Modern Optics Drawings

The ISO 10110 Companion

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Preface

The purpose of this book is to provide optical engineers, fabricators, and all parties in between a better understanding of the ISO 10110 drawing standard, and how to use the standard to create modern optical drawings. The authors presume that the reader has access to all parts of ISO 10110 and associated standards, and at least a basic familiarity with optics component technical drawings.

The world of standards is very small, and volunteer-based. Those who work on these committees are trying to do the right thing for our industry. Those few people are willing to take the time to draft, edit, and review these standards. Most of the time the result of their efforts is the result of compromise, and often it is far from perfect. Pursuit of an international standard that reflects the diversity of opinions, applications, and needs of the community comes at a price.

The first version of ISO 10110 was published in 1995 and has been the subject of multiple revisions, additions, and subtractions over the past 25 years. Today, there are twelve parts; 1, 5, 6, 7, 8, 9, 11, 12, 14, 17, 18, and 19. Because of this international effort over the past fifteen years, the ISO 10110 drawing standards have become a truly international standard reflecting the needs of the global optics community. It is vastly better today than in 1995 or 2005, and much more in harmony with US industry.

Even so, the standards can be difficult to read, more complex than we would like, and sometimes seem unfamiliar and unfriendly. We have written this book as a friendly guide to unfamiliar language, symbols, and a way of thinking about optics tolerances and specifications. However, the book is meant as a guide—not a replacement—for reading the standards themselves.

Additionally, there are a half-dozen other standards that are essential to using ISO 10110, and even more that can be used to make ISO 10110 more effective. As a result, this book is structured in chapters by subject, rather than by part of 10110, with related standards grouped within a chapter. Many practical examples are provided with a view toward a complete adoption of the methodology of standardized optics drawings including the drawing notation standards; and the metrology, environmental, and system performance test standards. It is the authors' hope that the book is readable enough to be read and understood by the uninitiated, and that the book serves as a useful reference or guide to users of the standard as they navigate the details of full implementation.

Chapter 1
Drawing Notation and Default Tolerances

ISO 10110: Optics and Optical Instruments – Preparation of drawings for optical elements and systems can seem complicated due to the coded tolerances and notation required. The barrier in understanding this standard is interpreting the coded notation. While initially challenging, this coded notation of a requirement becomes a significant and unambiguous benefit of the standard when analyzed further. The reduction of text description on a print increases the number of qualified fabricators a designer may use for their optics. The ISO system of normative callouts obviates the need for interpreting a specification and makes requirements clearer than without normative callouts regardless of communication factors. All that is required is an understanding and a proficient use of the standard.

1.1 Background

ISO Technical Committee 172—Optics and photonics (ISO/TC 172) was created in 1978 to address the need for worldwide optics and photonics standards. The Technical Committee is composed of seven subcommittees, each of which is tasked with developing standards for a different aspect of the optics and photonics community. Subcommittee SC 1, first convened in 1986, is responsible for fundamental standards for optics and photonics. The most important working group within ISO/TC 172/SC 1 for optics drawings is WG 2—which has been convened by various countries across Europe, the United States (US), and Asia. Within WG 2, the critical ISO 10110 series of standards was developed and is maintained.

The purpose of a technical drawing is to convey the requirements and tolerances of a component or system as clearly and unambiguously as possible. ISO 10110 strives to present optical components on drawings with a minimum number of notes and ambiguity. Clarity is achieved through use of a large array of symbols and indications. When the symbols and indications are

1.5 Table and Drawing Field

Within an ISO 10110 drawing, it is possible to list the specifications for a single optical component, a cemented component, or an entire optical subassembly. Through most of the discussions within this book, a single optical component is discussed for ease of explanation. These can be expanded upon for optics drawings of various other types of optical assemblies and systems.

ISO 10110 specifies that a drawing is broken up into three fields (Fig. 1.2): the table field, the drawing field, and the title field (or title block).

For a drawing of a simple optical component with two optical surfaces, the table field is broken into three subfields. The leftmost subfield refers to the requirements of the left surface (or surface 1), and the rightmost field refers to the requirements of the right surface (or surface 2). The middle field refers to the requirements of the material.

The drawing field will contain a view of the optical component and its dimensional information, and any information not provided in the table field, such as additional notes and notations that apply to the entire component. Any datums necessary for interpretation of the centering requirement will be

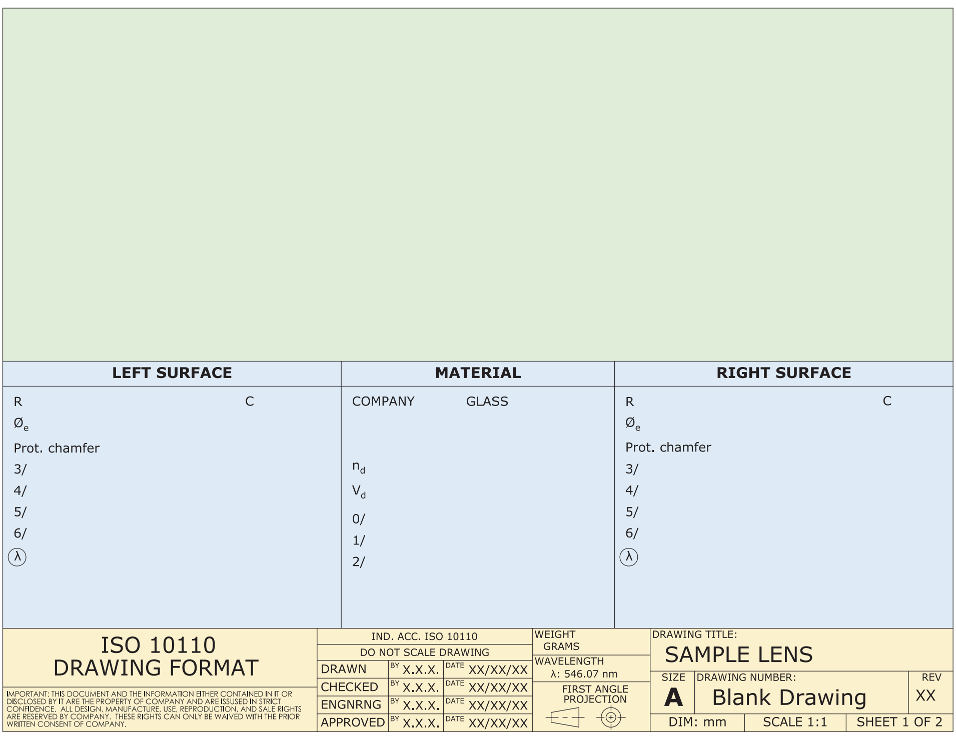


Figure 1.2 Table and drawing view.

Figure 1.11 (a) Image plane and (b) pupil plane.

1.8 Non-Toleranced Data (Default Tolerances)

For any optical component, there are tolerances that are applied to all specifications. In ISO 10110, for many of the common requirements, if a specification does not have an associated tolerance with it a set of default tolerances are applied. For linear or angular values, there are typically sheet tolerances listed on the drawing that are applied given the number of digits that follow the decimal places. For optical component drawings, a list of sheet tolerances may not be listed in the title block.

These dimensional values and optically required values have their own set of default tolerances that are tabulated in ISO 10110-11. These tolerances are listed based on the diameter ranges of the component. The diameter ranges are broken up into four groups: between 2 mm and 10 mm, between 10 mm and 30 mm, between 30 mm and 100 mm, and between 100 mm and 300 mm. The tolerances associated for each range are very loose relative to manufacturing capabilities and are meant to be a safeguard against missing data. These tolerances are considered either commercial-grade or looser.[15] As shown by DeGroote et al.,[16] for tolerances of a diameter between Ø 30 mm and Ø 100 mm, these tolerances may not be acceptable for diffraction-limited or high-performance designs. It is possible to use tolerances that are looser than default tolerances, but looser tolerances must be explicitly listed.

If a dimension is not listed but a dash is listed instead with the associated code, no requirement should be applied to the given tolerance. There is no default tolerance for laser damage threshold or for some other less-common specifications. It is necessary to list the surface texture on a print, even if it only specifies that a surface is polished or ground.

1.9 Discussion of Other Standards in Use

1.9.1 MIL-STD-34[4]

MIL-STD-150 defines terms used in photographic lenses and how to analyze an optical system.[17] Although many critical aspects of optical fabrication are defined, and metrology methods discussed within MIL-STD-150, no single drawing standard is provided. MIL-STD-34 was first introduced in 1960 to

Chapter 2
Optical Materials

In addition to the material properties (e.g., index, dispersion, manufacturer, and material type) discussed in Chapter 1, there are material tolerances that are key to specifying optical component substrates. These additional essential material tolerances are stress birefringence, bubbles and inclusions, homogeneity, and striae. While these material tolerances are usually thought of in terms of optical glass, they can also be present in components made from other materials. Each of these tolerances can impact the overall optical performance, albeit they require an understanding of the material fabrication process.[1,2]

Stress within optical materials is a mechanical stress that is typically a function of the type of material and the annealing process, creating a birefringent effect in transmissive optical elements. This stress in the refractive element leads to an anisotropic optical retardation between the electric field component directions. Stress birefringence variation with temperature can cause thermal instability in both the refractive and reflective optical elements.[3] This is especially true for optics made from plastics and some crystal materials.

During the melting and annealing processes multiple types of imperfections can arise. Pockets of air and small contaminants, typically toleranced together and referred to as bubbles and inclusions, are produced from the raw materials in the melting and thermal cycling processes. These imperfections in the optical material lead to scattering effects within the optical material.[4] In the melting and annealing cycles, both occurring over a thermal cycling process, variations of refractive index continuity are created. The variations are known as striae or homogeneity. The distinction between these two types of refractive index variations is attributed to the range length through the optical material.[5,6]

2.1 Background

Preparation of an optical material may lead to imperfections in the blank optic and subsequently the final component. Each of the stress birefringence, melting process of the glass. This results in a gradual variation of the consistency of the refractive index over the optical path length. Inhomogeneity leads to slowly varying optical path variations (i.e., gradient index effects) over the entire optical component rather than just a small region. Increases in the size of the optical component may increase the possibility of appreciable inhomogeneity across an optical component.

2.3.5 Striae

Striae are variations in refractive index over a short scale.[6] Unlike homogeneity, striae may be found in different regions across the optic and vary with propagation direction. Striae are caused by not allowing the material to become homogenous during the melting process. Striae usually appear as swirl patterns in the optic. Most common optical glasses are extremely free of striae, but more exotic or rarely melted glasses such as filter glass or plastics can exhibit significant striae in some directions.

2.4 Indications on Drawings

There are a few parameters between ISO 12123 and ISO 10110-18 that do not overlap with their overall notation. When following ISO 12123, the notation required for a raw material may not require an optical drawing. In contrast, the purpose of the ISO 10110 series is to create optical drawings. A larger description of the differences between ISO 10110-18 and ISO 12123 is discussed in Sec. 2.4.5.

2.4.1 Material property notation

As discussed in Chapter 1, basic material information such as manufacturer and glass type, international glass code, index and Abbe number, or material chemical composition (e.g., MgF_2) is listed within the material section of the print. There are no specified drawing symbols or qualifiers for these terms. The tolerance of index and Abbe number are typically listed explicitly as values without an associated notation code.

2.4.2 Stress birefringence

The drawing symbol for stress birefringence is `0/`. The quantifier added after the `0/` is the amount of stress birefringence, in retardation versus distance traveled, allowed in a part in units of nm/cm. Calculation of stress birefringence is found by analyzing the optical path difference between the two orthogonal axes. Additionally, determining the amount of stress within the optic leads to a calculation of the stress birefringence

Specifying bubble and inclusion tolerances using ISO 10110-18 requires the quantity and maximum grade of bubbles or inclusions allowed in the optical component. This coded notation leaves this tolerance as a grade system that can be calculated for the area of each bubble or inclusion. In contrast, the ISO 12123 specification for bubbles and inclusions has independent preceding notations for both the number of bubbles or inclusions and their size. The grade notation for the number of bubbles is `IN` and the grade notation for the size of the bubbles is `IC`. If, for example, the bubble and inclusion indication for a finished component was `1/ 10` $\times$ `0.1`, the same specification for the raw material could also be written as `01/ IN010;IC10`.

Lastly, specifying homogeneity and striae is consistent between the finished optical component and the raw material. Both specifications use the same preceding code of `NH` and `SW` for homogeneity and striae, respectively.

2.5 Infrared versus Visible Materials

Infrared optical components may differ from visible-light-based systems because of the material properties required for the different wavebands.[17,18] Tolerances that might be considered loose for a visible optical component may be considered normal or tight for an infrared component.

There are certain additional specifications that should be considered when making a drawing for an infrared optical component. As many infrared materials do not transmit through the visible wavelength region, specifying the refractive index a n_e or n_d wavelength is impractical. Considering the various wavebands that infrared components may be used (short-wavelength infrared, long-wavelength infrared, etc.), specifying the reference wavelengths for the refractive index and dispersion calculation is crucial.[19]

2.6 Drawing Example

An example print is shown below in Figure 2.2 to clarify effective use of ISO 10110-18. Along with explaining the notation on this drawing, the specifications given can also be applied to the raw material as well.

2.6.1 Material property notation

The glass information on this print is listed as both the glass vendor and type (light blue). This print allows two different vendors to provide the substrate material. In addition to the glass vendors and types, the refractive index (purple) and Abbe number (green) are listed. Additionally, tolerances on the refractive index and Abbe number are listed as well. The tolerances for the refractive index and dispersion for the raw material could instead be given per ISO 12123 as `NP50` and `AN5`, respectively.

Chapter 3
Surface Figure and Form

Surface figure and form tolerances are low spatial frequency errors in an optical surface that directly contribute to the wavefront error on an optical surface. For surfaces sufficiently near the stop or a pupil conjugate, these errors are scaled and applied to the wavefront error of the system. Surfaces that are nearer than other surfaces to the object or an image conjugate will have the illuminated region affecting the wavefront. Such field lens and flattener types of optics can also have slope requirements depending on the required field flatness, distortion, and piston. These types of form errors are critical in defining the expected tolerances on an optical surface and may drive the tolerance budget for the entire optical system. Surface figure errors can be measured using numerous methods such as profilometry and interferometry. Data is assessed using different performance metrics such as power, irregularity, wavefront error [root mean square (RMS), peak-to-valley (PV), or robust peak-to-valley (PVr)]. Data can be analyzed in other various ways including decomposition into Zernike polynomials. In general, the measurement of precision optics' surface figure errors is often performed with an interferometer. Because there are multiple ways to describe the surface figure error for an optical surface there are many ways to describe the surface figure tolerances with ISO 10110.

3.1 Background

Much has been written about surface figure and how it can be measured.[1–3] For an ISO 10110 drawing, the notation for surface figure is specified in ISO 10110-5.[4] Along with measuring an optical surface, ISO 10110-14 is in place to specify an entire optical element or system figure wavefront deformation.[5] In conjunction with ISO 10110-5 and ISO 10110-14, the ISO 14999 series can be used to interpret the descriptions of each quantifier, as well as the methods for measuring said deformations.[6]

Since it is possible to measure the surface figure error in multiple ways, there are many different types of quantifiers available in ISO 10110-5.

notation with Zernike terms is the additional space it provides on a drawing.

3.3.6 Table notation

Rather than describe the surface form tolerance across the entire surface, it is possible to list the surface deviations in a table rather than in the surface form indicator, 3/. When describing the surface form deviation with a table, the deviation quantifier value is listed in a separate column of the reference table. Either a Cartesian or polar coordinate system is necessary because it is possible to have deviation tolerances at varying locations across the surface. This indication lists where on the surface a slope or position deviation occurs as a point cloud of data for the surface figure.

3.4 Surface Figure

ISO 14999-4 is often used in conjunction with ISO 10110-5 to assist in describing the surface figure and provide a description of measurement techniques.

Historically, a test plate was used to measure the power and irregularity of an optical surface interferometrically. In this case an optical surface with the near perfect radius was manufactured of the negative curvature, known as a test plate. The optical surface to be measured would then be placed against this surface and viewed under a nearly monochromatic light source. Under these viewing conditions the difference in surface form could be seen with Newton's rings, or fringes. The power measurement is the number of fringes found and the irregularity is the difference in number of fringes between orientations (vertical versus horizontal). An example of how a test plate would be used is shown in Fig. 3.1. In both orientations shown in Fig. 3.1, the difference in curvature from the ideal radius, or test plate, is the surface power. The difference in curvature between the two orientations of this example (*xz* and *yz*) is the irregularity of the optical surface.

Describing surface figure in its most basic form uses the general notation described in Sec. 3.3.1, where the power and the irregularity of the surface are

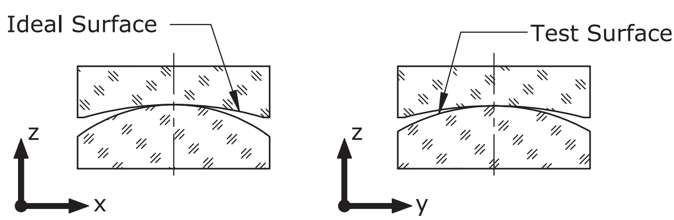
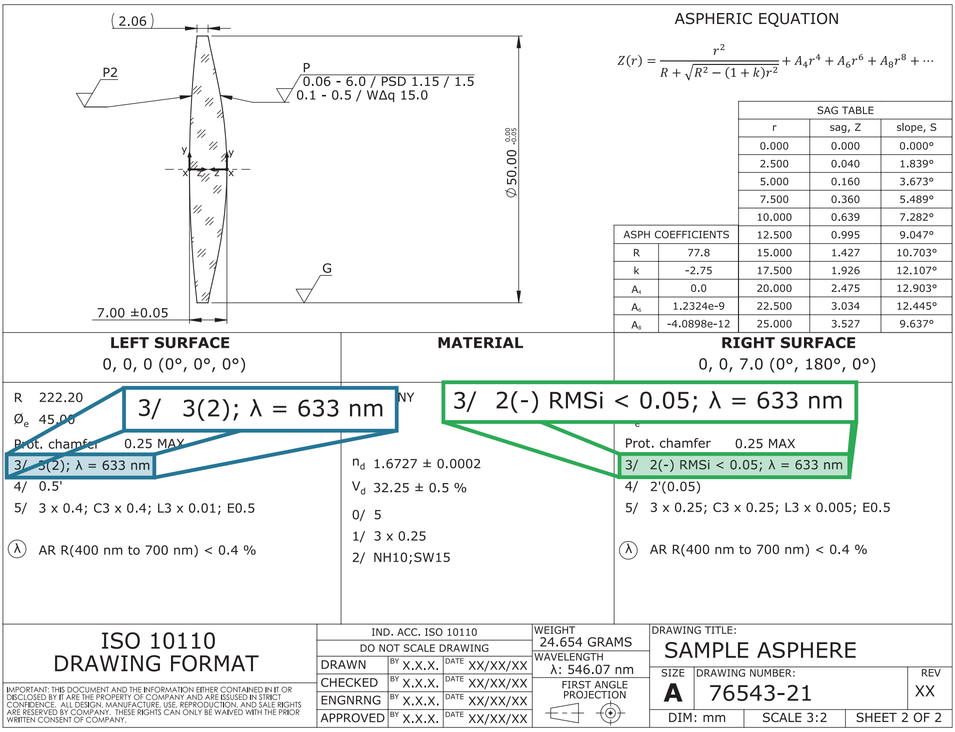


Figure 3.1 Metrology method of measuring an optical surface with test plates. The curvature difference between the test surface and the ideal surface is the power. The difference in curvature between the two orientations (*xz* and *yz*) is the irregularity of the optical surface.



ASPH COEFFICIENTS	
R	77.8
k	-2.75
A_4	0.0
A_6	1.2324e-9
A_8	-4.0898e-12

SAG TABLE		
r	sag, Z	slope, S
0.000	0.000	0.000°
2.500	0.040	1.839°
5.000	0.160	3.673°
7.500	0.360	5.489°
10.000	0.639	7.282°
12.500	0.995	9.047°
15.000	1.427	10.703°
17.500	1.926	12.107°
20.000	2.475	12.903°
22.500	3.034	12.445°
25.000	3.527	9.637°

Figure 3.12 Example drawing with a spherical surface on the left surface having power and irregularity,and an aspheric surface on the right surface having power and RMSi irregularity tolerance; along with a sag table.

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2. W. J. Smith, *Modern Optical Engineering*, 3rd ed., McGraw–Hill (New York: 2000).
3. E. P. Goodwin and J. C. Wyant, *Field Guide to Interferometric Optical Testing*, SPIE (Bellingham, Washington: 2006).
4. International Organization for Standardization (ISO), *Preparation of Drawings for Optical Elements and Systems—Part 5: Surface Form Tolerances*, ISO 10110-5 (Geneva: 2015).
5. ISO, *Preparation of Drawings for Optical Elements and Systems—Part 14: Wavefront Deformation Tolerance*, ISO 10110-14 (Geneva: 2018).
6. ISO, *Optics and Photonics—Interferometric Measurement of Optical Elements and Optical Systems*, ISO 14999 (Geneva: 2019).
7. C. J. Evans, "Robust estimation of PV for optical surface specification and testing," *Proc. Opt. Soc. Am. Front. Opt.*, 2008, OWA4 (2008).

Chapter 4
Surface Texture: Roughness and Waviness

Surface roughness tolerances are requirements for the level of smoothness of the polish of an optical surface, typically expressed as a maximum allowed RMS surface height error and evaluated with a profilometer. The advent of highly deterministic small-tool polishing has led to increased importance of spatial frequencies lower than traditional roughness scale-lengths but higher than those more easily controlled using surface form tolerances described in Chapter 3. To cover this need, the standard includes notation to control such mid-spatial frequency errors with more rigor.

ISO 10110-8 provides the notations for a variety of tolerancing methods of varying complexity and sophistication.[1] The simplest form of surface texture tolerance is a simple polishing grade based on a standard level of RMS roughness. If the standard polish grades are not suitable, any level of RMS roughness tolerance can be defined. Moreover, the scale-lengths over which the RMS roughness requirement is to be evaluated can be customized. This same tolerance methodology can be used to specify deliberately rough surfaces, such as the ground edge of a lens, using both upper and lower bounds on the roughness. In addition to these fairly conventional notations, the standard provides for more complex tolerances often used to control mid-spatial frequency surface form errors, or waviness, based on peak slope, RMS slope, and even a power spectral density (PSD). The most recent edition of the standard adds the areal (2D) versions of these notations.

4.1 Background

Tolerances on surface texture are not unique to the optics industry. Indeed, specifying the smoothness of a bearing surface is quite old. Today, the study of friction, wear, and lubrication is referred to as tribology; and is greatly concerned with characterizing the texture of a surface. Leonardo da Vinci (1452–1519) is considered by some to be the first tribologist.[2] His notebooks range for that measurement would be only 0.0025 mm to 0.16 mm or even less.

4.4 Drawing Example

Example drawings with some specific tolerance notations and their meaning are given below. In addition, ISO 10110-8 has an extensive Annex B containing many more examples.

Figure 4.14 shows an ISO 10110 drawing with four surface texture notation symbols. The face-flat on the right surface is given as a ground surface, with at least 0.05 μm RMS roughness and no more than 2 μm RMS roughness for all spatial scales less than 2 mm. The cylindrical edge is defined simply as a "ground" surface, with no particular requirement on roughness. The two optical surfaces are each specified with three different surface texture requirements. The first is that the surfaces be polish grade 2 or better; that is, no more than 4.0 nm RMS over the spatial band from 0.002 mm to 1.0 mm. The second requirement is that the surface roughness over the spatial band from 0.0025 mm to 0.080 mm shall be less than 2.0 nm RMS. The third

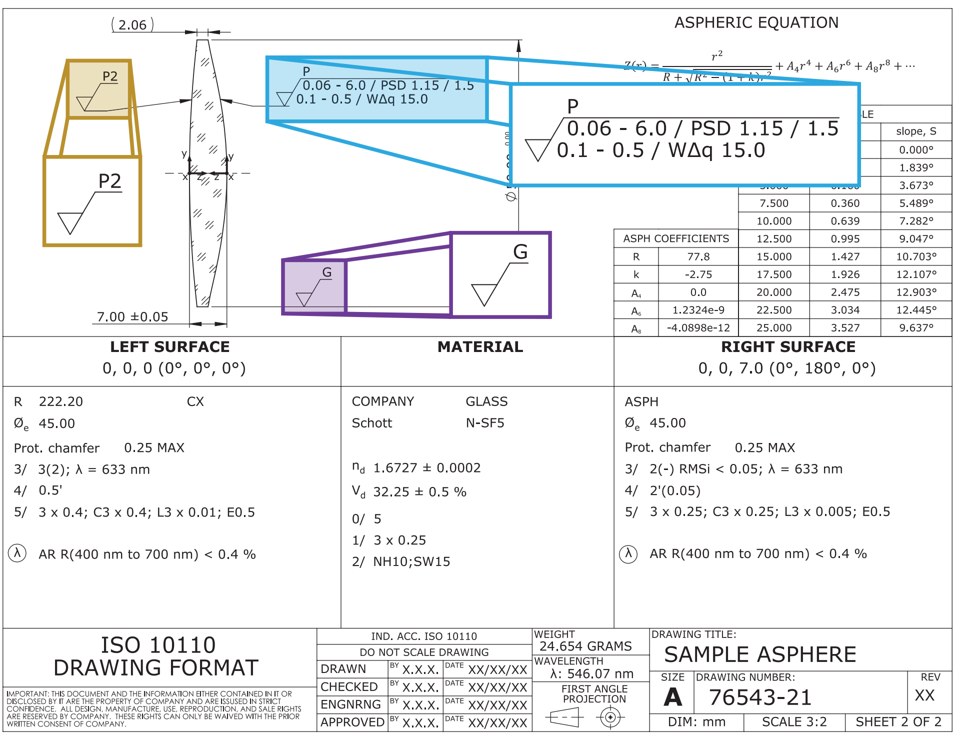


Figure 4.15 Example drawing with a spherical left surface having polish grade P2 and an aspheric right surface, with the texture specified using an RMS slope waviness and an additional surface PSD requirement.

Chapter 5
Surface Imperfection Tolerances

Surface imperfections are localized flaws, such as scratches and digs, on the surface of an optical element. Surface imperfections that are not localized—i.e., cover the entire surface—are considered texture and are toleranced using the notation given in Chapter 4. Typically, when considering surface imperfections we include other features such as edge chips and coating imperfections. The ISO 10110 standard includes two methods of indicating surface imperfections. The first method is analogous to the scratch and dig visibility standard found in US MIL-PRF-13830B and the related visibility method described in ANSI/OEOSC OP1.002. The second method is analogous to the withdrawn DIN 3140's dimensional specification.

5.1 Background

Surface imperfection specifications are among the most misunderstood and misapplied standards in the world of optical engineering.[1–3] Most indications fail to even reference a standard, trusting instead that the manufacturer will interpret the notation in the intended manner with no further guidance than `60-40` scratch and dig or `5/ 4 × 0.1`. The long and complex history of these specifications combined with their frequent citation as cause for rejection requires more attention from the optical engineer in preparing a surface quality tolerance. In the event that one should attempt to develop a meaningful surface quality specification from existing standards, one is often confronted with bad options: a standard that is expensive to implement, is often misinterpreted, or might not fit the required application.

The surface imperfection notation for optical surfaces, often referred to as "scratch and dig," is found today in Section 3.5 of MIL-PRF-13830B,[4] an active standard supported by the US military. It is based on MIL-O-13830A, first released as a military standard in the US in 1954 and revised once in

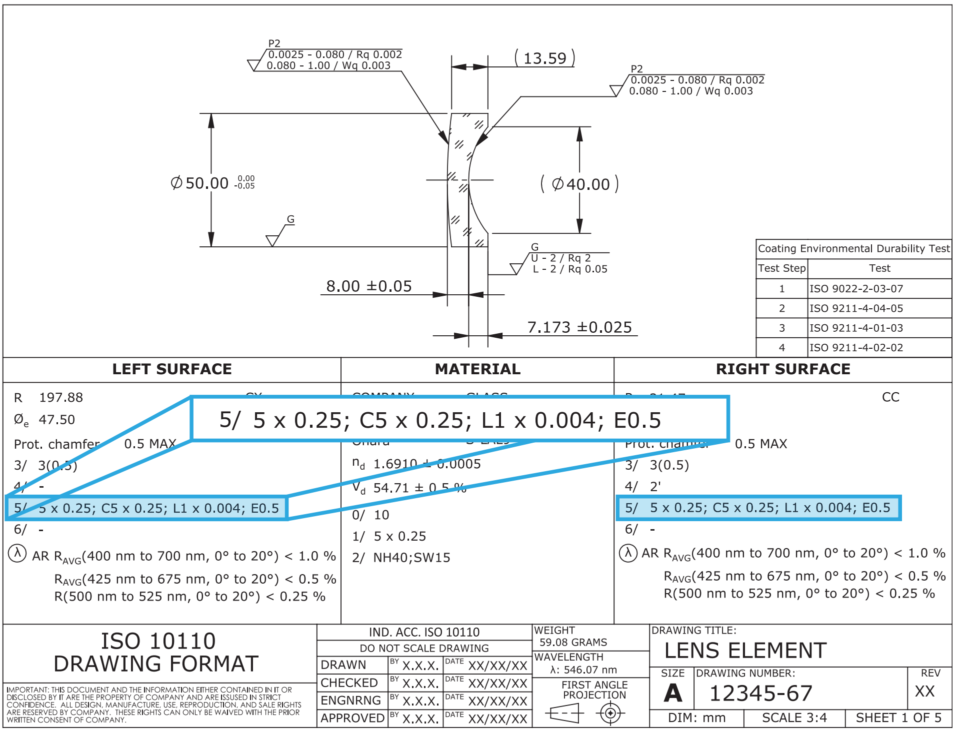


Figure 5.3 Example for dimensional method for surface imperfection specification.

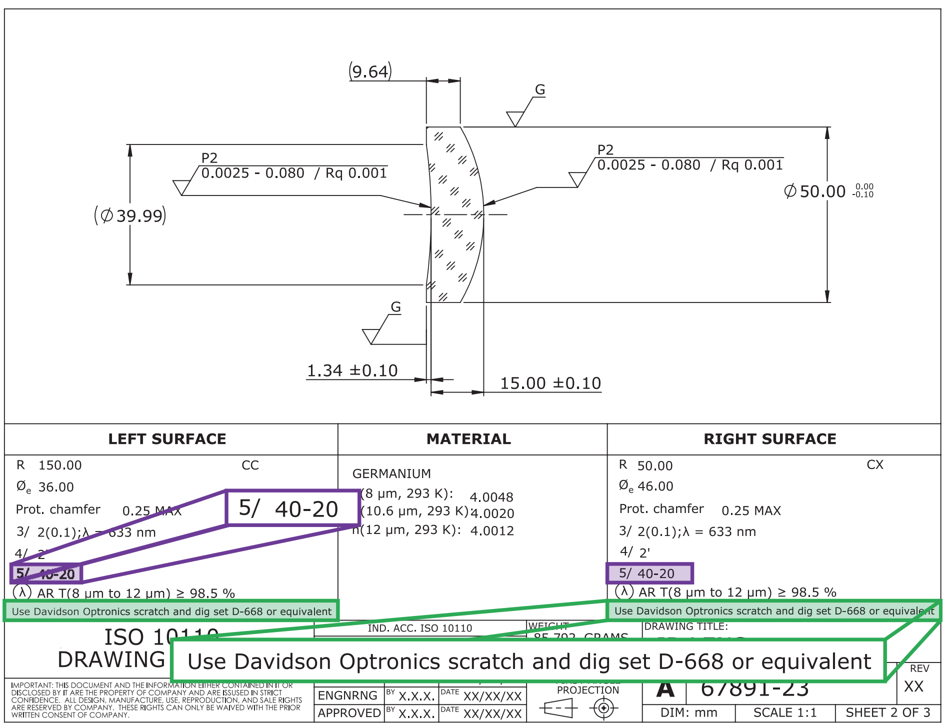


Figure 5.4 Example of visibility method for surface imperfection specification.

Chapter 6
Laser Damage

Laser damage is a major concern if an optical element or optical system involves high-power or high-energy lasers. The concern with optics in these systems is that a flaw in the optic may cause light to scatter or be absorbed and subsequently cause damage. Designation of a laser-induced damage threshold (LIDT) for these optical elements is intended to convey the message to a fabricator that additional care must be taken when manufacturing these types of optical elements or systems.

6.1 Background

For an ISO 10110 drawing, the notation for laser damage threshold is specified in ISO 10110-17.[1] Additional resources for understanding laser-damage thresholds and methods for evaluating laser-damage results are listed in the ISO 21254 series.[2–5] It is necessary to use the four parts of the ISO 21254 series with ISO 10110-17 to understanding laser-damage threshold specifications, testing conditions, and evaluation techniques.

High-power or high-energy laser light passing through an optical system may induce damage to the optical system or optical components. This is due to the laser power density or energy density—depending on the pulse duration, duty cycle, and type of laser. Laser damage will create irreversible damage due to ageing, microdamage, and induced defects.[3] The laser induced damage threshold is defined as the highest quantity of laser radiation incident on the component for which the extrapolated probability of damage is zero.[2] Due to the statistical nature of this extrapolation, the LIDT should not be considered the level below which damage will not occur; more that it is the level of laser radiation below which damage probability is less than the critical risk level.[6]

Laser damage for optics is typically a higher concern for optical surfaces rather than the bulk optical material. This is due to imperfections in the polishing of the optical surface or imperfections in coatings causing localized absorption. Typically, an optical element or system that will be used for high

6/ $F_{th};\lambda;\tau_{eff}$

where:

F_{th} = threshold linear power density (W·cm^{-1}).

The distinction for a pulsed laser to be a long pulse refers to when the thermal transit distance is on the same order as the test spot. This distinction is shown in Eq. (6.1). The approximate equality between the parameters is intended to show that if these terms are on the same order of magnitude, a long pulse should be considered.

$$(2D\tau_{\text{eff}})^{(1/2)} \approx d_{(T,eff)} \tag{6.1}$$

where:

D = thermal diffusivity,

τ_{eff} = effective pulse duration (seconds), and

$d_{T,\ eff}$ = test spot diameter.

In the case that the time of the pulse is greater than 0.25 s, the laser damage is considered CW. For these types of lasers, the effective pulse duration is not specified. Instead, τ_{eff} becomes the exposure duration of the CW laser test.

6.4 Test Methods

ISO 10110-17 references ISO 11254-1 and -2, both of which have been withdrawn.[9,10] A schematic of the testing configuration described in ISO 11254 is shown in Fig. 6.1.

Laser damage may be performed in one of two different methods, depending on the type of laser in question and information needed. Damage testing may be done in a 1-on-1 test where a single shot occurs on a single unexposed part of the optical component in question. The other test

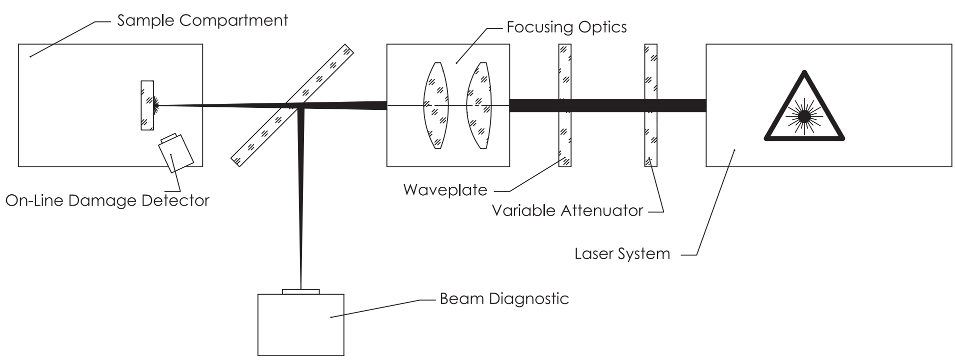


Figure 6.1 Basic approach to damage testing.

Chapter 7
Surface Treatment and Coating

Surface treatments and coatings are applied to an optical surface at the end of the component fabrication process. Optical coatings involve the addition of material on the polished optical surface while surface treatments are generally applied to the edges of the components. The type of optical coating depends on the functional purpose of the optical element in the application. In ISO standards, the ISO 9211 series and ISO 10110-9 work in conjunction with each other to provide detailed descriptions of optical coatings, as well as their notation for drawings.[1–9] ISO 10110-9 contains notation methods for specifying the optical coating on a drawing. While it is certainly possible to use this notation for the specification of a coating, a very detailed description of optical coatings and test methods is provided in the ISO 9211 series. Optical coatings are used to alter the transmission, reflection, or absorption properties of an optical element's surfaces. Further, these key properties of the surface may be described by wavelength regions, angles of incidence, phase, or polarization. Optical coatings are ubiquitous and a key factor for many optical drawings.

7.1 Background

Much has been written about the design, fabrication, and functionality of optical coatings without consideration for the rest of an optical system.[10–13] An optical coating is typically the only aspect of the optical fabrication process where additional material is deposited or added to an optical surface.[14] These optical coatings may be as simple as a single layer of an additional material or as complex as a multi-layer stack-up of various materials.[11] Many optical coatings are interference coatings wherein reflected or transmitted light from various layers produce different wavelength, angle, and polarization dependent constructive and destructive interference. Thus, a common function for optical coatings is to alter the transmission, reflection, or absorption for an optical element or system.

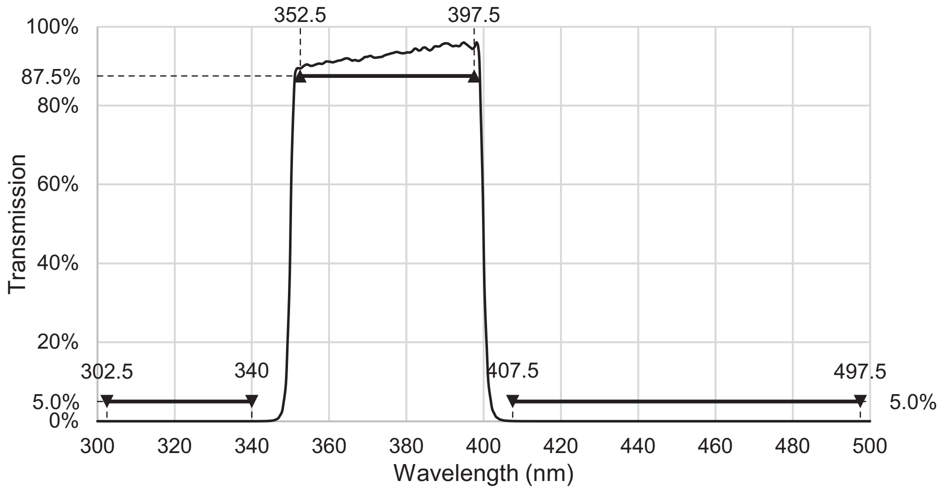


Figure 7.13 Notation for a graphic representation of a bandpass filter where the transmission band and rejection band are noted by the wavelength and transmission percentage (coating data for figure courtesy of Edmund Optics, Inc.).

7.4 Standard Coatings

As the ISO standards for optical coatings continue to evolve, three of the ISO 9211 standards (Parts 5, 6, and 7 for antireflective, reflective, and beamsplitter coatings respectively) specify standard optical coatings that may be used. Antireflective coatings are simply identified as a single layer (U), double layer (V), multilayer broadband (W), and other (X). The first three coatings [U, V, and W] are basic types of antireflective coatings that are named based on their reflectance curve shape. The U and V coatings are specified for a single wavelength. The W multilayer broadband coating is meant for a range of wavelengths. The reflectance designations for these three types of coatings are listed in Table 7.4. Lastly, an X coating type is a multilayer coating that does not have reflectance properties as described by U, V, or W coatings.

The coatings described for reflective surfaces are based on the metallic material that should be used. These specifications are shown in Table 7.5.

Table 7.4 Coded notation for antireflective coatings associated with ISO 9211-5.[5]

Coating Type	Refractive Index	Wavelength	Reflection
U	1.45 to 1.5	λ	≤2%
	1.5 to 1.7	λ	≤1.5%
	≥1.7	λ	≤1%
V	–	λ	≤0.2%
W	–	λ_1 to λ_2 where $\frac{\lambda_2}{\lambda_1} \geq 1.57$	≤0.5%

Chapter 8
Centering and Tilt Tolerances

Optical centering is the alignment of optical surfaces or elements with respect to a datum or datum system. The datum may either be a point, an axis, a surface, or a cylinder. The method of describing optical centering is unlike other sections of ISO 10110 because optical centering relies heavily on mechanical engineering methods and geometrical dimensioning and tolerancing (GD&T). ISO 10110-6 specifies surface tilts, surface decenters, runouts, and beam deviations that can be used to tolerance the centering of an optical surface, an optical element, or a subsystem.[1]

8.1 Background

Centering tolerances for an optical element are applied near the final stages of fabrication.[2] The process of centering relates the surface normal of the optical surfaces to a datum, which is frequently an axis defined by a cylindrical surface (in many cases, the outer diameter). Throughout the remainder of this chapter, all outer diameter surfaces will be referenced as a cylindrical edge surface. The centering tolerances of optical surfaces reference datums or datum systems by a tilt, or a tilt and a decenter. There are multiple ways to describe the surface tilt and/or decenter because of the different methods by which optical surfaces are manufactured and tested. Although referred to as centering, it is most often specified in the form of a tilt angle of the surface normal with respect to some reference axis, or a datum axis. The definition of the datum or datum system is critical to the centering tolerance and how the tolerance should be interpreted. An understanding of each of the different datum reference methods and the intended use of the optic are key to how the centering tolerance should be assigned.[3,4] The centering of an optical element is one of the most important aspects of the fabrication process to ensure that system alignment tolerances can be met.[5]

The method of centering an optical surface—and subsequently defining a tolerance with an ISO 10110-6 callout—depends on the type of surface or surfaces, and how the element will be mounted in the final assembly.

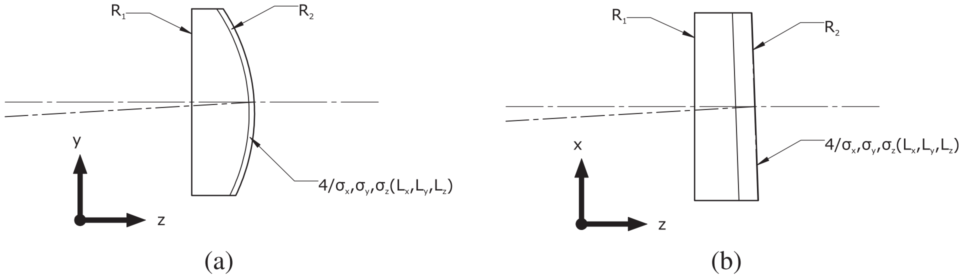


Figure 8.7 Cylinder optical element with tilt present in both the *yz*- and *xz*-orientations.

Freeform optical surfaces may also be designed where the surface definition uses Zernike coefficients, other mathematical functions, or even point cloud data. The more-complex methods create additional challenges for optical centering. These types of surfaces may require multiple surface tilts but a decenter tolerance must also be present. When working with these types of surfaces, the coordinate system in place is critical to ensure the types of decenters and tilts are properly represented. Use of explicit datum systems is encouraged. Implicit centering tolerances may not be enough of a descriptor if their fiducials or datums are not clearly understood. As freeform optical surfaces become more prevalent, their use may not solely be in two-surface optical elements.[8] In these cases, the full Cartesian coordinate including origins is necessary to ensure metrology is possible for each of the centering tolerances.

8.5 Indications on Drawings

The drawing symbol for centering is 4/. The quantifiers following the drawing symbol are different depending on the centering tolerance method. There are multiple methods to quantify the type of centering tolerance. As such, it is possible to define the datum and centering tolerances of an optical element differently with the same intended result. Subsequently, it might be beneficial to take a tolerance quantifier method and then convert it to a another method based on metrology methods.[9] The quantifier for a centering tolerance also requires an understanding of the associated datum(s). Abbreviated indications are allowed in which the datum(s) are implied in some specific cases. Where two surface tilts are indicated without an explicit datum, the sole datum is the cylindrical edge and the datum axis is the cylindrical axis. Where only one surface tilt is indicated without explicit datums, the datum is the axis connecting the center of curvature and mechanical center of the unspecified surface.

As with other tolerance parameters in ISO 10110, if a dash (–) is present then no tolerance is associated. This is necessary to understand as defining centering tolerance in a tabular format may require no tolerance to achieve the necessary centering method.

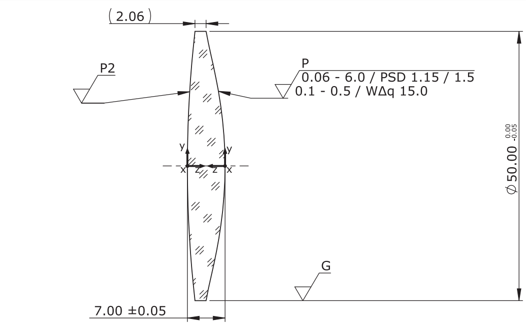
Chapter 9
Nonspherical Surfaces

The advantages of nonspherical (that is, rotationally invariant aspheric) profiles for optical surfaces to correct aberrations in optical systems have been known since the early days of geometrical optics and optical design.[1,2] More recently freeform surfaces (that is, rotationally varying surfaces or surfaces with bilateral or no symmetry) have been used in ophthalmic and nonimaging applications.[3] As fabrication and metrology methods have advanced, these surfaces have been increasingly used in imaging applications.[4] Due to the need for standards to cover drawing notations for many different types of aspheres and general surfaces, two parts of ISO 10110, Parts 12 and 19,[5,6] are dedicated to the specification of the theoretical (nominal) aspheric and general surfaces, respectively, in drawings. Additionally, other parts of ISO 10110 have been written (and revised) to support these types of surfaces; notably Parts 5, 6, 8, and 14. In this chapter, we provide background to using ISO 10110-12 and ISO 10110-19 to create drawings for numerous types of nonspherical surfaces. Development and a summary of descriptions in these standards can be studied independently of this book in the article by Schuhmann[4] and the freeform paper by Youngworth et al.[7]

9.1 Background

Optical systems have long incorporated various nonspherical surfaces, including rotationally variant and rotationally invariant surfaces. The critical factor for deciding when to use an asphere (here, we use this term interchangeably with a nonspherical rotationally invariant surface) or freeform (here, we use this term interchangeably with a nonspherical, rotationally varying surface) ultimately is a balance between the functional requirements of the optical assembly and the additional expense incurred. Exceptions are cases for the following:

- Inclusion of the nonspherical profile surface renders the overall system simpler,
- The surface is required for performance with all given constraints, or



ASPHERIC EQUATION

$$Z(r) = \frac{r^2}{R + \sqrt{R^2 - (1+k)r^2}} + A_4 r^4 + A_6 r^6 + A_8 r^8 + \cdots$$

SAG TABLE		
r	sag, Z	slope, S
0.000	0.000	0.000°
2.500	0.040	1.839°
5.000	0.160	3.673°
7.500	0.360	5.489°
10.000	0.639	7.282°
12.500	0.995	9.047°
15.000	1.427	10.703°
17.500	1.926	12.107°
20.000	2.475	12.903°
22.500	3.034	12.445°
25.000	3.527	9.637°

ASPH COEFFICIENTS	
R	77.8
k	-2.75
A_4	0.0
A_6	1.2324e-9
A_8	-4.0898e-12

LEFT SURFACE	MATERIAL	RIGHT SURFACE
0, 0, 0 (0°, 0°, 0°)		0, 0, 7.0 (0°, 180°, 0°)
R 222.20 CX Ø$_e$ 45.00 Prot. chamfer 0.25 MAX 3/ 3(2); λ = 633 nm 4/ 0.5' 5/ 3 x 0.4; C3 x 0.4; L3 x 0.01; E0.5 (λ) AR R(400 nm to 700 nm) < 0.4 %	COMPANY GLASS Schott N-SF5 n_d 1.6727 ± 0.0002 V_d 32.25 ± 0.5 % 0/ 5 1/ 3 x 0.25 2/ NH10;SW15	ASPH Ø$_e$ 45.00 Prot. chamfer 0.25 MAX 3/ 2(-) RMSi < 0.05; λ = 633 nm 4/ 2'(0.05) 5/ 3 x 0.25; C3 x 0.25; L3 x 0.005; E0.5 (λ) AR R(400 nm to 700 nm) < 0.4 %

ISO 10110
DRAWING FORMAT

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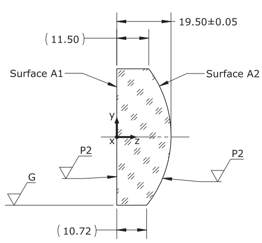
IND. ACC. ISO 10110		
DO NOT SCALE DRAWING		
DRAWN	BY X.X.X.	DATE XX/XX/XX
CHECKED	BY X.X.X.	DATE XX/XX/XX
ENGNRNG	BY X.X.X.	DATE XX/XX/XX
APPROVED	BY X.X.X.	DATE XX/XX/XX

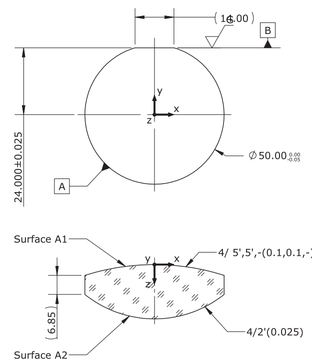
WEIGHT 24.654 GRAMS
WAVELENGTH λ: 546.07 nm
FIRST ANGLE PROJECTION

DRAWING TITLE: SAMPLE ASPHERE
SIZE A | DRAWING NUMBER: 76543-21 | REV XX
DIM: mm | SCALE 3:2 | SHEET 2 OF 2

Figure 9.2 Example asphere using ISO 10110-12.

SURFACE A2 SAG TABLE		
r	sag, Z	slope, S
0.00	0.0000	0.000°
2.50	-0.0781	-3.581°
5.00	-0.3125	-7.162°
7.50	-0.7031	-10.743°
10.00	-1.2500	-14.324°
12.50	-1.9531	-17.905°
15.00	-2.8125	-21.486°
17.50	-3.8281	-25.067°
20.00	-5.0000	-28.648°
22.50	-6.3281	-32.229°
25.00	-7.8125	-35.810°





SURFACE A1	MATERIAL	SURFACE A2
CYL 82.50 CX Ø$_e$ 45.00 Prot. chamfer 0.25 MAX 3/ 1;10(1/0.25;0.5); λ = 632.8 nm 5/ 60 - 40; E0.25 (λ) AR R_{AVG}(400 nm to 700 nm) ≤ 1 % Use Davidson Optronics scratch and dig set D-668 or equivalent	COMPANY GLASS Schott N-BAF52 n_d 1.6086 ± 0.001 V_d 46.60 ± 0.8% 0/ 10 1/ 5 x 0.25 2/ NH40;SW15	ASPH Ø$_e$ 45.00 Prot. chamfer 0.25 MAX 3/ 1(-)RMSi < 0.25;λ = 633 nm 5/ 60 - 40; E0.25 (λ) AR R_{AVG}(400 nm to 700 nm) ≤ 1 % Use Davidson Optronics scratch and dig set D-668 or equivalent

ASPH COEFFICIENTS	
R	-40.00
k	-1

ASPHERIC EQUATION

$$Z(r) = \frac{r^2}{R + \sqrt{R^2 - (1+k)r^2}}$$

ISO 10110
DRAWING FORMAT

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IND. ACC. ISO 10110		
DO NOT SCALE DRAWING		
DRAWN	BY X.X.X.	DATE XX/XX/XX
CHECKED	BY X.X.X.	DATE XX/XX/XX
ENGNRNG	BY X.X.X.	DATE XX/XX/XX
APPROVED	BY X.X.X.	DATE XX/XX/XX

WEIGHT 85.53 GRAMS
WAVELENGTH λ: 546.07 nm
FIRST ANGLE PROJECTION

DRAWING TITLE: ASYMMETRIC LENS
SIZE B | DRAWING NUMBER: 78901-23 | REV XX
DIM: | SCALE 1:1 | SHEET 5 OF 5

Figure 9.3 Example asymmetric lens requiring ISO 10110-12.

Chapter 10
System Evaluation

Although not covered in the ISO 10110 series, understanding how to evaluate a complete optical system is important when creating component specifications. Such considerations are especially crucial when determining tolerances for an optical design. Optical components may be manufactured for a variety of systems with different applications, and therefore benefit from different requirements and specifications. The same factors are true for system evaluation metrics. Optical system metrics may vary from basic optical properties (such as focal length or field of view) to complex measurements of image quality [such as the modulation transfer function (MTF)]. Along with fundamental optical system metrics, additional aspects of the complete system may drive requirements—such as stray light, eye relief, or system transmittance. Understanding the stray light (unwanted radiation), for example, may drive mechanical aspects of the system design and influence the optical system functionality even more than, for example, surface form or other conventional optical tolerances in some applications.

There are many different ISO standards that can be used to evaluate an optical systems performance. As this book is intended as a guide to the specification and tolerancing of optical components using the ISO 10110 series on drawing notation and not *per se* about system evaluation, only basic descriptions are provided here to introduce some of the key optical system functional metrics and their evaluation.

10.1 Background

The functional evaluation of an optical system is ultimately the final determining factor when verifying the finished optical assembly meets its specification. Specifying functional metrics for optical system performance may result in confusion because of a potential difference between what is expected from the manufacturers, and the manufacturers' understanding or interpretation of how they should perform the functional testing. By having functional testing standards, the communication between fabricators and

Chapter 11
Environmental Testing

Outside of the functional testing that occurs on an optical system, considerations must be made for the operating conditions of the optical system as well. Environmental conditions such as temperature and humidity can become critical when taking the optical system out from the lab. While not a direct aspect of ISO 10110, listing the environmental conditions for an optical system can be important when specifying a final assembly. This is especially true for systems with dielectric or metallic coatings that are exposed to the environment when used.

The ISO 9022 series is a group of test standards that define the environmental tests and levels at which a system or component will be tested. Most of the standards in the ISO 9022 series are for specific different environmental conditions. There are also three, more rigorous ISO 9022 standards that combine the individual environmental conditions that the optical system may truly experience.

In each part, a series of conditions, termed "*conditioning methods*," are described. These conditioning methods are identified by a numeric "*condition code*." To specify a test, the condition code for that test must be identified as well as the "*severity code*" and the operating state of the instrument being tested. The method of indicating an environmental test on an optics drawing is discussed more in Sec. 11.7.

In addition to the ISO 9022 series of standards, there is another standard (ISO 10109) that provides guidance for environmental conditions an optical system may experience depending on a specific application or global location. This standard lists expected temperature ranges, humidity, pressure, and rain conditions for a series of standard environments. These standard environments are based on global data collected and are meant to guide the user on which parts of ISO 9022 may be applicable for a given situation. These environmental conditions are in place to assist the user if temperature, humidity, and pressure are not known but the type of environment is known. The standard also includes a framework (ISO 10109, Table 9) for identifying

Chapter 12
Standards in Practice

We have shown in previous chapters that ISO 10110 can be a very powerful method for conveying information between the optical designer and the fabricator. The coded notation may seem confusing at first, but once understood, it obviates the need for significant additional communication throughout the fabrication process. By instituting the ISO 10110 drawing format, it is also possible to define an entire optical system specification and acceptance test. Starting the entire project with ISO 10110 and the associated ISO performance standards in mind allows the designer to have a concise set of requirements defined that can also be easily documented and communicated.

Users should develop an understanding of how to use standards holistically; in other words, how to specify full optical systems and assemblies. In order to better understand how to use standards successfully for both tolerances and for performance, in this chapter we provide a complete example. The goal is to help users understand how to take advantage of the ISO 10110 drawing notation from the beginning of an optical design, through tolerancing, and result in finished drawings.

Along with component drawings made with the ISO 10110 drawing format, the finished optical system may require overall performance verification. As discussed in chapter 10, there are many different types of performance metrics that can be used. In this chapter, we discuss specifications for an optical system that must be tested for multiple parameters.

12.1 System Parameters

To begin the optical system example, basic parameters must be established for the optical system itself. The requirements below are assumed to be reasonable for the example optical design to avoid needless complexity.

- Wavelength: Visible (400 nm to 700 nm)
- Effective focal length: 100 mm
- F/#: F/5

12.4 Optical Assembly Drawing

The last drawing in this example is the assembly drawing (Fig. 12.8). As this is an optical assembly without component manufacturing tolerances that must be defined, the tabular field is removed.

The full optical layout is shown in the drawing field with the axial spacings defined and toleranced accordingly. Each of the three optical elements are identified by an element number. A table in the top right of the drawing associates these element numbers with their part number and description, as well as the required tilt and decenter tolerances for each. The spacing from the aperture stop to element 3, and between elements 3 and 4, is identified as variable axial spacings. These spacings are used in the tolerance analysis to maintain a one-time, factory-set internal focus compensation adjustment. This choice is noted with the reason for this variation in the bottom right corner. Additionally, the back-focus distance is specified as an adjustable axial separation. This spacing is used in the tolerance analysis to achieve best focus, as stated in the bottom right corner of the print. The placement and diameter of the aperture stop between doublet 1 and element 3 is shown with tolerances. There is also a physical aperture defined at the front of the optical system for testing purposes. This aperture is not critical to the functionality of the optical system but is necessary for the required testing of the transmitted wavefront error and transmission.

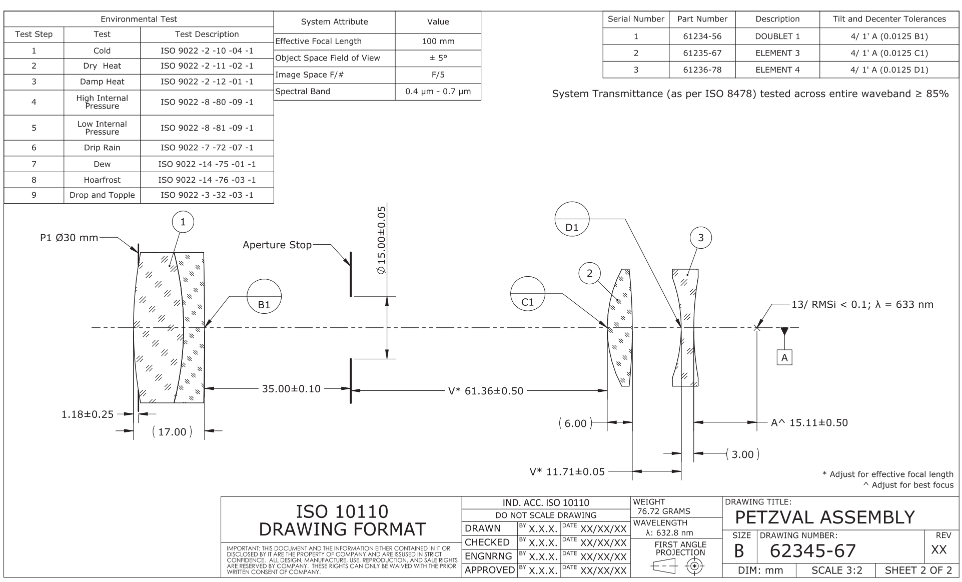

Figure 12.8 Optical system sample drawing for the entire optical assembly using the ISO 10110 drawing format.

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