3 Materials for Optical Systems

Trent Newswander and Roger A. Paquin

CONTENTS

3.1 Introduction ............................................................................................................................ 53
3.2 Applications........................................................................................................................... 53
  3.2.1 Refractors .................................................................................................................... 54
  3.2.2 Reflectors .................................................................................................................... 54
  3.2.3 Structural Optical Metering Components ................................................................. 55
  3.2.4 Adhesives and Cements ..............................................................................................55
3.3 Material Properties .................................................................................................................56
  3.3.1 Important Properties and Figures of Merit .................................................................56
    3.3.1.1 Physical ........................................................................................................ 56
    3.3.1.2 Mechanical ................................................................................................... 56
    3.3.1.3 Thermal ........................................................................................................ 58
    3.3.1.4 Optical .......................................................................................................... 60
  3.3.2 Typical Requirements .................................................................................................61
  3.3.3 Dimensional Stability .................................................................................................62
    3.3.3.1 Types of Instability ......................................................................................63
    3.3.3.2 Sources of Dimensional Change ..................................................................65
  3.3.4 Changes in Internal Stress ..........................................................................................66
  3.3.5 Microstructural Changes ............................................................................................ 70
  3.3.6 Inhomogeneity/Anisotropy of Properties ....................................................................70
  3.3.7 Promoting Dimensional Stability ...............................................................................71
    3.3.7.1 Refractive Materials .....................................................................................72
    3.3.7.2 Adhesives and Cements ...............................................................................83
3.4 Summary ................................................................................................................................ 87

References ........................................................................................................................................87

3.1 INTRODUCTION

Any optical system of necessity consists of many components often fabricated from and joined by a variety of materials. The choice of materials depends on the system performance requirements and many other factors including size, weight, mechanical loading, environment, number of systems required, and, of course, cost. This chapter provides discussion of the multiple applications of materials in an optical system; the importance of various properties and figures of merit; and the typical requirements, including a detailed discussion on dimensional stability. These introductory discussions are followed by sections detailing and providing properties for refractive materials and adhesives.

3.2 APPLICATIONS

In general, materials for optical systems include almost all available materials, the choice depending on the requirements of the particular application. For simplicity, these materials can be divided into four applications categories: refractors, reflectors, structural components, and adhesives. Typical applications are discussed in the following.
3.2.1 REFRACTORS

Refractors are generally defined as those optical elements that are transmissive to light. These may include image-forming lenses, which generally have one or both surfaces curved to a spherical or aspherical shape. Another class of transmissive optical elements includes optical windows, which are commonly used at the front end of an optical system to protect and seal the critical components of an optical assembly from adverse environmental effects such as dirt, dust, and humidity. Usually, optical windows are plane-parallel plates of optical quality glass, but sometimes a small wedge may be introduced between the two surfaces to correct the errors introduced by the window itself. In some applications involving a large field of view, optical windows are shaped like a shell or dome with a significant curvature. Although optical windows are not a part of the image-forming optics, these can have a significant effect on the wavefront and image quality of the system if they have a significant thickness and are located in a converging or diverging beam. Therefore, the selection of an appropriate material and thickness of the windows is critical to optimize the performance of the system. Another important class of refractive optics includes filters, which are extensively employed in photography, spectrometers, and other chemical analysis equipment. Such absorption filters may be made of glass or optical grade plastics. The glass absorption filters with multilayer coatings can be designed to isolate specific transmission bands in environmental monitoring instruments to detect the presence of specific gases and chemicals.

The choice of material used for making refractors depends on the wavelength and application. Although hundreds of optical glasses are available from major manufacturers in the United States and Europe, only 50 or so are most commonly used for making refracting components. Most of the other glasses tend to stain, have poor machinability, or thermal properties, or are too expensive. The commonly used glasses are available in various formulations of silicon dioxide (SiO₂) plus small amounts of the oxides and fluorides of barium, boron, calcium, lanthanum, sodium, and potassium. A number of lightweight glasses have also been developed for head-mounted displays, binoculars, and other airborne and space applications, where the overall weight of the system may be critical. Most of these lightweight glasses also have good hardness and better resistance to acids and alkalis.

The transmission of different glasses greatly varies over the spectral region from ultraviolet (UV) to IR. The crown glasses have good transmission at shorter wavelengths, while flints have good transmission in the near-IR region. Fused silica, Schott Ultraflint 30, and a few crystals transmit well in the near-UV region between 200 and 350 nm. A large variety of synthetic crystalline materials are available for UV and IR applications. These materials include alkali halides (KCl, NaCl, LiF, etc.) and alkaline earth halides (BaF₂, MgF₂, etc.), oxides (quartz, fused silica, etc.), semiconductors (Si, GaAs, Ge, diamond, etc.), and calcogenides (CdTe, ZnS, ZnSe, etc.). New optical quality plastics are becoming more readily available. Plastics are lightweight, have low fabrication cost, and are resistant to mechanical shock and vibrations. The plastics do have low scratch resistance and softening temperature and may be difficult to coat. They often exhibit birefringence due to stresses from the molding process. The plastics, in general, have low refractive index, and not as many optical grade plastics are available as compared to glasses. Some of the commonly used polymers are polycarbonates, acrylics, and polystyrenes.

3.2.2 REFLECTORS

Reflective elements are all mirrors, but include scanners, reflecting prisms, diffraction gratings, and other specialized components. The reflecting surface of a mirror can be bare, as for certain infrared telescopes of beryllium, or have an optical coating for specific wavelengths. All glass mirrors are coated. A mirror then consists of the reflective surface and the substrate that supports it. That substrate can be anything from a simple plane-parallel flat disk to a lightweighted, off-axis asphere of nonsymmetrical geometric form. They range in size from millimeters to meters and can be made from glasses, ceramics, metals, composites, or plastics. The classical reflective optical system, such
as an astronomical telescope, usually consists of glass mirrors metered with a metal support structure. For light weight, whether for space applications or thermal considerations, the glass can be lightweighted and metered with carbon fiber-reinforced polymer (CFRP). Additionally, other materials, such as aluminum (Al), beryllium (Be), silicon carbide (SiC), or composite material solutions can be used. The HST has a lightweight ultralow expansion-fused silica (ULE™) primary mirror, a Zerodur secondary, and a CFRP structure.

For high heat load applications, such as synchrotron or laser optics, actively cooled mirrors of copper (Cu), molybdenum (Mo), silicon (Si), or silicon carbide (SiC) are usually specified. These mirrors are fabricated with internal cooling channels, the complexity of which depends on the incident heat flux. Cooled mirrors have also been successfully fabricated with internal heat pipes. For lower heat loads, the low expansion materials such as ULE or Zerodur can be used. Heat absorption is minimized with high efficiency optical coatings and/or by using the optical surface at grazing incidence.

At the opposite end of the temperature scale, cryogenic mirrors are typically fabricated from fused quartz/fused silica, aluminum, and beryllium. For production systems where cost is critical, replicated optics are popular. Manufacturing involves building a mandrel with a precision inverse master surface on which a thin polymer layer is formed then lifted onto a mirror substrate. This technique is extensively used for small aspheric mirrors and for diffraction gratings. In the latter application, a master grating is ruled into a metal surface, often plated or otherwise consisting of deposited gold (Au) or Al. See Chapter 4 for a detailed discussion of materials used for reflectors.

### 3.2.3 Structural Optical Metering Components

While optical components, both reflective and refractive, may have to be designed as structures, the components referred to here are those that mechanically support, connect, and provide precision metering for the system’s optical components. Typical examples are optical benches, metering structures, mounting hardware, and lens housings. These components must be relatively stiff and dimensionally stable (but not necessarily to the same tolerance as optical components) and should be thermally matched to the optics in thermal expansion.

In many production systems that are primarily used at room temperature, Al is the preferred material because of its low cost and fabricability. Wrought products such as rod, bar, tube, plate, or extrusions are used as well as castings. For systems where weight is critical, such as space systems or inertia-critical systems, Be and CFRP are the preferred materials. Metal matrix composites (MMCs) can provide intermediate properties and can be more cost effective in production applications. While CFRP has become a common material in optical structures, each application requires a custom design and fabrication process. As with the MMCs, larger production quantities can be cost effective for demanding applications. For extremely stable and/or controlled expansion applications such as optical benches and metering structures, the low expansion materials such as Invar and CFRP composites are most often used, but Zerodur and ULE have also been used in critical metering applications such as the BEPOP telescope.

Component interface joining of structural components can be accomplished in many ways. All metals, including Be and the MMC components, can be assembled with conventional fasteners such as screws. Some Al, Cu, Be, MMC, and steel components can be brazed or welded as well. Just about all materials can be adhesively bonded. For more details on materials for structural optical metering components, see Chapter 4.

### 3.2.4 Adhesives and Cements

Adhesives can be either structural or optical. Structural adhesives have no transmissive optical requirements and are strictly used to mechanically bond components to each other such as a baffle to a support structure or a lens to its housing. When used on optical elements, desirable
adhesive properties include low thermal expansion, low stiffness, and low shrinkage during curing. Optical cements are part of the optical train since they are in the light path where they join refractive components such as cemented doublets and, as such, must have high transmission and index homogeneity.

A structure in which optical and mechanical components are secured together by adhesives as opposed to traditional fasteners can be lighter in weight and may be less expensive to fabricate due to mechanical housing simplifications. Moreover, the required machining tolerances (flatness, parallelism, etc.) for the bonded components can be generally looser compared to parts that must be rigidly bolted together. Also, bonded joints are flexible to a degree, thereby providing a better stress distribution under high loads, damping in vibration and shock environments, and allowing differential expansion between parts made from dissimilar materials. The silicone elastomers can also be used for sealing and damping. All adhesives have good shear strength, but have lower strength in tension and peel modes.2

Adhesives and cements are formulated from many different polymers. The most common structural adhesives are epoxies, polyurethanes, modified acrylis, cyanoacrylates, and anaerobics. Silicones are used in structural applications where resiliency is required, such as for joining of materials with disparate thermal expansions.

Optical cements can be epoxies, silicones, or other polymers. They can be thermosets, that is, two-part systems, thermoplastics that are heated to a liquid state and applied, photosetting, for example, UV curing or solvent loss cements. The latter are seldom used in modern optical systems because of the stress induced in the components by shrinkage during and after curing.

3.3 MATERIAL PROPERTIES

Important properties vary with the type of material: refractor, reflector, structure, or adhesive. For all materials, the properties fall into four categories: physical, mechanical, thermal, and optical. The most significant of these properties are discussed here along with some applicable figures of merit, and those properties more appropriate for a specific type of material are discussed under that section.

3.3.1 IMPORTANT PROPERTIES AND FIGURES OF MERIT

All material properties vary with temperature, some in a linear fashion, but most are nonlinear. For systems that operate at temperatures other than room temperature, great care is required in selecting and matching materials in order to ensure that the system will meet specifications over the required temperature range.

General references for properties include Handbook of Optics3; The Infrared Handbook4; Handbook of Infrared Optical Materials5; CRC Handbook of Laser Science and Technology6; ASM Handbook7,8; and Engineered Materials Handbook9-12

3.3.1.1 Physical

For all materials under consideration here, the physical properties of interest are mass density, electrical conductivity, and/or electrical resistivity. Electrical conductivity is inversely proportional to electrical resistivity and for most materials, one or the other is normally reported. These properties vary with temperature, but density varies slowly.

3.3.1.2 Mechanical

The design of optical components often involves some structural aspects where mechanical properties can be used as a basis for comparison. Deflection in any application is a function of five parameters: support conditions, materials, structural efficiency of the design, size (i.e., diameter), and loading.
The easiest of the five parameters to control is the material, the subject of this chapter. The important mechanical properties include elastic and/or plastic, strength, and fracture. Figures of merit for structural efficiency are used to rapidly compare materials for a given structural application, particularly in the design of lightweight reflective systems.

The elastic properties of crystalline materials can be described by a 6 × 6 matrix of constants called elastic stiffness constants. From these constants, the elastic properties of the material, Young’s modulus \( E \) (the elastic modulus in tension), bulk modulus \( K \), modulus of rigidity \( G \) (also called shear modulus), and Poisson’s ratio \( \nu \), can be calculated. The constants, and consequently the properties, vary as functions of temperature. Young’s modulus of elasticity \( E \) is the measure of stiffness or rigidity of a material, the ratio of stress, in the completely elastic region, to the corresponding strain. Bulk modulus \( K \) is the measure of resistance to change in volume, the ratio of hydrostatic stress to the corresponding change in volume. Shear modulus, or modulus of rigidity \( G \), is the ratio of shear stress to the corresponding shear strain under completely elastic conditions. Poisson’s ratio is the ratio of the absolute value of the rate of transverse (lateral) strain to the corresponding axial strain resulting from uniformly distributed axial stress in the elastic deformation region. For isotropic materials, the properties are interrelated by the following equations:

\[
G = \frac{E}{2(1 + \nu)} \quad (3.1)
\]

\[
K = \frac{E}{3(1 - 2\nu)} \quad (3.2)
\]

A group of structural figures of merit, all utilizing combinations of density and Young’s modulus, have been used to compare the structural efficiency of materials. The most commonly used term is specific stiffness \( E/\rho \). Specific stiffness has application for comparing structures of equal geometry in self-weight deflection and resonant frequency performance since natural frequency is proportional to the square root of specific stiffness. When the system volume constraint is less restrictive than the mass constraint, then a material’s low density is more valuable than its high stiffness. For equal mass comparison, \( E^{1/3}/\rho \) should be used. This parameter is derived from plate bending accounting for the moment of inertia where the less dense material can be slightly thicker. For illustration, consider that a mirror’s cross-sectional area can be approximated as a rectangular shape. A rectangle’s area moment of inertia is increased by the cubic power with thickness. Therefore, increasing the thickness of the mirror can significantly reduce its deflection due to an applied load. Furthermore, lightweighting or shape optimization can further increase the moment of inertia advantage of a structure dependent on available fabrication capabilities.

Mechanical strength and fracture properties are important for the structural aspects of the optical system. The components in the system must be able to support loads with no permanent deformation within the limits set by the error budget and certainly with no fracture. For ductile materials, the yield and/or microyield strength (MYS) may be most important, but for brittle or near-brittle materials, fracture toughness and/or modulus of rupture are more significant. A listing of definitions for each of these and other related terms follows:

- **Creep strength**—Creep strength is the stress that will cause a given time-dependent plastic strain in a creep test for a given time.
- **Ductility**—Ductility is the ability of a material to deform plastically before fracture.
• **Fatigue strength**—Fatigue strength is the maximum stress that can be sustained for a specific number of cycles without failure.

• **Fracture toughness**—Fracture toughness is a generic term for measures of resistance to extension of a crack.

• **Hardness**—Hardness is a measure of the resistance of a material to surface indentation.

• **Microcreep strength**—Microcreep strength is the stress that will cause 1 ppm of permanent strain in a given time, usually less than the MYS.

• **Microstrain**—Microstrain is a deformation of $10^{-6}$ m/m (1 ppm).

• **Microyield strength**—MYS is the stress that will cause 1 ppm of permanent strain in a short time; also called precision elastic limit or PEL.

• **Ultimate strength**—Ultimate strength is the maximum stress a material can withstand without fracture.

• **Yield strength**—Yield strength is the stress at which a material exhibits a specified deviation from elastic behavior (proportionality of stress and strain), usually $2 \times 10^{-3}$ m/m (0.2%).

**Hysteresis** is a term that has more than one meaning. In terms of mechanical behavior, it is the time-dependent strain from an applied mechanical or thermal load, also referred to as anelasticity. In this case, the removal of the load causes the strain to eventually return to zero. It also refers to the accumulated strain when a component is subjected to cyclic loading and unloading, a factor in fatigue failures. Another use of the word refers to the residual plastic strain in a component that has been thermally or mechanically cycled. This type of hysteresis is due to combined applied and residual stresses that exceed the MYS of the material. Further discussion of residual stress and hysteresis is given in Chapter 4.

The most often misunderstood family of properties for optical materials relates to the issues of stiffness and yield. First, the operating requirements will dictate the material and design selections. The optical system will not remain in alignment during use if the elastic yield of material due to self-weight, vibration, or other forms of loading exceeds the precision optical tolerances. Optical tolerances are far more stringent than those required in most mechanical equipment designs. Furthermore, the system will not return to alignment upon removal of the load if the plastic yield exceeds similar stringent requirements. The optical component yield strength is defined in terms of microyield or changes in a few tens of parts per million at most. The engineering onset of plastic yield strength of a material is usually specified at a stress which causes 0.2% or 2000 ppm offset after the return to zero stress. This is, of course, completely unacceptable in the case of precision optics. Fortunately, the relationship is not typically linear. It is possible to select materials with a yield strength which is nearly the same as the ultimate strength. These materials are known as being completely elastic (or at least nearly so). Materials in this category include glassy materials with the crystalline size typically below 1 nm, and as such, these materials are considered for all purposes to be amorphous.

It is important not to confuse the issue of elastic yielding in service with the yielding due to loading, shock, acceleration, or vibration not occurring during use, but perhaps only during transportation. For a system which must image during high vibration or acceleration, the use of very high specific stiffness materials and designs is required and may include beryllium, silicon carbide, or CFRP designs. The use of conventional aluminum alloys such as A-201 or 6061-T6 may suffice if the load is temporary and not a service requirement.

### 3.3.1.3 Thermal

The significant thermal properties are coefficient of linear thermal expansion (CTE) $\alpha$, thermal conductivity $k$, and specific heat $C_p$. Diffusivity $D$, a derived property equal to $k/\rho C_p$, is also important. All these properties vary with temperature, $\alpha$ and $C_p$ tending to directly vary with temperature and $k$ and $D$ varying inversely.
Thermal expansion is a generic term for a change in length for a specific temperature change, but there are more precise terms that describe specific aspects of this material property. CTE is the most generally applicable version and is defined as

$$\alpha \equiv \frac{1}{L} \left( \frac{\Delta L}{\Delta T} \right).$$  \hspace{1cm} (3.3)

Many materials are also anisotropic in thermal expansion. This is particularly true in polycrystalline materials and fiber-reinforced composites. Lower CTE is better for optical system performance as it minimizes the effect of thermal gradients on dimensional changes of components. It is important to match the CTE of adjacent components to minimize thermally induced strain in the system.

Thermal conductivity is the quantity of heat transmitted per unit of time through a unit of area per unit of temperature gradient. Higher thermal conductivity is desirable to minimize temperature gradients when there is a heat source in or close to the optical system. Specific heat, also called heat capacity per unit mass, is the quantity of heat required to change the temperature of a unit mass of material by one degree under conditions of constant pressure. A material with high specific heat requires more heat to cause a temperature change that might cause a distortion. High specific heat also means that more energy is required to induce a temperature change (e.g., in cooling an infrared telescope assembly to cryogenic temperatures).

Thermal diffusivity determines the rate at which a nonuniform temperature distribution reaches equilibrium through conductive heat transfer acting alone.

Shape factor plays a part in thermal stability through the role of cross-sectional area in conductivity: Two-dimensional conductive heat transfer is proportional to cross-sectional area ($A_c$). The relationship is shown in Fourier's law:

$$q = -KA_c \left( \frac{dT}{dx} \right).$$  \hspace{1cm} (3.4)

For equal mass thermal performance, the cross-sectional area influence should be considered in the thermal steady-state figure of merit. It is best accounted for with density. This assumes that the extra material of the lighter material will be used to thicken conduction paths. Density is volumetric, such that $\rho^{2/3}$ is proportional to steady-state conductive heat transfer, and the figures of merit for equal mass are

$$\text{Stability}_{\text{Steady-State}} = \frac{\alpha \rho^{2/3}}{K}, \quad \text{Stability}_{\text{Transient}} = \frac{\alpha \rho^{2/3}}{D}. \hspace{1cm} (3.5)$$

Three thermal figures of merit should be considered when comparing the thermal performance of materials. These include steady-state distortion coefficient $\alpha/k$, transient distortion coefficient $\alpha/D$, and CTE $\alpha$. The first is a measure of the total thermal displacement for a given steady-state thermal input. The transient distortion coefficient indicates the relative time for a thermal distortion to dissipate per unit of temperature gradient. However, for applications where convection or radiation heat transfer dominates conductive heat transfer, both of these thermal conductivity-based metrics will incorrectly predict performance. Typical applications include actively cooled mirror applications such as laser mirrors and high-emissivity highly lightweighted open-back mirrors. For these mirrors, the single most important factor is the CTE, $\alpha$.

The great importance of low thermal expansion properties has led to the use of low expansion materials for many years for precision instrumentation to minimize thermal dimensional changes in
service. Near-zero thermal expansion properties have been developed and realized for some glass, ceramic, and CFRP composite materials. Excluding the high-performance CFRP materials, these materials have low thermal conductivity, resulting in low thermal diffusivity and relatively high steady-state and transient distortion coefficients. This presents the user an important systems engineering decision regarding the best approach for realizing a low thermal distorted optical system: either select a material with high conductivity, which provides a high diffusivity but comes with a relatively high thermal expansion, or select a material with near-zero thermal expansion, but comes with a very low conductivity and associated low diffusivity. The system design approach for each is quite different with high ramification on system resilience, mass, cost, complexity, and power. Figure 3.1 plots the equal mass metrics for transient thermal stability versus stiffness for many materials used in optical systems. Isopleths are plotted to show lines of equal weighting of stiffness and thermal stability.

3.3.1.4 Optical

Optical properties of solids are complex tensors and, as such, will not be described in depth here. For a more complete treatise, see the study by Wooten or Born and Wolf.

The most important optical property used in geometric optics is the index of refraction \( n \). The index of refraction is the ratio of the velocity of light in a vacuum to that in the material. In its general form, it is a complex quantity expressed as

\[
\bar{n} = n - ik,
\]

where \( n \) is the real index and \( k \) is the imaginary part, called the index of absorption or extinction coefficient. For normal incidence, only the real part is important in optical design. For isotropic and cubic materials, there is one index, but for more complex crystals, the index varies with crystallographic direction. For an in-depth treatment of the optical properties of crystals and glasses, see the study by Tropf et al.

The index of refraction varies with wavelength, temperature, and applied stress. The variation of refractive index with wavelength is called dispersion. The index of all transmitting materials...
increases with decreasing wavelength as shown in Figure 3.2. One way to characterize the dispersion, as devised for optical glasses, is with the Abbe number $\nu_d$ where

$$
\nu_d = \frac{n_d - 1}{n_F - n_c}.
$$

(3.7)

The subscripts $d$, $F$, and $c$ refer to the wavelengths for the emission lines of hydrogen and helium at 587.56 nm, 486.13 nm, and 656.27 nm, respectively. There are other dispersion parameters, such as partial dispersions, that are discussed in more detail in the study by Yoder² and in optical glass catalogs.

The variation of refractive index with temperature $dn/dT$ is positive for most glasses, but negative for a few. When combined with CTE, the change in optical path length with temperature can be obtained from the thermooptical constant $G = \alpha(n - 1) + dn/dT$. The change in path length is then $t \cdot G \cdot \Delta T$, where $t$ is the mechanical thickness of the element. Note that a material can be athermal if $\alpha$ and $dn/dT$ have opposite signs.

### 3.3.2 Typical Requirements

Optical systems are built for a great variety of purposes and, therefore, have driving requirements that substantially vary across the optical system landscape. Some optical design requirements are less constraining and can be met relatively easily, but others must be met by careful design optimization and materials selection for both the optical elements and the supporting structures. For example, optics used in relatively inexpensive web cameras have an entirely different list of operating constraints and, therefore, use relatively simple designs and inexpensive materials compared to those used in space missions, large ground observatories, and lithography systems.¹⁵

Some requirements that frequently affect interdisciplinary design and materials selection include spectral region, stray light requirements, mass, minimum fundamental frequency or structural rigidity, and thermal design constraints. The selection of the optimum material for an optical application is best accomplished with a complete understanding of the application field.
A successful design meets the performance criteria for the specified environment and lifetime for a reasonable cost. This requires trade-offs among materials, fabrication methods, structural considerations such as mirror design and mounting scheme, and of course, cost. The challenge in achieving this is the multitude of constraints that impact the design. Typical among these constraints are the following:

- Thermal, such as operating temperature range and incident thermal/energy fluxes
- Mechanical, such as applied forces and dynamic conditions
- Size and weight
- Schedule and cost

In general, these constraints are best met by using dimensionally stable materials that are lightweight or can be built into lightweight structures with high stiffness and mirror materials that can be optically surfaced.

Beyond the optical elements requirements to appropriately transmit and reflect the electromagnetic radiation of interest, the first basic optomechanical performance requirement of optical structural materials is to maintain the optical elements positions and surface shapes in the operational environment for the specified optical performance. Maintaining position or metering of optical elements requirements can be as loose as tenths of a millimeter to as tight as tenths of a micron, dependent on the optical element, the wavelength, and the systems optical application. Optical element shape requirements are typically much tighter, especially for mirror elements. They can be as loose as tens of microns or as tight as single digit nanometers. Refractive elements are typically less sensitive to surface shape distortion, but additionally, they may be sensitive to any induced stress in the optical transmitting medium. A material's capability of maintaining dimensional positions and form is dependent on not only its mechanical and thermal responses to external loads and environments but also its inherent dimensional stability. The following section discusses dimensional stability issues for the typical materials.

### 3.3.3 Dimensional Stability

For the optical system engineer, it is imperative to appreciate the microscopic dimensional changes due to loading, either self-induced by gravity or by acceleration, vibration, or shock. These changes may be temporary for low loading or permanent for higher loading. The magnitude of either may need to be one or two orders of magnitude lower than for conventionally engineered mechanical hardware. Additionally, it is also imperative to appreciate the similar changes due to differential temperature, which may include operation over a wide temperature range, or less stringent, to survive a wide temperature range but recover without displacement hysteresis. The acceptable stress in an optical system material will be far below the engineering practice for most designs of equipment. For retaining alignment or flatness (curvature control) in precision designs to microstrain units, it is imperative to define both operational (working) loads and nonoperational load conditions such as vibration during transportation or launch of a space-borne system. The operating load is usually much lower, but if the nonoperational loads deform the system, it may not function well at all.

The dimensional stability of a component is actually the degree to which instabilities are controlled. Therefore, any discussion of dimensional stability is really a discussion of instabilities, and dimensional instability is simply the dimensional change that occurs in response to internal or external influences. All materials are dimensionally unstable to some degree. In preparing to design and fabricate dimensionally stable mirrors, it is important to realize that this implies controlling the sources of dimensional instabilities to a level such that any dimensional changes that occur are kept within specified tolerances. To be able to accomplish this requires an understanding of the sources of these instabilities.
The key to stability is knowing the performance requirements. Stable materials can then be chosen from which mirrors and optical structures can be fabricated utilizing the methods that minimize introduction of dimensional instabilities. The balance of this section contains examples of common types of instabilities and their sources and gives some suggestions as to how they can be controlled. While this section is an overview, the following references are recommended for further study:

- Marschall and Maringer, an excellent book on the subject, although it is unfortunately now out of print
- Paquin and Paquin and Vukobratovich, the two volumes of SPIE proceedings specifically dealing with dimensional stability
- Paquin, the paper on which this section is based

3.3.3.1 Types of Instability

Instabilities can be categorized as follows:

- Temporal instability
- Thermal/mechanical hysteresis
- Thermal instability
- Mechanical load instability
- Other instabilities

Each of these factors can have magnitudes ranging from nanostrain to very large numbers and is described in the following section.

3.3.3.1.1 Temporal

Temporal instability is the change that takes place in a component as a function of time in a fixed environment. It is a permanent change. For example, two sets of nominally similar 1 in. gauge blocks were tested at the National Bureau of Standards (NBS) over a period of roughly 30 years. One set exhibited a positive and relatively constant rate of change of dimensions of as much as $10^{-6}$ m/m/year. That is a very small amount, and yet, it is totally unacceptable for optical applications. The other set typically changed only 25 nm in 22 years. This kind of dimensional instability is generally associated with relaxation of residual stress.

3.3.3.1.2 Hysteresis

Thermal/mechanical hysteresis is the change measured in a fixed environment after exposure to a variable environment, that is, measured in a laboratory environment before and after exposure to changes in temperature and/or mechanical loading. It, too, is a permanent dimensional change. A common example is the dimensional change that takes place in fiber-reinforced composites when subjected to thermal cycling over a wide temperature range. The behavior typically shows a substantial change in length of up to 1% on the first cycle, but the amount of change decreases with each succeeding cycle, approaching an asymptote. This kind of behavior is discussed later in this section for other materials. For composites, the cause for the dimensional changes is usually internal microcracking of the fibers, while in single-phase materials, it is usually some other form of internal stress relief. Similar behavior has been observed with mechanical cycling and vibration.

3.3.3.1.3 Thermal

Thermal instability is the dimensional change measured in one fixed environment after a change from another fixed environment, independent of the environmental path. This dimensional change is reversible upon returning to the original conditions. Figure 3.3 shows evidence of just such a
change. This beryllium (Be) mirror was made from an experimental billet produced in the late 1960s which had a substantial amount of thermal expansion inhomogeneity. It was interferometrically tested many times over a period of almost 10 years and exhibited the same distortion shown in the figure when heated and always returned to the same optical figure at room temperature, within the 0.02 wave accuracy of the instrument. This behavior has been virtually eliminated in modern Be materials.

3.3.3.1.4 Other Instabilities

The other principal type of instability is the change measured in a fixed environment after being exposed to a variable environment where the change is dependent on the environmental path between the fixed environment measurements. This type of distortion can be permanent or reversible. For example, in Figure 3.4, the length of Zerodur on cooling from 300 to 20°C depends on the cooling rate. This is typical behavior for glasses containing MgO. But note that the curves are parallel below 150°C, indicating that the temperature range of sensitivity is between 150 and 300°C. This behavior has been eliminated in a new version of this material called Zerodur M. This type of behavior is rarely observed in metals. These are the major types of dimensional instability that can be encountered in optics and precision instruments. Many of the other commonly observed instabilities can be placed into one or more of these four categories.
3.3.3.2 Sources of Dimensional Change

The sources of dimensional changes such as those described earlier can be attributed to one or more of the following factors:

- Externally applied stress
- Changes in internal stresses
- Microstructural changes
- Inhomogeneity/anisotropy of properties

3.3.3.2.1 External Stress

When an external stress is applied to a component, if it behaves according to Hooke’s law, it should deform elastically no matter how long the stress is applied and return exactly to its original shape when the stress is removed. But this being an imperfect world, and most materials not being perfect, there are other responses to externally applied stress. If a load is suddenly applied, held for a length of time, and then released, the elastic response has exactly the same square wave shape as the applied load. An anelastic strain shows a time-dependent elastic response with respect to the applied load. For this type of behavior, there is no strain when the load is first applied, but it increases toward an asymptote with time; when the load is removed, the strain asymptotically returns to zero. Anelastic behavior is rarely observed in metals and ceramics, has been observed in some glass-ceramics at low temperature, but is more commonly observed in polymers. Plastic strain is permanent and does not decrease as the load is removed. The most common behavior for metals is a combination of elastic and plastic response to stress. Time-dependent plastic strain is called creep. Most of the time, many materials exhibit a combination of these elastic responses to externally applied loads.

There are a number of material properties that are important to dimensional stability. Among these are thermal properties such as the CTE, thermal conductivity, and mechanical properties: elastic modulus (Young’s modulus), a measure of stiffness and the slope of a stress vs. strain curve; Poisson’s ratio, the relationship between tensile (or compressive) and shear strain; yield strength (at 0.2% offset), the stress to cause $2 \times 10^{-3}$ permanent or plastic strain; ultimate or fracture strength; MYS, the stress to produce $1 \times 10^{-6}$ plastic strain (one unit microstrain); and microcreep strength, which has no acceptable definition other than that it is less than the MYS and is a constant stress that produces microstrain after some.

Microyield behavior cannot be directly inferred from the macromechanical properties of either yield strength or modulus. For example, when the behaviors of I-400 Be and 2024-T4 aluminum, metals with approximately the same yield strength, are compared, Be exhibits a MYS of approximately 50 MPa, but with increased stress, it yields little more. However, the Al alloy resists yielding for a high MYS of 250 MPa, but then continues yielding readily. Recent analyses have shown, however, that for any given family of alloys of the same base material, MYS is proportional to yield strength.

MYS is strongly dependent on the prior history of the material. If it has been annealed, the microyield will be lower than in almost any other condition. Conversely, if there has been prior straining, either through intentional or inadvertent applications, the MYS will be raised. While prestraining produces a stronger material, it also leaves a level of residual stress that may be detrimental. Residual stress is discussed further in the next section.

Since high MYS is a desirable property, and since many materials have relatively low MYS, it is important to know that there are methods for increasing it. Prestrain, as mentioned earlier, is one method, but it has its disadvantages. Many aluminum alloys, after rolling into plate form, are stretched to a few percent to both straighten and level the stress through the thickness of the plate, which also increases the MYS; but this process also seems to lower microcreep strength. Since the process of microyielding occurs, at least in the early stages, by the movement of dislocations, anything that pins or prevents
dislocation movement will increase MYS. By reducing the grain size of a material, dislocations are more readily pinned, as they are when particle or fiber reinforcement is added to a single phase material. Multiphase materials almost always have higher MYS than similar single-phase alloys. Thermal treatments that precipitate a second phase or produce a metastable phase tend to increase strength, and alloying a pure material usually produces dislocations and lattice strains that likewise increase MYS.

3.3.4 Changes in Internal Stress

While external stress is applied and removed from a component and is readily observed and measured, internal stress is not obvious. A component can be free of external attachments, even floating in a zero-g environment, and have internal stresses. They are in equilibrium and consist of balanced tensile and compressive stresses.

There are two types of internal stress called short range and long range. The spatial extent of these is, as the name implies, microscopic and macroscopic, respectively. The long-range internal stress is better known as residual stress. To illustrate both types, consider a component machined from an inherently anisotropic metal such as Be. If the component was annealed prior to machining, the bulk of the material will consist of Be grains that vary in crystallographic orientation and, therefore, in CTE at the grain boundaries. This produces short-range internal stress at the grain boundaries. At the surface of the part, the machining will have plastically deformed a surface layer within which the residual or long-range stress will be approximately equal to the yield strength, approximately 275 MPa for Be. Below the deformed layer, there would be a partially deformed transition layer where the residual stress level would rapidly decrease from 275 MPa (probably tensile), through 0, to a low-level compressive stress.

Short-range internal stress can result from unequal amounts of distortion between neighboring crystals in plastically deformed material. It can also arise from inhomogeneous CTE: in a two-phase material, between adjacent crystals with anisotropic CTE as described earlier for Be, or in a matrix with a dispersed phase or reinforcing particles, whiskers, or fibers. Table 3.1 lists the theoretical maximum values of thermally induced microstrain due to CTE mismatch between adjacent grains of a few noncubic materials. In practice, the average values are approximately one-third of these calculated maxima. It can be seen that for Be, one-third of the 437 KPa/°C value over a 100°C temperature change results in a short-range stress of over 14 MPa, a value that exceeds the MYS of some Be alloys.

Long-range internal stress, residual stress, is usually the result of processing operations such as forming, heat treating, welding, machining, or plating. As you would expect, the level of the stress is dependent on the severity of the operation, as shown in the following examples. Figure 3.5 shows how the temperature of quench water affects the residual stress in Al alloys. The yield strength also

<table>
<thead>
<tr>
<th>Material</th>
<th>Lattice</th>
<th>Kpa/°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>Hexagonal</td>
<td>1212</td>
</tr>
<tr>
<td>Calcite</td>
<td>Rhombohedral</td>
<td>1130</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Hexagonal</td>
<td>626</td>
</tr>
<tr>
<td>Beryllium</td>
<td>Hexagonal</td>
<td>437</td>
</tr>
<tr>
<td>Quartz</td>
<td>Rhombohedral</td>
<td>295</td>
</tr>
<tr>
<td>Indium</td>
<td>Tetragonal</td>
<td>223</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Hexagonal</td>
<td>19</td>
</tr>
<tr>
<td>Graphite</td>
<td>Hexagonal</td>
<td>6.5</td>
</tr>
</tbody>
</table>
drops when the water quench is less severe. Polymer quenchants are available that can provide the low residual stress of a boiling water quench with the strength of the cold water quench.

The introduction of residual stress, or any change in the balance of the stress, will cause changes in dimensions of the component. This means that the removal of a stressed layer will cause dimensional changes as demonstrated in Figure 3.6. When two specimens with surface residual stress are acid etched, they both shrink, the one with the higher stress (deeper cut) shrinking more. This principle is used in the manufacture of dimensionally stable components where after heavy material removal operations the surfaces are acid etched to restore unstressed dimensions to the part. Residual stress can also decrease spontaneously with time with a related change in dimensions. This

![Figure 3.5](image1.png)

**FIGURE 3.5** Residual stresses in specimens of 7075-T6 aluminum plate quenched in water at different temperatures.

![Figure 3.6](image2.png)

**FIGURE 3.6** Dimensional changes in 3.0 in. long specimens of Ni-Span-C on chemical removal of residual stresses due to machining.
effect is called stress relaxation and the decrease in stress is proportional to the stress level as shown in Equation 3.8, where \( s \) is stress, \( t \) is time, and \( \tau \) is the relaxation time.

\[
(-\frac{ds}{dt})\tau = s
\]  

(3.8)

But stress also decreases exponentially with time as shown by

\[
s = s_0 e^{-\nu t}.
\]  

(3.9)

Note that when time \( t \) is equal to the relaxation time \( \tau \), the ratio of stress to original stress \( s/s_0 \) is equal to \( 1/e = 0.37 \). This behavior is shown in Figure 3.7, where a Be mirror was fabricated with no treatment for stress relief after annealing the rough blank. Note the exponential shape to the curve for optical figure change.

Stress relaxation is also a thermally sensitive process, behaving according to the Arrhenius relationship of Equation 3.10, where \( E \) is the activation energy, \( k \) is Boltzmann’s constant, and \( T \) is absolute temperature.

\[
\frac{1}{\tau} \propto e^{-E/kT}
\]  

(3.10)

This phenomenon can be used to reduce the stress level with thermal treatment, that is, stress relief. However, the question is often raised whether an isothermal treatment for some reasonable time or thermal cycling between elevated and reduced temperatures is a more effective stress relief treatment. Much has been written on this subject as summarized in Chapter 6 of Marschall and Maringer, but the best answer is “it depends.” It depends on the crystal structure and purity of the material; it depends on the prior thermomechanical history of the component; it depends on the temperature, time, and rate of change of temperature; and, of course, it depends on the level, type, and distribution of the internal stresses.

One example of what can happen is given in Figure 3.8, where both isothermal and thermal cycling treatments were applied to Be specimens previously stressed to 77 MPa. In this case, the low annealing temperatures of 100 and 190°C do very little but relieve peak stresses. The best treatment is a 600°C stress relief treatment, but this is higher than most designers would want to subject a semifinished
optic to. A temperature of 400°C still only removes 40% of the stress, but note that thermal cycling from 400°C to either −70 or −196°C provides a 55% reduction. The cycling is more effective than the isothermal treatment to the same upper temperature. This cycling effect may only hold for noncubic materials with reasonably high expansion anisotropy as listed in Table 3.1, or for materials with more than one phase such as composite materials. There is conflicting evidence in the literature on the effect of thermal cycling on stress relief of homogeneous cubic or amorphous materials.

For those materials where thermal cycling is more effective than isothermal exposure at the same elevated temperature for the reduction of residual stress, the proposed mechanism is as follows. These materials develop short-range internal stress when the temperature is changed due to the expansion mismatch between adjacent grains and/or phases. When this stress is added to the long-range, or residual, stress, the yield or MYS is exceeded locally and plastic strain results. When the temperature is returned to room temperature, the plastic strain remains, but the level of the residual stress is reduced. Holding at the elevated temperature provides no further benefit unless it is close to either the creep or annealing temperature. When the temperature is then reduced below room temperature, the sign of the short-range stress is reversed, exercising the material further and providing more stress relief. In a similar manner, vibration, or mechanical cycling, can provide stress relief, although, as for thermal cycling, there are resulting dimensional changes.

For reducing stress levels in critical components, we then have a number of options:

1. Thermal treatments such as isothermal exposure or thermal cycling
2. Mechanical treatments such as vibration or mechanical working
3. Removal of surface material by chemical etching, controlled grinding, and/or polishing or other stress-free methods
4. Time

FIGURE 3.8 Comparison of the effects of thermal cycling and isothermal exposure on stress relaxation of pure beryllium. (From Lokshin, I. Kh., *Metal Science and Heat Treatment*, Heat 426, 426–427, 1970.)
3.3.5 **Microstructural Changes**

Microstructural changes in materials can result in both induced dimensional change and internal stress. The type of response depends on the material type and the kind of microstructural change. Changes can take place in mirror materials: phase transformations, recrystallization, and grain growth in metals and ceramics and devitrification, phase transformations, recrystallization, and grain growth in coatings. This cause of dimensional instability is quite common, but cannot be adequately covered here. Two examples illustrate the principle.

The dimensional change that takes place in heat-treatable aluminum alloys during precipitation heat treatment, also called precipitation hardening, is illustrated in Figure 3.9. This shows that a component aged from the solution-treated and quenched condition to obtain maximum mechanical properties, normally from 4 to 8 hours, will undergo a dimensional change due to the precipitation of the second phase. The change is small for 6061 aluminum, a significant shrinkage for 7075 aluminum, and a significant expansion for 2014 aluminum. But notice that additional hours of aging, often performed for stress relief, induce additional significant dimensional change, particularly for the 2014 aluminum alloy. The 6061 aluminum alloy, most often used for precision optical structures and mirrors, changes the least, verifying its applicability for these applications.

The second example involves electroless nickel coatings which are extensively used, both for polishable coatings and for corrosion protection of Al, Be, and iron alloy components. The coatings are nickel–phosphorous alloys that may be amorphous and are thermodynamically unstable as deposited. During thermal treatment (annealing) immediately after plating, hydrogen is driven off, adhesion improves, hardness increases, and low phosphorous coatings can devitrify (change from amorphous to polycrystalline). There is shrinkage and a decrease in CTE that takes place during thermal treatment, the magnitude of which depends on the annealing conditions. For higher temperatures and longer times, nickel phosphide (NiP), which has a smaller specific volume than pure nickel, forms as a precipitate in the coating. The annealing temperature used in the referenced studies is 190°C, with 4 hours at temperature for Be and 1 hour for the other materials.

3.3.6 **Inhomogeneity/Anisotropy of Properties**

Most materials, as fabricated, are neither completely isotropic nor homogeneous; they are to some level anisotropic, that is, having some preferred directionality of properties, and/or inhomogeneous, that is, having a spatial variation in properties. The anisotropy of properties exists in pure single crystals of materials. The inhomogeneity of properties occurs in bulk and is a function of raw material fabrication processes.
Cubic materials generally have anisotropy in their elastic properties. For example, the Young’s modulus of elasticity of pure iron varies with crystallographic direction from 132 to 282 GPa. Similar variations in shear modulus and Poisson’s ratio are also present. Comparable variations in these properties occur in other cubic materials such as Cu, Ni, Si, and beta SiC. When these materials are used in polycrystalline form, the variations average out and are not noticed. In components that are fabricated from single crystals, or applications that have crystallographic texture such as plated or chemically vapor deposited (CVD) materials, there can be substantial elastic property anisotropy, and this should be included in any detailed deformation modeling of such components. Thermal properties such as CTE are isotropic for cubic materials. Thermal conductivity, which is also isotropic, is affected by grain size and grain boundaries so that for plated or CVD materials, the anisotropy is present. For example, CVD SiC has a deposition texture, and both the elastic modulus and thermal conductivity have approximately 15% anisotropy.

In a similar manner to the cubic materials, there are variations in elastic properties in noncubic materials, that is, hexagonal, rhombohedral, tetragonal, orthorhombic, etc. However, the thermal properties of the noncubic materials are anisotropic. For example, the CTE of Be is 38% higher in the basal plane than it is in the axial direction of a Be crystal or grain. This anisotropy leads to the microstructural strains listed in Table 3.1. Some materials such as graphite and quartz have negative CTE in some directions and positive in others. The effects of thermal properties anisotropy, for the various crystalline materials that exhibit it, can be minimized with a fine-grain, randomly oriented microstructure.

Inhomogeneity can be attributed to spatial variations in chemistry, grain size, and/or grain orientation, and many other factors. In general, CTE inhomogeneity in metals and ceramics is due to compositional or microstructural variations where the latter can be due to crystal orientation differences and/or the presence of other phases. For composites, CTE inhomogeneity is a given due to the presence of multiple phases. The inhomogeneity can be caused by variations in the orientation of the reinforcement, or from variations in the concentration of the reinforcement. Care should be exercised in the selection of multiphase materials that may be used over a wide temperature range to ensure dimensional stability.

Components having CTE inhomogeneity can behave in the manner shown in Figure 3.3. In this particular case, the cause is a combination of Be powder with basal plane cleavage, a poor distribution of grain sizes, and inappropriate consolidation parameters. Current Be fabrication processes have virtually eliminated these types of inhomogeneities through the use of impact ground or spherical powder with well-controlled chemistries combined with hot isostatic pressing of the powder.31–33

### 3.3.7 Promoting Dimensional Stability

There are many potential pitfalls in the design and fabrication of dimensionally stable components. In order to avoid these pitfalls, there is a sequence of actions that can be implemented that should lead to stable components.

The first step is to establish a budget for the allowable dimensional change for each component in the system and allocate a tolerance to each element. Structural components will probably not have as tight a tolerance as optical components, and all components of each type will not necessarily have the same requirements. Then, consider the sources of dimensional change as they relate to the components to be fabricated. For example, if the system is to operate at reduced or elevated temperatures, then both thermal instability and thermal cycling instability are potential types of instability, and the sources for such behavior are changes in internal stress, inhomogeneity and/or anisotropy, and microstructural changes. Consider the fabrication options and how they relate to the dimensional instability sources and the component performance requirements. With all these factors in hand, select the candidate materials and reevaluate the sources and fabrication methods for each material with respect to meeting the budgeted dimensional tolerances in the specified use environment.
In order to make the final materials and fabrication method selection, you need to demonstrate that external stresses will not cause excessive strain in the component, that internal stresses in the component due to fabrication methods or inhomogeneities and/or anisotropies will not change excessively, and that any microstructural changes will not cause excessive strains. While this method sounds complicated, once you understand the basic sources of potential instability and the magnitude of the possible changes for each of the common candidate materials and their respective fabrication methods, the selection process becomes almost intuitive. The difficult part is when you must produce a component that operates in an environment for which the material properties information is severely limited, or when designing components to nanotolerances.

3.3.7.1 Refractive Materials

The refractive materials commonly used for making lenses, prisms, optical windows, and filters can be broadly classified into three distinct categories, namely: glasses, plastics, and lastly, optical crystals and semiconductor materials.

3.3.7.1.1 Properties

The physical, mechanical, and thermal properties of selected refractive materials, which are most commonly used for optical and mechanical components, are covered in the subsequent sections. To keep the material property tables concise, only the nominal values at room temperature are listed and, therefore, must only be used for preliminary evaluation and comparison purposes. Since the mechanical and thermal properties of materials can vary from one manufacturer to another and even from lot to lot for the same material from the same manufacturer, it is advisable to contact the manufacturer for obtaining more exact values of these properties for critical applications.

The optical properties of materials such as refractive index, Abbe value, reflectivity and transmittance, and variations of these properties as function of wavelength and temperature have deliberately been left out of these tables to avoid duplication of property tables from other sources. Some excellent and comprehensive references for optical properties of materials are Handbook of Optics, the Infrared Handbook, and Yoder.

3.3.7.1.2 Typical Requirements

The selection of refractive materials is most often driven by the material’s optical properties applicable to the optical system. Optical throughput is dependent in part on the transmission of its refractive materials in the wavelengths of interest. Materials with high transmission over broad regions of the electromagnetic spectrum such as sapphire, fluorides, and zinc selenide have wide applicability in optical systems. Materials are also carefully selected for their optical index and dispersion properties so that they support the desired optical imaging or light-gathering purposes when combined with the other refractive materials in the optical system. In general, high indexes of refraction materials are desirable as they accomplish increased light bending with reduced element curvature. Refractive materials are often selected in combination with other specific optical materials for their combined achromatic potential. For instance, in the visible wavelength, flints are combined with crowns. In the infrared wavelength, germanium is often used in conjunction with a chalcogenide material.

Although the mechanical properties of the glass being used in a system may be of secondary importance, they do play a critical role in ensuring dependable performance during operation. The mechanical and thermal properties of the selected refractive materials such as density, elastic modulus, MYs, coefficient of thermal expansion, and thermal conductivity are of special significance if the designed optical system must be lightweight, rugged, and capable of retaining its performance over a large temperature range. Therefore, rather than selecting a particular glass merely on the basis of its optical properties, due consideration must also be given to its mechanical and thermal properties before finalizing the choice.
In addition to mechanical properties, a refractive element’s fabrication and robustness to its intended application environment must be considered when selecting a material. Lens and window refractive elements are most often cut from larger billets or boules and generated or ground to shape. Then, the optical surface(s) are generated through various techniques that often include polishing for visible glass materials and/or single-point diamond turning for IR crystals and plastics. For high-quantity manufacturing where the material is capable, molding may be used to provide a finished product at reduced reoccurring costs. Available fabrication techniques are greatly dependent on the material. For instance, silica-based glass materials cannot be single-point diamond turned. Chapter 14 provides a more detailed and comprehensive discussion of fabrication approaches applicable to specific materials.

The intended environment will also play a major role in the selection of the refractive material. Optical windows and domes may see very severe environments, including thermal extremes, rain, sand, and salt fog. For example, sapphire is often used because of its high surface hardness, good thermal conductivity, and resistance to acids and alkalis. Space environments can expose optical materials to high radiation, which can cause darkening or have other negative effects on the materials performance. Radiation-hard materials are often selected to eliminate or minimize these effects. Salts such as potassium bromide (KBr) are very useful with their very broad and long wavelength transmissivity. However, these salt materials are hygroscopic, which makes them vulnerable to environments that may expose them to water or excessive humidity.

### 3.3.7.1.3 Glasses

Glasses are the most commonly used class of refracting material in optical systems. Glass is an amorphous material primarily composed of silica with additional materials added to alter the optical properties, chemical reactivity, and manufacturability. Boric oxide, alumina, alkaline earths, and alkali oxides are commonly added to produce high optical transparency and chemical resistance with the desired optical index and optical dispersion. Glass with a relatively low index and low dispersion are referred to as crown glass. Higher density material such as lead, zirconium, titanium, or other metal oxides are added to produce higher-index glass with higher dispersion, which is categorized as flint glass. Additionally, glass with longer infrared wavelength application is achieved by replacing the oxygen element with other elements of the chalcogenide group such as sulfur, selenium, or tellurium. For a more detailed discussion and explanation of the various terms used in describing the properties of optical glasses, see the study by Marker and the catalog Schott Optical Glass.

Most glass used in optical systems is rapidly quenched from liquid in order to accomplish solidification in an amorphous condition. This provides the most clarity by preventing additional transmission loss due to scattering along with the absorption. This also assures from a mechanical point of view that the material is completely elastic. The notion that glass is elastic is not always clear to an inexperienced designer. The elastic modulus is actually quite low and comparable to aluminum at about 70 GPa (10 Mpsi) for most glass. The obvious concern is although the glass is able to recover from any induced strain short of breaking, this amount of strain is very small. Thus, when the glass is anything short of perfectly smooth on the edges and even on the surfaces, the stress will be higher at defect sites resulting in premature fractures since the material does not yield plastically. The area under the stress–strain curve is very low. This value is the strain energy and is very important in the design of lightweight optical components.

The normal design stress limit for most silicate glass including quartz is only 7–14 Kpa (1 or 2 Kpsi). This is in spite of the fact that very smooth small fibers in bending modes may exhibit a tensile (and yield) strength of several hundred thousands of pounds per square inch. This in turn creates a dichotomy with regard to lightweight glass optics. It is possible to improve the resistance to breakage by using resilient mounts at the edges of the glass and by smoothing the edges of the lens or other component by firing the edges either with a flame or with a laser of proper wavelength for the energy to be absorbed and cause rapid localized heating of the edge.
In addition to the chemical composition of a glass, its properties are dependent on the fabrication process, including the thermal time history. For example, there is a difference between fused silica and fused quartz, or quartz glass. Fused silica is manufactured by the pyrolytic decomposition of reactive gases and usually has high water content and no metallic impurities. Fused quartz is made by fusing crystalline quartz to form a glass. Fused quartz has some level of metallic impurities that can cause UV fluorescence, and the water content depends on the firing method. Fused quartz can have some granularity, a residual of the original quartz crystal structure. Therefore, these nominally identical materials will have slightly different index and dispersion from different manufacturers.

Table 3.2 lists physical, mechanical, and thermal properties of selected optical and specialty glasses which are most commonly used in a majority of the optical systems.1,41

3.3.7.1.4 Crystals and Semiconductors

Optical crystals and ceramics are widely used in broadband optical systems and include both synthetic and naturally occurring materials. Optical crystal materials are available as single and polycrystalline forms. The polycrystalline form of a material consists of small, randomly oriented individual crystals and are manufactured by various methods such as by hot pressing of powders, sintering, and chemical vapor deposition. On the other hand, single crystals are typically grown from dissolved and molten materials. Polycrystalline materials, in general, have higher strength and hardness as compared to single crystal materials.16 Polycrystalline materials generally have isotropic properties while single crystals have directionally dependent anisotropic properties.

Optical crystals are widely used in IR applications, but there are a number of crystals which have good transmission over a wide band from ultraviolet to far-IR wavelengths; for example, CaF2 and LiF are extensively used for achromatized lenses in far-UV to mid-IR (0.11–10 μm) applications. CaF2 has the best strength and moisture resistance of all fluoride crystals and has a very low thermo-optic coefficient.

Another very useful material for high-temperature application is sapphire, which is the single crystal form of aluminum oxide. It has high strength and hardness and excellent thermal shock resistance. It is widely used in specialized optical systems subjected to severe environments. Another useful naturally occurring optical crystal is quartz, which is commonly used for UV prisms and windows and in IR applications with up to 4 μm wavelength. Quartz and sapphire are also grown artificially to improve transmission by controlling the amount of impurities. The thermal properties such as the CTE of these materials are direction dependent and quite sensitive to thermal shock.42

Silicon and germanium (Ge) are extensively used in IR systems for lenses, windows, and domes. Silicon is very suitable for missile domes because of its good mechanical and thermal properties. Germanium is quite hard but is susceptible to brittle fracture. Both materials have high index of refraction and are therefore very suitable for making multiple lens assemblies to keep the thicknesses and weight within reasonable limits. Due to the high index of these materials, efficient anti-reflection coatings are required to minimize internal reflection losses. The optical properties of Ge, such as index of refraction and absorption, are quite sensitive to temperature. Table 3.3 lists optical, physical, mechanical, and thermal properties of selected crystalline materials, while Tables 3.4 and 3.5 list the same properties for IR-transmitting materials. A more extensive list of materials and properties can be found in the study by Tropf.43

3.3.7.1.5 Plastics

This section summarizes the application of plastics in optical application. More details on this topic are presented in Chapter 5. Optical plastics are used in a small fraction of optical systems compared to optical glasses and crystal materials. The use of plastic lenses is finding favor in systems of lower precision requirements. The plastic lens is not brittle like the glass, and some plastics have higher index of refraction and low density permitting thin and very lightweight designs. Plastic is not stable over a wide temperature range and typically exhibits high chromatic dispersion or wavelength-dependent changes. The index of refraction typically varies unacceptably with both temperature and
### TABLE 3.2
Properties of Selected Optical Glasses

<table>
<thead>
<tr>
<th>Glass Code</th>
<th>Schott Type</th>
<th>Density $\rho$: g/cm$^3$</th>
<th>Young's Modulus $E$: Gpa</th>
<th>Poisson's Ratio $\nu$</th>
<th>Knoop Hardness HK</th>
<th>Thermal Expansion $\alpha$: ppm/K</th>
<th>Specific Heat $c_p$: J/kg K</th>
<th>Thermal Conductivity $k$ or $\lambda$: W/m K</th>
</tr>
</thead>
<tbody>
<tr>
<td>487 704</td>
<td>FK 5</td>
<td>2.45</td>
<td>62</td>
<td>0.232</td>
<td>520</td>
<td>9.2</td>
<td>808</td>
<td>0.925</td>
</tr>
<tr>
<td>517 642</td>
<td>BK 7</td>
<td>2.51</td>
<td>82</td>
<td>0.206</td>
<td>610</td>
<td>7.1</td>
<td>858</td>
<td>1.114</td>
</tr>
<tr>
<td>518 651</td>
<td>PK 2</td>
<td>2.51</td>
<td>84</td>
<td>0.209</td>
<td>640</td>
<td>6.9</td>
<td>736</td>
<td>0.755</td>
</tr>
<tr>
<td>522 595</td>
<td>K 5</td>
<td>2.59</td>
<td>71</td>
<td>0.224</td>
<td>530</td>
<td>8.2</td>
<td>783</td>
<td>0.950</td>
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<tr>
<td>523 515</td>
<td>KF 9</td>
<td>2.71</td>
<td>67</td>
<td>0.202</td>
<td>490</td>
<td>6.8</td>
<td>720</td>
<td>1.160</td>
</tr>
<tr>
<td>532 488</td>
<td>LLF 6</td>
<td>2.81</td>
<td>63</td>
<td>0.203</td>
<td>470</td>
<td>7.5</td>
<td>700</td>
<td>1.000</td>
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<td>540 597</td>
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<td>71</td>
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<td>8.0</td>
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<td>548 458</td>
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<td>573 576</td>
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<td>0.252</td>
<td>530</td>
<td>7.6</td>
<td>687</td>
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<td>575 415</td>
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<td>0.213</td>
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<td>0.879</td>
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<td>0.256</td>
<td>590</td>
<td>5.5</td>
<td>560</td>
<td>0.990</td>
</tr>
<tr>
<td>617 366</td>
<td>F4</td>
<td>3.58</td>
<td>56</td>
<td>0.222</td>
<td>420</td>
<td>8.3</td>
<td>553</td>
<td>0.768</td>
</tr>
<tr>
<td>620 364</td>
<td>F 2</td>
<td>3.61</td>
<td>57</td>
<td>0.220</td>
<td>420</td>
<td>8.2</td>
<td>557</td>
<td>0.780</td>
</tr>
<tr>
<td>620 603</td>
<td>SK 16</td>
<td>3.58</td>
<td>89</td>
<td>0.264</td>
<td>600</td>
<td>6.3</td>
<td>578</td>
<td>0.818</td>
</tr>
<tr>
<td>626 390</td>
<td>BaSF 1</td>
<td>3.66</td>
<td>62</td>
<td>0.242</td>
<td>460</td>
<td>8.5</td>
<td>553</td>
<td>0.741</td>
</tr>
<tr>
<td>636 353</td>
<td>F 6</td>
<td>3.76</td>
<td>57</td>
<td>0.224</td>
<td>410</td>
<td>8.5</td>
<td>510</td>
<td>0.755</td>
</tr>
<tr>
<td>648 339</td>
<td>SF 2</td>
<td>3.86</td>
<td>55</td>
<td>0.227</td>
<td>410</td>
<td>8.4</td>
<td>498</td>
<td>0.735</td>
</tr>
<tr>
<td>651 559</td>
<td>LaK N22</td>
<td>3.73</td>
<td>90</td>
<td>0.266</td>
<td>600</td>
<td>6.6</td>
<td>550</td>
<td>0.797</td>
</tr>
<tr>
<td>652 449</td>
<td>BaF 51</td>
<td>3.42</td>
<td>89</td>
<td>0.266</td>
<td>590</td>
<td>8.4</td>
<td>620</td>
<td>0.870</td>
</tr>
<tr>
<td>658 509</td>
<td>SSK N5</td>
<td>3.71</td>
<td>88</td>
<td>0.278</td>
<td>590</td>
<td>6.8</td>
<td>574</td>
<td>0.773</td>
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(Continued)
### TABLE 3.2 (CONTINUED)
Properties of Selected Optical Glasses

<table>
<thead>
<tr>
<th>Glass Code</th>
<th>Schott Type</th>
<th>Density $\rho$: g/cm$^3$</th>
<th>Young's Modulus $E$: Gpa</th>
<th>Poisson's Ratio $\nu$</th>
<th>Knoop Hardness HK</th>
<th>Thermal Expansion $\alpha$: ppm/K</th>
<th>Specific Heat $c_p$: J/kg K</th>
<th>Thermal Conductivity $k$ or $\lambda$: W/m K</th>
</tr>
</thead>
<tbody>
<tr>
<td>670 471</td>
<td>BaF N10</td>
<td>3.76</td>
<td>89</td>
<td>0.281</td>
<td>590</td>
<td>6.8</td>
<td>595</td>
<td>0.798</td>
</tr>
<tr>
<td>673 322</td>
<td>SF 5</td>
<td>4.07</td>
<td>56</td>
<td>0.233</td>
<td>410</td>
<td>8.2</td>
<td>488</td>
<td>0.738</td>
</tr>
<tr>
<td>699 301</td>
<td>SF 15</td>
<td>4.06</td>
<td>60</td>
<td>0.235</td>
<td>420</td>
<td>7.9</td>
<td>464</td>
<td>0.741</td>
</tr>
<tr>
<td>702 410</td>
<td>BaSF 52</td>
<td>3.96</td>
<td>86</td>
<td>0.283</td>
<td>550</td>
<td>5.2</td>
<td>540</td>
<td>0.737</td>
</tr>
<tr>
<td>717 295</td>
<td>SF 1</td>
<td>4.46</td>
<td>56</td>
<td>0.232</td>
<td>390</td>
<td>8.1</td>
<td>415</td>
<td>0.702</td>
</tr>
<tr>
<td>717 480</td>
<td>LaF 3</td>
<td>4.14</td>
<td>95</td>
<td>0.286</td>
<td>580</td>
<td>7.6</td>
<td>465</td>
<td>0.690</td>
</tr>
<tr>
<td>720 504</td>
<td>LaK 10</td>
<td>3.81</td>
<td>111</td>
<td>0.288</td>
<td>720</td>
<td>5.7</td>
<td>580</td>
<td>0.840</td>
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<tr>
<td>740 282</td>
<td>SF 3</td>
<td>4.64</td>
<td>56</td>
<td>0.236</td>
<td>380</td>
<td>8.4</td>
<td>423</td>
<td>0.706</td>
</tr>
<tr>
<td>744 448</td>
<td>LaF 2</td>
<td>4.34</td>
<td>93</td>
<td>0.289</td>
<td>560</td>
<td>8.1</td>
<td>480</td>
<td>0.648</td>
</tr>
<tr>
<td>750 350</td>
<td>LaF N7</td>
<td>4.38</td>
<td>80</td>
<td>0.280</td>
<td>520</td>
<td>5.3</td>
<td>440</td>
<td>0.770</td>
</tr>
<tr>
<td>755 276</td>
<td>SF 4</td>
<td>4.79</td>
<td>56</td>
<td>0.241</td>
<td>390</td>
<td>8.0</td>
<td>410</td>
<td>0.650</td>
</tr>
<tr>
<td>785 258</td>
<td>SF 11</td>
<td>4.74</td>
<td>66</td>
<td>0.235</td>
<td>450</td>
<td>6.1</td>
<td>431</td>
<td>0.737</td>
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### TABLE 3.3
Properties of Selected Alkali Halide Crystalline Materials

<table>
<thead>
<tr>
<th>Material Name and Symbol</th>
<th>Useful Spectral Range: μm</th>
<th>Refractive Index $n$ at $\lambda$: μm</th>
<th>Density $\rho$: g/cm$^3$</th>
<th>Young's Modulus $E$: GPa</th>
<th>Poisson's Ratio $\nu$</th>
<th>Thermal Expansion Coefficient $\alpha$: ppm/K</th>
<th>Specific Heat $C_p$: J/kg K</th>
<th>Thermal Conductivity $k$: W/m K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barium fluoride, BaF$_2$</td>
<td>0.13–15</td>
<td>1.463 (0.6) 1.458 (3.8) 1.449 (5.3)</td>
<td>4.89</td>
<td>53</td>
<td>0.343</td>
<td>6.7 at 75 K 19.9 at 300 K 24.7 at 500 K</td>
<td>402</td>
<td>11.7</td>
</tr>
<tr>
<td>Calcium fluoride, CaF$_2$</td>
<td>0.13–10</td>
<td>1.431 (0.7) 1.420 (2.7) 1.411 (3.8) 1.395 (5.3)</td>
<td>3.18</td>
<td>96</td>
<td>0.28</td>
<td>18.9</td>
<td>854</td>
<td>10</td>
</tr>
<tr>
<td>Calcium fluoride, CaF (Kodak Irtran 3)</td>
<td>0.15–11.8</td>
<td>1.434 (0.6) 1.407 (4.3)</td>
<td>3.18</td>
<td>99</td>
<td>18.9</td>
<td>853</td>
<td>9.7</td>
<td></td>
</tr>
<tr>
<td>Potassium chloride, KCl</td>
<td>0.21–25</td>
<td>1.474 (2.7) 1.472 (3.8) 1.469 (5.3) 1.454 (10.6)</td>
<td>1.98</td>
<td>30</td>
<td>0.216</td>
<td>37.1</td>
<td>678</td>
<td>6.7</td>
</tr>
<tr>
<td>Lithium fluoride, LiF</td>
<td>0.12–8.5</td>
<td>1.394 (0.5) 1.367 (3.0) 1.327 (5.0)</td>
<td>2.63</td>
<td>65</td>
<td>0.33</td>
<td>5.5</td>
<td>1548</td>
<td>11.3</td>
</tr>
<tr>
<td>Magnesium fluoride, MgF$_2$</td>
<td>0.15–9.6</td>
<td>1.384 (0.4) 1.356 (3.8) 1.333 (5.3)</td>
<td>2.18</td>
<td>169</td>
<td>0.308</td>
<td>14.0 (P) 8.9 (N)</td>
<td>1004</td>
<td>21</td>
</tr>
<tr>
<td>Magnesium fluoride, (Kodak Irtran 1)</td>
<td>0.6–8</td>
<td>1.378 (1.0) 1.364 (3.0) 1.337 (5.0)</td>
<td>3.18</td>
<td>73</td>
<td>0.25–0.36</td>
<td>10.7</td>
<td>502</td>
<td>14.6</td>
</tr>
<tr>
<td>Sodium chloride, NaCl</td>
<td>0.17–18</td>
<td>1.525 (2.7) 1.522 (3.8) 1.517 (5.3) 1.488 (10.6)</td>
<td>2.16</td>
<td>40</td>
<td>0.28</td>
<td>39.6</td>
<td>837</td>
<td>6.5</td>
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### TABLE 3.4
Properties of Selected IR Materials

<table>
<thead>
<tr>
<th>Material Name and Symbol</th>
<th>Useful Spectral Range μm</th>
<th>Refractive Index $n$ at $\lambda$ μm</th>
<th>Density $\rho$: g/cm$^3$</th>
<th>Young's Modulus $E$: GPa</th>
<th>Poisson's Ratio $\nu$</th>
<th>Thermal Expansion Coefficient $\alpha$: ppm/K</th>
<th>Specific Heat $C_p$: J/kg K</th>
<th>Thermal Conductivity $k$: W/m K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond C</td>
<td>0.25–200</td>
<td>2.382 (2.5)</td>
<td>3.51</td>
<td>1050</td>
<td>0.16</td>
<td>−0.1 at 25 K</td>
<td>108</td>
<td>2600</td>
</tr>
<tr>
<td>Gallium arsenide, GaAs</td>
<td>1–16</td>
<td>3.1 (10.6)</td>
<td>5.32</td>
<td>83</td>
<td>0.31</td>
<td>5.7</td>
<td>326</td>
<td>48–55</td>
</tr>
<tr>
<td>Silicon, Si</td>
<td>1.2–15</td>
<td>3.436 (2.7)</td>
<td>2.329</td>
<td>131</td>
<td>0.22</td>
<td>2.7–3.1</td>
<td>53</td>
<td>150–163</td>
</tr>
<tr>
<td>Cadmium telluride, CdTe</td>
<td>0.9–15</td>
<td>2.682 (6)</td>
<td>5.85</td>
<td>37</td>
<td>0.41</td>
<td>5.9 at 300 K</td>
<td>234</td>
<td>6.3</td>
</tr>
</tbody>
</table>

(Continued)
### TABLE 3.4 (CONTINUED)
Properties of Selected IR Materials

<table>
<thead>
<tr>
<th>Material Name and Symbol</th>
<th>Useful Spectral Range μm</th>
<th>Refractive Index $n$ at $\lambda$: μm</th>
<th>Density $\rho$: g/cm³</th>
<th>Young’s Modulus $E$: GPa</th>
<th>Poisson’s Ratio $\nu$</th>
<th>Thermal Expansion Coefficient $\alpha$: ppm/K</th>
<th>Specific Heat $C_p$: J/kg K</th>
<th>Thermal Conductivity $k$: W/m K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc sulfide, ZnS (Raytheon Standard grade)</td>
<td>0.5–12</td>
<td>2.36 (0.6) 2.257 (3.0) 2.246 (5.0) 2.192 (10.6)</td>
<td>4.08</td>
<td>75</td>
<td>0.29</td>
<td>4.6 at 173 K 6.6 at 273 K 7.7 at 473 K</td>
<td>2.257 (3.0) 6.6 at 273 K 2.246 (5.0) 7.7 at 473 K</td>
<td>2.192 (10.6)</td>
</tr>
<tr>
<td>Zinc sulfide, ZnS (Kodak Irtran 2)</td>
<td>0.5–14</td>
<td>2.37 (0.6) 2.249 (4.3)</td>
<td>4.09</td>
<td>96</td>
<td>0.25–0.36</td>
<td>6.6</td>
<td>962</td>
<td>15.4</td>
</tr>
<tr>
<td>Zinc selenide, ZnSe (Raytheon CVD Raytran)</td>
<td>0.6–20</td>
<td>2.61 (0.6) 2.438 (3.0) 2.429 (5.0) 2.403 (10.6) 2.376 (14)</td>
<td>5.27</td>
<td>70</td>
<td>0.28</td>
<td>5.6 at 163 K 7.1 at 273 K 8.3 at 473 K</td>
<td>2.438 (3.0) 7.1 at 273 K 2.429 (5.0) 8.3 at 473 K</td>
<td>2.403 (10.6) 3.32 2.376 (14)</td>
</tr>
<tr>
<td>Zinc selenide, ZnSe (Kodak Irtran 4)</td>
<td>0.5–20</td>
<td>2.485 (1.0) 2.440 (3.0) 2.432 (5.0) 2.418 (8.0) 2.407 (10.0) 2.394 (12.0)</td>
<td>5.27</td>
<td>71</td>
<td>7.7</td>
<td>335</td>
<td>335</td>
<td>335</td>
</tr>
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</table>

### TABLE 3.5
Properties of Selected IR-Transmitting Glasses and Other Oxide Materials

<table>
<thead>
<tr>
<th>Material Name and Symbol</th>
<th>Useful Spectral Range: μm</th>
<th>Refractive Index n at λ: μm</th>
<th>Density ρ: g/cm³</th>
<th>Young's Modulus E: GPa</th>
<th>Poisson’s Ratio ν</th>
<th>Thermal Expansion Coefficient α: ppm/K</th>
<th>Specific Heat C_p: J/kg K</th>
<th>Thermal Conductivity k: W/m K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium alumino-silicate (Schott IRG 11)</td>
<td>0.5–5</td>
<td>1.684 (0.55) 1.635 (3.3) 1.608 (4.6)</td>
<td>3.12</td>
<td>108</td>
<td>0.284</td>
<td>8.2 at 293–573 K</td>
<td>749 at 293–373 K</td>
<td>1.13</td>
</tr>
<tr>
<td>Calcium alumino-silicate (Corning 9753)</td>
<td>0.6–4.2</td>
<td>1.61 (0.5) 1.57 (2.5)</td>
<td>2.798</td>
<td>99</td>
<td>0.28</td>
<td>5.95 at 293–573 K</td>
<td>837 at 373 K</td>
<td>2.5 at 373 K</td>
</tr>
<tr>
<td>Calcium alumino-silicate (Schott IRGN6)</td>
<td>0.4–4.5</td>
<td>1.592 (0.55) 1.562 (2.3) 1.521 (4.3)</td>
<td>2.81</td>
<td>103</td>
<td>0.276</td>
<td>6.3 at 293–573 K</td>
<td>808 at 293–373 K</td>
<td>1.36</td>
</tr>
<tr>
<td>Fluoro phosphate (Schott IRG9)</td>
<td>0.4–4</td>
<td>1.488 (0.55) 1.469 (2.3) 1.458 (3.3)</td>
<td>3.63</td>
<td>77</td>
<td>0.288</td>
<td>6.1 at 293–573 K</td>
<td>694 at 293–373 K</td>
<td>0.88</td>
</tr>
<tr>
<td>Germanate (Corning 9754)</td>
<td>0.4–5</td>
<td>1.67 (0.5) 1.63 (2.5) 1.61 (4.0)</td>
<td>3.581</td>
<td>84</td>
<td>0.290</td>
<td>6.2 at 293–573 K</td>
<td>544</td>
<td>1.0</td>
</tr>
<tr>
<td>Germanate (Schott IRG 2)</td>
<td>0.4–5</td>
<td>1.899 (0.55) 1.841 (2.3) 1.825 (3.3)</td>
<td>5.00</td>
<td>96</td>
<td>0.282</td>
<td>8.8 at 293–573 K</td>
<td>452 at 293–373 K</td>
<td>0.91</td>
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</table>

(Continued)
## TABLE 3.5 (CONTINUED)
Properties of Selected IR-Transmitting Glasses and Other Oxide Materials

<table>
<thead>
<tr>
<th>Material Name and Symbol</th>
<th>Useful Spectral Range: μm</th>
<th>Refractive Index n at λ: μm</th>
<th>Density ρ: g/cm³</th>
<th>Young’s Modulus E: GPa</th>
<th>Poisson’s Ratio ν</th>
<th>Thermal Expansion Coefficient α: ppm/K</th>
<th>Specific Heat C_p: J/kg K</th>
<th>Thermal Conductivity k: W/m K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lanthanum-dense flint (Schott IRG3)</td>
<td>0.4–4</td>
<td>1.851 (0.55) 1.796 (2.3) 1.776 (3.3)</td>
<td>4.47</td>
<td>100</td>
<td>0.287</td>
<td>8.1 at 293–573 K</td>
<td>1.796 (2.3)</td>
<td>1.776 (3.3)</td>
</tr>
<tr>
<td>Lead silicate (Schott IRG7)</td>
<td>0.4–4</td>
<td>1.573 (0.55) 1.534 (2.3) 1.516 (3.3)</td>
<td>3.06</td>
<td>60</td>
<td>0.216</td>
<td>9.6 at 293–573 K</td>
<td>1.534 (2.3)</td>
<td>1.516 (3.3)</td>
</tr>
<tr>
<td>Magnesium oxide, MgO₂ (Kodak Irtran 5)</td>
<td>0.2–6</td>
<td>1.723 (1.0) 1.692 (3.0) 1.637 (5.0)</td>
<td>3.58</td>
<td>332</td>
<td>0.2</td>
<td>11.5</td>
<td>879</td>
<td>50</td>
</tr>
<tr>
<td>Sapphire, Al₂O₃</td>
<td>0.15–7.5</td>
<td>1684 (3.8) 1586 (5.8)</td>
<td>3.97</td>
<td>400</td>
<td>0.27</td>
<td>5.6 (P) 5.0 (N)</td>
<td>753</td>
<td>25–33</td>
</tr>
<tr>
<td>Silica, fused, SiO₂ (Corning 7940)</td>
<td>0.15–3.6</td>
<td>1.566 (0.19) 1.460 (0.55) 1.433 (2.3) 1.412 (3.3)</td>
<td>2.202</td>
<td>73</td>
<td>0.17</td>
<td>−0.6 at 73 K 0.52 at 278–308 K 0.57 at 273–473 K</td>
<td>108.8</td>
<td>13.8</td>
</tr>
</tbody>
</table>

wide band-pass for high performance systems. For selective wavelength or relatively narrow band-pass, however, one of the better substitutes for brittle glass optics is the use of polycarbonate plastics such as is used in millions of eyeglass lenses. These materials can be made into lightweight and shock-resistant optics. Low-end camera, microscope, and binocular lenses are also large markets for plastic optics.

The manufacturing methods for various plastic lenses vary, but usually consist of casting or injection molding principles starting with the liquid plastic monomer or dimer and heating to produce the polymeric solid plastic lens. This can even be performed in an optician’s office for a customer on the same day. The molds are typically made by electroforming nickel over a very carefully prepared glass master. The master can be used many times to produce the same lens mold for many vendors and the molds are used by independent lens fabricators many times over. Certain other plastics may be melted and directly injection molded.

Advanced designs in plastic optics are favoring the use of solid optics. Such designs use plastic or even plastic and glass lenses in contact with each other to eliminate the air space and provide very light compact optical systems with excellent durability. The plastic or glass lens, which is exposed to the environment, must usually be coated to prevent scratching and for antireflection purposes.

The number of optical plastics available is quite limited compared to the number of optical glasses. The optical plastics can be classified into two broad categories: thermoplastics and thermosets. The term thermoplastic means a “material which flows when heated,” but there are some thermoplastics that do not flow when heated. Thermoset plastics can be set by heating these materials. Thermoplastics, or linear plastics as they are sometimes called, do not undergo any chemical change during the molding process and, therefore, can be remolded several times without affecting their properties. On the other hand, thermosets, also known as cross-linked plastics, start with a linear polymer chain, which gets permanently cross-linked in the presence of heat during molding.44

The most widely used optical plastic is acrylic, specifically known as polymethyl methacrylate. It is a low-cost plastic that can be easily molded, machined, and polished and has the best combination of optical properties. It has a low thermal conductivity and a high linear coefficient of thermal expansion (70 ppm/K), which is 8–10 times greater than that of typical optical glass. It has a shrinkage of 0.2–0.6% and a good optical memory, which is the ability to return to its original shape after exposure to heat. Acrylic has very good transmission (92%) and low internal scattering, and its refractive index varies from 1.483 for \( \lambda = 1 \text{ \mu m} \) to 1.510 for \( \lambda = 380 \text{ nm} \). The index of refraction varies from about 1.492 to 1.480 over a temperature range of 20–90°C.44

Polystyrene is a second common optical plastic that can be combined with acrylic to obtain highly corrected achromatic lens designs. Its index of refraction is 1.590, and transmission is about 90%. It can be easily injection molded, and it is the lowest-cost optical plastic. It has a lower moisture absorption than acrylic, but it is more difficult to machine and polish as compared to acrylic.

Polycarbonate is another widely used optical plastic for ophthalmic lenses, street lights, and automotive tail light lenses due to its high durability and impact resistance. It is more expensive than acrylic and styrene because it is more difficult to mold, machine, and polish, and it scratches easily. Its refractive index ranges from 1.560 to 1.654, and the transmission is about 85%. It retains its performance over a broad range of temperature (−137 to 121°C).

The only thermoset optical plastic used is allyl diglycol carbonate, commonly known as CR 39. It is extensively used in making cast ophthalmic lenses, which are subsequently machined and polished, which makes it more expensive. It cannot be injection molded. It has excellent optical and mechanical properties such as clarity, impact, and abrasion resistance. It can withstand continuous temperature of up to 100°C and up to 150°C for short periods, but it also has a high shrinkage rate of up to 14%.14

Other less commonly used optical copolymers of styrene and acrylic include methyl methacrylate styrene, styrene acrylonitrile, methyl pentene, and clear acrylonitrile butadiene styrene. Table 3.6 lists physical, mechanical, and thermal properties of some of the optical plastics discussed here. A more detailed discussion of optical properties and design and fabrication methods for plastic lenses can be found in the studies by Lytle43 and Welham.34
3.3.7.2 Adhesives and Cements

Adhesives and cements are powerful tools for constructing and retaining elements in an optical system. Like the other materials making up an optical system, adhesives and cements must be carefully selected.

3.3.7.2.1 Properties

Selection of adhesive materials involves engineering trades. The adhesive must be adequately strong and stiff to effectively act as the joining method. However, these same properties result in the stressing of the optical element, which can produce optical surface distortion and optical index variation in transmissive optical media. Initially, stress results from the adhesives cure shrinkage with compounding effects created from elevated temperature curing. Adhesives can have very high coefficients of thermal expansion, especially above its respective glass transition temperature. Glass transition is the transition of the material from an amorphous rigid state to a more flexible state, which produces substantial property changes in strength, stiffness, and rate of thermal expansion. This nonlinear temperature-dependent change in properties must be accounted for in the design, analysis, and use of adhesives.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\rho$: gm/cc</th>
<th>CTE $\alpha$: ppm/K</th>
<th>Maximum Service Temperature $T_v$: °C</th>
<th>Thermal Conductivity $k$</th>
<th>Water Absorption $A$: %</th>
<th>Luminous Transmittance: %</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-methylmethacrylate (acrylic)</td>
<td>1.18</td>
<td>6.0</td>
<td>85</td>
<td>4–6</td>
<td>0.3</td>
<td>92</td>
</tr>
<tr>
<td>P-styrene</td>
<td>1.05</td>
<td>6.4–6.7</td>
<td>80</td>
<td>2.4–3.3</td>
<td>0.03</td>
<td>88</td>
</tr>
<tr>
<td>Methyl methacrylate styrene</td>
<td>1.13</td>
<td>5.6</td>
<td>85</td>
<td>4.5</td>
<td>0.15</td>
<td>90</td>
</tr>
<tr>
<td>Styrene acrylonitrile</td>
<td>1.07</td>
<td>6.4</td>
<td>75</td>
<td>2.8</td>
<td>0.28</td>
<td>88</td>
</tr>
<tr>
<td>P-carbonate</td>
<td>1.25</td>
<td>6.7</td>
<td>120</td>
<td>4.7</td>
<td>0.2–0.3</td>
<td>89</td>
</tr>
<tr>
<td>P-methyl pentene</td>
<td>0.835</td>
<td>11.7</td>
<td>115</td>
<td>4.0</td>
<td>0.01</td>
<td>90</td>
</tr>
<tr>
<td>P-amide (Nylon)</td>
<td>1.185</td>
<td>8.2</td>
<td>80</td>
<td>5.1–5.8</td>
<td>1.5–3.0</td>
<td>88</td>
</tr>
<tr>
<td>P-arylate</td>
<td>1.21</td>
<td>6.3</td>
<td>160</td>
<td>2.8</td>
<td>0.1–0.6</td>
<td>88</td>
</tr>
<tr>
<td>P-sulfone</td>
<td>1.24</td>
<td>2.5</td>
<td>160</td>
<td>7.1</td>
<td>0.26</td>
<td>88</td>
</tr>
<tr>
<td>P-styrene co-butadiene</td>
<td>1.01</td>
<td>7.8–12</td>
<td>170</td>
<td>0.25</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>P-cyclohexyl methacrylate</td>
<td>1.11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-ally diglycol carbonate</td>
<td>1.32</td>
<td></td>
<td>100</td>
<td>4.9</td>
<td></td>
<td>93</td>
</tr>
<tr>
<td>Cellulose acetate butyrate</td>
<td>1.20</td>
<td></td>
<td></td>
<td>4.0–8.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-ethersulfone</td>
<td>1.37</td>
<td>5.5</td>
<td>200</td>
<td>3.2–4.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-chlorotrifluoroethylene</td>
<td>2.2</td>
<td>4.7</td>
<td>200</td>
<td>6.2</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>P-vinylidene fluoride</td>
<td>1.78</td>
<td>7.4–13</td>
<td>150</td>
<td></td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>P-etherimide</td>
<td>1.27</td>
<td>5.6</td>
<td>170</td>
<td></td>
<td>0.25</td>
<td></td>
</tr>
</tbody>
</table>

To reduce stressing the optical element, it is best practice to accurately control the volume and extent of the adhesives material. For instance, long effective lengths are inadvertently created with fillets and full injection holes, increasing the stressing effects of the adhesive’s large CTE. Furthermore, the effectiveness of the adhesive to meet requirements is dependent on the process controlling the adhesive’s components, mixing, cure schedule, and application. Therefore, a number of the adhesives’ characteristics and properties must be carefully considered, including cure shrinkage, CTE, glass transition temperature, outgassing, shear and peel strengths, stiffness, and Poisson’s ratio.

Compatible application processes and appropriate cure schedules and temperature must also be considered. Adhesives and cements are nonlinear elastomer materials with properties that vary with temperature, stress, and cure temperature. Tables in the following sections list physical, mechanical, and thermal properties of a number of commonly used structural adhesives and optical cements at room temperature. These properties’ values are nominal values and, therefore, must be used for comparison and preliminary design purposes. For critical applications, it is advisable to obtain the actual data and specification sheets from the manufacturers and complete internal testing to better understand the expected properties for specific application processes, geometries, and environments.

3.3.7.2.2 Structural Adhesives

Structural adhesives and elastomers can be used to bond structural components to each other or to bond optical components such as mirrors and lenses to their cells or mounts. The three main classes of structural adhesives are epoxies, urethanes, and cyanoacrylate adhesives. The thermosetting epoxy adhesives have high bonding strengths and good thermal properties. The epoxies are available in one- or two-part types, and some are room-temperature curable. The urethanes or polyurethanes have fairly high strength and can be used to bond together a variety of materials. They are flexible and, therefore, susceptible to creep and not suitable for high temperature (>100°C) applications, but are well suited for cryogenic applications. The one-part cyanoacrylate adhesives have low viscosity and are suitable for bonding smooth surfaces with very thin bond joints. They have cure times of less than 30 s, so proper fixturing is a requirement, and care must be taken to protect the skin from accidental bonding. These materials outgas more than other adhesives and are suitable for applications where the humidity is low and the temperature stays below 70°C. The key physical, mechanical, and thermal properties of some commonly used structural adhesives in optical applications are listed in Table 3.7.

The two-part room temperature vulcanizing rubbers (RTVs) available from GE and Dow Corning are extensively used to bond mirrors, lenses, filters, and optical windows to their mounts. These silicone rubber elastomers are chemically inert and can tolerate a temperature variation of −80 to 200°C or more. The two main reasons for their popularity are the low cost and ability to accommodate differential thermal expansion between high-expansion metal mounts and low-expansion optical elements. Since a fairly thick bond layer of RTV is needed, the edges or diameters of the optical elements and their mounts do not need to be machined to close tolerances, thereby reducing their fabrication cost. Moreover, retainers, clips, and screws for securing the optics in their mounts are eliminated, resulting in a much simpler design. RTV is resilient and allows for the differential expansion between the optic and its metal mount when the ambient temperature changes, without introducing any adverse stresses in the optic. The key physical, mechanical, and thermal properties of some commonly used silicone rubber-type elastomers in optical applications are listed in Table 3.8.

3.3.7.2.3 Optical Cements

Optical cements are the adhesives used for bonding the refracting optical elements to each other. Therefore, these adhesives must have good transmission and homogeneity over the desired spectral wavelengths in addition to the desirable mechanical properties such as low shrinkage and outgassing; good strength and stability; and resistance to adverse environmental effects such as humidity,
**TABLE 3.7**  
Properties of Representative Structural Adhesives

<table>
<thead>
<tr>
<th>Material</th>
<th>Mfr. Code</th>
<th>Recommended Cure Time at °C</th>
<th>Cured Joint Strength: MPa (psi) at °C</th>
<th>Temperature Range of Use: °C</th>
<th>Thermal Expansion Coefficient: ppm/°C at °C</th>
<th>Recommended Joint Thickness: mm</th>
<th>Density at 25°C: g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-part epoxies</td>
<td>3M</td>
<td>40–60 min at 121</td>
<td>13.8 (2000) at 24</td>
<td>−55 to 177</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2214Hi-Tempb</td>
<td></td>
<td>20.7 (3000) at 82</td>
<td>14.5 (2099) at 25</td>
<td>0.381 ± 0.025</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two-part epoxies</td>
<td>SL</td>
<td>7 days at 25</td>
<td>6.8 (992) at 70</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milbond</td>
<td></td>
<td></td>
<td>14.5 (2099) at 25</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC-2216B/A</td>
<td>3M</td>
<td>Fix: 2 hours at 65</td>
<td>17.2 (2500) at 24</td>
<td>−55 to 150</td>
<td>102 at 0–40</td>
<td>0.102 ± 0.025</td>
<td></td>
</tr>
<tr>
<td>Gray</td>
<td>L</td>
<td>Full: 7 days at 75</td>
<td>2.8 (400) at 82</td>
<td>134 at 40–80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Translucent</td>
<td></td>
<td>Fix: 6 hours at 65</td>
<td>8.3 (1200) at 24</td>
<td>81 at 50–0</td>
<td>107 at 60–150</td>
<td>0.102 ± 0.025</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full: 30 days at 75</td>
<td>1.4 (200) at 82</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27A/B</td>
<td>L</td>
<td>24 hours at 25</td>
<td>13.8 (2000)</td>
<td>−65 to 105</td>
<td></td>
<td></td>
<td>1.34–1.18</td>
</tr>
<tr>
<td>45</td>
<td>L</td>
<td>24 hours at 25</td>
<td>21.4 (3100)</td>
<td>−40 to 90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>324</td>
<td></td>
<td>Fix: 3 minutes at 20</td>
<td>10.3 (1500)</td>
<td>−54 to 135</td>
<td>12.6 (7.0)</td>
<td>&gt;1.0 (0.040)</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full: 24 hours at 20</td>
<td>13.8 (2000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3532B/A</td>
<td>3M</td>
<td>3 days at 24</td>
<td>2.1 (300) at 82</td>
<td>170 at &gt; −69</td>
<td></td>
<td></td>
<td>1.05</td>
</tr>
<tr>
<td>5753</td>
<td>H</td>
<td>24 hours at 25</td>
<td>5.5 (800) at 24</td>
<td>−25 to 125</td>
<td>&lt;3.2 (0.125)</td>
<td></td>
<td>1.04</td>
</tr>
<tr>
<td>UV-curable</td>
<td>L</td>
<td>UV cure: 15 s at 200</td>
<td>19.3 (2800) at 25</td>
<td>−45 to 170</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OP-61</td>
<td>D</td>
<td>5 s</td>
<td>5.2 (750)</td>
<td>−54 to 130</td>
<td></td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>349</td>
<td>L</td>
<td>Fix: 20 s at 0.25</td>
<td>5.2 (750)</td>
<td>−54 to 130</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full: 36 s at 0.25 gap</td>
<td>12.1 (1750)</td>
<td>100 (56)</td>
<td>0.100 max</td>
<td></td>
<td>1.06</td>
</tr>
<tr>
<td>460</td>
<td>L</td>
<td>Fix: 1 minute at 22</td>
<td>13.8 (2000)</td>
<td>−54 to 71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full: 7 days at 22</td>
<td>14.5 (2099)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


a Mfr. code: 3M, SL = Summers Optical; L = Loctite; H = Huntsman; D = Dymax.

b Also available in varieties with higher density, greater flexibility, or increased electrical resistivity.
temperature variations, and UV exposure. The optical cements come in four basic types: solvent loss, thermoplastic, thermosetting, and photosetting cements.

The solvent-loss cements, such as Canada balsam, have a high viscosity and are heat cured by the elimination of solvent to a refractive index ~1.53. They have poor bond strength, can introduce distortion in the bonded optical surfaces due to high shrinkage on curing, and are therefore seldom used in precision optical systems. The thermoplastic cements, such as cellulose caprate with $n = ~1.48$, are colorless or lightly colored solids that liquefy when heated to about 120°C. Their principle advantage is that the bonded elements can be separated by applying heat, which is easy and risk free. The thermosetting cements are two-part adhesives, which can be cured at room temperature by the addition of an appropriate catalyst. The room temperature curing time for this type of adhesive varies from 3 to 7 days. The cure time can be reduced to a few hours with a low elevated temperature cure, typically 70°C. Summer’s C-59, M-62, F-65, RD3-74, Lens Bond’s, and MasterBond’s EP30LV-1 are some of the commercially available thermosetting cements with $n$ of 1.55–1.57.34

Photosetting optical cements are generally one-part clear adhesives that are cured by exposure to UV light of 250–380 nm wavelength. These cements are suitable for bonding small low-mass optics that have transmission in this spectral region. Bondline thickness must be kept small to prevent excessive stress due to shrinkage. Norland’s NOA-61 ($n = 1.56$), Dymax’s OP-4-20632 ($n = 1.55$), and Summer’s UV-69 ($n = 1.55$) and J-91 are some of the UV-curing optical cements available. A two-step curing process, a short exposure for 20 s, followed by a long exposure of up to 60 minutes, is used for some of these cements. The bonded parts can be gently handled and cleaned, or debonded if needed, after the short exposure. Once the adhesive is fully cured after the long exposure, it becomes quite difficult to separate the parts. The entire area of the bond joint must be completely exposed to a uniform intensity UV illumination to obtain complete curing of the joint to prevent surface distortions. If feasible, the strength of the bond joint can be improved by heating the bonded parts to 40°C. Typical properties of optical cements are shown in Table 3.9. For specific properties, manufacturer’s data sheets should be obtained.
3.4 SUMMARY

This chapter introduces materials used for various applications in optical systems, including refractors, reflectors, structural optical metering components, and adhesives and optical cements. Relevant physical, mechanical, thermal, and optical properties of these materials are discussed, along with important figures of merit and typical requirements. Material selection methods are also briefly addressed.

The dimensional stability of optical materials is presented along with a discussion of the various types of dimensional instability. The sources of these instabilities are presented in detail, with the major source shown to be due to residual stress. Methods for obtaining dimensionally stable mirrors and structures are also described.

More detailed discussions of refractive materials and adhesives and cements are also provided. The various types of glasses, crystals, and other materials typical for optical application are presented along with material properties applicable for typical applications in various wavelength ranges. Structural adhesives and optical cements are discussed and include their typical properties and requirements. Reflective materials are discussed in detail in Chapter 4.

REFERENCES


