Surface Irregularity

Specifying, measuring and meeting surface form error

Surface irregularity is an important design attribute considering surface control and a powerful way to tolerance the surface accuracy of optical elements. Surface irregularities can result from many sources and in many forms and therefore can be difficult to model using optical design software. Surface irregularity can contribute to aberrations because of changes in the expected path of light, so it should be a consideration when designing an optical system. In high-precision optical systems, the effects become more evident, and surface irregularity must always be a consideration.

This paper will begin by defining surface irregularity and how it is measured. Next, it will look at the history of surface irregularity tolerancing and metrology and modern methods for testing and analyzing surface irregularities. Finally, the paper will present the impact on manufacturing optics and general specification guidelines.

This paper is specific to spherical lenses because aspheres are often toleranced differently. For more information on that topic, see Optimax white papers on asphere metrology.

What Is Irregularity

Irregularity is the non-sphericity of a surface or how much a lens deviates from a perfect sphere of the same radius as shown in Figure 1. This can be confused with the power of a lens, which gives a measure of how the overall spherical radius of curvature differs from the nominal value as shown in Figure 2. Power is a measure of radius error, not sphericity, and indicated as such when giving the specifications for a lens; irregularity is a measure of the point to point changes in local curvature.[1]

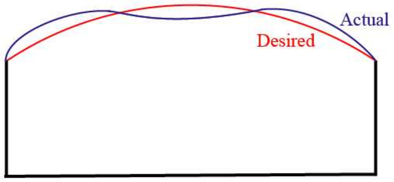


Figure 1: Irregularity

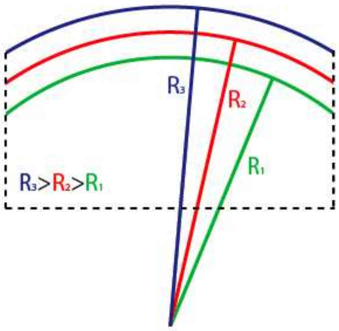


Figure 2: Power

Irregularity is specified as a peak-to-valley (P-V) measurement. The P-V irregularity value of a lens is a measure of the distance between the highest and lowest points of the surface relative to the perfect theoretical spherical surface; this is illustrated in Figure 3.[1] While this is a physical distance, irregularity is specified in interference fringes. Each interference fringe represents a deviation of actual from ideal by a magnitude of one-half the wavelength ($\lambda/2$) of light used in the test. For example, a tolerance of 2 fringes irregularity indicates that the maximum difference between high and low points on the surface of the lens could be no more than the test wavelength.

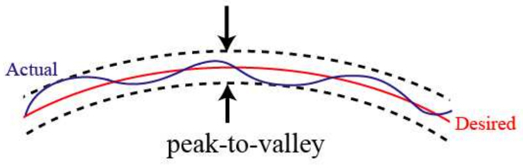
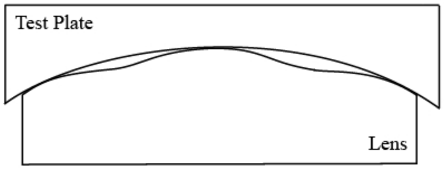


Figure 3: Peak-To-Valley

Historical Testing

Figure 4: Test Plate



Traditionally, the shape and irregularity of spherical lenses were measured using test plates. A test plate is a very carefully fabricated and measured reference surface of known radius but has a curvature opposite to the surface under test. Placed together as illustrated in Figure 4 and viewed under monochromatic light, a Newton fringe pattern or interference fringes appear as shown in Figure 5. When the lens and test plate do not fit uniformly together because of imperfections in the lens, differences in the path of the light rays, due to the uneven air gap, form interference fringes. However, because both power and irregularity stop the two pieces from fitting uniformly together, both contribute to the fringe pattern. (For a more detailed explanation of interference fringes, see Chapter One of Malacara's Optical Shop Testing.)[2] Historically, allowed power was a function of the needed irregularity specification. Power hides irregularity and needs to be controlled in order to determine irregularity while using test plates. It is also important to consider any imperfections in the test plate. The two surfaces should be compared at various orientations and locations so that error in the test plate, if any, can be separated from error in the lens. There are methods to analyze these fringe patterns, but they are often complicated and open for interpretation, making the measurements subjective.

Current Methods

Test plates are still used, most often to travel with a job for in-process use. The optician can use them to calibrate a spherometer to check the overall shape of the lens during generating, grinding, or early in the polishing process. Irregularity is not even considered until polishing, where the optician will use the test plate to see any fringes before moving to the interferometer. The test plate is used to obtain a general idea of the form of the lens and identify any needed adjustments to the process. This is iterative, making new adjustments with each measurement. After the lens appears adequate with the test plate, it is then measured with the interferometers. Most final testing to provide quantifiable measurements of both power and irregularity is done using an interferometer. Blocked parts tend to develop cylindrical irregularity in polishing while large, single elements develop slightly aspheric, sometimes toroidal, irregularity.[1] This is shown when the lens is measured using an interferometer and can be accurately corrected when the lens is re-polished.

Figure 5: Test Plate Fringe Pattern

The lens is measured after polishing using a combination of specialized software and two interferometers, a Fizeau phase shifting interferometer (PSI) and a displacement measuring interferometer (DMI). These use a HeNe laser with a wavelength (λ) of 632.8nm. Therefore, each fringe (λ/2) represents 316.4nm of spherical departure. The part is imaged at two points, where the light from the interferometer is focused (cat's eye position) and where the spherical wavefronts match the curvature of the lens (confocal position). They are separated by a distance equaling the radius of curvature of the lens as shown in Figure 6.[3] In both places, the light is normal to the lens at all contact points, therefore creating a

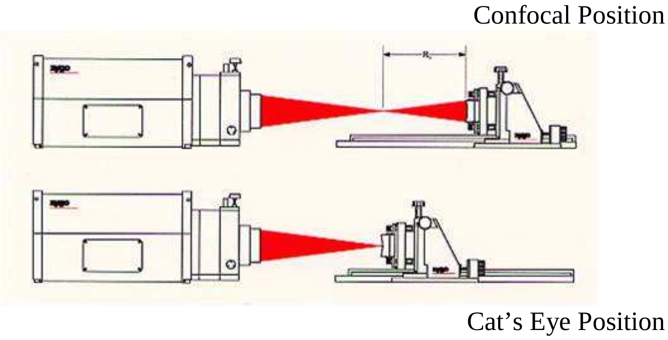


Figure Six: Interferometric Measurements[3] null configuration. The DMI analyzes the distance between the two positions (each position determined extremely accurately by phase shifting on the PSI) to determine radius. The PSI analyzes the interferogram from the confocal position to determine irregularity separate from power. A distinction is made between power and irregularity and accurate numerical values are calculated for both radius and irregularity independently. At Optimax, the standard collimated test beam from the PSI is a maximum of 150mm in diameter. Ability to get full aperture coverage with this setup depends how this beam is modified by the f/number of the transmission sphere and the reference surface diameter. This needs to be considered for each lens design individually.

Specifications

Optimax has defined commercial quality surface irregularity as a tolerance of 2 fringes, precision quality as 0.5 fringes and 0.1 fringes as approaching the manufacturing limit on P-V. This is summarized in the Optimax Manufacturing Tolerance Chart, which is posted on the Optimax website. Typically, tolerances for spherical lenses can be met using basic interferometry techniques with a repetitive testing and traditional polishing process.

A subaperture stitching interferometer (SSI) can be used for larger clear apertures if necessary. Multiple subapertures, providing additional coverage, are imaged with the interferometer's motion capability and stitched together to quantify irregularity over the entire surface. For the tightest tolerances, an interferometric data file can be used with QED's magnetorheological finishing (MRF) machine, which determines and carries out an extremely precise corrective process. Using MRF contains the cost to finish a high precision optic because of the deterministic nature the fabrication process.

Tighter tolerances on irregularity can be a major cost driver in producing a lens. Surface irregularities can introduce various types and orders of aberration into an image due to disruptions from the expected path of light; fewer fringes and a more uniform surface are obviously preferred. However, while performance of a lens is always essential, it is important to model and predict the image quality of the system as a whole considering all factors. For illumination systems, an irregularity tolerance of 1 to 2 fringes might be sufficient, but a tolerance of less than 1 fringe is often desired for high quality imaging systems. Applications such as photolithography begin approaching manufacturing limits. Different types of irregularity have varying effects on design performance; both quantity and type need to be considered to set a tolerance that is optimal for price and performance. For some systems, a cost effective option may be using a corrector plate. A corrector plate is an optic that is designed to correct for a lens system's existing irregularity. The irregularity tolerance for each lens can be loosened, reducing cost, when a corrector plate is to be used for the system. The system is assembled, total irregularity is measured, and a final lens, the corrector plate, is designed that corrects for the system's overall irregularity errors. Optimax can manufacture the corrector plate after the system performance or transmitted wavefront error (TWE) has been evaluated and the corrector plate is designed. This method is sometimes better for overall system performance and cost. More information on using a corrector plate is provided in the Optimax paper "Improving Lens Performance with TWE Testing."[4] Considering the final application of the lens or lens system and determining the acceptable amount of aberration is extremely important before setting a tolerance on irregularity as it will significantly affect the cost of the optic.

REFERENCES

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