Metal Mirrors

Roger A. Paquin

4.1 Introduction

Mirrors come in all shapes and sizes, but from an engineering point of view, just what is a mirror? There are large mirrors such as the highly structured lightweight Hubble Space Telescope's primary mirror, the segmented 10-m mirror of the Keck telescope, and the active thin shell primary mirror of the 8-m Gemini telescope. There are small scanner mirrors, flip mirrors in cameras, and cooled mirrors in high energy systems. Is the mirror the reflecting surface or the structure that contains the reflecting surface? A good definition is that the mirror consists of the reflecting surface and whatever it takes to support that surface. A mirror is then an optomechanical system in itself.

Mirrors can come in many forms, but generally fall into one of three categories:

1. Passive mirrors — self-supporting for minimum deflection in a 1-g field on a simple, nonadjustable mount; can be solid or lightweighted
2. Semiactive mirrors — semirigid, usually lightweighted mirrors with more complex mounts, usually with multipoint mounts that are in dynamic systems that require occasional figure correction
3. Active mirrors — thin facesheets with fully adjustable, computer-controlled, multipoint actuator/mounts for wavefront correction in real time; the number of actuators and actuator density varies with application

Cooled mirrors can take any of these forms and can be cooled in any number of ways — from passive heat sinks to heat pipes to high flow, pumped fluid heat exchangers. The majority of cooled mirrors are small to moderate size and passive, but there are a growing number of relatively small, high actuator density, high speed mirrors for wavefront correction in high energy systems.

The mirror assembly includes the mirror surface (reflective coating and/or polished faceplate), substrate, mounts/actuators, and, for active mirrors, the reaction structure. For passive mirrors, the mounts may incorporate actuators to provide tip/tilt or chopping functions where the mirror

surface is not distorted by the motion. In semiactive mirrors, the actuators may either be in addition to or replace the mounts. They are used for final and/or periodic figure adjustment to a relatively flimsy mirror.

A successful mirror 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 problem in achieving this is the multitude of constraints that impact the design. Typical among these constraints are

- Environmental, such as operating temperature range and incident thermal/energy fluxes
- Mechanical, such as applied forces and dynamic conditions
- Weight and deflection (figure) limits
- Schedule and cost

The following sections discuss dimensional stability issues for these materials and mirror material characteristics, primarily metal and silicon carbide (SiC), blank fabrication methods, and the kinds of lightweighting achievable with each of them.

4.2 Dimensional Stability

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 can be fabricated utilizing the methods that minimize introduction of dimensional instabilities. The challenge is to control the dimensional change, a distortion or strain in the mirror, to levels that will not compromise the performance requirements. If required stability is on the order of machining tolerances, strain of approximately 10^{-3}, there is no serious problem. If dimensional tolerances must be maintained to parts per million, e.g., microns/meter, then care and consideration must be given to materials selection and processing steps. This is the realm of precision instruments and optics. If nano-tolerances are required, e.g., nanometers/meter, there is little help available, although this has recently become the subject of increasing study. For nano-stability, the principles of controlling the sources of dimensional instability must be diligently applied — and then hope for the best.

Once a tolerance has been specified to bound the amount of allowable instability, the next step is determining the potential sources of instability and controlling them to meet the specification. 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 recommend for further study:

- Marschall and Maringer,[1] an excellent book on the subject, although it is unfortunately now out of print
- Paquin[2] and Paquin and Vukobratovich,[3] the two volumes of SPIE proceedings dealing specifically with dimensional stability
- Paquin,[4] the paper on which this section is based

Types of Instability

Instabilities can be categorized as:

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

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

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.-gage blocks were tested at NBS over a period of roughly 30 years.[5] 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 the application. The other set typically changed only 25 nm in 22 years. This kind of dimensional instability is generally associated with relaxation of residual stress.

Hysteresis

Thermal/mechanical hysteresis is the change measured in a fixed environment after exposure to a variable environment, i.e., 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.

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 4.1 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.[6] 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.

Other Instabilities

The principle "other" 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 4.2, the length of Zerodur® on cooling from 300 to 20°C depends on the cooling rate.[7] 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
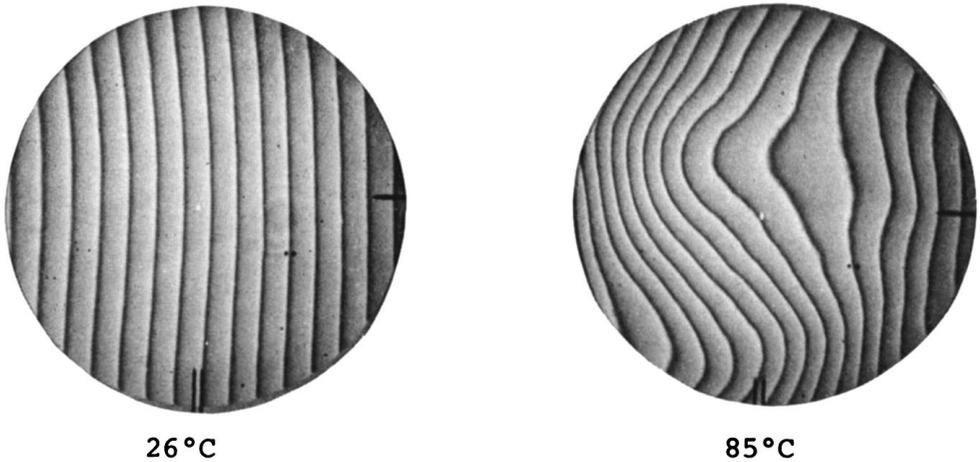
26°C   **85°C**

FIGURE 4.1   Optical interferograms of an electroless nickel-coated experimental beryllium alloy mirror (circa 1968) showing a reversible thermal instability of approximately two waves. *Source:* Paquin, R.A. 1981. Workshop on Optical Fab. and Test, Technical Digest. Optic Society of America, TB-1.
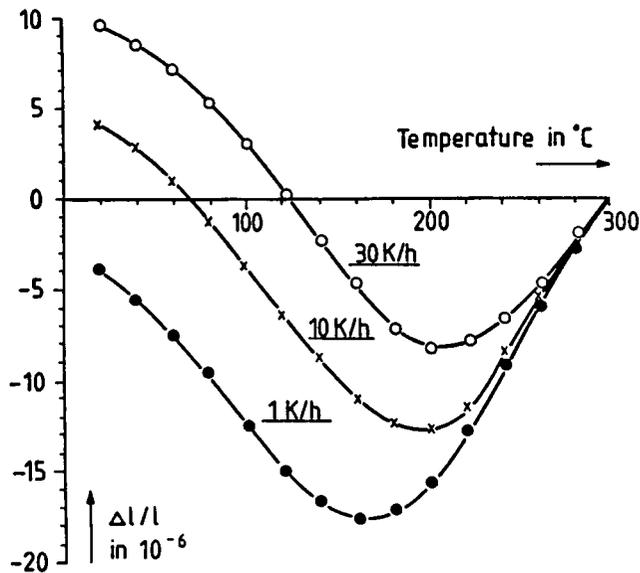

FIGURE 4.2   Thermal length contraction of Zerodur® for three cooling rates from 300 to 20°C illustrating a hysteresis type of dimensional instability. *Source:* Lindig, O. and Pannhorst, W. 1985. *Appl. Optics*, 24, 3330.

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.

Sources of Dimensional Change

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

- Externally applied stress
- Changes in internal stresses

- Microstructural changes
- Inhomogeneity/anisotropy of properties

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 applied suddenly, 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, most of which are covered in Chapter 3. Among these are thermal properties such as the coefficient of thermal expansion (CTE) and 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 2×10^{-3} permanent or plastic strain; ultimate or fracture strength; microyield strength (MYS), the stress to cause 1×10^{-6} plastic strain (one 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 period of time.

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 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.

Microyield strength 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 above, is one method, but it has its disadvantages. Many aluminum alloys, after rolling to plate form, are stretched a few percent to both straighten and level the stress through the thickness of the plate, which also increases MYS; but this process also seems to lower microcreep strength. Since the process of microyielding occurs, at least in the early stages, by 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.

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 like 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 as further described below. 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 decrease rapidly from 275 MPa (probably tensile), through zero, 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 above for Be or in a matrix with a dispersed phase or reinforcing particles, whiskers, or fibers. Table 4.1 lists the theoretical maximum values of thermally induced microstrain due to CTE mismatch between adjacent grains of a few noncubic materials.[8] 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 microyield strength of some Be alloys.

TABLE 4.1 Theoretical Maximum Values of Short-Range Internal Stresses Due to Thermal Expansion Anisotropy

Material	Lattice	Kpa/°C
Zinc	Hexagonal	1212.
Calcite	Rhombohedral	1130.
Cadmium	Hexagonal	626.
Beryllium	Hexagonal	437.
Quartz	Rhombohedral	295.
Indium	Tetragonal	223.
Magnesium	Hexagonal	19.
Graphite	Hexagonal	6.5

Source: Adapted from Likhachev, V. A. 1961. *Sov. Phys. Solid State*, 3, 1330.

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 4.3 shows how the temperature of quench water affects the residual stress in Al alloys. The yield strength also 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 removal of a stressed layer will cause dimensional changes as demonstrated in Figure 4.4. 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
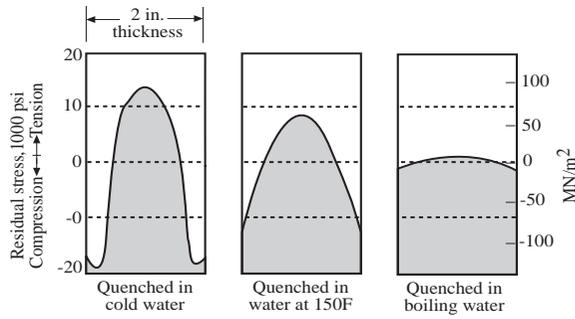
FIGURE 4.3 Residual stresses in specimens of 7075-T6 aluminum plate quenched in water at different temperatures.
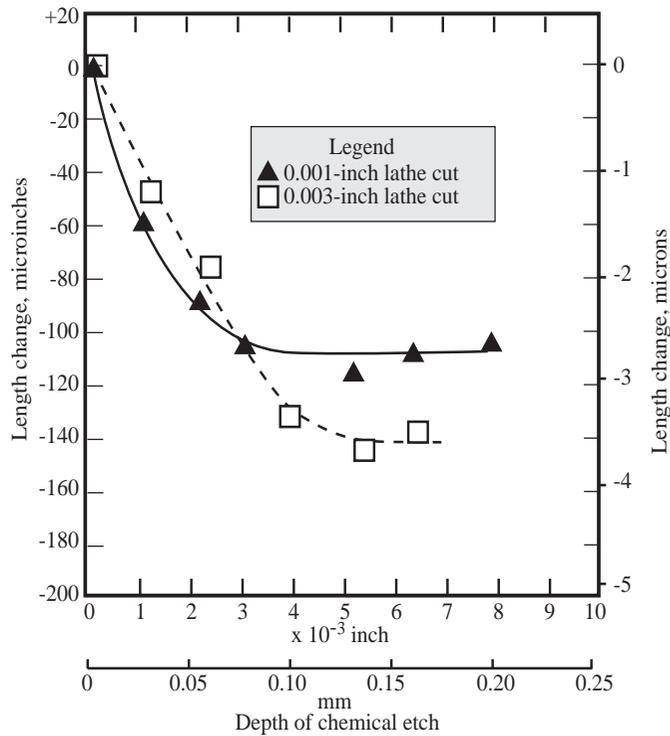

FIGURE 4.4 Dimensional changes in 3.0-in.-long specimens of Ni-Span-C on chemical removal of residual stresses due to machining.

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 effect is called stress relaxation and the decrease in stress is proportional to the stress level as shown in Equation (1), where s is stress, t is time, and τ is the relaxation time.

$$\left(-ds/dt\right)\tau = s \tag{1}$$

But stress also decreases exponentially with time as shown by Equation 2.

$$s = s_o \, e^{\upsilon\tau} \tag{2}$$

Note that when time, t, is equal to the relaxation time, τ, the ratio of stress to original stress, s/s_o, is equal to $1/e = 0.37$. This behavior is shown in Figure 4.5, 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.
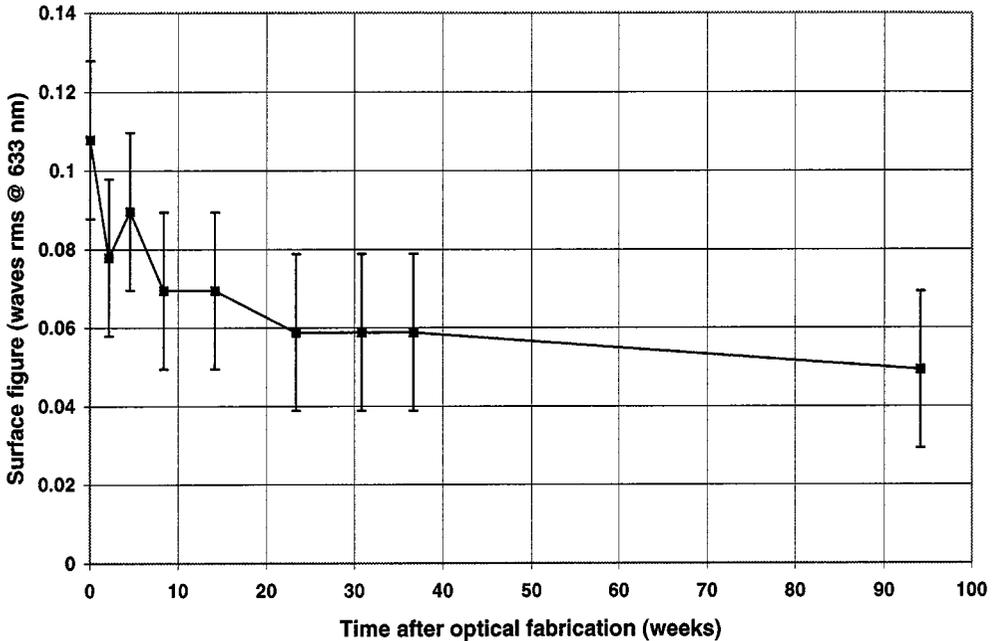

FIGURE 4.5 Temporal stability of a commercial 13-in.-diameter beryllium mirror fabricated from vacuum hot pressed block. *Source:* Paquin, R.A. 1992. *Optomechanical Design*, Yoder, P.R., ed., p. 160. CR43, SPIE Optical Engineering Press, Bellingham, WA.

Stress relaxation is also a thermally sensitive process, behaving according to the Arrhenius relationship of Equation 3, where E is the activation energy, k is Boltzmann's constant, and T is absolute temperature.

$$1/\tau \propto e^{-E/kT} \tag{3}$$

This phenomenon can be used to reduce the stress level with thermal treatment, i.e., 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,[1] 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 4.6, where both isothermal and thermal cycling treatments were given to Be specimens previously stressed to 77 MPa.[9] 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
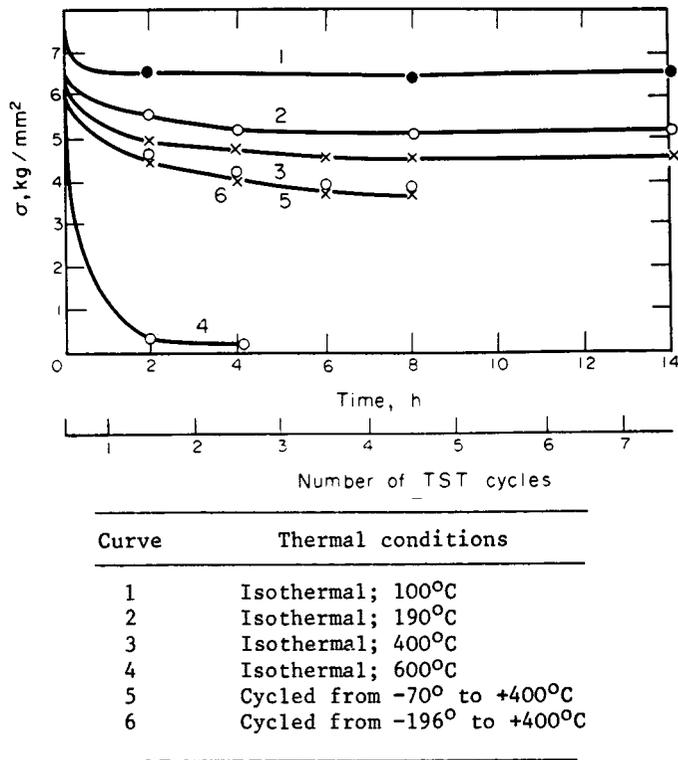
FIGURE 4.6 Comparison of the effects of thermal cycling and isothermal exposure on stress relaxation of pure beryllium. *Source:* Lokshin, I.Kh. 1970. *Metal Sci. Heat Treat. (U.S.S.R.)*, 426.

thermal cycling from 400 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 above in Table 4.1, 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 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 microyield strength, 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

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 covered adequately here. An example illustrates 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 4.7. This shows that a component aged from the solution-treated and quenched condition to obtain maximum mechanical properties, normally from 4 to 8 hr, will undergo a dimensional change due to the precipitation of the second phase. The change is small for 6061, a significant shrinkage for 7075, and a significant expansion for 2014. But notice that additional hours of aging, often performed for stress relief, induce additional significant dimensional change, particularly for the 2014 alloy. The 6061 alloy, most often used for precision optical structures and mirrors, changes the least, verifying its applicability for these applications.
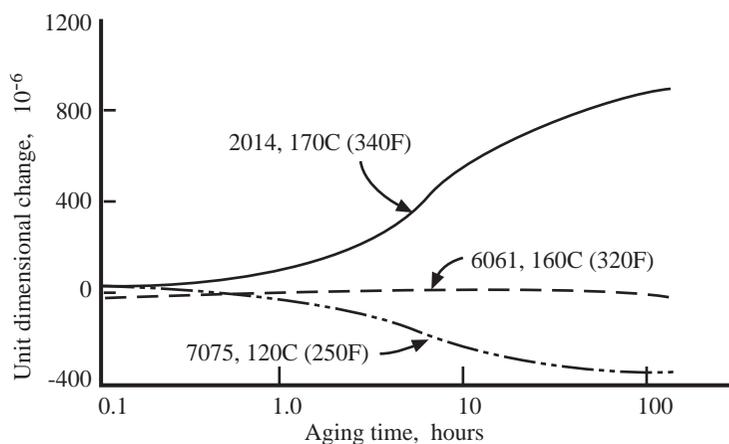

FIGURE 4.7 Dimensional change as a function of time at the precipitation heat treating temperature employed to produce the T6 temper for three aluminum alloys.

Electroless nickel coatings are used extensively, 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. Coatings can have significant residual stress[10] depending on phosphorous content and substrate CTE, and annealing changes the stress level as shown in Figure 4.8. 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.[11] 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 hr at temperature for Be[11] and 1 hr for the other materials. Stress goes from tensile to compressive with increasing phosphorous content and increasing substrate expansion coefficient. Annealing changes the stress toward compression for high expansion materials and toward tension for low expansion materials. What this all means is that for a particular substrate, to obtain zero stress at room temperature after
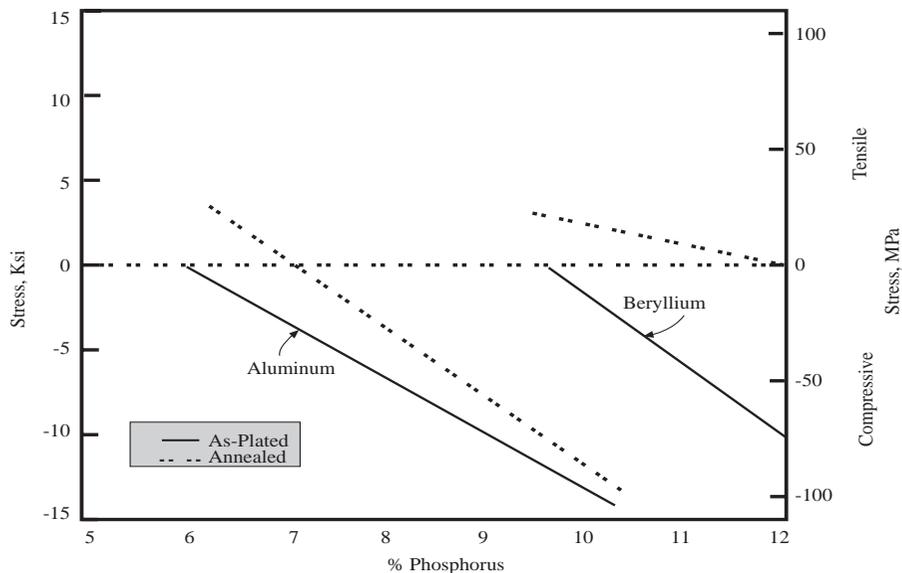
FIGURE 4.8　Stress of electroless nickel on aluminum and beryllium as a function of phosphorous content.

annealing, the right phosphorous content must be chosen, e.g., 5% on Al and >11.5% for Be. For use at lower or higher temperatures, different phosphorous contents should be chosen to minimize the stress.

Inhomogeneity/Anisotropy of Properties

Most materials, as fabricated, are neither completely isotropic nor homogeneous; they are to some level anisotropic, i.e., having some preferred directionality of properties, and/or inhomogeneous, i.e., having a spatial variation in properties. Anisotropy of properties exists in pure single crystals of materials. 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, beta SiC, etc. 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 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, i.e., 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 4.1. 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 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 4.1. 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.[12-14]

Low Expansion Materials

Low expansion materials have been used for many years for precision instrumentation to minimize thermal dimensional changes in service. For optics, fused silica and fused quartz have replaced borosilicate glasses in many applications, and ULE and the low expansion glass ceramics have been used extensively for more critical applications. Invar alloys have been used in precision metering applications for many years, especially in combination with fused silica optics because of the excellent CTE match at room temperature. More recently composite materials, particularly graphite-epoxy composites, have been used for precision structures since they can be tailored for near-zero expansion over a fairly wide temperature range. However, each of these material types has distinct advantages and disadvantages.

Composite materials, by their very nature, have the disadvantage of having built-in residual stress at the phase boundaries which usually leads to temporal dimensional instability. Graphite-epoxy composites can be designed and fabricated with near-zero CTE, low density, and high modulus. The properties can be tailored to the application, but are usually anisotropic due to the fabrication methods that require a preferred fiber direction or, at best, a pseudoisotropic lay-up. The biggest drawback of graphite-epoxy is its moisture sensitivity which affects dimensions, CTE, and mechanical properties.

Further information on low expansion material dimensional stability is available in Jacobs,[15,16] while further information on composites can be found in the papers of Session 2 of Paquin.[2]

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 taken 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 probably will 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 nano tolerances.

4.3 Metal Mirror Materials

Mirrors can be fabricated from any number of materials. Traditionally, glasses such as fused silica and borosilicate glass have been used, with an emphasis for high performance applications on near-zero expansion materials such as ULE™ and Zerodur®. With modern fabrication techniques such as those discussed here and in Chapter 10, metals and ceramics are being used more frequently. When designing a mirror, there are many metals from which to choose. Of course the first step is to consider the properties of individual materials with regard to the requirements of the actual application. But beyond that there are a number of other considerations including fabricability, corrosion resistance, availability, cost, and probably many others. Paquin[17] has addressed some of these trade-off issues.

Aluminum and Aluminum Matrix Composites

Aluminum (Al) is a low cost, easily fabricated mirror material. The main drawbacks are high thermal expansion and low elastic modulus. This metal is available in many alloys and can be fabricated in many ways, including casting and the wrought processes that produce plate, bar, and other forms, and can be machined with many techniques as described in Chapter 10.

The common wrought and cast alloys are listed in Table 4.2 with their compositions and normal heat treatments. In general, there are two types of Al alloys: those that can be heat treated to improve strength and those that cannot. The common heat-treatable alloys have two or more phases and are usually rough machined, heat treated at a temperature near the melting point (solution treated), partially aged (a lower temperature heat treatment), finish machined, and further aged for near-maximum strength and dimensional stability. The nonheat-treatable alloys can be annealed and still retain some strength. These alloys usually do not have a second phase and are therefore better for diamond turning. They are also preferred for large components with disparate section thicknesses that do not respond in a uniform manner or have a substantial risk of distortion in heat treatment. Wrought alloys are usually machined to shape when the number of identical components is small. Very large components are sometimes forged from billets for

TABLE 4.2 Characteristics of Common Aluminum Alloys for Mirrors

Alloy No.	Form	Hardenable	Remarks
1100	Wrought	No	Relatively pure; low strength; can be diamond turned
2014/2024	Wrought	Yes	High strength and ductility; multiphase; must be plated
5086/5456	Wrought	No	Moderate strength when annealed; weldable; available in large plate
6061	Wrought	Yes	Low alloy, all purpose; reasonably high strength; weldable; can be diamond turned and/or plated; all forms readily available
7075	Wrought	Yes	Highest strength; usually plated; strength more temperature sensitive than others
B201	Cast	Yes	Sand or permanent mold cast; high strength; can be diamond turned
A356/357	Cast	Yes	Sand or permanent mold cast; moderate strength; most common; extensive processing for dimensional stability
713/Tenzalloy	Cast	Yes	Sand or permanent mold cast; moderate strength
771/Precedent 71A	Cast	Yes	Sand cast; moderate strength; very stable; expensive casting procedures required; easiest to machine

TABLE 4.3 Characteristics of Aluminum Matrix Composites

Property	Instrument Grade	Optical Grade	Structural Grade
Matrix alloy	6061-T6	2124-T6	2124-T6
Volume % SiC	40%	30%	20%
SiC form	Particulate	Particulate	Whisker
CTE (10^{-6}/K)	10.7	12.4	14.8
Thermal conductivity (W/m K)	127	123	n/a
Young's modulus (Mpa)	145	117	127
Density (g/cm^3)	2.91	2.91	2.86

Source: Mohn, W.R. and Vukobratovich, D. 1988. *Opt. Eng.*, 27, 90.

better grain structure and stability. Castings are most often used when there are many identical parts. Aluminum foam has been effectively used as core material in lightweight mirrors.[18,19]

Aluminum mirrors are not normally finished bare by polishing, but are diamond turned and/or nickel plated and polished or diamond turned.[20] More complete information on Al alloys, their properties, and fabrication techniques can be found in the *ASM Handbook 2*[21] and optics-specific fabrication information can be found in Chapter 10.

Al matrix composites, usually SiC loaded, can be effective where a somewhat higher elastic modulus and/or lower CTE than can be obtained with the Al alloys are required. Typically 15 to 40% SiC, either whisker or particulate, is employed in a 2024 or 6061 matrix. Typical formulations and some properties are shown in Table 4.3. For optics, 30 vol% particulate in a 2124-T6 matrix has been most successful.[22]

Beryllium

Of the metals, beryllium (Be) has the most attractive properties for lightweight mirrors, but has high thermal expansion and relatively low microyield strength. The very high reflectance of bare Be[2] allows use without optical coatings in infrared systems. However, anomalous scatter observed on Be and some other bare polished metals may require a Be or other coating to meet system requirements.[23]

Beryllium is particularly suited for cryogenic systems since the thermal expansion drops rapidly below room temperature and approaches zero below approximately 80 K, while at the same time thermal conductivity increases to a maximum below 150 K. A unique property is its low absorption of X-rays, making it useful in nuclear systems and for X-ray windows. This property also means that Be mirrors can withstand high levels of nuclear energy without appreciable damage.

Beryllium has anisotropic properties, as do most crystalline materials. The thermal expansion of Be is approximately 30% higher in the basal plane of the hexagonal crystal than in the axial

direction, normal to the basal plane. For this reason, to end up with isotropic bulk material, it is essential to have fine grains of average size ≤15 µm. Section 4.4 of this chapter contains additional information on this subject.

Beryllium is available in several grades suitable for mirrors as shown in Table 4.4. All Be mirrors should be made from hot isostatically pressed (HIPed) material for virtual elimination of both inhomogeneity and anisotropy. Of the Be grades, O-50 and I-70-B are most suitable for polishing bare because of their low impurity content. If nickel plating is to be used, then any of the structural grades are appropriate, with I-250 having the highest microyield strength. I-250, because of very fine powder particle size, is not available HIPed in very large sizes. I-400, due to the high BeO content and very fine powder particle size, is not normally HIPed and size is limited to approximately 40 cm (16 in.). Where ductility is critical, the lower oxide grades provide a reasonable amount, while the highest oxide material, I-400, has virtually none.

TABLE 4.4 Beryllium Grades and Their Properties

Property	O-50	I-70-H	I-220-H	I-250	S-200-FH
Max. beryllium oxide content (%)	0.5	0.7	2.2	2.5	1.5
Grain size (µm)	15	10	8	2.5	10
2% offset yield strength (Mpa)	172	207	345	544	296
Microyield strength (Mpa)	10	21	41	97	34
Elongation (%)	3.0	3.0	2.0	3.0	3.0

Source: Brush Wellman, Inc. Elmore, Ohio.

Beryllium has earned an unjustified reputation as being an extremely hazardous material. Studies that conclude that Be is a potential human carcinogen have been shown to be flawed, but the EPA continues to claim that Be is a "probable" human carcinogen. Recent medical data[24] have shown that only about 3% of workers exposed to Be appear to be susceptible to chronic Be disease. The disease results from inhalation of Be particles, is immunologically initiated, and has a genetic basis similar to an allergy. Simple exhaust systems at the source of the particle generation with absolute filters are very effective, and machine shops using these devices have had no incidences of Be disease. OSHA permissable exposure limits are

- 2 µg/m³ average for an 8-hr day (an amount not visible to the eye)
- 5 µg/m³ ceiling
- 25 µg/m³ peak for 30 min maximum duration in an 8-hr day

In loose abrasive grinding/polishing, there is no hazard as long as the slurry is captured and not allowed to dry. The contaminated waste is not considered hazardous waste under Federal Law. Disposal of the contaminated waste by a licensed disposal firm is usually not a problem. By contrast, inhalation of similar amounts of almost any fine particulate, but particularly SiO_2 and SiC, can also lead to a chronic respiratory disease commonly called silicosis.

Invars

Invars are alloys of primarily iron and nickel that exibit a minimum CTE at approximately 36% Ni. The invar alloys can have near-zero CTE with special processing, but only over a limited temperature range. While a few lightweight mirrors have been made from brazed invar sheet, the material is usually used for components and attachments for ULE™, Zerodur®, fused silica, silicon, and SiC mirrors.

Invar 36, an iron/36% Ni alloy with small amounts of manganese and silicon, is the most common of the invars. Invars with 39 and 42% nickel are less common, but have CTEs closely matched to that of silicon and silicon carbide. Super invar, an alloy with cobalt substituted for some of the nickel, has the lowest CTE but can have an irreversible phase transition at low

temperatures that substantially changes properties if the composition departs much from the nominal.

Components can be readily fabricated using conventional metalworking processes. The materials have high fracture toughness but relatively low strength compared to other iron alloys, and almost all invar specimens measured have temporal dimensional instabilities. In addition, invar alloys are ferromagnetic, have high density and a relatively low elastic modulus, and one of the lowest specific stiffnesses of any material used for precision applications. All of the invars should be given a three-step heat treatment for the optimum combination of CTE, strength, and dimensional stability:

- Anneal at 830°C for 30 min/in. of thickness in inert atmosphere and quench in polyalkaline glycol/water solution.
- Reheat to 570°C for 1 hr and air cool.
- Heat at least 48 hr at 95°C and air cool.

Other Metals

Silicon (Si), copper (Cu), and molybdenum (Mo), as well as invar, are used for cooled mirrors because of the high thermal conductivity and relatively low CTE. Components are usually brazed together to form heat exchanger mirrors for high energy systems. While most of these mirrors are passive, and massive for the size of the aperture, fully active cooled mirrors of invar, Si, and Mo are used for wavefront correction in high energy optical systems. Titanium (Ti) is not a common mirror material, but has been used in applications where strength/weight is the important parameter. While Ti is polishable, it is usually electroless Ni plated. Electroforming is used for production of reflectors for lighting systems where Ni is the material of choice.

The most common form of Cu used is wrought oxygen-free copper, but where higher strength is needed without sacrificing thermal conductivity, chromium copper is preferred. The preferred form of Mo is low carbon, vacuum arc remelted material. A Mo alloy with small additions of Ti and zirconium called TZM has been used because of its higher recrystallization temperature, but it usually contains carbide inclusions that make optical fabrication difficult. Stainless steels are usually used for small mirrors in harsh environments where the exceptional corrosion resistance of the 300 series austenitic steels are preferred. In some cases the lower carbon martensitic stainless steels, such as 416, are used for their lower CTE and slightly higher thermal conductivity.

Silicon Carbide

Silicon carbide is a ceramic material that is available in many types and grades. It has high stiffness, strength, hardness, and thermal conductivity at low to high temperatures. It has moderate density and CTE, but low fracture toughness. Compared to other mirror materials it is stiffer and less fragile than glass, and has lower thermal expansion than Be. Silicon carbide in any of its forms is second only to Be in specific stiffness, but has much lower thermal distortion than Be. Pure forms have high reflectivity in the ultraviolet, but reflective coatings are required for most other wavelengths. The high Young's modulus and refractory properties of all forms mean that SiC can withstand very high heat loads with little or no damage and with very little distortion compared to most other mirror materials.[25]

There are two common types of crystal structure for pure SiC: hexagonal alpha (α) and cubic beta (β). Both structures have elastic anisotropies and α has CTE anisotropy.[26] Depending on crystal orientation, Young's modulus varies from 280 to 510 GPa for α and 340 to 510 GPa for β. The CTE for all directions of α and the basal plane of β are the same, while for all other directions in β CTE is up to 8% smaller. This means that if there is anisotropy in a formed, single-phase polycrystalline component of each material, when temperature is changed the thermal distortion will be up to 8% greater in β, but the internal stress at the grain boundaries will be as much as 40% higher in α.

There are four major types of SiC based on the fabrication method, listed in order of current volume of mirrors produced:

- Reaction bonded/sintered
- Chemically vapor deposited (CVD)
- Hot pressed
- Hot isostatically pressed (HIP)

The major characteristics of these types of SiC are given in Table 4.5 and fabrication methods are described in the next section. All except the reaction bonded are essentially pure SiC. Hot pressed and HIPed can be either all α, or β with some α that forms during processing. CVD is all β except that when deposited at lower temperatures some α is also formed. CVD SiC has preferred orientation that imparts higher thermal conductivity and lower Young's modulus perpendicular to the surface by approximately 15% compared to in-plane values. Hot pressed and HIPed SiC are normally very fine grained and essentially isotropic in all properties.

TABLE 4.5 Characteristics of Major Silicon Carbide Types

Sic Type	Structure/ Composition	Density	Fabrication Process	Properties	Remarks
Hot pressed	>98% alpha plus others	>98%	Powder pressed in heated dies	High E, ρ, K_{ic}, MOR; lower k	Simple shapes only; size limited
Hot isostatic pressed	>98% alpha/beta plus others	>99%	Hot gas pressure on encapsulated preform	High E, ρ, K_{ic}, MOR, lower k	Complex shapes possible; size limited
Chemically vapor deposited	100% beta	100%	Deposition on hot mandrel	High E, ρ, k, lower K_{ic}, MOR	Thin shell or plate forms; built-up shapes
Reaction bonded	50-92% alpha plus silicon	100%	Cast, prefired, porous preform fired with silicon infiltration	Lower E, ρ, MOR, k; lowest K_{ic}	Complex shapes readily formed; large sizes; properties are silicon content dependent

Reaction-bonded SiC can be formed by a number of related processes that determine the amount of SiC in the final component. The SiC content can be as low as 50% or as high as 92%, and consists of mostly α with some β formed during the final processing. The remaining material is Si, infiltrated into the SiC in final processing. Siliconized or reaction-sintered material is the simplest form of reaction-bonded SiC and has the highest Si content and, therefore, the lowest mechanical properties.

The highest quality surfaces can be obtained on CVD SiC because it is fully dense, fine grained, and single phase. Surface roughness less than 1 Å rms has been achieved on small mirrors.[27] HIP and hot-pressed SiC can be readily polished to low roughness, the level achieved depending on the grain size as well as porosity size and distribution. Reaction-bonded material can be finished to low roughness, the level depending on Si content and grain size.[28] Since the removal rates for Si and SiC are vastly different, the smaller the distance across Si between SiC grains that a grinding/polishing lap has to bridge, the better the finish. To reduce the difficulty in meeting figure and surface requirements, cladding of Si or SiC has been effectively used on reaction-bonded SiC.[28]

4.4 Fabrication Methods and Lightweighting

There are two basic methods for fabricating metal mirrors: machining from a solid or near-net-shape (NNS) forming with machining to finish. Machining causes surface damage and residual stress that must be removed for dimensional stability. This damage/stress condition also reduces strength and fatigue strength. Removal is normally through acid etching, annealing, and/or loose abrasive grinding/polishing. Some materials are often clad or plated for improved polishability.

Specific fabrication methods for each material or material type are presented in the following subsections.

Beryllium

Beryllium mirrors are typically fabricated from HIPed impact ground powders to produce homogeneous and isotropic blanks.[29] The vacuum hot-pressed Be used through the early 1970s was both anisotropic and inhomogeneous and often contained an unacceptable level of porosity. Electroless Ni was used in many applications to simplify the optical fabrication and obtain a better surface finish than could be obtained on the bare Be. Electroless Ni is still used in many applications where use temperature range is narrow enough so that the bimetallic distortion is small. For cryogenic (primarily infrared) applications, bare-polished Be is preferred. When all components of an on-axis telescope are HIPed from the same powder lot in the same HIP run, the telescope will be truly isothermal with only a magnification change as a function of temperature. Off-axis systems may require active alignment or passive compensation to remain in focus.

The majority of Be mirrors are now machined from solid HIPed billets. The HIP process consists of the following steps:

- Fabricate HIP container (can) of appropriate shape from low carbon steel sheet.
- Load Be powder into can with vibration assist for powder packing and weld lid onto can.
- Outgas the can at >670°C and seal off outgas tubes.
- HIP in autoclave at 103 MPa (15 Ksi) and 825 to 1000°C.
- Remove container and anneal at 790°C.

Near-net-shape mirrors, both open back[30] and closed back,[14] have been fabricated using a modification of this method where the container can be shaped and can contain precisely shaped and positioned formers of monel or copper.[31] Small mirrors have also been fabricated with replicated aspheric optical surfaces directly from the HIP process.[32]

For either machined or NNS mirrors, it is essential to provide adequate annealing and thermal cycling during the processing to ensure dimensional stability. A typical sequence for cryogenic mirrors, after HIP can (and formers) removal, consists of the following steps:

- Rough machine.
- Acid etch.
- Anneal at 790°C.
- Finish machine.
- Acid etch.
- Thermal cycle three to five times (limits determined by application, but at least –40°C to +100°C).
- Grind, etch, and thermal cycle.
- Figure and thermal cycle.
- Final polish and thermal cycle.

When electroless nickel or Be coatings are used, the coating should be deposited after the grind/etch/thermal cycle step. For thin Be coatings, deposition should be after the figure/thermal cycle step.

Other Metals

The metals such as Al, Cu, Mo, Ti, and stainless steels are fabricated by conventional methods as described in Chapter 10. Various plated layers can be used to enable diamond turning of the mirror face, sometimes after diamond turning of the bare substrate. Fluid-cooled mirrors are often brazed

to assemble various elements of the heat exchanger to the mirror face. Anthony[33] contains an excellent overview of cooled mirror fabrication technology and Kittell and La Fiandra[34] describe a unique cooled deformable invar mirror. It is important to remember that appropriate annealing or other heat treatment, acid etching, and thermal cycling must also be applied to these materials to obtain dimensionally stabile mirrors. For precision components that must be quenched after heat treating, polyalkylene glycol solutions[35] are recommended to substantially reduce the distortion and residual stress while still maintaining optimum mechanical properties. This technique applies to all metals, but particularly Al alloys, invars, and steels.

Silicon

Silicon, being a semiconductor and a so-called semimetal, is fabricated by methods somewhat different than either metals or ceramics. It has primarily been used for the fabrication of fluid-cooled and/or deformable mirrors.[33,36] Mirrors have been fabricated from both single crystal and polycrystalline Si with great success. The components can be machined using small "conventional" tools or by ultrasonic machining. Brazing is the standard joining method, and both metal and glass have been used for this purpose. Acid etching of machined surfaces is essential since the fracture toughness is as low as glass in this brittle material. Optical finishing is accomplished using conventional metal polishing techniques, with alkaline slurries preferred.

Silicon Carbide

Section 4.3, "Silicon Carbide", of this chapter described four types of SiC: reaction bonded, hot pressed, HIPed, and CVDed. Each of these has distinctly different blank fabrication methods. All are optically finished with diamond tools and slurries unless Si cladding is used on the mirror surface.

Reaction Bonded

High tonnage quantities of reaction-bonded SiC are produced in many shapes, often complex, for industrial purposes. Of the four types, reaction bonded is by far the best choice for complex shapes. However, tooling costs can be substantial. The process for siliconized SiC, the simplest form of reaction-bonded SiC, consists of the following steps:

- Prepare a slurry of SiC powder.
- Form a porous shape (preform) by one of the methods described below.
- Fire to burn off non-SiC material and introduce Si at the high temperature that wicks into the resulting pores.
- Clean off the excess Si.
- Machine to final shape with diamond tools.

Forming can be accomplished by injection molding, dry pressing with a binder, or, the most appropriate method for mirrors, casting into precise molds. The casting is then dried and/or prefired to drive off volatiles to produce the porous preform. The component can then be siliconized or other options are available. If the casting is made oversize and prefired at a temperature high enough to provide some strength, then the preform can be machined to finish dimensions prior to final firing. Other options change the process from simple siliconizing to reaction bonding. For example, the original slurry can contain carbon that will react with Si in final firing to produce more SiC, a process that increases SiC content in the final part to 75 to 90%. Another method to obtain the high SiC is infiltration of the porous preform with a carbonaceous material that will later react with the Si, providing as much as 92% SiC.

Both open- and closed-back mirrors can be fabricated using this technology. The closed-back structure is formed with soluble tooling that is subsequently dissolved, melted, or burned out,

forming the interior cavities. Structural components with complex geometries can also be formed in this manner.

Hot Pressed and Hot Isostatically Pressed

In these methods fine grain SiC usually is pressed at high temperature and pressure. Current hot-pressed blank fabrication methods employ relatively low pressure (compared to HIP) and several hours to consolidate in closed dies that are size limited to about 0.5 m. Sintering aids such as Al are usually added in small quantites to aid in densification. Simple shapes can be obtained by varying the shape of the dies, but unless production quantities are required, cost of the dies is probably not justified. Final shaping can be accomplished with diamond machining tools. In contrast, the HIP process uses pressures as high as 210 MPa to fully consolidate preformed, encapsulated components. Solid billets can be fabricated directly from powder in shaped containers, but NNS components can be fabricated by cold pressing the powder to shape in a flexible bag, encapsulating the preform, and then HIPing.

Chemical Vapor Deposited

The CVD process relies on the reactive decomposition of gases on a hot mandrel in a low pressure chamber to form the SiC.[27] The mandrel is normally a graphite chosen to match the contraction of SiC from the deposition temperature. The mandrel can be polished and treated with a release agent for replication of the mandrel in the SiC surface. Since the SiC is formed directly by decomposition of the reactive gases, the deposited material is very pure and dense. This method produces thin shells in the form of dishes, tubes, plates, and related shapes. To fabricate a light-weight mirror, the faceplate is formed, taken out of the chamber, and the rear surface is ground smooth. A graphite eggcrate-type rib structure with vent hole between cells is made from slotted sheet and is placed on the back of the facesheet in the chamber where deposition is continued. An additional layer of SiC forms on the graphite and back of the facesheet tying it all together. When cooled, the trapped graphite rib formers shrink away from the SiC, but are held in place at the rib vent holes. Mirrors have been fabricated up to 0.5 m, with a capacity somewhat larger than 1.0 m.

4.5 Summary

This chapter addresses the material selection, dimensional stability, and fabrication issues for various types of mirrors in common use including the passive, fully active, and actively cooled type of mirrors.

The dimensional stability section describes the four types of dimensional instability with examples, namely: temporal, thermal/mechanical hysteresis, thermal, and one other type that is related to hysteresis. The sources of these instabilities are presented in some detail, with the major source shown to be the residual stress. Methods for obtaining dimensionally stable mirrors are also described.

The characteristics of specific metal alloy types, including aluminum, beryllium, the invars, copper, molybdenum, aluminum metal matrix composites, silicon, and silicon carbide, are presented in some detail with the tables of comparative properties. The discussion on silicon carbide includes a description of various kinds of this common ceramic, and the advantages and disadvantages of each type for mirror applications.

A brief discussion of mirror blank fabrication methods is also given, with an emphasis on obtaining light-weighted blanks. Beryllium and various types of silicon carbide have been covered in more detail. The hot isostatic pressing (HIP) of beryllium is discussed, with the near-net-shape HIP method compared to the machined HIP billet method. An extended discussion of fabrication of the lightweight structures from the various types of silicon carbide concludes the chapter.

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