Understanding Optical Specifications

Optics can be found virtually everywhere, from fiber optic couplings to machine vision imaging devices to cutting-edge biometric iris identification systems. Despite the many applications that depend on optics, most of our customers are not optical engineers. As a result, they require aid in specifying the correct optical components for the mechanical, electrical, and various other existing applications.

Even qualified engineers send us prints that are at either of two extremes: under-specified or over-specified. In either case, understanding the application is the key to satisfying the needs of the customer. This understanding allows us to offer our advice as to the correct choice of components, specifications and tolerances. These factors need to match the requirements of the application in question and need to justify the associated costs. Simply copying catalog specifications is not the best solution. This article will concentrate on the use of common optical specifications.

SURFACE ACCURACY

After a design is successfully completed, we can determine the characteristics of each optical surface in the system and tolerance them according to manufacturing capabilities. This is done with an emphasis on the value and uniformity of the shape, as well as on the cosmetics of each surface. The maximum allowable deviation of an optical surface from a perfect surface is described by Surface Accuracy. There are several terms associated with accuracy, as follows:

**Surface Flatness** is the deviation for a plano surface such as a window or mirror. When a test plate (typically an optical flat, see Figure 1) is held in contact with the work piece (the part under inspection), a contour map is visible as light and dark bands. These dark bands are called Newton's rings or fringes. Due to the air gap between the surfaces, each ring corresponds to the vertical distance between the test plate and the surface under inspection. Since the test plate in this case is a clear, flat reference, the air gap is very small so the surface flatness is defined in terms of wavelength (very small unit of measure); i.e. 1/4 wave or λ/4. The spacing between rings is equal to one-half the wavelength of the illumination source; i.e. 1/4 wave = 1/2 ring. A monochromatic green light at the 546.1 nm mercury line or helium-neon red laser line at 632.8 nm is used for illumination. Typically, only values less than 1/4 wave are considered to be precision and values less than λ/10 to be high precision.

**Power** is used when dealing with a curved surface to define the deviation of the fabricated surface radius from the radius of an inversely shaped test plate. The test plate is a highly calibrated reference gauge (see Figure 2). This deviation is also referred to as surface fit; i.e. how well the work piece "fits" the test plate. The number of rings visible is used to identify the power of the surface. Again, each ring is equivalent to 1/2 of the test wavelength. The surface is checked using this...
procedure at several different stages of production. Note that even though our optical prints use power and irregularity to specify maximum allowable deviations (see Figure 3), radii tolerances are used for the fabrication of actual test plates.

Irregularity is used to define how the surface deviates from the perfect shape of the test plate, as demonstrated by a spherical or cylindrical surface. Thus, the uniformity of the rings' shape indicates the limit of the surface's regularity. This deviation is also known as surface figure. As a specification, it is important to note that in order to properly inspect irregularity, it cannot be much smaller than the power or else you will not be able to ensure the irregularity value. A typical rule of thumb is to use a maximum power of 4 or 5 times the irregularity. Most optic shops work the power out from a stated irregularity. As a common practice, irregularity is easier and more accurately inspected using a laser-based interferometer, such as our Zygo GPI-XP Interferometer (Figure 4). A power/irregularity ratio of 4/1 is an acceptable tolerance to meet in volume production.
Please note that the overall focal length tolerances provided in our catalog are tested as final overall performance - they are not manufacturing tolerances, but determined from limitations set by the power and irregularity specifications.

SURFACE QUALITY
This refers specifically to the cosmetic condition of an optical element's surface. During the grinding and polishing stages of fabrication, small defects can occur, such as scratches and digs. A scratch is any mark or tear and a dig is any pit or divot in the element's surface. The specification used for the maximum allowable flaws is denoted by a combination of numbers, the scratch number followed by the dig number; for example 60-40. The lower the number, the higher the level of quality. For example, a 60-40 value is common for research and industrial applications, whereas a 10-5 value represents a high quality standard for laser applications.

It is important to note that neither the scratch nor the dig numbers actually correspond to a specific number of defects. Instead, they reflect the quality of an optical surface as determined by a visual comparison to a precisely manufactured set of standards. This process is in accordance with the MIL Spec. Scratch and dig evaluation is defined by the US Military Specification for the Inspection of Optical Components, MIL-O-13830A.

There is no direct correlation between scratch number and the actual size of a scratch on an optical element's surface. As a common reference, the scratch number relates to the "apparent" width size of an acceptable scratch. However, there is some ambiguity since it also includes the total length and number of allowable scratches. Dig numbers do relate to a specific size of dig. For example, a 40 dig number relates to a 400 µm (or 0.4mm) diameter pit. Coating quality is also held to the same Scratch-Dig specification as the surface of an optic.

Surface Quality inspection typically includes additional criteria, such as staining and edge chips. Overall cosmetic inspection also includes defects within the material, such as bubbles and inclusions, including striae. Imperfections of this nature can contribute to scattering in systems involving lasers and image defects (if at or near the image plane). Inspection of surface accuracy and quality is limited to the component's clear aperture.

CENTRATION
Centration is defined as the maximum allowable deviation between the optical and mechanical axes for a spherical lens. The optical axis is defined as the line connecting the centers of curvatures of both lens surfaces (Figure 5). The mechanical axis is the centerline of the outer cylindrical edge of the lens or simply its geometrical axis. The mechanical axis coincides with the rotating axis of the centering machine that edges the lens to its final diameter. This centering process also, in turn, defines the diameter tolerance, which is typically +0, given mounting considerations.

If a ray of light is coincident with the mechanical axis, then a lens will deviate the ray so that it passes the optical axis at the focal plane (see Figure 5). The separation of the two axes at the focal plane is then defined as the decentration, or axial displacement centering error. The centering accuracy value used in optical fabrication is actually twice this value and is often called the Total Indicator Run-out or TIR. The deviation is then the angle equal to the decentration divided by the
focal length of the lens. The concentricity or centration of a lens is typically specified by the deviation angle, however it is typically tested at double the value while the lens is rotated. An angular deviation of 1 to 3 arc minutes is common for precision components.

![Diagram](image)

**Figure 5: Centration**

**EDGE TREATMENT**

There are several terms associated with the treatment of edges. The most basic is a cut edge; this is literally what it means. A large sheet of glass is either "cut" using a scribe and break technique or cored for circular pieces. The edges are left as is which can leave sharp edges. The next edge type is swiped or **seamed edges** which means that all the sharp edges are removed. The final type is a **ground edge** which provides an even mounting surface and gives a uniform cosmetic appearance to the perimeter of the optic. The better the treatment of the edge, the less likely it may become chipped in handling. Edge chips are not permitted within the optics’ stated clear aperture. **Edge chips** are typically defined for optical windows and first surface mirrors to have maximum values of 0.25 to 0.5mm.

**Bevels** are clean ground edges used to prevent edge chips or simply as protective chamfers. Our bevels are defined as maximum face widths at 45°, with a standard tolerance of ±15°. For micro optics, we do not bevel the edges (since the attempt will likely cause chips). Also, we do not bevel the edges for small radii meeting the diameter edge at large angles. If the diameter = (0.85 x radius of curvature), then no bevel is used. The actual clear aperture (CA) value used will typically be smaller than that defined by the bevels with a maximum possible CA calculated as follows:

\[ CA = \text{Dia.} - 2\sqrt{\text{bevel}^2 / 2} \]

**PRISM ANGLE ACCURACY**

Typically, the relative angle between the reflecting surfaces (as in a roof) needs to have a critical tolerance in order to maintain a maximum allowable angular deviation. However, depending on placement in a system, the other angle(s) could be tolerated to limit aberration effects. Angle tolerances for prisms are inspected using an autocollimator with the prism oriented as a retro-reflector. This is only suitable for testing 90° and 45° angles; i.e. as in a right angle prism. Note that although this specification relates to the physical edge of two reflecting surfaces, it is typically tested as beam deviation.

**THICKNESS**

The importance of an element's axial thickness depends greatly on its role in a system and can vary dramatically. Thickness refers specifically to the **center thickness** of a lens or spacing between elements. For curved surfaces, a reasonable operating tolerance runs ±0.1mm. For flat surfaces, however, the production of large
sheets of non-polished glass yields larger variances in thickness. Thickness will vary greatly depending on sheet size and where on the sheet the measurement is made. In order to accommodate this fact a **nominal** tolerance value is used meaning that no specific thickness tolerance is defined. Over time, nominal thickness tolerance has generally been accepted to be ±0.015" to 0.020". Again, this refers to glass that is not polished after fabrication.

If a specific thickness or precision surface accuracy is needed then polishing is clearly required and higher orders of tolerancing can be maintained. Typically, a 6:1 diameter to thickness ratio is used as a rule of thumb for high accuracy plano surfaces in order to prevent warping in fabrication or in the final mounting. Higher ratios may be used for lenses depending on radii and diameter values.

**Edge thickness** is used as a "reference" for lenses meaning that it is not a manufacturing limit. Edge thickness is actually a calculated value which depends on radii, diameter, and center thickness. It is thus used as a reference to indicate physical limitations for mounting considerations.

**MATERIAL**

**Glass Index** and **Abbé Number** values are the most important criteria in comparing one material to the next. The index of refraction is actually a ratio of the speed of light in a vacuum to that of light in a medium (i.e., a specific type of glass). Since the speed of light in any glass varies with the wavelength of light, the index of refraction also changes with wavelength. Typically, a glass is defined at $n_d$, which is the index at yellow helium or 587.6 nm.

Dispersion, or spectral variations in index of refraction, results in differences of focal distances for light of different wavelengths. This means that even though a lens will transmit a particular wavelength, if it was not designed at that wavelength then the performance will not be the same as that stated for the design wavelength. The Abbé number ($v_d$) quantifies the amount of dispersion for a particular frequency range. This defines how much index changes with wavelength and the smaller the value means the quicker the change; $v_d=(n_d-1)/(n_F-n_C)$, where $n_F=486.1$nm and $n_C=656.3$nm. Glasses are typically defined as either crowns or flints. Crown glasses have the following combination of values: $n_d<1.6$ and $v_d>55$ or $n_d>1.6$ and $v_d>50$. Flints define the rest and are typically referred to as high index glass.

Source: Edmunds Optical