Analysis of Lens Mount Interfaces

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ABSTRACT

Lenses are typically mounted into precision machined barrels and constrained with spacers and retaining rings. The details of the interfaces between the metal and the glass are chosen to balance the accuracy of centration and axial position, stress in the glass, and the cost for production. This paper presents a systematic study of sharp edge, toroidal, and conical interfaces and shows how to control accuracy, estimate stress, and limit production costs. Results are presented from computer models, finite element simulations, and experimental testing.

Keywords: lens mounts, lens seats, lens survivability, lens stresses geometric dimensioning & tolerancing

1. INTRODUCTION

Lenses are typically mounted into metal barrels that use well defined, accurately manufactured surfaces that contact the polished glass surfaces. Additional spacers and retainers also contact the lenses to hold the lens in place. This paper summarizes both the art and the science that are used for the design of the glass to metal interfaces. We focus on three common configurations of lens interfaces – the sharp edge, a radiused toroid, and a conical or tangent interface. The intent of this analysis is to develop a greater understanding of what factors affect the accuracy of a lenses location within an optical mount as well as how different lens interfaces can influence the survivability of a lens.

The most accurate method of mounting a lens uses the polished optical surface itself as an interface datum. This method of mounting a lens provides the greatest potential for accuracy, but it can create highly localized contact stresses on the optical surface. These stress concentrations may or may not create issues with survivability that must be accounted for.

The details of the glass to metal interface, or the lens seat, provide the accuracy for positioning the lens. A toroidal lens seat refers to the standard rounded edge that a lens seats against. As the radius of the rounded edge reaches the minimum limit, the seat may be considered to represent the "sharp edge" lens seat that is most common in optical mounting. The conical lens seat refers to a lens seat that is designed and manufactured to be tangent to the curved surface of the lens at a specific axial radius. This cone shaped lens seat is also referred to as a "tangent lens seat" for the tangent nature of the interface. This seat is usually chosen because of an increased area for the distribution of contact forces, but there can be a trade-off for accuracy in manufacturing and inspection.

This paper will start by looking at mounting basics and achieving tight mechanical tolerances. In this section, the geometry and dimensioning of the toroidal and conical lens seats will be explored in detail. In the next section the focus of this analysis will shift to estimating the survivability of a lens and the reasons why one lens seat might be preferred to another.

2. ACHIEVING TIGHT MECHANICAL TOLERANCES

There are a few general considerations that need to be taken into account when it comes to achieving tight mechanical tolerances. In most opto-mechanical systems, cost is a factor that must be considered and can have an effect and be affected by the design. Focusing on the necessary tolerances of a design is not always obvious, but is important for not only the cost but also the manufacturability of a design. The capabilities and the standard practices of machine shops will vary but being aware of how they operate and what you can expect can also affect a design. Another feature of a design that can have larger than expected impacts on the survivability and accuracy of lens interfaces is the notes section of a drawing.

The cost of a design is driven by many factors. For the cases that are being analyzed here, the cost considerations will be limited to the number of features present and the level of the drawing's tolerances. When looking at a specific part, it is

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important to note that the more features a part has and the more tightly it is dimensioned will be driving factors in the difficulty of manufacturing a part and therefore the cost. It is therefore, more efficient and effective to develop designs that meet the system requirements with the fewer features designed and dimensioned. This method can improve accuracy as well.

In order to keep tight the necessary tolerances of a design and relax the tolerances of unimportant features, it is important to know what degrees of uncertainty are present in our chosen mounting interface. In Figure 1 there are three examples of lens mounting interfaces. On the left, there is the sharp edge lens seat which has the fewest degrees of uncertainty. In the middle is the toroidal lens seat which increases in features that need to be tolerance and detailed. On the Right is the conical lens seat which can be dimensioned in a few different ways, it also has more degrees of uncertainty than the sharp edge seat.

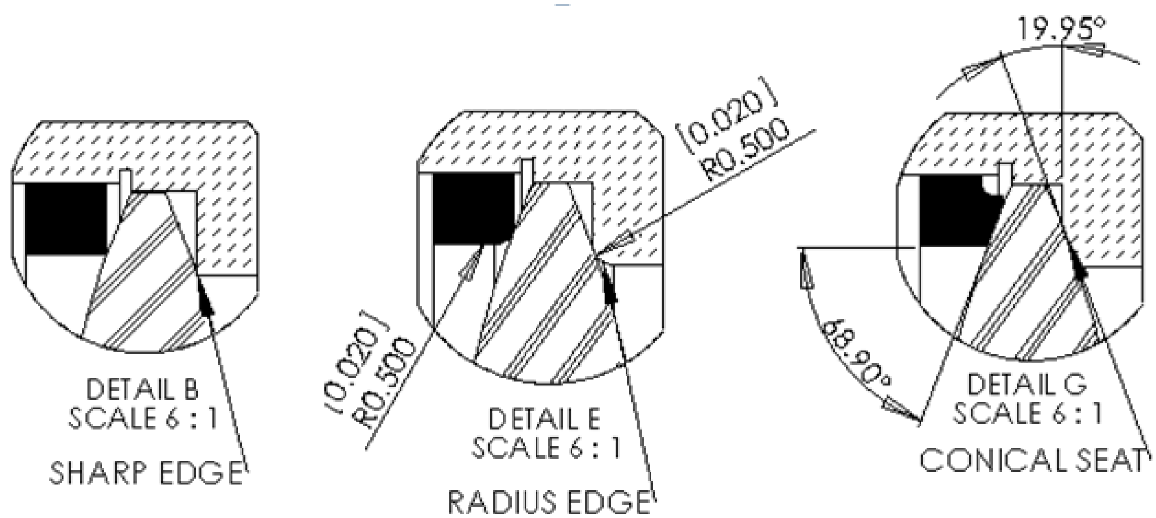

Figure 1. Design examples for sharp, toroid and conical lens interfaces. Each interface can be called out in the engineering drawings with specific notes for manufacturing. More details are required for a complete design, but these are good examples to start with for the necessary dimensions.

In the following sections of this paper more detailed examples of these interfaces will be explored in order to illustrate the most important features of the designs. Particular attention will be paid to what these features and tolerances can mean for the positional accuracy of the lens.

For various considerations it is also important that one pay particular attention to the engineering drawing notes and make sure that the tolerances for "unless otherwise specified" section of the drawing are not overly constrained. If the important features are dimensioned correctly, then the unspecified sections should be of little concern. Specifically, it is good to note whether or not all edges should be broken or left harp, what angular tolerances are present, and if there is a max radius for sharp corners.

Machines shops that have experience with optics and opto-mechanical elements have many variations when it comes to their methods, standards, and limitations for manufacturing accuracy and inspection accuracy. It is good practice to have a clear understanding of what their capabilities and standard procedures are when it comes to a design. By picking a machine shop that sees the design's requirements as standard, should provide a better end result along with a better cost level.

Now a few specific cases of how various manufacturing and inspection uncertainties may affect a final manufactured lens system will be examined. The specific changes that can be expected to show up for a toroidal lens seat and for a conical lens seat will be detailed.

2.1 The Toroidal Lens Seat

As was mentioned earlier, the toroidal interface is one of the most commonly used lens mounting interfaces that there are when it comes to standard lens barrels. The reasons for this are many, one of which being that the minimum toroidal limit, earlier referred to as the "sharp edge" lens seat, is one of the easiest and quickest to design, manufacture and inspect. The sharp edge and the toroidal interface are also the only methods available for locating a concave lens on its optical surface with a high degree of accuracy.

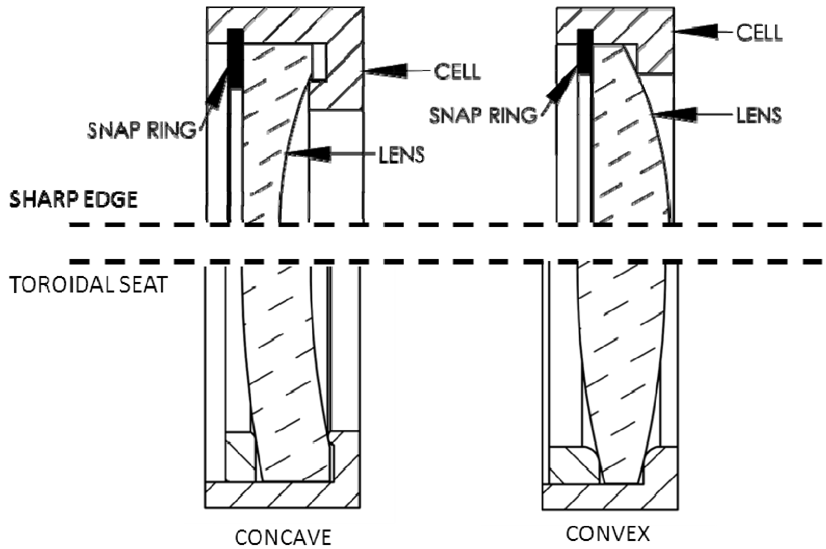

Figure 2: Examples mounting concave and convex surfaces on a sharp edge or toroidal lens seat. Also shown are different classes of retaining rings.

There is a good reason that the sharp edge lens seat is the most commonly used lens seat, as well as the most easy to design, manufacture and inspect. There are only two features that define the sharp edge accurately. As long as the bore diameter of a lens barrel is large enough to accommodate a lens to be fully seated on the sharp edge, then the only two variables determining the location of the lens vertex are the axial position of the seat and the bore of the lens seat. The cylinder of the bore intersecting the plane of the seat plane create a circle in space in which the lens is able to seat.

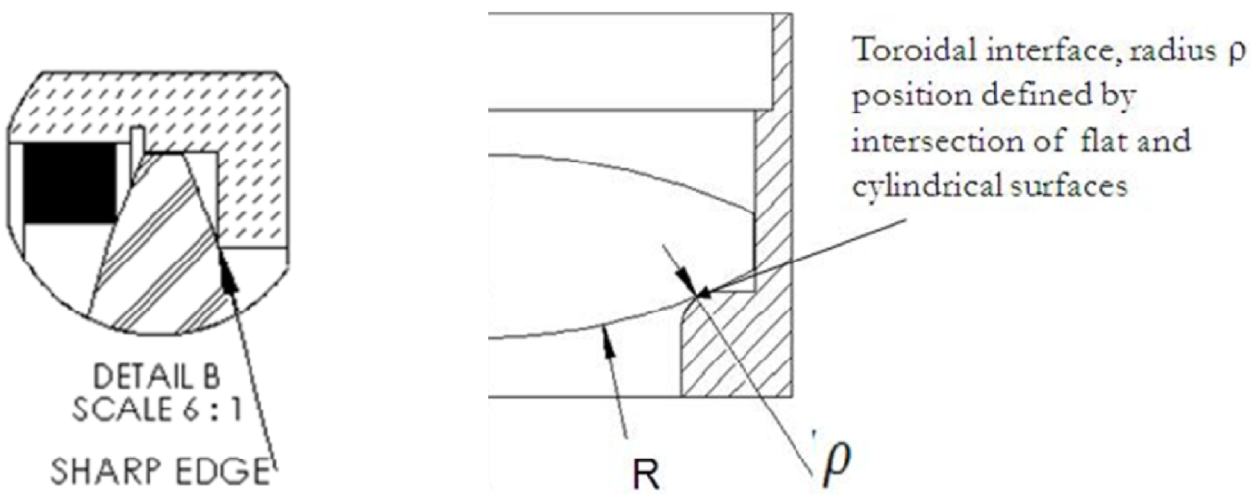

Figure 3. The sharp edge lens seat is never perfectly sharp. The "sharp edge" usually has a value from .1mm to .05mm

Although, there are only two intersecting geometrical shapes that define the sharp edge seat, it is not a perfectly sharp edge. The sharp edge lens seat will always have some radius to it. It should be noted that a sharp edge may vary depending on where the parts are being manufactured. For this reason it is a good practice to note a maximum sharp edge radius for corner features. The typical radii for sharp edges ranges from .1mm to .05mm. When a sharp corner is called out on a drawing and a radius of ρ is obtained, the axial shift of a lens vertex, ΔZ, from a perfect sharp corner to a toroidal seat of finite radius ρ is defined as:

$$\Delta z \cong \frac{r}{R}\rho \tag{1}$$

where R is the radius of curvature of the lens and r is half the seat bore diameter.

Breaking Edges or de-burring a sharp edge lens seat can degrade the accuracy of the seat due to the way that the operation may change the geometry of the interface. One problem, though, is that it may be difficult to inspect or characterize an unknown value for the toroidal seat. For this reason it is important to note on drawings that a sharp edge seat should either be left sharp, or a maximum radius should be called out for all corners.

A burr, which is a material build up from a machining operation, most typically on a lathe or milling machine, can also cause issues with accuracy and survivability. Seating a lens on a chamfered edge provides an obtuse angle to produce the sharp edge lens seat. This leads to less build up during machining and a smaller likelihood of producing a burr that would need to be removed which would result in a loss of accuracy for your lens seat. [1]

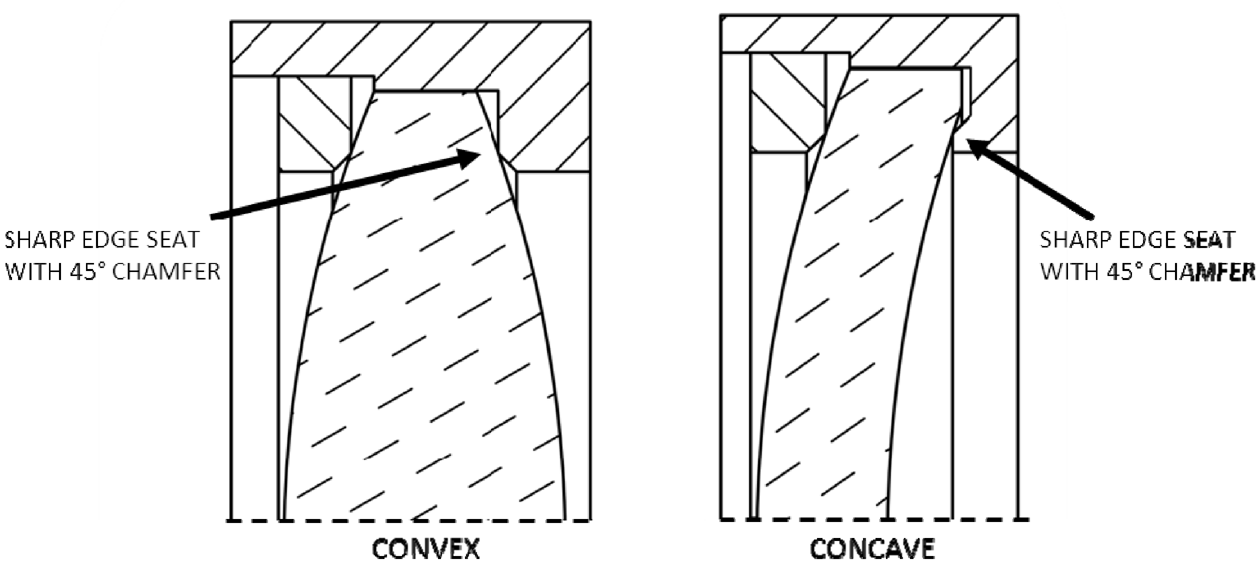

Figure 4. Two examples of a sharp edge lens seat chamfered at 45° to reduce the likelihood of burrs developing on the lens seat

In some cases it is desirable to define a specific toroidal radius, ρ, that is greater that the sharp edge limit. In this case, the degrees of uncertainty increase by one. The location of the lens is now dependent, not only on the bore of the seat and the plain of the axial seat, but also on the radius of the corner which must is more difficult to maintain and inspect.

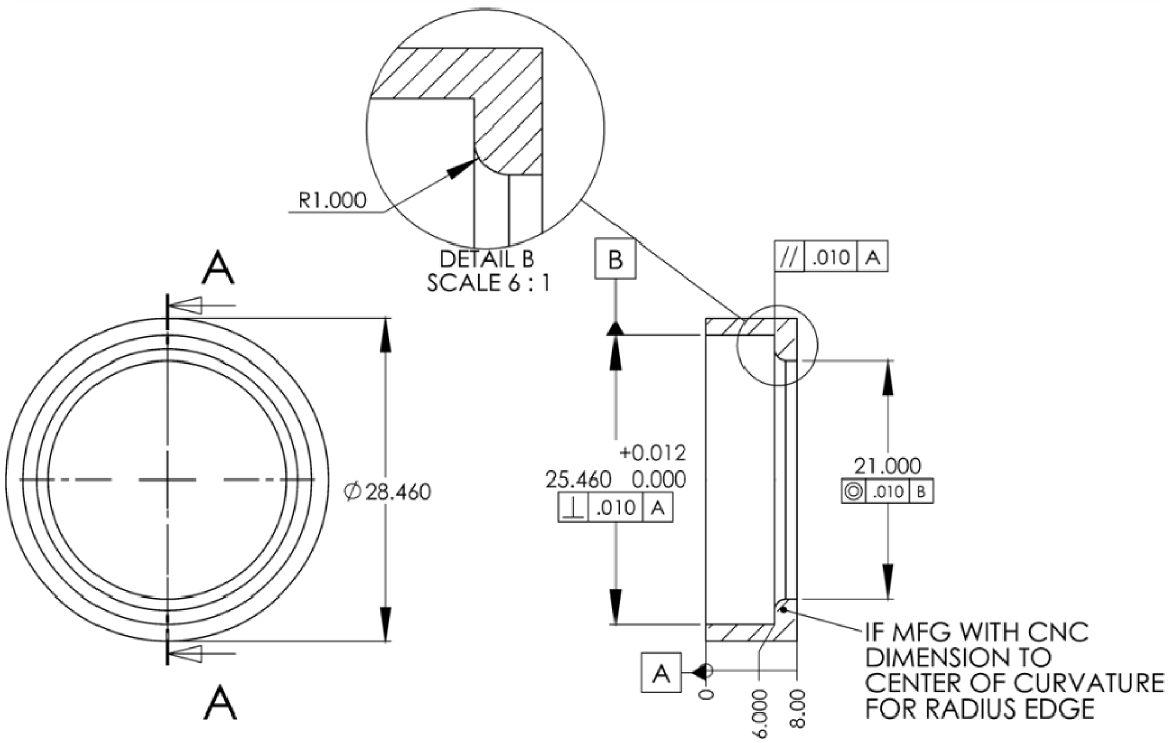

Figure 5. An example of a Toroidal lens cell engineering drawing. This example shows a detail which specifically calls out the radius of the toroidal lens seat. The number of decimal places determine the required tolerance in this case. A bi-lateral tolerance could be used just as easily.

Figure 5 shows an example a toroidal interface being specified. The depth of the barrel is left at a lower tolerance than all other dimension since that is not critical for this specific example. The critical features of this design are the flat surface which is called out by a parallelism specification in relation to another plane feature which is denoted by the datum A. For this design the cylinder that features the toroidal lens seat, our seat bore diameter, is called out to be concentric to datum B by a particular specification. The fact that this dimension is called out to 3 decimal places shows that this is also an important feature. In detail B of this figure, the radius is called out to within 3 decimal places and this is an important feature of the design. The radius of the toroidal interface should be called out with or well known to a limit that corresponds with the design's acceptable levels of error. It was noted previously that the three most important features of the toroidal lens seat in relation to axial position are the seat bore diameter, the toroidal radius and the axial position of the lens seat plane. Figure 5 is an example of a design that highlights those features with tighter tolerances.

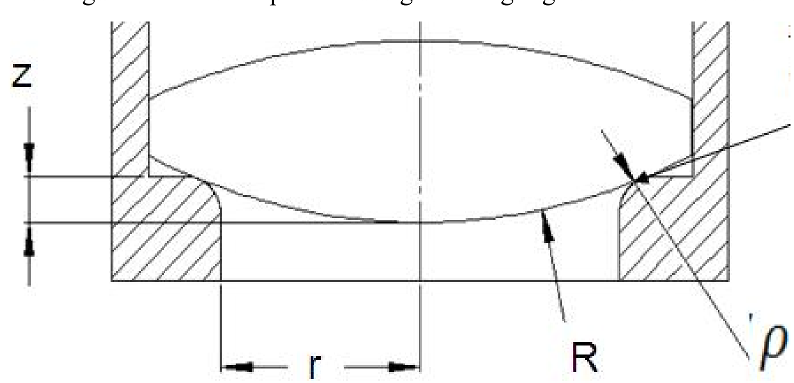

Figure 6. The geometry of the toroidal seat showing the location of the lens vertex with respect to the mounting parameters. This is also valid geometry for the sharp edge lens seat where ρ is 0.05 mm.

In Figure 6, above, we can see with equation (2), below, how the change in the toroidal interface radius can affect the axial position of the lens is shown.

$$z = R + \rho - \sqrt{(R + \rho)^2 - (r - \rho)^2} \tag{2}$$

2.2 The Conical Lens Seat

The conical lens interface is a lens interface that is tangential to the lens' curved surface at the point of interface. This form of contact can be useful for reducing a contact stress for the same preload if compared to a toroidal or sharp edge lens interface. The trade-off for that reduction in stress leads to an increased difficulty for holding the axial location of the lens accurately.

There is an interesting example for designing a conical lens seat that is easier to manufacture and measure than the standard. In figure 7 there are two ways to dimension the conical feature of a lens cell. On the left is a standard way of designing and dimensioning a conical seat with a flat surface followed by our angular cut and a depth dimension. On the right, is an example of a simple angular cut and a depth dimension. This method provides a design with fewer features and manufacturing steps as well as a feature that is easier to locate accurately for machinists. The corner made by the conical seat with the bore diameter is very easy to locate during machining and inspection.

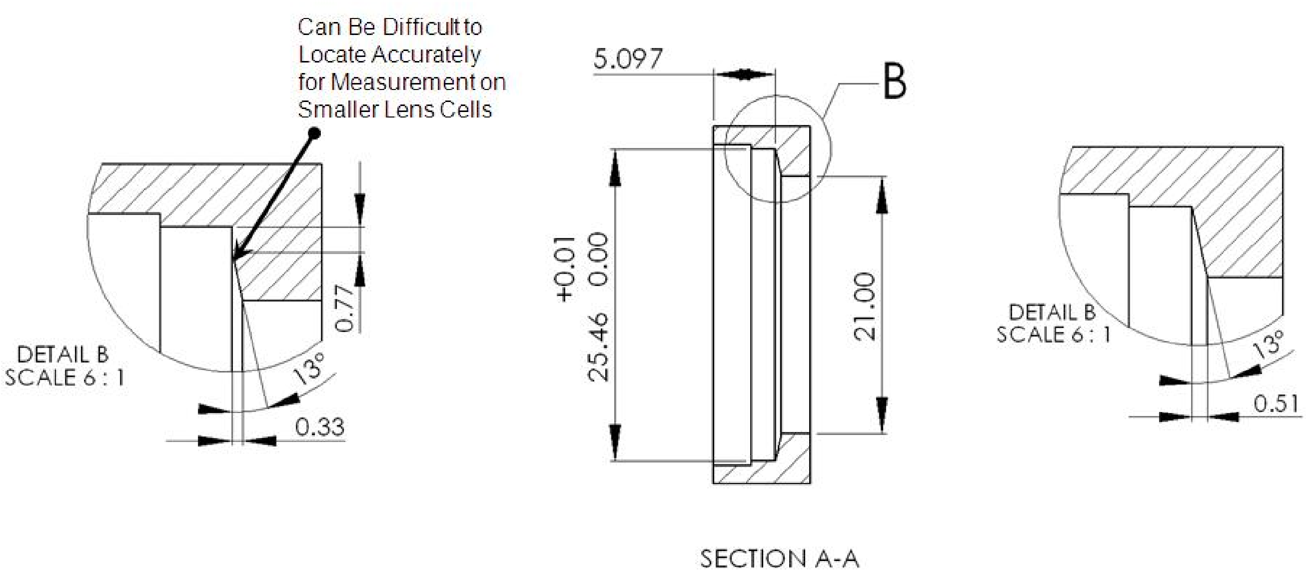

Figure 7. Examples of a standard conical lens seat on the left and another way to design the lens seat with fewer features to dimension.

In the case of angular tolerances the accuracy will be dependent on our ability to hold the cone angle of our tangent surface in relation to the normal of our barrel inner wall, the radial contact distance for our lens and the radius of our cone's start position.

Hopkins and Burge[1] have recently outlined a method for dimensioning a conical lens seat bye the contact radius of a lens on the tangent cone seat. This contact radius becomes a gauge diameter for manufacturing and inspection. By geometrically defining the part in this way, the angle of the taper becomes less sensitive in terms of the axial motion of the lens.

It is especially important to hold the angles of the tangent surface tight in order to ensure that the optical surface of the lens is seated on the flat seat. If the angles drift out of a maximum or minimum tolerance, then the lens will either be seated on its edge, or the sharp corner at the edge of the tangent face will be providing a contact on the optical surface. This is the exact case that was to be avoided by mounting on the conical interface.

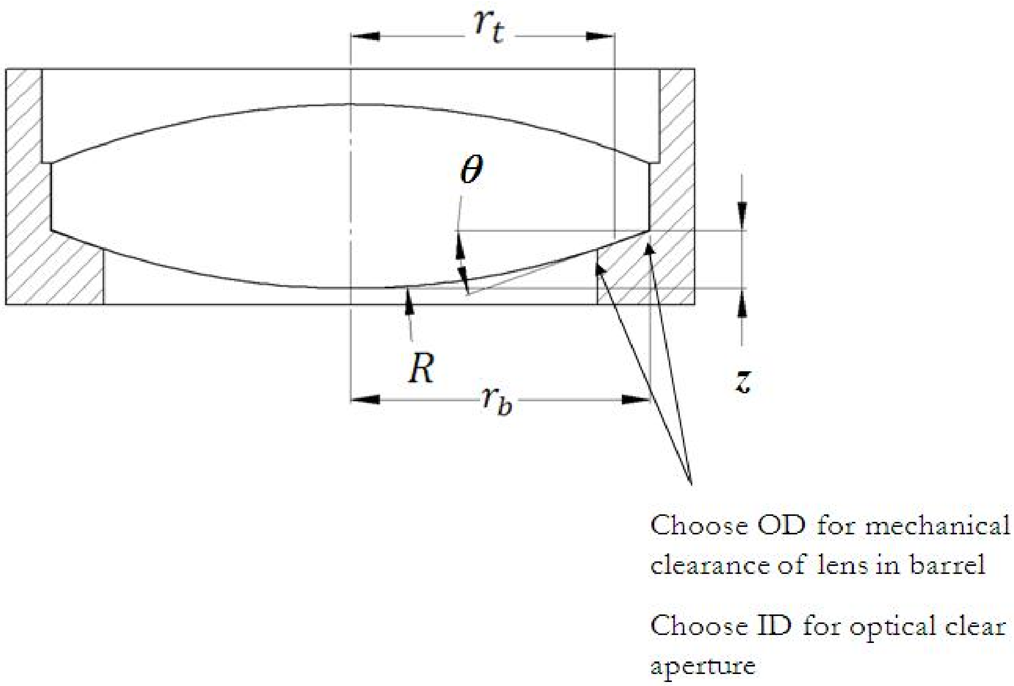

Figure 8. The geometry of the conical lens seat

In Figure 8 it is apparent that the corner of the one which is dimensioned by the angle θ is the same as the radius of the barrel for reasons that were outlined previously. It is important to call out your angular tolerance, which can be done on the specific dimension or in the notes section of your engineering drawings. From these points of interest combined with our lens' radius of curvature we can determine our axial location in z from the following equations referring to the dimensions outlined in Figure 8.

$$\sin\theta = \frac{r_t}{R} \tag{3}$$

$$z = R\left(1 - \frac{1}{\cos\theta}\right) + r_b \tan\theta \tag{4}$$

Where θ is the cone angle for our lens interface, r_b is the radius of our barrels datum cylinder which corresponds to the point at which the cone angle extends from, r_t is the radius for the point of contact between the cone and the spherical surface, z is the position of the lens vertex, and R is the radius of curvature for the spherical surface of the lens.

2.3 Using a Gauge For Manufacturing and Inspection

The use of a gauge to verify manufactured parts can improve accuracy. A gauge, in this case, is a specialty part used for assisting in the measurement and inspection of a lens seat. A gauge could be a sacrificial lens that matches the dimensions of the one to be used in the final system, or a specially designed and manufactured part with a specific radius or shape.

A gauge radius can be specified on a sharp edge lens seat, a toroidal lens seat, or a conical lens seat. In figure 9 a) is an example of how a gauge radius can be dimensioned. In the dimension a reference is made to a part number corresponding to the gauge to be supplied or manufactured.

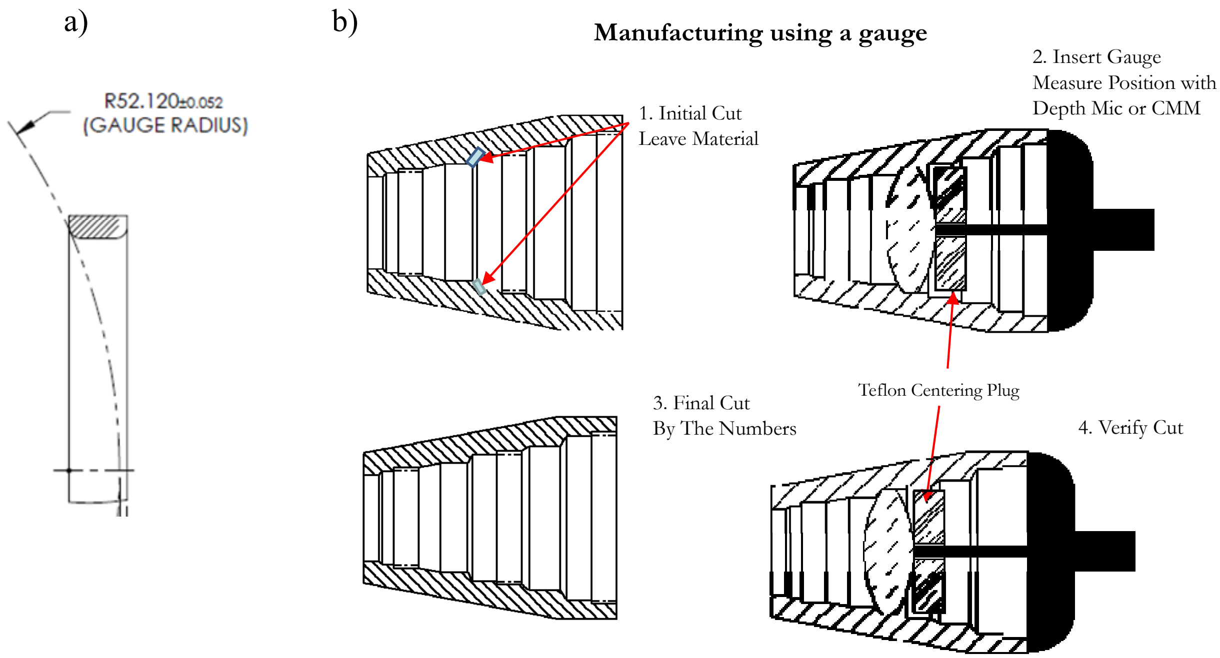

Figure 9. Using a gauge for manufacturing and inspection. a) an example of how to dimension a gauge properly b) the procedure for manufacturing and inspecting a feature defined by a gauge

For a machinist using a gauge, the procedure is rather straight forward. For an example using a sacrificial lens, the machinist will first make their initial cut, making sure to leave an excess of material for future adjustments. Next, they will insert the gauge provided along with some type of centering plug. By measuring the axial position of the sacrificial lens with a depth micrometer or coordinate measuring machine (CMM), the machinist can calculate how to make the final cut. After making the final cut, the machinist can then verify the cut in the same way as the initial measurement was made.

This is useful for working with all types of lens seat interfaces, given that the ability to obtain possibly sacrificial lenses or manufacturing specialized gauges is not limited.

3. ESTIMATING SURVIVABILITY

When it comes to survivability of lenses in our various mounting interfaces there are many factors that we can focus on in order to ensure lens safety. These factors that may lead to reduced glass strength can include micro-flaws in the surface of your part, simple humidity, as well as unexpected point stresses that may result from a burr or a buildup of material on your lens interface.

Micro-flaws, also known as subsurface damage, can be, for the most part, polished out of an optical surface. One issue that arises with subsurface damage is that it cannot be accurately measured or identified by non-destructive means after the polishing process is completed. These flaws, if present in conjunction with atmospheric humidity and global stress fields, can degrade the survivability of an optic.

Humidity and global stress fields can cause a flaw to propagate over time if the stress is of a significant magnitude[2]. Water is a catalyst for lens crack propagation and as such, it is important to avoid high contact localized stress fields when there are global stress fields present in a part. An example of this case would be for an optic that is exposed to high pressure differentials such as a vacuum window.

Burrs or the point stresses that result from them should not be common problems for the specified toroidal or conical lens seats due to their geometry. A method for avoiding burrs on a sharp edge lens seat was previously discussed but it should be noted that parts can develop buildups that would cause point stresses during an anodizing process. A note such as "Dimensions after anodizing" and an indication of the surface quality should prevent any issues that may arise with anodizing a part. This information with a caveat to indicate that point stresses should be largely avoided should be enough for any opto-mechanical designer to prevent point stresses from being an issue to the safety of their lenses.

Mounting interfaces on their own produces compressive and tensile stresses as a result of preload forces. It is important to understand how these different mounting interfaces will produce different stresses in the optic.

3.1 Stress in the Toroidal Interface

The Toroidal case for estimating survivability is well defined in some cases. For the sharp edge lens seat, axial contact stresses can be very high, these stresses are highly localized and for most environments and applications, these stresses are acceptable. Under typical conditions, glass can survive compressive stress of 50,000 lbs/in^2 and tensile stresses of about 1000 lbs/in^2 [3]. The tensile stresses are the limiting factor in most cases. Cai and Burge have determined that these estimates may be too conservative for polished optical glass.

It was mentioned earlier that cracks will propagate over time with stress and humidity. As long as the tensile stress field stays shallow, any micro flaws or subsurface damage that may be present on the surface of on optic will not propagate.

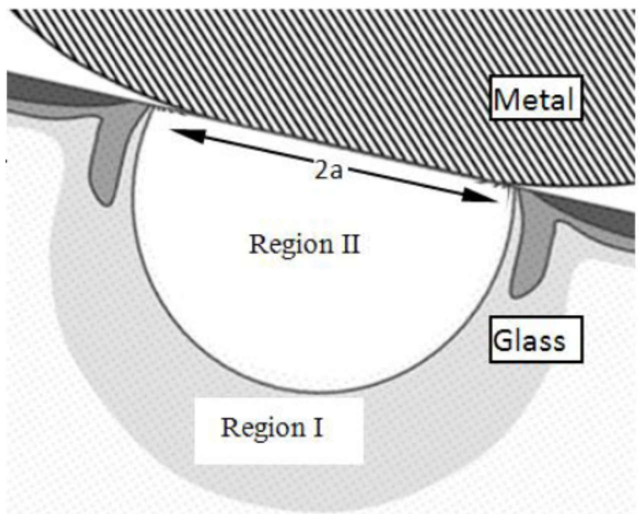

Figure 10. The stress field produced by a sharp edge lens seat. Region II is under compressive stress, Region I is experiencing tensile stress. The darker the stress field, the greater the tensile stress. [2]

If no flaws reach the critical depth in the presence of a high intensity deep stress field, then the lenses will survive. The stress intensity factor,

$$K_I \approx 2\sigma_0\sqrt{a} \tag{5}$$

is roughly equivalent to two times the nominal tensile stress perpendicular to the crack plane, σ_0, multiplied by the square root of the flaw depth, a. The fracture toughness, K_{IC} is the critical value of the stress intensity factor at which a failure of the optic may occur.

It has already been mentioned that the highest localized stresses will be produced by the sharp edge lens seat. Cai and Burge have demonstrated that there is no loss in strength for axial preload stresses under 100 lbs/in for a sharp corner interface. With typical preload torques around 10in-lbs, a preload force of only 16 lbs/in is applied for a 1 inch diameter barrel.

If larger lenses are being mounted, or there are global stress fields present, than it is important to mitigate the risks associated with high stress fields. For this reason, a designer should consider working with either a toroidal lens seat with a larger value for ρ or a conical lens seat.

The toroidal lens seat can be considered to live between the radii limits of the sharp edge on the lower limit and the tangential or conical interface at the upper limit. Because of this basic understanding of the interface we can note that as the radius of our toroidal interface increases, the stress experienced by our lens will decrease.

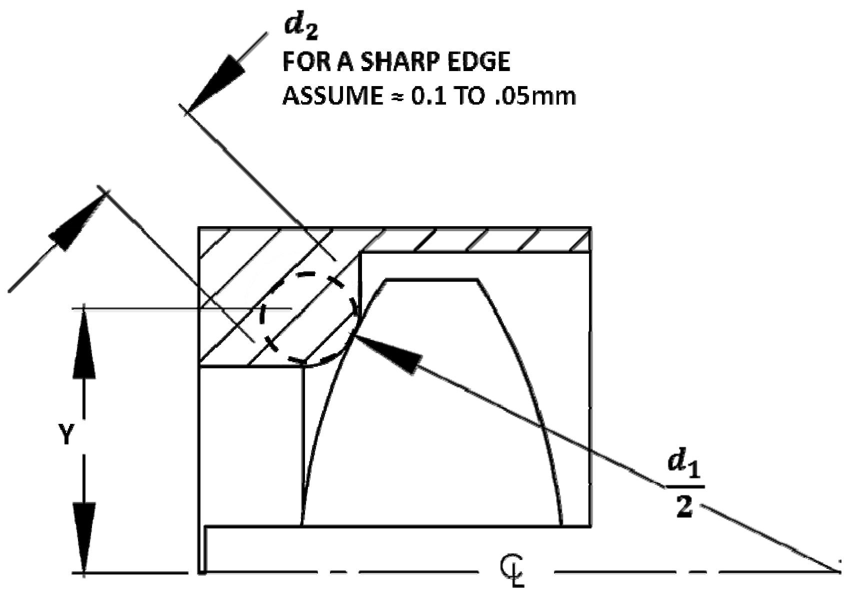

Figure 11. The sharp edge and the toroidal lens interfaces stresses are equated to two cylinders in contact with each other. Adapted from Yoder [3]

Yoder [3] and Vukobratovich [4] have adapted a method from Roark for computing the axial compressive stress in a lens mount with a toroidal lens seat. This is also the same method for dealing with the stresses that result from a sharp edge lens seat. The equation for calculating the stress is reproduced below.

Axial compressive stress, σ_A, is defined as

$$\sigma_A = 0.798\left[\frac{\frac{F(d_1+d_2)}{2\pi y d_1 d_2}}{\left(\frac{1-v_g^2}{E_g}\right)+\left(\frac{1-v_m^2}{E_m}\right)}\right]^{\frac{1}{2}} \tag{6}$$

Where F is the retainer preload, d_1 is twice the lens radius, d_2 is twice the toroid or corner radius, v_g is poisons ration for the lens, v_m is poisons ratio for the retainer, E_g is the elastic modulus for the lens, E_m is the elastic modulus for the retainer or seat, y is the height of the line contact on the lens. [3]

3.2 Stress in the Conical Interface

The axial contact stresses resulting from the conical lens interface are lower than those resulting from the toroidal and sharp edge lens seats. This is the case for interfaces with the same preload since the tangential interface provides a greater surface area over which to disturbed the contact stresses. For this reason the survivability is increased by a large margin.

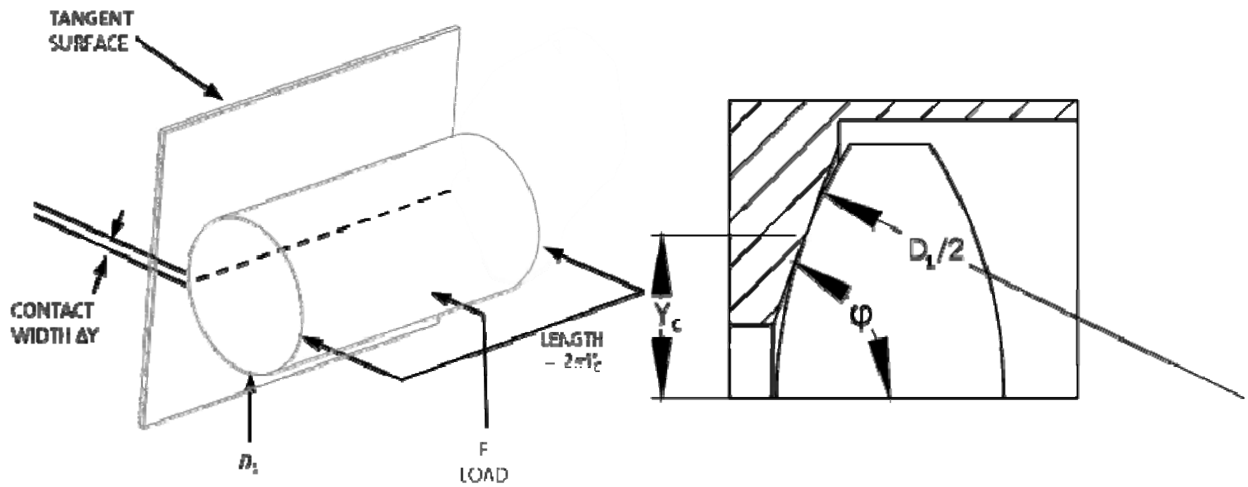

Figure 12. Conical tangent lens interface stresses are equated to cylinders contacting a tangent plane. Adapted from Yoder [3]

Yoder developed a rule of thumb that shows the contact stress resulting from a toroidal surface with a radius 10 times that of the lens radius being seated will be the same as the stress present in a conical lens seat with all else being equal. [3] this gives a good limit at which point we can consider changing our design for a different lens interface.

The axial compressive stress for the tangential surface can be calculated as

$$\sigma_A = 0.798\left[\frac{\frac{F}{2\pi y D_1}}{\left(\frac{1-v_g{}^2}{E_g}\right)+\left(\frac{1-v_m{}^2}{E_m}\right)}\right]^{\frac{1}{2}} \tag{7}$$

Where D_1 is twice the radius of curvature of the optical surface and all other values are the same as in equation (6) from the toroidal interface example above.

4. CONCLUSION

We have explored the factors that are most pertinent to the survivability and locational accuracy of 2 basic lens mount interfaces. We have seen that for both cases we have a trade-off between the ease of optical surface location accuracy and axial compressive stresses experienced by our lenses at their interfaces and retainers. We discussed briefly the other issues that may affect survivability in conjunction with contact stresses as well as the geometry of our lens interfaces and how to calculate the ways in which the errors in our manufacturing may affect the accuracy of our lenses location.

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