing. In some cases it has been seen that a lens is actually in tension rather than in compression, Case 1 from the earlier section on thermal expansion. This would imply that the lens would release from the insert after molding. However, in some cases the opposite has been found to occur[8]. This paper focuses on compressive case or Case 2 from the thermal expansion section. Further research needs to be conducted on cases where the lens is predicted by design to be in tension.

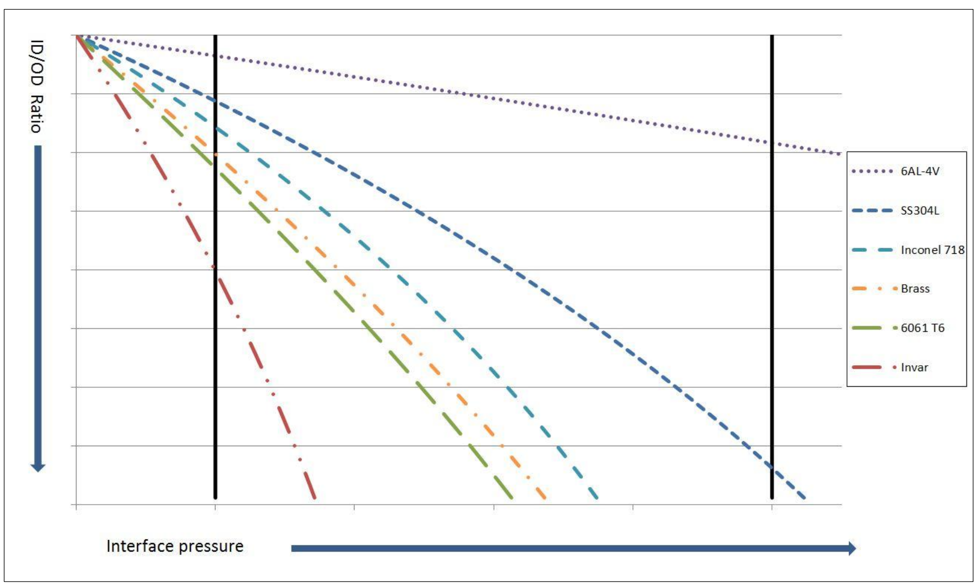

Figure 9. Inner diameter to outer diameter ratio versus interface pressure

Complicated FEA analyses can be completed by CAD tools however, for IPGM design interface pressure values are used to create an empirical design tool. Stress calculations would take the design a step further. Stress in glass is a difficult parameter to predict and even the most current CAD programs have a hard time calculating the stress in glass. Research has been done to estimate how residual stress from manufacturing or molding affects products made from glass. The main driving factor is the quality of the glass, before and after it is altered by post processing[20]. Higher quality glass is less susceptible to stress complications than lower quality glass. Tiny voids and scratches on the surface of an optic will easily propagate with the introduction of stress. Quality of the surface and glass is always a concern in glass molding and is treated no differently for IPGM.

2.3 Advantages

Insert molding presents a number of advantages to the designer. An optical component molded into another component is much easier to handle than a bare optic. The lens surfaces can be protected by the insert, as shown by the Type II and Type III holders in Figure 6. Mechanical features can be designed into the insert that can facilitate next level assemblies. Molding directly into a holder also significantly improves the alignment of the optical axis to the mounted component when compared to a similar bonded assembly. A bonded assembly will have three tolerances to consider—clearance for making the assembly, tolerance in the outer diameter of the lens, and tolerance in the internal diameter of the holder. Alternatively, with IPGM the glass is molded directly into the holder, essentially eliminating all three of these tolerance stack-ups. When the machined insert is put into the molding machine, it is typically aligned on the precision tooling as shown in Figure 4-(1a). The tooling is precision diamond ground, and the mounting features may even be constructed during the same machining process that generates the optical surface. A properly designed IPGM assembly will also minimize the wedge between the optic and insert, a sometimes difficult thing to minimize in a bonded assembly. By using the precision diamond ground surfaces of the mold to align the insert, the wedge can be greatly reduced, with the only contributors ending up as the tolerances of the holder itself and the alignment of the molds and insert.

3. IPGM MANUFACTURING

Insert precision molded optics must normally meet the same optical performance requirements as traditional precision molded optics. However, with IPGM there is a series of additional requirements which must be considered, including joint strength between the glass and holder, hermetic sealing between the glass and holder, and stress induced polarization in the lens that can occur from molding the glass into a metallic holder. In this section a baseline comparison of optical performance is first made between a standard PGM and an IPGM version of the same lens. Following this are studies of joint strength, hermetic sealing, and stress induced polarization. Finally, surface profilometry is used to examine the effects of a compressive or tensile force created by molding a lens into different materials on the lens aspheric curvature.

LightPath Technologies Inc. part number 355110 was chosen to design an IPGM case study for comparison. This lens was chosen because of the stable process already in place and readily available data for the PGM lens performance. Table 3 shows the relationship between the PGM and IPGM designs. The two designs are identical besides the addition of a type I insert to the IPGM design. The insert inner diameter and lens outer diameter are equal. Mechanical drawings of the two designs are show in Figure 10 below.

Table 3. PGM versus IPGM lens design parameters

Design	PGM 355110	IPGM 355110
Lens Outer Diameter	7.2mm	7.2mm
Center Thickness	5.18mm	5.18mm
Insert Outer Diameter	N/A	10.8mm
Insert Inner Diameter	N/A	7.2mm
Lens Edge Thickness	4.3mm	N/A
Insert Thickness	N/A	4.3mm

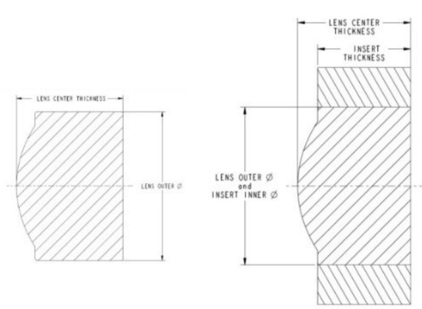

Figure 10. Mechanical Drawings of LightPath 355110 (left) and IPGM 355110 (right)

3.1 Performance

Optical

The qualification data for the 355110 production lens contains typical ranges for five different interferometer measurements of wave front error: RMS, P-V, astigmatism, coma, and spherical aberration. Below are the distributions for each in a qualification batch of the current non IPGM design for comparison to the IPGM lens values.

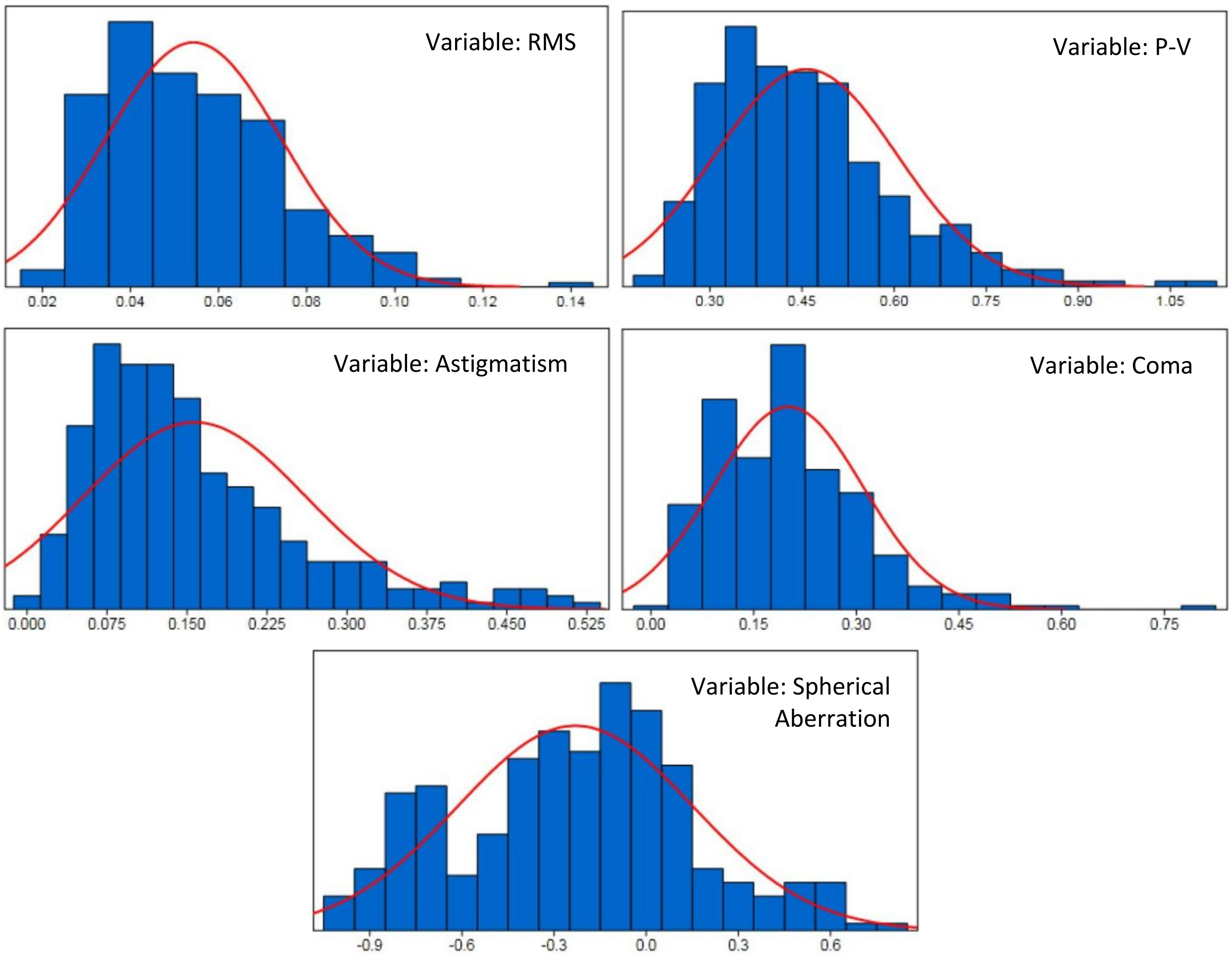

Figure 11. Optical Performance Data from non IPGM lens

The optical performance of the lens in the qualification report data was taken from a manufacturing lot after process engineering was complete. During process development a process engineer is able to optimize the potential process related factors which affect the optical performance. Typically hundreds of lenses are involved in this process, but in this case less were used because of the process had already been proven. All of the chosen designs varied only the insert material and not the glass material for interferometer measurement. Five different insert materials were chosen to mold this design and the interface pressure calculations indicated that each design was within the acceptable range. Two of the designs were near the edges of the empirically determined range for acceptable interface pressures. The following insert materials were chosen for molding CDGM D-ZLaF52LA glass: stainless steel 410 (SS410), free cutting brass, 6061 T6 aluminum, Kovar, and stainless steel 304L (SS304L). Perhaps the most interesting, was the aluminum insert. The molding temperature of D-ZLaF52LA is above the liquidus temperature of aluminum. After the molding process the insert had partially melted and attached itself to the tooling and glass. Needless to say this was the first and last trial with this material and it was confirmed as a non-viable IPGM option for this glass. The other two combinations near the edges of manufacturability used a SS304L insert, and the other Kovar. The thermal expansion of SS304L created a condition in which the pressure and induced stress on the glass were near the upper limit, the opposite was true in the case of the Kovar insert. The optic failed to remain in the Kovar insert when very minimal force was applied. One of the Kovar samples that remained in the holder was measured on the interferometer and the data is reported below. It should be noted that this lens was one of the very first to be molded and the optical performance suffered because the process had not yet been optimized. The SS304L case showed no signs of cracking or detrimental pressure. The interface pressure estimations for brass and SS410 put them well within the acceptable range and were expected successes. The interferometer used to record these measurements was a Fisba Optik uPhase 20T. After the process was stabilized it can be seen that each of these cases are just as viable optically as their predecessor, the non IPGM version (Figure 11).

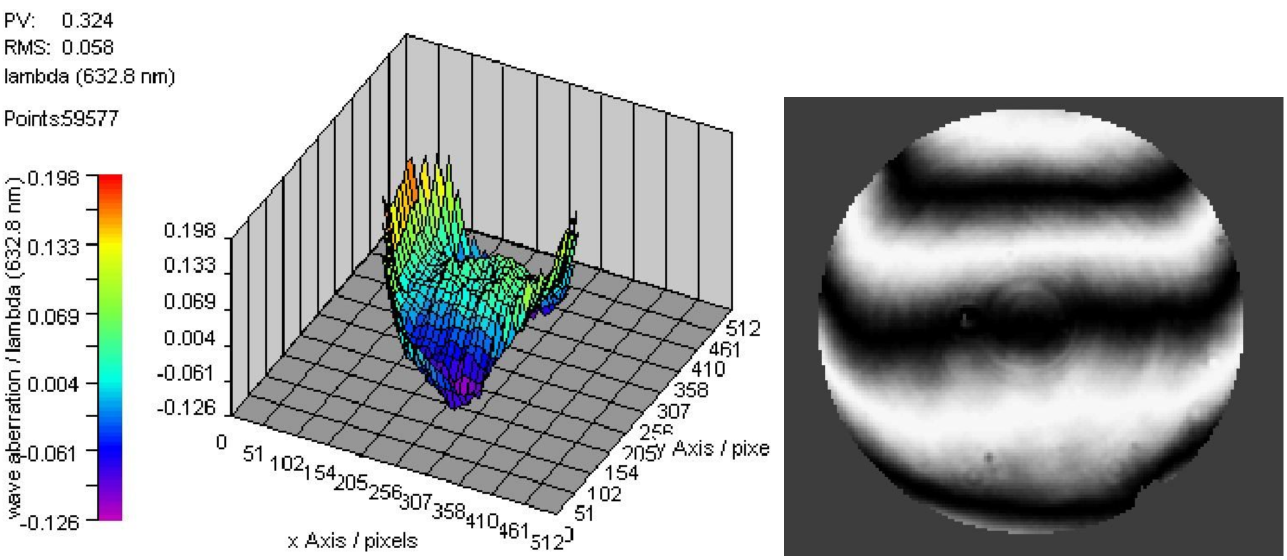

Figure 12. 3D wave aberration plot (left) and corrected wave aberration image (right) for D-ZLaF52LA and SS410 insert.

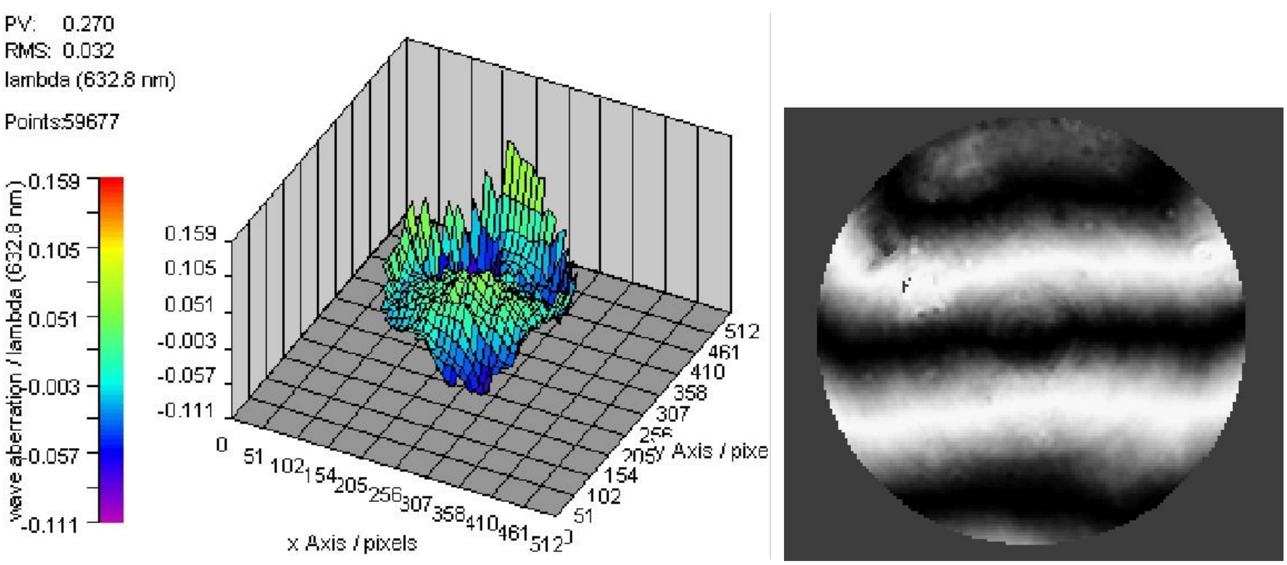

Figure 13. 3D wave aberration plot (left) and corrected wave aberration image (right) for D-ZLaF52LA and brass insert.

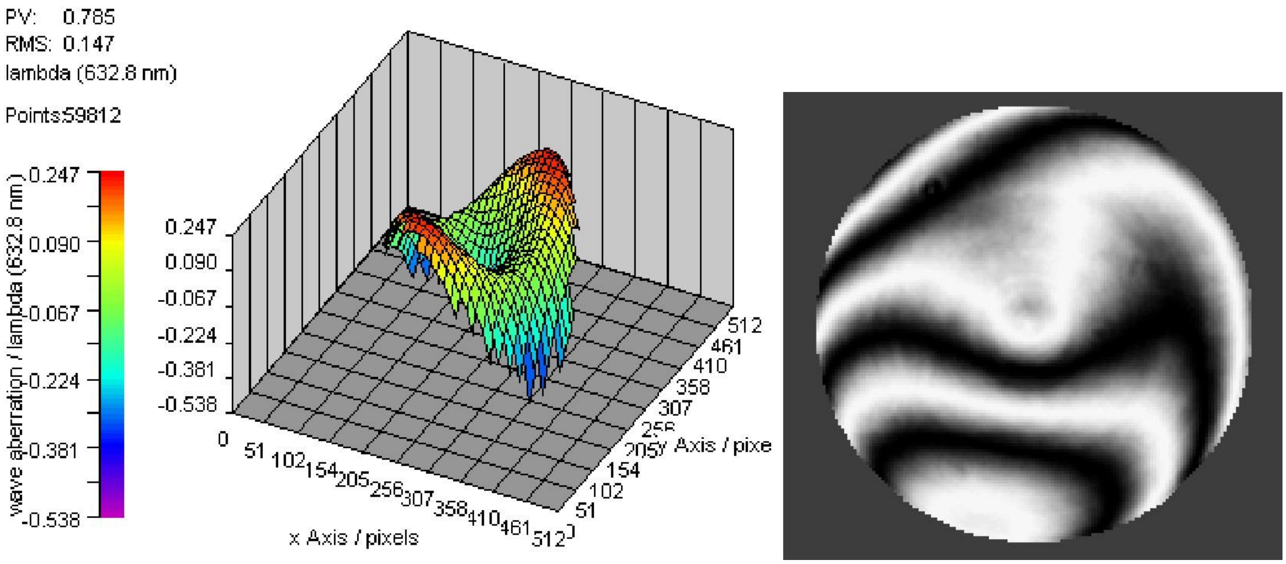

Figure 14. 3D wave aberration plot (left) and corrected wave aberration image (right) for D-ZLaF52LA and Kovar insert.

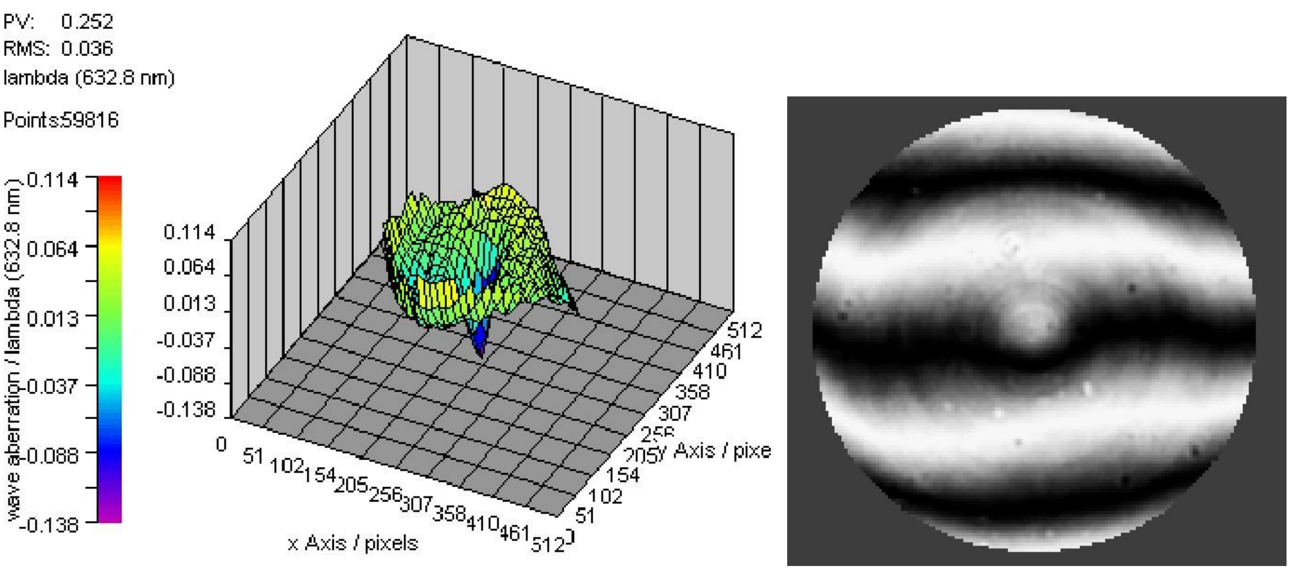

Figure 15. 3D wave aberration plot (left) and corrected wave aberration image (right) for D-ZLaF52LA and SS 304L insert.

Joint Strength

IPGM lenses rely on the strength of the bond between the glass and insert to ensure that the two remain as a monolithic assembly. The bond could be chemical or mechanical. As discussed earlier some cases have been found to be viable for IPGM manufacturing even though the interface pressure calculations determined that the lens was in tension, not compression. This type of bond is presumed to be because of the chemical interaction between glass and metal, and is not covered in this paper. The bonds that are tested in this strength test have all been determined to have mechanical bonds, meaning that the metal insert applies some compressive force to the glass in order to maintain the bond between the two materials. The IPGM lens assemblies were tested in a vertical force tester, a Chatillon DFGS50 force gauge. The vertical stage is lowered at a rate of 12.7mm per minute until one of three events occurs. If the force gauge reaches its maximum of 50 lbs. the test is stopped and the lens is determined to have a joint strength greater than 50 lbs. If the lens fails by way of cracking without pushing completely out of the insert it is determined that the glass was weakened in some manner and the maximum force shown on the force gauge is recorded. If the lens pushes out cleanly with no damage it is determined that the maximum force recorded is the push out resistance of the combination of lens and insert material. Below is a table of the results for the different combinations tested for this paper.

Table 4. Force out test results – Average force required to push out the optic.

		Average Force
D-ZLaF52LA	SS410	> 50 lbs.
	Brass	> 50 lbs.
	Kovar	4.82 lbs.
	SS304L	> 50lbs.
		Average Force
D-ZK3	SS410	> 50lbs.
	Brass	> 50lbs.
	Kovar	2.20 lbs.
	SS304L	> 50lbs.
		Average Force
H-QK3L	SS410	> 50lbs.
	Brass	> 50lbs.
	Kovar	0 lbs.
	SS304L	> 50lbs.
		Average Force
Ge(28) Sb(12) Se(60) LightPath BD2	SS316	48.63 lbs.
	Brass	> 50lbs.
	Kovar	18.7 lbs.
	SS304L	> 50lbs.
	6061 T6	42.99 lbs.
	Inconel 718	43.48 lbs.

The values from the table above show that the different materials have different effects on the bond created between the two elements. Generally the larger the interface pressure the stronger the bond. The oxide glasses D-ZLaF52LA, D-ZK3, and H-QK3L in all combinations except with Kovar, remained in the holders at the force gauge's maximum force of 50 lbs. and the glass was not damaged in any way by the steel tool used in the test. In the case of the Kovar inserts the bond created by the interface pressure was so weak that many of the lenses fell out without any force applied, and the assemblies that remained intact required very little force to remove them. The Kovar design was approaching the limit of a net zero force on the assembly and possibly due to machining tolerances could have swayed back and forth between small tensile forces and small compressive forces.

The chalcogenide IPGM lens design was different than the others and the results should not be compared against that of other glasses, rather against itself and the different insert materials used, more details on the insert molding of this chalcogenide design can be found in reference 21. Similar to the other designs Kovar was the weakest bond requiring only 18.7 lbs. of force on average to force the assembly apart without damaging the glass optic. The stronger bond between the chalcogenide glass and Kovar seems to imply that the glass has a different reaction with the metal and there are other bonds besides simple compressive force at play with IPGM. In general the chalcogenide glass has lower interface pressures with an equivalent design in a non chalcogenide glass because of the lower temperatures used when molding. Even with the lower interface pressures the glass still held up to the force of a push out test quite well, with all of the remaining designs requiring at least 42.99 lbs. of force to remove the optic from the insert.

Hermetic Seal

The seal between the optic and the mechanical insert in an assembly can be very important depending on the application. Similar to the joint strength testing described above a hermetic seal requires some force between the glass material and the optical material to prevent the seepage of gasses between the two. Many devices rely on this seal to ensure correct operation. Laser systems are among the many types of machines that require a hermetic seal. Hermetic seals are often needed in infrared applications. With the introduction of molding chalcogenide glass it has become increasingly important to measure the hermeticity of advanced manufacturing techniques such as IPGM with these glass types.

A selection of LightPath lenses were chosen for hermeticity testing. The parts were tested on a SFJ261 helium mass spectrum leak detector for leak rates of helium, He. Different combinations of glass and insert materials were tested and have shown sealing capabilities on par with that of an assembly bonded with epoxy. The table below summarizes the results from the hermetic seal testing. It is recommended that any IPGM design that requires a hermetic seal be explicitly tested for the specific requirements of the end application.

Table 5. He Leak rate test results for LightPath IPGM lenses

LightPath Part #	Glass Material	Insert Material	Average He Leak Rate
355940	D-ZLaF52LA	SS416	2.65E-10 $Pa{\cdot}m^3/sec$
355940	K-VC89	SS416	4.25E-10 $Pa{\cdot}m^3/sec$
355411	D-ZLaF52LA	SS416	2.24E-10 $Pa{\cdot}m^3/sec$
390137	LightPath BD2	SS316	> 10E-9 $Pa{\cdot}m^3/sec$
		6061 T6	> 10E-9 $Pa{\cdot}m^3/sec$
		SS304L	> 10E-9 $Pa{\cdot}m^3/sec$
		Inconel 718	> 10E-9 $Pa{\cdot}m^3/sec$

Polarization Disruption

Along with optical performance with a random polarized light source, such as that of an interferometer used to create the images in Figures 12 through 15 above, polarized light sources are also used in optical systems that could contain IPGM lenses. The possibility of adding stress to a lens by molding has provided reasons for investigating the effects on polarization before, and it has been documented that a stress condition can be created in a lens using traditional PGM process[22]. Now with the addition of a metal insert to shrink around a lens during the IPGM process the potential for more polarization disruption due to birefringence from stress in the glass exists. The refractive index of a translucent material changes as load and consequently stress is introduced to the material. Stress birefringence happens because of this index change in the plane of polarization which causes polarization retardance. A relation can be formed between the principal stresses and the amount of polarization retardance; however this paper only seeks to prove that a disruption in polarization could occur due to the IPGM process and make some comments on the effect.

In order to determine if there was any effect on the polarization of the light passing through an IPGM lens a polarized light source of λ=488nm was used. This beam was aligned with a linear polarizer on a rotating stage and a detector was placed at the end of the setup. When the linear polarizer is rotated to a parallel orientation with the polarized light source transmission is at a maximum and the detector is set to reference this as a 0dB attenuation of the light. Then the linear polarizer is rotated to an orthogonal orientation with the source polarization until the beam is attenuated to maximum. The maximum was typically in the range of 31dB of attenuation for a non IPGM lens and as the lens was rotated the transmission stayed relatively constant ranging from the maximum of 31dB to 29dB. These measurements indicate that a PGM lens of this design does not inherit an overbearing pattern of stress in the lens. Investigating this one step further, a simple polarimeter was used to capture images to visually examine the stress birefringence pattern.

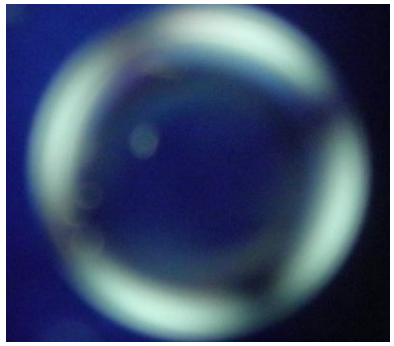

Figure 16. PGM lens polarimeter image.

Figure 16 shows that the lens has very little polarization disturbance across the physical aperture because of the lack of light and dark transition zones. To the naked eye a non IPGM lens has a slight cross pattern; however the camera has a hard time picking up the slight contrast differences. The pattern is indicative of the small variation in attenuation when the lens was rotated in the polarized test setup.

IPGM designs which included four different insert materials and three different glass materials were studied in this fashion. The insert materials are the same from the interferometer measurements: SS410, free cutting brass, Kovar, and SS304L. Three different glasses were tested in this manner with each of the insert materials: CDGM D-ZLaF52LA, CDGM D-ZK3, and CDGM H-QK3L. After a few tests of the insert molded lenses it became clear that there was a definite effect on the polarization for a few of the insert materials. As expected the Kovar inserts had a small, if any, effect because of the lower interface pressures. Both of the stainless steels seemed to have similar effects across all of the glasses. The lenses molded in brass showed an effect, but the pattern appeared slightly different than the effect of the steel when rotating the lenses. The table below lists the range of measurements taken from each configuration as the lenses were rotated.

Table 6. Polarization Drift Test Results – Maximum and Minimum Attenuation between two Polarizers

		Minimum	Maximum
D-ZLaF52LA	Stainless steel 410	9 dB	29 dB
	Brass	6 dB	24 dB
	Kovar	27 dB	29 dB
	Stainless steel 304L	18 dB	29 dB
		Minimum	Maximum
D-ZK3	Stainless steel 410	18 dB	30 dB
	Brass	12 dB	25 dB
	Kovar	28 dB	30 dB
	Stainless steel 304L	9 dB	29 dB
		Minimum	Maximum
H-QK3L	Stainless steel 410	7 dB	20 dB
	Brass	24 dB	30 dB
	Kovar	N/A	
	Stainless steel 304L	13 dB	29 dB

In order to verify what was observed from the polarization test setup the IPGM lenses were also photographed in a simple polarimeter to observe the stress patterns. As predicted from the test the steels both showed similar patterns, while the brass inserts created a different pattern. The steel inserts created a cross shaped pattern of stress in the lens which is typical from uniform radial pressure. The brass pattern differed slightly and showed two semi-circular arcs extending from each end of the lens and the two did not meet in the center. This could explain the improved performance improvement seen in the test when compared to the steel counterparts. The Kovar inserts appeared as if very little stress remained in the glass, very similar to the non IPGM lens. Below are the photos of the different materials and their respective patterns. There were no Kovar lenses that remained in the inserts for H-QK3L glass, so the photo has been omitted.

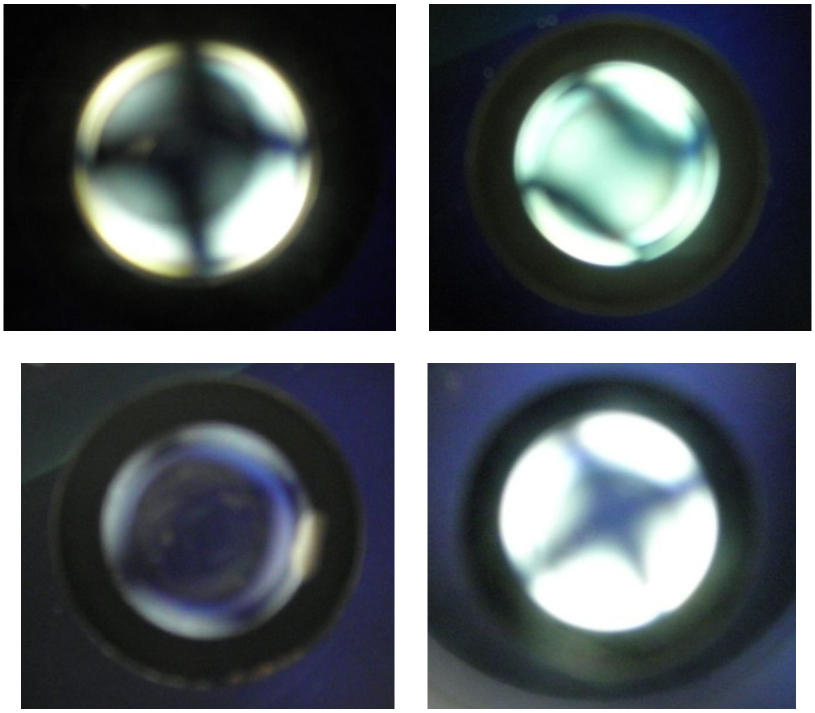

Figure 17. D-ZLaF52LA polarimeter images. From top left SS410, brass, Kovar, SS304L

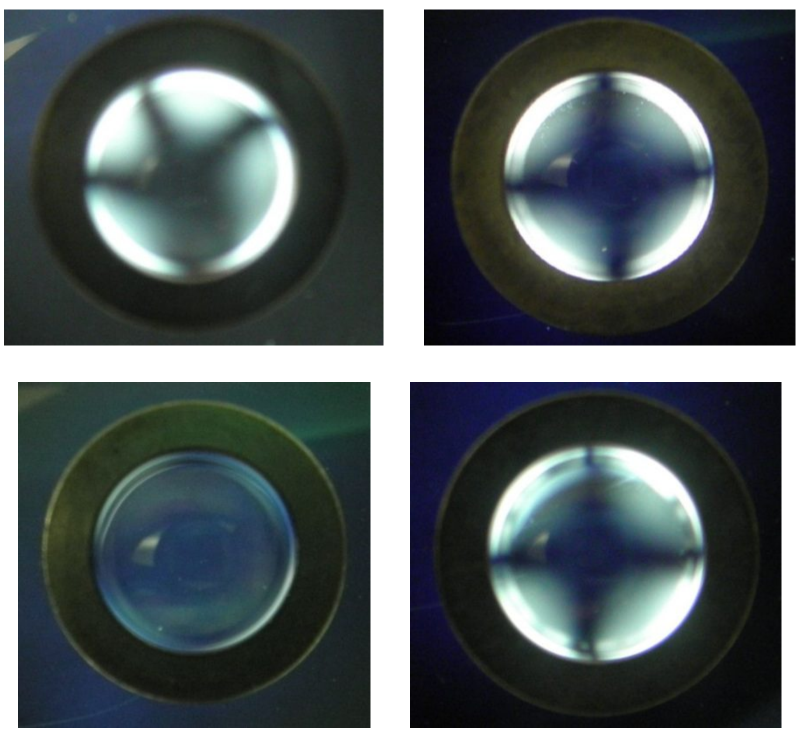

Figure 18. D-ZK3 polarimeter images. From top left SS410, brass, Kovar, SS304L

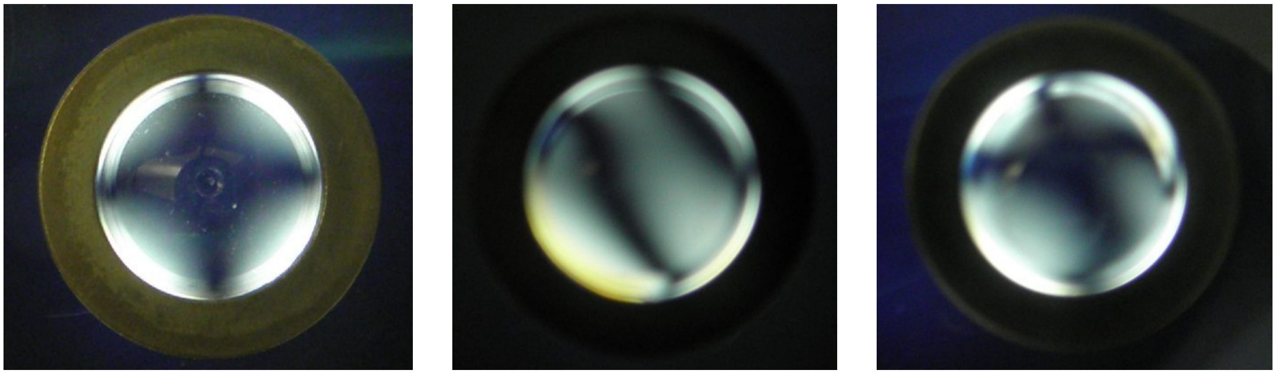

Figure 19. H-QK3L polarimeter images. From left to right SS410, brass, SS304L

Aspheric Surface Profile

The aspheric surface or surfaces of an optical design are precisely machined into tooling specific for that design. This fundamental method does not change from PGM to IPGM. The whole idea revolves around having a mold that has a surface that can be replicated many times over until the surface degrades and a new mold needs to be manufactured. It is important to check that the mold surfaces are being accurately replicated on a lens surface. An interferometer test similar to the results above will tell you if the lens is functioning as intended but may not be applicable to all lenses. It is often helpful to know how the form transfers from the mold to the glass optic to improve mold manufacturing. Ideally both forms of measurement, interferometer and surface profilometry, create a more complete picture for determining the success of the design. Concerns may arise when insert molding lenses that added stress may misshape the intended surface profile of the lens design. A Taylor-Hobson talysurf profilometer was used to define the profile of the mold used in the IPGM process and is compared against the lens surface. The surface profile data from the two aspheric cavity molds used to manufacture the lenses used in this experiment can be seen below.

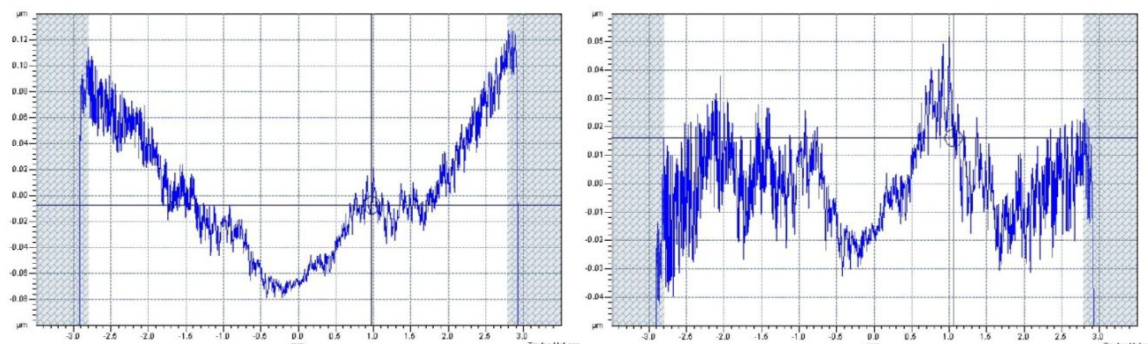

Figure 20. Mold #1 Surface Form Plot (left) & Optimized Radius Form Plot (right)

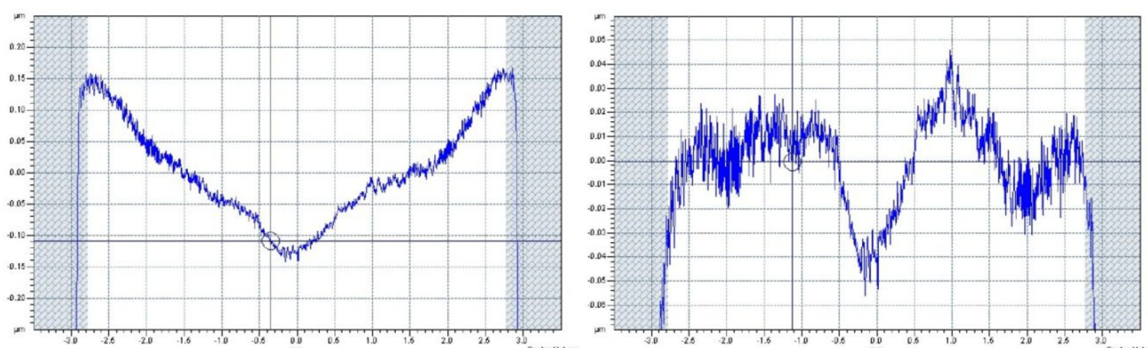

Figure 21. Mold #2 Surface Form Plot (left) & Optimized Radius Form Plot (right)

These figures represent, visually, the error in the surface of the mold. The first mold, Figure 20, had a RMS error of 47nm from the surface form plot, and when the radius was optimized the deviation between the design radius and best fit radius was 0.959µm. The RMS error for the optimized radius plot was reduced to 14.6nm. The second mold, Figure 21, measured a RMS error of 80nm and when the radius was optimized the difference measured 1.680µm from the design. The RMS error with the optimized radius was reduced to 17.7nm for the second mold pin. These values are well within the standard tolerances for mold manufacturing.

The tooling is designed with a slightly modified profile when compared to the intended final shape of the optic. This compensation is used to predict the small amount of change in the shape due to shrinkage and the thermal differences of the two materials. After the tooling has been measured and verified to be within the tolerances for manufacturing a good lens they are put to use in the molding machines. Following the steps provided in Figure 1, lenses are manufactured and then measured in the same manner as the mold. The measurement data can then be compared along with the optical performance data from the interferometer to ensure that the final product is as intended. Following the old adage function over form, typically optical performance supersedes surface form data, but the two measurements combined offer a complete picture of the design. Below are the surface form plots and the optimized radius plots for the different glass and insert combinations.

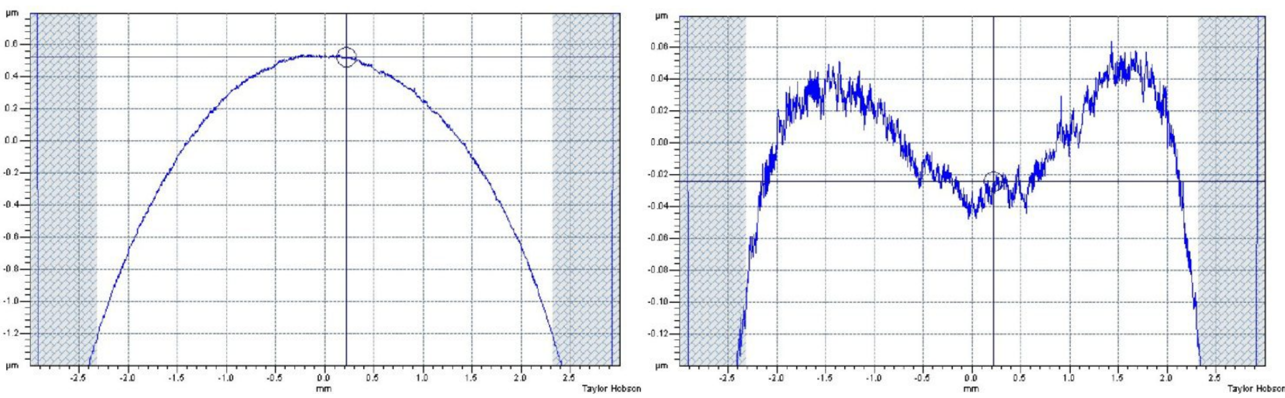

Figure 22. D-ZLaF52LA lens in a Stainless Steel 410 insert Surface Form Plot (left) & Optimized Radius Form Plot (right)

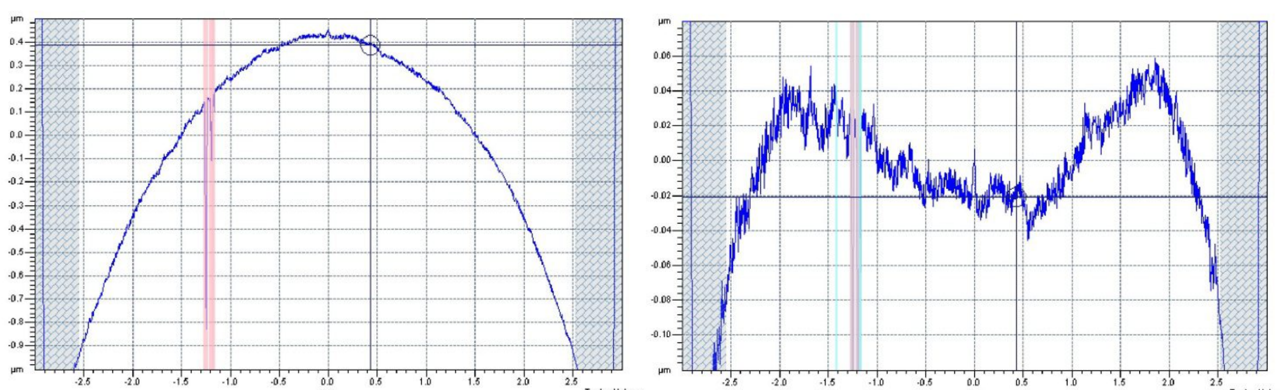

Figure 23. D-ZLaF52LA lens in a brass insert Surface Form Plot (left) & Optimized Radius Form Plot (right)

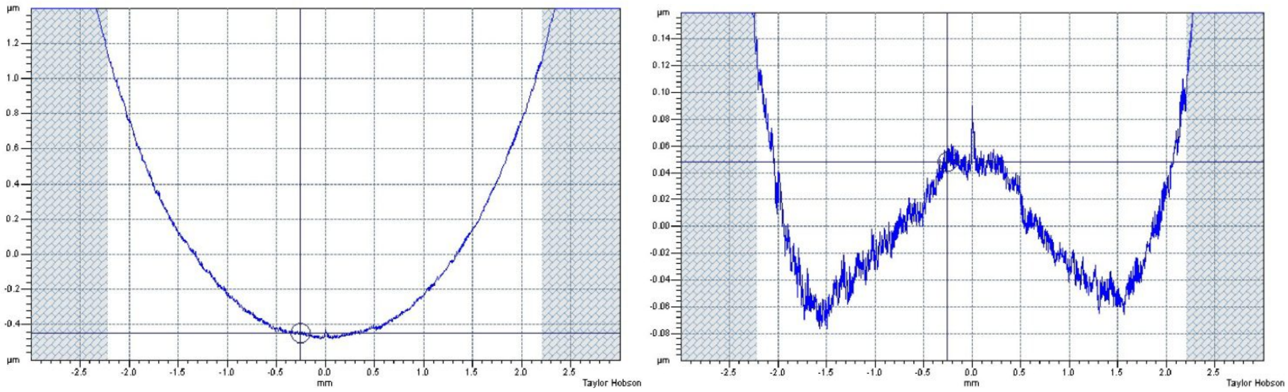

Figure 24. D-ZLaF52LA lens in a Kovar insert Surface Form Plot (left) & Optimized Radius Form Plot (right)

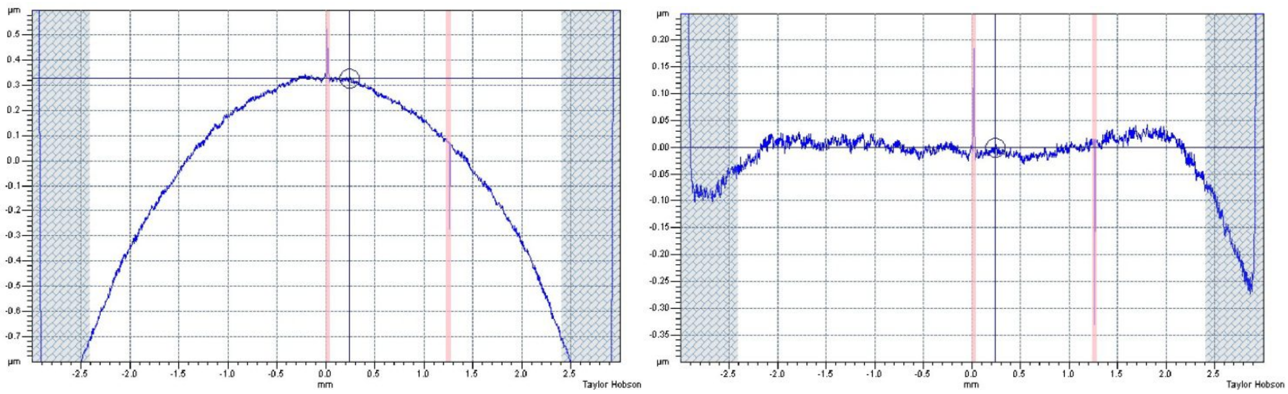

Figure 25. D-ZLaF52LA lens in a Stainless Steel 304L insert Surface Form Plot (left) & Optimized Radius Form Plot (right)

These measurements show that all of the D-ZLaF52LA combinations missed the target radius short. The SS410 difference between design radius and optimized radius was -15.5µm; the brass missed the target radius by -9.9µm, and finally the SS304L was off by -8.8µm. The short radii for these three cases imply that the compressive force of the insert contracting as it cools has some effect on the form of the lens. The opposite was seen with the Kovar insert. In the case of the Kovar the radius was long and the optimized radius missed by a positive value of 16.6µm. The Kovar insert was not applying a compressive force, and possibly even applying a tensile force which either allowed the glass to expand past its designed radius, or actually pulled the radius long by way of a chemical or other type of bond between the insert and glass. Although these lenses all missed the design radius, and therefore were slightly off the designed form, the RMS error and best fit RMS error values were within or very near typical manufacturing tolerances. The RMS error for the SS410 insert assembly was 50.6nm, and when optimized to the best fit radius the RMS error was reduced to 34.5nm. When the brass assembly was analyzed it had a RMS error of 33.4nm, and after optimization the RMS error was reduced to 20.1nm. The RMS error for the Kovar insert was 59.3nm and when the radius was optimized the RMS error increased slightly to 64.9nm. The SS304L insert assembly had a RMS error of 35.8nm and after optimization the RMS error was reduced to 24.8nm. It is important to keep in mind that although some of these form specs may be near the edge or beyond PGM manufacturing limits, these lenses all passed optical inspection. The surface form data allows for a more thorough picture of the true functionality to be seen.

4. CONCLUSIONS

4.1 Advantages and Design Considerations

Insert Precision Glass Molding is a viable manufacturing technique for many different optical systems and applications, from high index glass molded into gold coated metallic inserts to chalcogenide glass for quantum cascade lasers molded into a metallic insert for easy assembly in large arrays IPGM. Controlling optical centration is made easier by IPGM and is only limited by machining capability. Similar to plastic injection molded optics, mechanical features can be incorporated into the design of an insert for alignment or mounting purposes. A metal surface can be used to weld an IPGM assembly directly into its final assembly, and there is no need for epoxy or extraneous materials. The possibilities are seemingly endless.

In order to effectively design an IPGM assembly careful attention must be paid to certain aspects of the design. Material selection is important and is the main driving factor behind the success or failure of an IPGM design. Thermal expansion differences create a compressive or tensile force depending on the differential relationship between the glass and the insert's thermal expansion coefficients. In cases where the interface pressure is too low, the assembly may not remain as a solid unit causing the optic to fall out or the optical surface form can be distorted. In cases where the interface pressure rises above the acceptable range glass can be exposed to forces that are too large and the glass may crack or optical performance can be distorted severely. Once the appropriate materials have been selected it is important to volumetrically fit the preform. Increasing tooling life by practicing good design methods by increasing counter bore diameters to minimize sharp points on tooling also helps with manufacturability. Using the appropriate design criteria IPGM is a viable method of manufacturing precision optics with benefits that include but are not limited to ease of mounting, welding directly to final assembly, increased centration, and eliminating extraneous materials such as epoxies.

4.2 IPGM Manufacturing Limitations and Experimental Results

An IPGM lens shows no different traits than a PGM lens optically. One trait that a PGM lens would not encounter unless bonded to a separate holder would be joint strength. The results found from the experiments showed that in general IPGM lens designs with higher interface pressure due to thermal expansion mismatch and other factors require more force to remove from the insert. Kovar proved to be the least effective material all around for creating a monolithic IPGM assembly. Other bonds such as a chemical reaction between the glass and metal may be a factor in the bond strength of IPGM assemblies; however more specific research to this phenomenon is required. Related to the bond strength is the hermeticity of the completed assembly. A He leak test of IPGM designs showed that a near gas tight seal can be formed in an IPGM assembly. As interface pressures rise, so does the resulting stress in the lens. Stress in glass causes birefringence and creates a polarization drift when a lens is rotated in a polarized beam. Stress patterns were shown with a polarimeter and lower interface pressure designs had less of an effect on the polarization of a light beam passing through the optic. The compressive and tensile forces present in IPGM lens designs appear to have an affect on the final form of a lens' optical surface. Compressive forces caused a shortening of the designed radius and a net zero or partially tensile force caused the final form of the lens to miss the radius long.

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