

Engelhaupt, D. "Fabrication Methods"
Optomechanical Engineering Handbook
Ed. Anees Ahmad
Boca Raton: CRC Press LLC, 1999

Fabrication Methods

Darell Engelhaupt

10.1 Introduction

10.2 Fabrication Method Section

Machining Tolerances • Fabrication Logistics

10.3 Manufacturing Methods

Description of Optical Materials • Machining, Finishing, and Coating of Optical Materials • Replication Methods • Composite Material Processing • Assembly Methods and Facilities • Inspection

10.4 Fabrication of Lightweight Components

Material Selection • Cost Comparisons

10.5 Dimensional Stability Requirements for Optical Materials

Definition of Requirements • Material Categories for Optical Systems • Strengthening Mechanisms • Heat Treatment of Optical Materials • Stabilization of Selected Advanced Materials

10.6 Chemical and Vacuum Coating Processes in Optics

Vacuum Coating Processes • Aqueous Coating Processes

10.7 Summary

10.1 Introduction

Fabrication methods and performance requirements for the production of precise optical and optomechanical support systems are necessarily quite variant. As pointed out in Chapter 4, optical components consist of an almost endless list of forms and requirements. (The reader is referred to Chapter 4 for additional information regarding materials and fabrication requirements). The entire optical or optomechanical device must, therefore, be proposed and subsequently designed as a complete compilation of performance and cost issues. Many optical development efforts have relied on “breadboarding” components to determine the system performance characteristics without regard to subsequent fabrication consequences. Modern integration of computer optical design programs, computer-aided-design (CAD) and thermal, mechanical, and material properties programs using finite element analysis (FEA) now permits a very reasonable prediction of performance. This effort can be used prior to prototyping or breadboarding in the more provincial approaches. By developing the entire system using integrated design approaches, the very data set from the ray-trace can be superimposed on the 3-D CAD drawing package, and critical issues such as interference, vignetting, and component mounting can be resolved prior to material selection or fabrication efforts.

This design data set can next be transferred to a 3-D FEA package and the performance aspects based on conventional machining and materials can be tested with respect to more elaborate and expensive choices. Interactive design efforts then allow for a substantial improvement in the

fabrication flow time and the material selections. Also, it is plausible during this design stage to input experienced or intuitive design parameters. As described in Chapter 4, the selection of fabrication methods and materials is dependent on the optical system performance criteria.

Trade-off in cost, materials, and fabrication capabilities must usually be determined in a formal quotation and prepared, without compensation, in a competitive bidding process. This intensifies the need for integrated computer designs beyond the traditional repetitive design, breadboarding, prototyping, testing, and finally fabrication procedures used in the past. With today's demands on optimum performance for the available funding, optical and optochemical engineers are expected to minimize the steps and the development efforts, yet not incur excessive risk. This, in turn, requires a comprehensive team effort, developing both optical and fabrication design aspects concurrently. Figures 10.1 to 10.3 depict the interactive optical system development, optical design, and optochemical design processes. Figures 10.4 and 10.5 are typical examples of 3-D models of a UV imager and imaging spectrometer, respectively, which were produced by employing the computer integrated design approach.^{1,2}

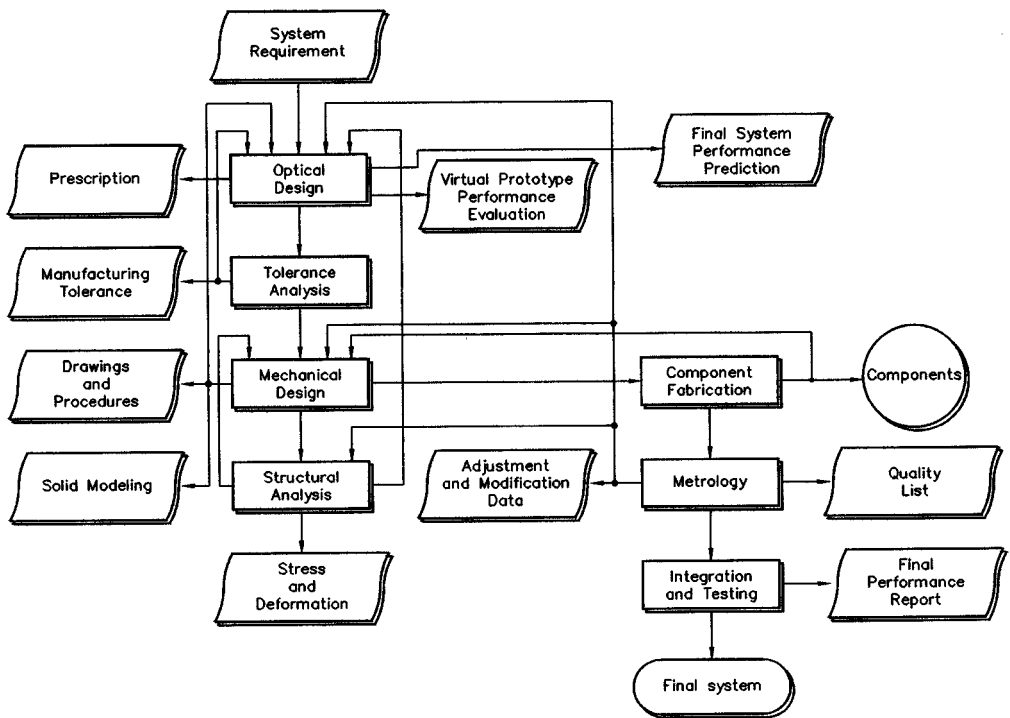


FIGURE 10.1 Major steps involved in an interactive optical system development process.

10.2 Fabrication Method Selection

The selection of a fabrication method for any precision system or component of the system depends primarily on the material selection. The material selection, in turn, is related to the required system reliability, dimensional stability, and thermal and mechanical performance requirements. All of these issues must be balanced by a design which not only functions to meet the design specifications, but one which is also affordable.

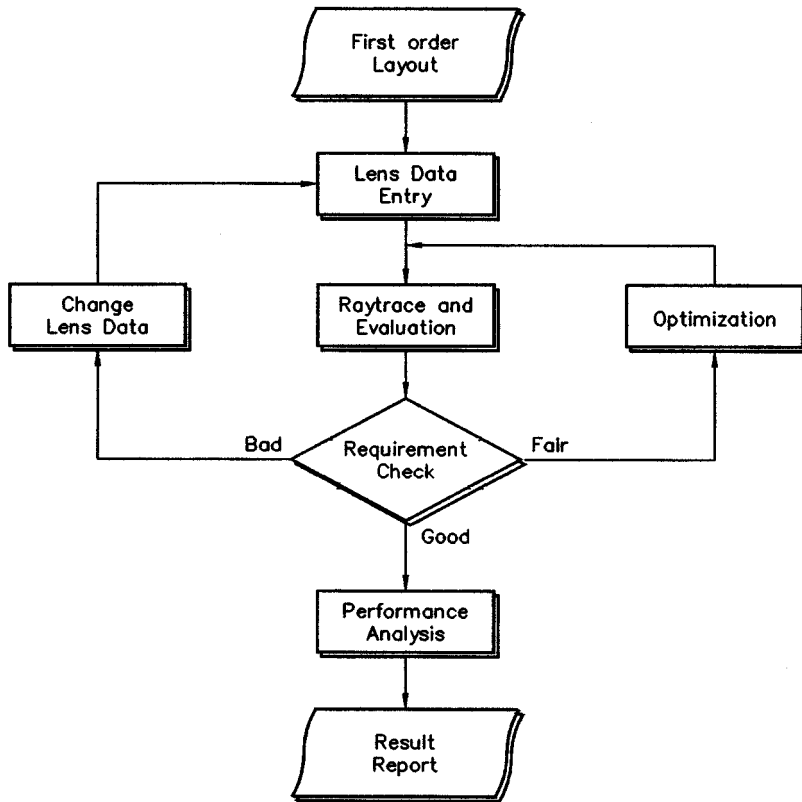


FIGURE 10.2 Major tasks involved in an interactive optical design and analysis process.

Machining Tolerances

Modern optical systems include reflective, refractive, diffractive, fiber optics, acousto-optical, and other disciplines. This includes both imaging and nonimaging systems with possibly reflective and refractive (catadioptric) combinations.

Performance requirements may include functioning for years in deep space for X-ray or XUV (extreme ultraviolet) instruments. Actually these instruments, while operating at very low temperature, usually operate at a reasonably constant temperature. Other systems may need to function over a wide fluctuation in temperature and mechanical shock or vibration with less emphasis on absolute optical finish or figure. The overall system tolerances are determined by the statistical compilation of the individual component requirements.

The selection of modern optical manufacturing methods is dependent on the following information:

- Product requirements
- Material selection
- Personnel capabilities
- Performance vs. cost
- Time to fabricate first system
- Anticipated production quantity

Product Requirements

The utmost in optical form and surface finish is required for the shorter wavelength optics such as soft or medium X-rays and XUV. In this type system, the energy is usually nonimaging and

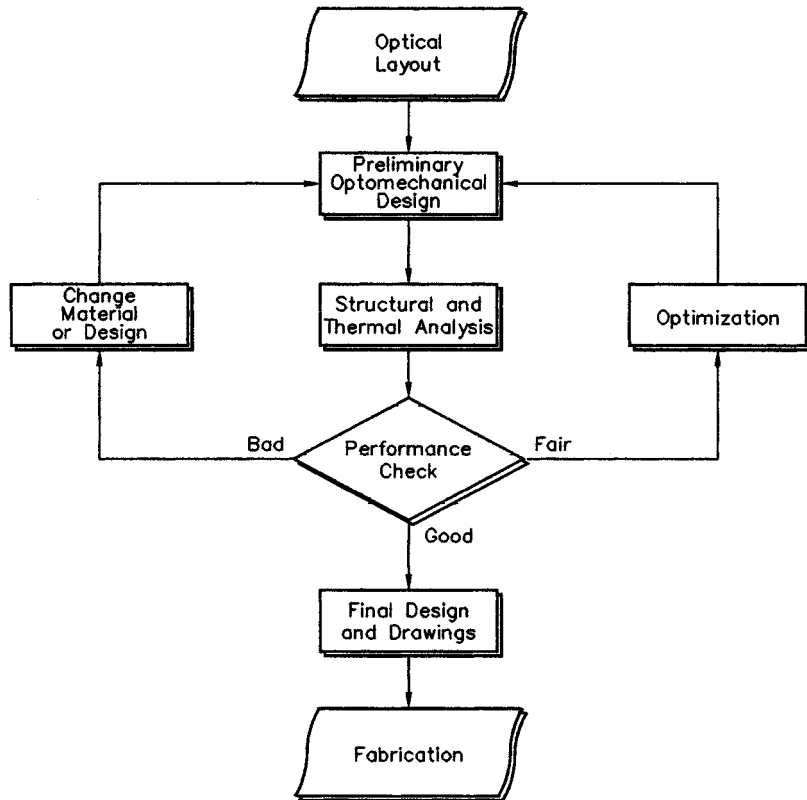


FIGURE 10.3 Major steps involved in an interactive optomechanical design and analysis process.

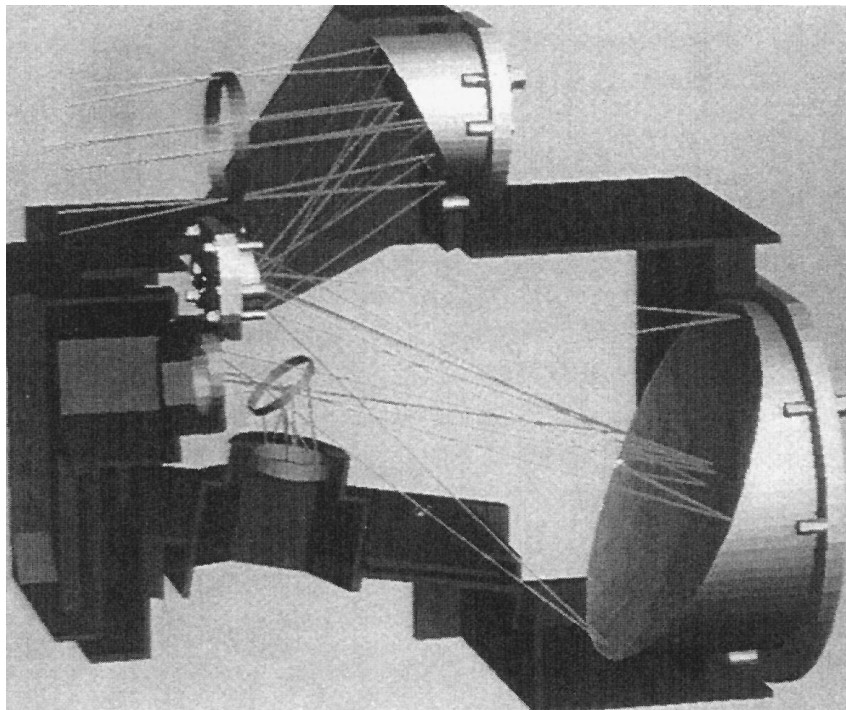


FIGURE 10.4 A 3-D model of an ultraviolet imaging camera showing the actual ray-trace and optical surfaces.

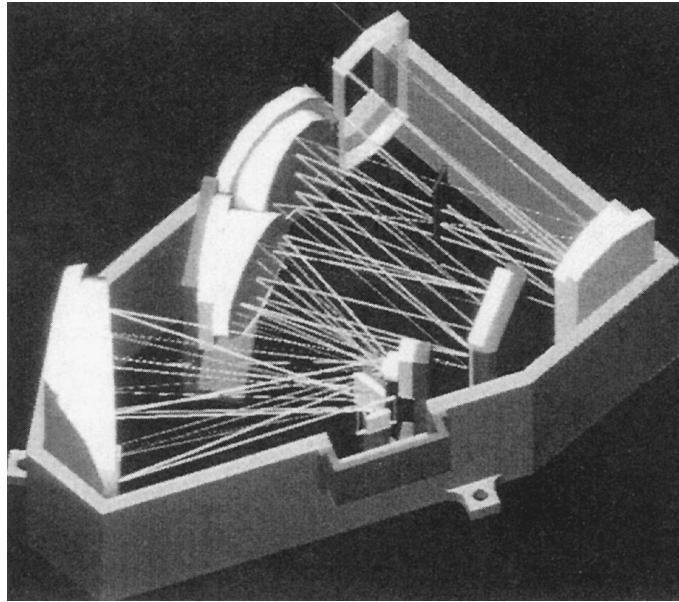


FIGURE 10.5 A solid model of a compact all-reflective imaging spectrometer.

made to collimate or condense only. However, imaging X-ray and ultraviolet systems are also a reality and indeed have been fabricated for about 40 years. It is difficult to think in terms of the scattering and short-period surface finish requirements. Improved and yet affordable systems are eminent which will image or at least guide focused energy in these very short wavelength regimes. These systems include infinite focus instruments for space observation as well as extreme precision clinical devices for advanced medical applications.

Recently reported cancer treatment procedures require photon, gamma, and neutron concentration with focusing of energy, including optical and these other sources to a precision of 1- μm spot size and location. This requires restraining the patient to stabilize the target to the same precision. Such extraordinary optics are saving lives. Also, an intense effort is in progress to focus short wavelength energy to pattern submicron feature microcircuits and nanostructures.

These optical devices may require surface finishes of less than 1 nm rms and surface figure of $\lambda/50$ at 1 μm wavelength. Additionally, this surface must be preserved during operation. This, in turn, requires the use of ceramic coatings to provide an ultrahard optical surface. Such tolerances are in atomic dimension regimes and require the limit of today's capability in manufacturing and performance measurements.

More conventional optical components operating in the ultraviolet to near infrared may still demand optical surfaces of 3 to 10 nm rms to remain diffraction limited and perform with low scatter. Infrared and even millimeter wave devices typically still require precision beyond the best of conventional CNC machining methods. Optical manufacturing procedures may be used to fabricate such devices at a cost savings. Single-point diamond machining and polishing remain as one of the most often used combinations to achieve high surface finish and figure tolerances for metal optics. Further discussion of these requirements will follow in the subsequent sections of this chapter.

Personnel Capabilities

To competitively produce high tolerance optical systems, a team of skilled persons must be available. While this seems obvious, it is not easily accomplished or maintained. For a skilled person to properly perform polishing operations, for example, sophisticated measurements are required on an interim basis. For the production of very high performance systems it becomes mandatory to

be able to interpret the measurement data and determine the extent to which a given step has been performed. 2-D and 3-D interferometric analysis, scattering data, BRDF, BTDF, and sophisticated electron beam, X-ray diffraction, and scanning tunneling microscopy (STM) or atomic force microprobe (AFM) analysis are some of the sophisticated inspection tools which might be required to be used.

It is not easy to find a single skilled person to do all of the required tasks. When polishing a surface below 30 to 40 Å rms (3.0 to 4.0 nm) on any given materials, the use of frequency spectrum analysis such as Fourier transform frequency or power spectrum methods may be required. For the optician to determine if a given polish medium has extinguished in terms of uniform removal of disparities larger than it creates, the data must be analyzed, not just observed, to conserve time and to avoid losing the overall surface figure of the part.

Optical fabrication may involve experts in the following disciplines:

Optical engineering personnel

- Optical design engineer or scientist
- Ray-trace expert
- Optical materials engineer
- Fiber optic expert
- Diffractive optic expert (depends on system)
- CAD operator
- FEA scientist
- Optomechanical design expert
- Materials engineer
- Purchasing expert
- Manager

Fabrication personnel

- Diamond machining
- Multi-axis work center
- Polishing (automated)
- Coating/plating
- Replication processing
- Material selection and control
- Material processing and heat treatment
- Fabrication supervisor

Inspection

- AFM — nanometer surfaces
- BRDF — reflectance, baffles
- Interferometer — surface, form, figure
- Profilometer — figure, coarse surface
- Scatterometer — surface texture, stray light control
- SEM/STM/AUGER — surface microstructure, chemical composition
- Quality control supervisor

Undoubtedly, many persons will be responsible for multiple tasks during the life of a larger program, particularly as more severe funding limitations are imposed.

When such modern inspection methods are available, it is not unusual to find that the capabilities are personnel rather than equipment limited. With present trends to consolidate cash flow activities and dispense with less profitable capabilities, it is common to lose an important resource in

manufacturing capabilities. In the case where this is inevitable, the prudent choice for fabrication of high precision optics is to recruit specific capabilities through subcontractual efforts rather than investing in very expensive equipment and consequent training, which may not be properly utilized to amortize the cost of the personnel or the equipment purchase past a given task.

Perhaps another overlooked issue is the promotional requirements of highly skilled personnel. In order to retain such persons it is absolutely mandatory to develop a professional growth plan which allows personnel with such unique skills to move up as they demonstrate enhanced personal proficiency. This usually means providing an educational and training program and ultimately replacing their previous task assignments with more challenging tasks.

Fabrication Logistics

Information from the CAD and FEA designs, based on the end-product requirements, must be analyzed to determine the type of machining, coating, and inspection capabilities needed. This depends first on the materials and then on the tolerances required.

Next, a schedule of the overall task is prepared including purchased materials and subcontracted efforts and includes input from each responsible person to be involved. When a particular capability does not exist in-house, the technical and cost response of vendors and subcontractors must be verified.

An assessment of common machining methods and tolerances achieved is given in Section 10.3.

Time to Perform

Management decisions on manufacturing methods must be made far in advance of the actual operation. The schedule to which a contract will truly adhere relies on the intelligence of the planning with regards to the fabrication methods. As mentioned both here and in Chapter 4, the material in large part determines the fabrication processes, including machining, heat treatment, etching, annealing (also heat treat), polishing, coating, inspection prior to assembly level testing, and assembly level inspection including the final assembly inspection.

Serious schedule impact is often caused by the selection of the wrong material and manufacturing method to satisfy the performance requirements. This may be the result of either over- or under-specification. It is important to understand appropriate details of the various types of interactions between the materials and fabrication requirements for stabilized optics. This is usually avoided early in the project by insisting on interfacing the design efforts with other tasks to be performed concurrently by a complete project team.

Make Vs. Buy Decisions

The decision to make or buy components is often overlooked from the point of economics. Often a component, which is close to the design requirement, is available commercially and can be suitably redesigned or modified by the original equipment manufacturer (OEM) vendor, thereby resulting in a significant cost saving. Another option is to buy a component which meets most of the requirements and refine it in-house. This may be the case for a lens, since most of the cost of a very high quality lens is in the labor to polish it to a particular aspheric shape. If the material is not correct, however, the lens cannot be produced to high quality. For example, it may be wise to buy a high quality material near-net-shape lens from a production manufacturer and perform the polishing labor in-house.

The reputation of a vendor is paramount in any decision to buy long lead time or extremely critical items. Such is particularly the case with coatings such as electroless nickel and vacuum coatings. If the precision machined parts are not coated properly, expensive rework is in order. Often rework is not possible and the parts must be made a second time. The vendors who coat conventional machine parts may not know the true diligence required for an optical component. The use of modern analytical methods and control should be demonstrated by the selected vendors. The vendors must adhere to performance, material, and selected method specifications.

The most often confused issue between a contractor and a vendor is the controversy over whether a part should be built to an exact method specified by the contractor or whether the contractor

should specify an exact tolerance and performance and allow the vendor to pursue his own manufacturing methods. There is no clear-cut answer except that if the contractor insists on an exact method, the vendor is wise to insist on the purchase and acceptance of the part regardless of the outcome. This is not usually the most desirable relationship. Typically, the better choice is to require quality assurance to meet the specifications and allow the vendor to pursue his own course of action in accordance to the specifications set forth. If the item is truly developmental, then the opposite may be true or the contractor may wish to invest in the capability to produce the components in-house so that any engineering changes can be determined experimentally and recorded for future fabrication efforts.

Return on Investment

The bottom line on most projects is the return on investment. Complete courses are taught on this subject but it suffices to say in this chapter that the most significant loss of potential revenue is due to lack of proper communication in almost any unsuccessful optics project. This is especially true if the principals do not understand or seek understanding on the true optical performance, and all of the mechanisms which must go into the manufacturing and inspection to achieve this prior to committing. Tens of thousands of scientists and engineers, thousands of affiliations, millions of man-years experience, and certainly billions of dollars have been committed to the understanding and design of optical systems worldwide. While the research must continue, it is imperative for the staff and management to rely on the almost countless resources through literature searches and council with knowledgeable experts in their fields.

10.3 Manufacturing Methods

Description of Optical Materials

Optical materials are essentially the highest quality available for a given application. The end-product stability requirements are notably more stringent than for most other applications. The material properties must satisfy the reflective, refractive, and perhaps diffractive optical requirements of the complete system. The structural and mounting components must also meet the same stringent stability and thermal performance requirements. Optical device engineers are concerned with not only the most exacting behavior of the material used in the optical path of an optical system, but in the overall performance of the complete system of materials used for the device. A typical example is the need to match the expansion coefficient of a relatively thin coating to the substrate to avoid thermally induced bimetallic deformation. The enhanced performance required of an optical system generally leads to deformation and stability calculations of at least two orders of magnitude finer than most precision mechanical components.

Machining, Finishing, and Coating of Optical Materials

The following guide, shown in [Table 10.1](#), will be used to outline advanced topics covered in this chapter.

Optical Component Machining

Machining, in the most general context of producing shapes from bulk material or from near-net shape billets, is typically not adequate for producing optical components. Final machining on the very best conventional machines is most often referred to as “rough machining” when optical quality components are at stake. This is true in spite of the additional tolerance requirements imposed on the machinist. Experienced machinists and tool and die makers are typically preferred for premachining the optical components.

Principal machining concerns include the precision attained along with temporal and thermal stability of the final optical components. Most important is the concern for the cost in time and

TABLE 10.1^a

Material	Figure Control Method	Surface Finish Method	Coatings
Al alloys	SPDT, CS, CM, EDM, ECM, IM, PL, IM	PL	MgF, SiO, SiO ₂ , Au, EN, and most orders
Al matrix	HIP, CS, SPDT, EDM, ECM, IM, PL, IM, CM (hard)	EN	MgF; SiO, SiO ₂ , Au, EN, AN, PL, most others
Al castings			
A-201	EDM, ECM, IM,	PL or coated	Same as Al
A-356.0	SPDT, CS	EN	Coat Ni
520			Same as Al
Al silicon	CS, EDM, CE, IM, SPDT, GR,	Coated EN, PL	Coat Ni
hypereutectic 393.2	CM		
Beryllium alloys	CM, EDM, ECM, EM, GR, HIP, not SPDT	EN	No coating Coat Ni
Magnesium alloys	SPDT, CS, CM, EDM, ECM, IM	EN	Same as Al
SiC	HIP		
Sintered	CVD		Vacuum
CVD	HIP, added	PL, EN	processes
RB	metal		
Steels	CM, EDM, ECM, GR, not SPDT	PL, EN	EN
Titanium	CM, HIP, ECM, EDM, GR, not SPDT	PL	EN
Glass-quartz	CS, GR, IM, CE, PL	PL	MgF, Au Al203/Ag
most			
ULE-Zerodur	CS, GR, IM, PL	PL	MgF, Au

^a Legend: AN = anodize

CE = chemical etching

CM = conventional machining

CS = casting

CVD = chemical vapor deposition

ECM = electrochemical etching

EDM = electrode discharge machining

EN = electroless nickel

GL = glazing

GR = grinding

HIP = hot isostatic pressing

IM = ion milling

PL = polishing

RB = reaction bonded

SPDT = single-point diamond machining

materials to achieve proper performance. Dimensional stability of an optical system is related to the distribution of stored energy (internal stress) and the introduction of differential displacements inconsistent with axisymmetric behavior. If a system is truly performing axisymmetrically, then the focus and distortion correction remain accurate independent of thermal changes. A common analogy is that upon thermal expansion or contraction, the axisymmetric unit behaves as a system of a different scale. Unfortunately, the fabrication of a complete system is not easily accomplished with triaxially uniform behavior. The use of different materials is essential and can only be matched within a particular range of precision. Extremely important is the material processing along with machining operations to reduce the induced internal stresses.

The reduction of surface stress has been referred to in Chapter 4. The methods by which this is achieved will be discussed in more detail in this chapter. First, the stress introduced into a surface to be machined may be either compressive or tensile in nature. This stress is (in a complete analysis) always triaxial and will typically diminish rapidly and then reverse from tensile to compressive or vice versa with regards to depth into a surface. Typical stresses are introduced into an optical component by one of several mechanisms. The principal cause is the work put into the machining

of a piece of metal. A second reason is the thermal energy in casting of either metal or glass which may account for stored energy (or stress) if the cooling is such that the bulk solidification is not uniform in time. Another common stress malady is the stress induced by a coating or a system of coatings. A systematic discussion of all these causes, effects, and cures for the stress-induced deformation in all optical systems is beyond the scope of this chapter; however, some classic cases will be discussed in later sections.

Finishing and Coating

Analysis of performance for coated parts includes the temperature at which a coating is applied as well as differences in thermal expansion and operating temperature range of the component. A coating applied to one side of an optical component with a different expansion coefficient from the substrate will cause a predictable distortion based on the following factors:

1. Coating physical properties

- Thickness of the coating
- Thickness of the substrate
- Stress in the coating at temperature of application
- Difference in the Young's modulus of elasticity
- Yield strength of coating and substrate
- Subsequent or multiple coating combinations

2. Thermal properties

- Coefficient of expansion difference in materials
- Temperature difference from coating temperature
- Stress relaxation in coating and substrate interface
- Heat treatment process after coating
- Rate of change of expansion coefficient vs. temperature

The system is better stabilized if the coating layer completely surrounds the base component.⁶ A commonly applied coating is the electroless nickel-phosphorous alloy applied to single-point diamond-machined aluminum mirrors. The intrinsic or internal stress in the alloy is a direct function of the percentile of phosphorus if all other conditions are the same. The Ni-P alloy in all composition has significantly lower thermal expansion (or contraction) than nearly all aluminum alloys commonly used in optics such as 6061 or 2024. A commonly desired composition is the ratio of 11% phosphorus and 89% nickel, which corresponds with $[\text{Ni}_3\text{P}]$ where the brackets indicate the material is more nearly amorphous than the crystalline allotrope. If the nickel is applied at neutral stress at the plating temperature of about 190°F and the coating and substrate subsequently cooled to room temperature, then the aluminum will contract more than the coating, placing the coating in compression. Since the part must come to equilibrium, the substrate interface with the coating is in tension. A flat aluminum plate or strip coated on one side with NiP during plating at elevated temperature will then deflect such that it becomes convex on the plated surface when cooled. If, however, the coatings is the same thickness on both sides, the deformation in the coating will be distributed with linear deformation of the substrate interfacial surface and the distortion will be minimal, albeit the stored energy may be higher.

Replication Methods

Many optical components can be manufactured to the needed tolerances by replication methods with significant savings, the most common of which are hot isostatic pressing, casting, electroforming, CVD, and epoxy composite manufacturing processes. Electroforming and CVD processes will be covered in this chapter under Chemical and Vacuum Process in Optics (section 6.0).

A complete description of each is beyond the scope of this book. However, a brief description is in order for selection of the preferred manufacturing method in a given case.

Hot Isostatic Pressing (HIP)

Hipping of powders to form a free-standing shape is commonly used when the material is available as a powder and is not readily cast as a molten liquid. Materials in this category vary widely and for many different reasons. One common example is beryllium, which is often preferred for ultrastiff metal optics for a device that must sustain a high loading in use. Note that this is very different than a device that must sustain the same load but not necessarily while performing an optical function. The beryllium powder is produced as a mixture of Be and BeO. The BeO acts as a second phase for the purpose of pinning the grain boundaries, and also to promote very small grains on the order of the size of the powder used in the HIP operation. The hipping process allows for higher concentrations of BeO to be added to the metal than is possible by casting process.

The anisotropic properties are much improved due to the uniform dispersion of the second phase and small grain size. This also improves the microyield properties, which otherwise mitigates the desirable high elastic modulus of beryllium for use as a stiff optical material, as previously described in Chapter 4.

Another example is the entire family of refractory ceramic materials. The definition of refractory is a high temperature use material. Although few optical systems need this advantage, the refractory materials also commonly share the property of very high elastic modulus and lightweight, thereby imparting them high stiffness.

Some of these materials are of interest in optics such as silicon carbide, with a higher stiffness than beryllium. Since the melt point is very high and the materials often react with air, casting becomes difficult. Usually the HIP or reaction bonding process involves addition of a second lower melt point powder such as glass, which will bond to the ceramic material and yield a high strength free-standing shape. Glass products of lower melting point (and lower elastic modulus) are sometimes fabricated in this fashion using glass powders of different composition to achieve a particular set of properties not otherwise easily obtained. Subsequent heat treatment to partially vitrify one phase in the presence of an amorphous glass can yield a nearly zero or even negative thermal expansion coefficient as in Zerodur™.

The drawback to this process is that unlike most casting operations, the mold must be designed and built to withstand both high temperature and high pressure. A typical complex HIP structure may cost many times that of a cast structure due to first item mold costs. However, this cost can be amortized over a larger quantity of parts to the advantage of the fabricator.

Cast Optical Components

Casting of optical components has usually been limited to aluminum alloys containing silicon, copper, or silver and, of course, materials cast from either glass or plastic. Other materials infrequently cast into optics include titanium and magnesium. Casting methods are currently under development for beryllium aluminum alloys and some composite materials of silicon carbide filled aluminum (DURALCAN™, ALCOA of Canada), and also silicon carbide-filled beryllium. The difficulty in casting composites is in the nonuniform dispersion of the second phase material. While methods have been in place for some time to cast composites, the uniformity has often not satisfied the requirements of an optical system. As pointed out in Chapter 4, the internal stresses may be unacceptable in composite materials unless the dispersion is both very fine and uniform. Additional problems arise in the form of anisotropic properties from preferential alignment or coagulation of particles, particularly fibers. Material experiments in space have shown that in zero gravity, it is possible to achieve very uniform properties for such materials, although these materials are not yet commercially available.

Casting of aluminum optical products is complicated by the issues of porosity. For aluminum alloys, a great deal of information is available on the causes of porosity in castings, but typically not much is done to remedy the porosity to the levels acceptable in optics. Hydrogen formed by

dissociation of steam and also air stirred into the aluminum melt are two common causes of porosity. The hydrogen inclusion is reduced by the use of electric heat and a blanket of dry nitrogen or other gas over the casting melt as opposed to gas heat. This is due to the fact that combustion of hydrocarbon fuel produces water vapor, which, at high temperature in contact with many metals, produces hydrogen and oxygen by dissociation. Phosphorus may be added to some alloys as copper phosphate to assist in hydrogen removal. An additional method suitable for some aluminum alloys is the addition of chlorine or another reactive halogen gas to the melt to form hydrogen chloride, which is volatile but difficult to cope with due to corrosion of equipment. The true cure is to first X-ray the casting to assure that a minimal porosity exists, and then to perform a type of autoclaving operation wherein the component is placed in a sealed stainless steel bag and subjected to high pressure at the solution temperature for the alloy. This virtually eliminates the porosity in a normally sound casting. Precision die castings are preferred but are also more expensive. The use of spinning for centrifugal force to remove gas (porosity) and vacuum melt and pour methods are also effective, but increase the cost of fabrication significantly.

The typically preferred cast aluminum alloy is A-201, which is the refined grade of 201 containing a small amount of silver and essentially pure aluminum. The omission of silicon in this alloy allows first surface optics to be fabricated with conventional single-point diamond turning with low wear rates using single crystal diamond tools. This alloy also poses a variety of desirable properties including a somewhat lower thermal expansion coefficient than most wrought alloys, and a low as-cast porosity and inclusion level if filtered while molten through a ceramic filter. Some 500 series aluminum alloys are also used for optics and can be polished better than most wrought alloys for first surface aluminum optics. The 500 series of alloys is not readily heat treated to a high strength or hardness and must be limited to heavier, less stable applications. This material is acceptable for production quantities of small instrument mirrors which are not very lightweight nor subjected to severe shock or vibration.

An interesting cast aluminum alloy is 393.2 combustion engine piston material. This material is a hypereutectic alloy of 23% by weight silicon and other trace elements including vanadium for stabilization. The material has been developed by the automotive industry at great expense for use in high performance automotive and diesel engines. This alloy composition actually is a co-continuous microstructure and will be described in a later section.

This alloy, known as Vanasil, has recently been successfully used in an optical system requiring extreme thermal, shock, and temporal stability, low expansion, and light weight, most all of which are mutually exclusive aluminum properties. The most interesting property of the material is perhaps the microyield resistance, which makes it suitable for millions of mechanical cycles at high loading without any detectable deformation in automotive engines. Also, the coefficient of thermal expansion (CTE) is about half that of most aluminum alloys. This CTE closely matches that of electroless nickel phosphorus at the desired 11% by weight phosphorus commonly preferred for diamond-machined and polished high quality optics. [Figure 10.6](#) shows the stability of an electroless nickel plated 393.2 alloy mirror after thermal cycling.¹

Most glass components are cast to some form of near-net shape due to the inherent difficulty in machining. When machining is required, ultrasonic methods using diamond powder or water jet machining are often used. One option, as mentioned earlier, is the increased use of HIP processes to form glass components from powders. This is usually different from other refractory materials in the sense that the parts can also be melted or at least sintered completely to an amorphous condition in the mold or die which actually makes the procedures somewhat hybrid.

Composite Material Processing

Matrix Metals/Graphite/Organics

The definition of a composite material is probably best stated as a mixture of two or more very different materials to achieve properties otherwise not achievable in either. This is very different

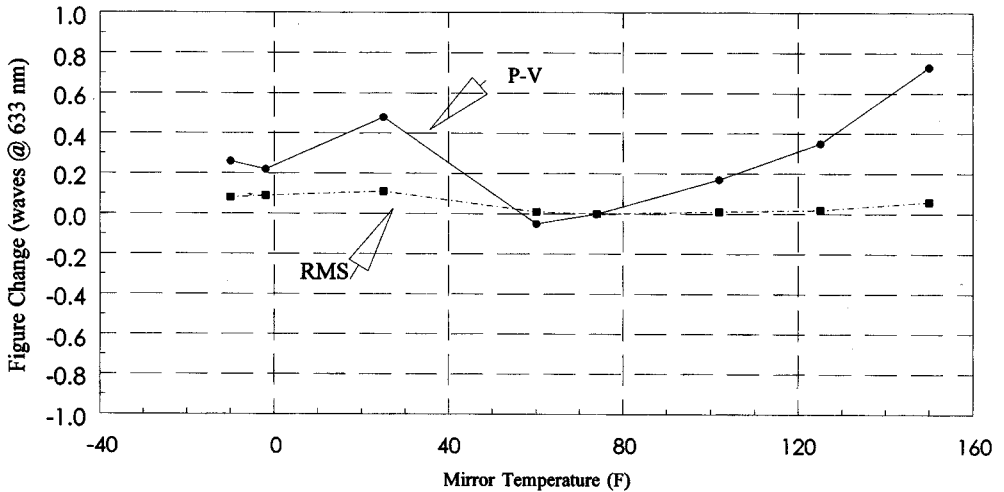


FIGURE 10.6 Figure stability of a Vanasil mirror as a function of temperature.

from alloys or specifically solid solution alloys which are an atomic mixture or a compound as such. On the other hand are the alloys which have precipitated phases or matrices of more than one discernible composition which do qualify as composites rather than alloys. Such is the case for hypereutectic or “oversaturated” alloys which will be described later under lightweight composite materials.

Design Considerations

When two (or more) very different materials are used to prepare a composite structure, the first approximation of the results is obtained by various “Rules of Mixture”. It is imperative that the anisotropic (directional) properties be considered. By laws of conservation, the equations for expansion, elasticity, and internal stress must be conserved. Therefore, if the expansion of an epoxy/graphite material is listed as very low, e.g., 1.5 ppm/°C, then a shape and direction must be considered. If low expansion fibers or particles constrain the bulk material from expanding in one direction preferentially, then it will expand much more rapidly in the orthogonal direction.

For a general case, the total forces in the composite are opposite but equal in a given direction. Also, if the temperature is assumed equilibrated, then the strain in the direction of concern for the matrix material and the binding material (epoxy or other resin) is also equal on an averaging basis. Then the axial or unidirectional CTE is

$$\alpha_c = \frac{E_R V_R}{E_F V_F + E_R V_R} (\alpha_R \alpha_F) + \alpha_F$$

where V_F = volume fraction of fiber
 V_R = volume fraction of resin
 E_F = elastic modulus of fiber
 E_R = elastic modulus of resin

The expansion coefficient in the transverse direction is nearly that of the resin.

When sheets or “phys” of the laminate are laid up, the fiber direction is alternated at 90° to produce a material with low x and y expansion. The diagonal expansion may increase somewhat. The thickness will change in order to compensate for the bulk expansion of the resin. Even though the resin elastic modulus is low, the bulk compression is also low much like liquids. This in turn leads to a large dimensional instability in the unconstrained direction of a uniaxial matrix material.

The thickness variations are not usually as critical since the elastic modulus of the base or resin material is lower than the filament, fiber, or powder filler material. Although the stress in the fibers is often high, the elastic modulus and yield strength of the fibers are extremely high compared to most materials. The net result is such that resin–fiber composites can be fabricated with higher strength and stiffness-to-weight ratios than possible in metals including beryllium alloys. The shock and impact resistance is also higher than for ceramics such as a silicon carbide, which makes these composites very attractive for lightweight precision systems.

One drawback is the fact that most resins and some fibers absorb significant moisture. Since the moisture is nearly incompressible, the resin swells upon moisture uptake. The transport of moisture is diffusion limited and obeys Fick's laws for diffusion.

Since the resin is viscoelastic, some stress relaxation is observed upon swelling from the moisture absorbed. This will then cause an opposite stress upon dehydration if the laminate has had ample time to equilibrate. The percentile of change that occurs in a given material due to moisture is⁷

$$G = (M - M_0)/(M_\infty - M_0) = 1 - \exp[-7.3(Dt/h^2)^{0.75}]$$

where D = diffusivity $\approx 1.8 \times 10^{-7}$ mm²/sec (50 – 150°F)

D = slope of m vs. $t^{0.5}$

t = time in seconds

h = thickness in millimeters

M = present moisture absorbed

M_∞ = end humidity

M_0 = starting humidity

Filament Winding Processes

Filament winding is a subset of the above composite material manufacturing process. Filament winding equipment using CNC control permits winding shapes of rotation with a continuously crossed pattern to provide very low expansion components in the circumferential and longitudinal directions. The typical applications include cylindrical or other items of rotation, which can be fabricated with high stability in the direction of a continuous fiber, which in turn is wound with a crossed radial pattern much like a radial tire is wound for the same reasons. Very stable cylindrical mountings for space-borne X-ray telescope optics have been manufactured in this fashion. The primary concern in most optical systems exposed to moisture is the expansion of the material due to moisture absorption, and a very slow release of this moisture over extended period of time.

Figure 10.7 shows the relative absorption and change in length with time for a 1.4-mm-thick by 76.2-mm-long sample of graphite epoxy composite. The absorption is governed by diffusion and obeys exponential time dependency. The desorption is similar in nature. This in turn places a strong dependency on the thickness of the sample for the time to reach a particular level of the relative humidity present.

The relative change in length is small for a filament wound piece since much of the length change is constrained by the crossed directional winding of the strong fibers. A typical change in length for a properly prepared material is about 50 to 100 ppm over 0 to 100% humidity and long time periods. If, however, the direction of expansion is dominantly governed by epoxy properties, the expansion will be many times this value. This can be serious in a low expansion optical system while probably passing unnoticed in most mechanical designs. The proper development of the material then depends on the application. Since the properties are essentially intermediate to the fiber and the resin, the material should be prepared from a selection of properties which gives a substantial percentile of fibers in order to achieve the desired expansion. This means that the fibers must have lower expansion than the desired end product, but not to the extent that a low volume is required. The graphite fiber is low expansion, although several versions are available with

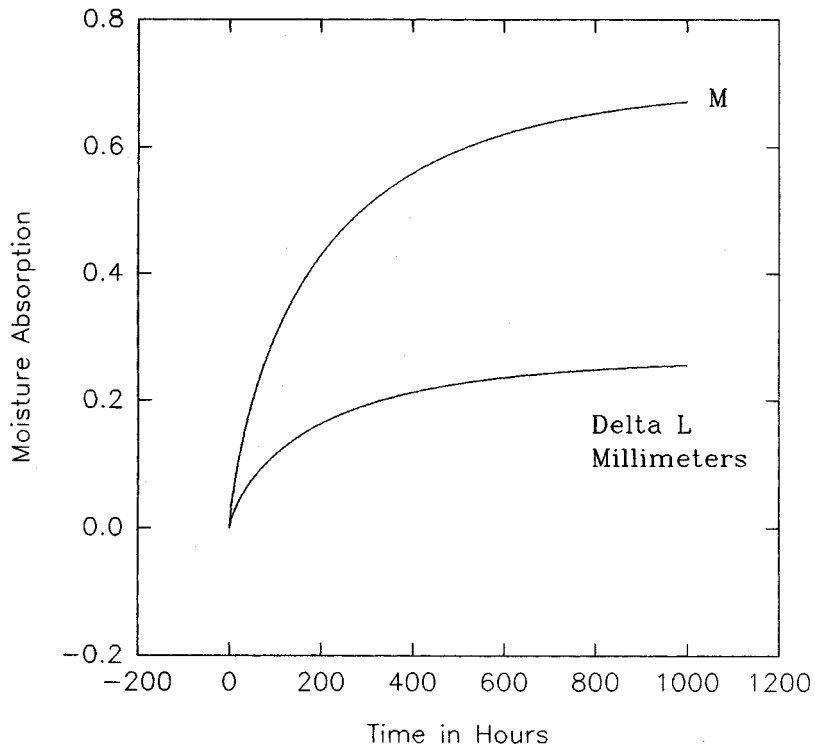


FIGURE 10.7 Moisture absorption and linear dimension change as a function of time for a 1.4-mm-thick sample of graphite epoxy composite. $M_0 = 0\%$; Relative Humidity = 70%.

differing properties. This material will usually be selected to match silicate glass, quartz, or other low expansion optical components.

The substitution of glass fibers can be made to tailor the material CTE upward to match higher expansion materials, such as beryllium, while containing a high percentile of the fiber. Care must be taken if the CTE is to be high such as for aluminum, since the volume of fibers of low expansion will be low resulting in a mechanically poor material.

Assembly Methods and Facilities

Assembly of optical systems usually requires the use of optical alignment equipment such as autocollimators and interferometers for wavefront correction. Automation is usually limited to automated polishing methods for lenses and pick-and-place assembly of the electro-optical sections. The assembly is nearly always performed by the contractor to assure perfection. The use of adjustable components is favored in low volume systems and is described under kinematic mounting, in Chapter 2. Most mirrors are preferably mounted with three-point mounting schemes to avoid torsional stresses set up across any virtual axis of symmetry.

The exception to this procedure is when a mirror system must perform to a specific vibration and shock load which simply precludes a three-point mount due to excessive stress and potential distortion induced. This case can be met with a quasi-three-point mount system with four or more mounting points of which three are match machined. The remaining mounting points may then be carefully shimmed, or a hardenable viscous adhesive such as filled epoxy composites can be used to fill the gaps. These additional mounting points can then actually be used to introduce a

correction in the optical performance. This method will provide a very stiff mirror mount with the minimum amount of assembly and alignment effort. The use of two co-aligned autocollimators may be required to align very precision optics such as ultraviolet or X-ray systems. By introducing the error of one into the other it is possible to achieve an arcsecond level of resolution.

By careful design and fabrication using single-point diamond tools or replication from very carefully prepared substrates, it has been possible to fabricate self-aligning optical systems. More of this type of technology is emerging as the precision of the machining and replication processes continues to improve. New diamond turning lathes and fly-cutters are using double-pass interferometers to control the defined position of the tool path.

Piezoelectric or extremely precise DC electrical actuators then resolve the positional errors to submicron resolution over the entire part. Computers capable of real-time translation of more than 1 million data points are in place. The surface finish directly achieved from some of these machines is less than 30 Å rms on certain materials, with figure controlled to less than 1 μm/dm.

The primary difficulty in highly precision alignment methods is the inherent vibration of any building or structure. For this reason the use of an isolated support structure for a complete optics laboratory was employed in the University of Alabama in Huntsville Optics Laboratory. This 110,000-ft² facility has the entire center laboratory section of four floors supported by concrete piers 40 ft into the bedrock. A complete vibration absorbing band of resilient rubber then separates the office and laboratory areas. The laboratories are isolated from equipment vibration further by separate support equipment hallways to avoid placing vibrating equipment in the optical laboratories. In this fashion, it is possible to perform optical alignments and assemblies even on the fourth floor of this building.

Inspection

Most optical fabrication requires sophisticated inspection methods and equipment. This can become a very expensive capital investment. The first requirement is to determine the proper methods to assure the quality of the devices under design or fabrication. The typical optical systems contain reflective or refractive components. Certainly more attention is being paid to fiber optical inspection equipment lately. Additionally, diffractive optical components capable of performing tasks of much heavier and more cumbersome conventional optics are being used.

Inspection must address mirror reflective surfaces and refractive lens behavior as well. In addition, nonreflective coatings must be characterized. As the designs of reflective or refractive optics such as collimators, microscopes, and telescopes become refined through better use of computer-aided design, the inspection becomes more difficult. The verification of an aspheric mirror is sometimes best performed by calibration of the machining center rather than development of null correctors, which usually must be as good or better than the mirror being inspected, making them very expensive.

By cutting a cylinder on a diamond turning machine, it is possible to readily inspect the X and Z components of resolved precision. Corrections of repeated error by the machine can usually be made through software adjustments rather than hardware. In extreme cases, such as new equipment setup or after moving such a machine, it may be necessary to align the hardware using a similar approach. Next a spherical shape can usually be cut with near-net dimensions outside the final aspherical part. This piece can then be easily inspected with conventional interferometric methods. Any disparity in the machining can then be adjusted once more through software error subtraction adjustments and the final surface may be cut with very high reliability to proper precision.

Once this procedure has been completed on any given component, the same software corrections apply for additional parts. The final inspection of such parts may be performed at the assembly level. For production runs of an optical system, an inexpensive method is to dedicate a system for use as a test set with various components readily removable and replaced with the components to be tested. The performance of an actual system is then verified. This type of dynamic assembly testing is often performed over much more elaborate and expensive component testing equipment.

It is important to remember that the surface of a mirror or lens produces a signature characteristic of fabrication history. The diamond turning marks, for example, have a specific frequency of occurrence on the surface of the turned parts. Polishing of surfaces must start with a larger mesh abrasive compound which fractures and breaks down at different rates under different conditions. Selection of subsequent compounds must be based on the complete, not statistical, background left by the previous operation. For example, if a compound of 1200 mesh is used for an insufficient time and then a mesh of, say, 2400 is used similarly prior to a final polish at 0.1 μm , then a proper Fourier transform analysis of the data will show a frequency characteristic of the 1200 and 2400 mesh superimposed on the final polishing. It will be necessary to return to the 1200-mesh step to correct this without losing the figure in some cases. With too many of these iterations, the dimensions and figure both may be destroyed. The best way to develop a polishing procedure is from the inspection data. Often the best assurance is to perform a frequency analysis on each step during the process development stage. This information is recorded and the repeated performance is compared prior to committing the process. In this way it is possible to sort out a host of problems such as a bad bearing in a machine or polishing table. One must also consider the changes in material such as alpha vs. gamma alumina or synthetic vs. natural diamond. Also, high purity water must be used for aqueous slurries. Sometimes the calcium and iron content of tap water can cause staining. The surface inspection interferogram may not detect this. For high end optics, such as X-ray mirrors, it may be necessary to use more sophisticated methods such as AFM and SEM instrumentation to achieve the required surface finish.

10.4 Fabrication of Lightweight Components

Material Selection

Fabrication of lightweight components is usually complicated by a number of mutually exclusive material properties and design issues, which are generally mandatory system requirements. This becomes formidable when precision systems such as optics are the end product. In order to develop stable lightweight optical systems it has become necessary to develop materials which can perform to the limit of scientific knowledge of material science. The requirement may be for the material to have very high stiffness of elastic modulus as such, and still absorb shock and vibration without failure. The first objective, therefore, is to determine the actual absolute requirements for the system. This is best accomplished during the virtual computer design stages to allow selection of materials with known properties. In this way, the design can be optimized to take advantage of stiffening ribs or cutout designs. The stiffness of a plate of glass or aluminum, which has about the same elastic modulus and density (specific stiffness = E/ρ), is by experience about 1/8 thickness to span. For a rib design, the face plate should follow this rule for each cell. To make the face very thin requires more closely spaced ribs. At some point the trade-off in weight is lost and should be predetermined.

The most often misunderstood family of properties for lightweight optics 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 below 1 nm typically, 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, graphite epoxy, or Vanasil (Al 393.2) 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.

Refractive Optical Materials

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 the 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, and since the material does not yield significant plastically, the piece prematurely fractures. 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 to 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 psi. 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 also 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. 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 also typically exhibits high chromatic dispersion or wavelength-dependent changes. The index of refraction typically varies unacceptably for high end use with both temperature and wide bandpass. For selective wavelength or relatively narrow bandpass, however, one of the better substitutes for brittle glass optics is the use of polycarbonate plastics such as used in millions of eyeglass lenses. These materials can be made into lightweight and shock-resistant 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 also used by independent lens fabricators many times over. Certain other plastics may be melted and directly injection molded. In the case of infrared optics, the halogen single-crystal ionic materials are often used for windows or lenses. Strontium fluoride, zinc selenide or sulfide, and some plastics are also selected. Silicon or germanium may also be selected. In this case it is the performance requirement and not the weight which typically becomes the driving motivation for selection, although a great deal of room exists for additional research in this area.

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 also for antireflection purposes. This will be discussed later under Section 10.6 (“Chemical and Vacuum Coating Processes in Optics”).

Composite Lightweight Optics

The use of composite materials in lightweight optics falls into two general categories, metallic and nonmetallic. Nonmetallic materials include graphite fiber with epoxy or other polymers. Metallic materials typically include ceramic-filled lightweight metals such as Al/SiC or Ti/SiC. An extremely light and stiff material is beryllium stiffened with either beryllium oxide such as in I-250 or I-450 alloys or those filled with silicon carbide. Several manufacturers now offer various aluminum alloys with silicon carbide fillers of either filaments or powder. These materials are usually formed by HIP methods which are generally expensive due to the need for high temperature and pressure molding equipment. Casting efforts have been somewhat successful but typically only produce uniform properties at the lower end of the ceramic material introduced into the melt. A combination of beryllium and aluminum with beryllium oxide is presently under study as a castable material and may soon become available for cast lightweight optics.

The nonmetallic materials with graphite filaments can be produced with stiffness and strength comparable to or even in excess of the filled metals. These materials are listed with the highest of all specific stiffness (elastic modulus/density). Section 10.3 describes the behavior of these materials which, although are extremely stiff, may also suffer from instability due to temperature change-induced internal stress due to the different coefficients of expansion of the materials involved and also due to the moisture absorption as described. For space applications these materials can provide the ultimate in weight savings and performance if the system can be temperature controlled. The atmosphere can be replaced with dry nitrogen or other gas, eliminating moisture issues.

Ceramic Materials

Ceramic materials have been used in numerous high precision applications. One of the most durable and stiff materials is silicon carbide. SiC can be HIP formed with a bonding glass or can be deposited to very thick free-standing shapes from silane and methane gas by hydrogen reduction in a heated chamber. Graphite substrates are prepared and after deposition of the SiC, the graphite is removed by reaction in air or oxygen to form carbon dioxide gas. In the case of nonreentry shapes, a release agent may be used to lower the adhesion and permit separation and reuse of the mandrel.

A common misconception is that this material has “no” elasticity when indeed it possess almost perfect elasticity. Like glass, however, the material is brittle. The elastic modulus is an astounding five times that for glass and the usable tensile and yield strength are the same number at about 90,000 to 100,000 psi if care in edge preparation and mounting methods is observed. Also, the specific stiffness is second only to the graphite composites. This makes the use of silicon carbide very attractive for lightweight high end optical systems. The cost of the sintered material is lower than for the CVD version, but the mechanical properties are also much lower. Thus, CVD silicon carbide ranks very favorably as the ultimate material for high end optical components. Drawbacks include high cost, relatively long manufacturing lead times, and poor ductility requiring care in handling and mounting of components to avoid formation of nicks or notches.

The silicon carbide is crystalline but is not a two-phase material as are the composites described above. Therefore, this material can be polished directly to extraordinarily fine surface finish in part due to its purity. Samples of less than 1 Å rms surface finish have been prepared for use as measurement standards. Unfortunately, the reflectivity is poor over most of the spectrum for optics, but the material is easily coated with gold or other materials. Reinforced structures and structures with incorporated fibers injected into the CVD gas stream have been fabricated resulting in exceptionally light and stiff components. Mirror substrates of up to 5 ft in diameter have been prepared from CVD SiC for the U.S. Air Force Rapid Optics Fabrication Technology program

(ROFT). Additional reference to actual fabricated SiC mirror blanks is given in Chapter 4. Section 4.4 (“Chemical Vapor Deposited”).

Co-Continuous Composites

Co-continuous composites are two or more phase materials which can be molten below vaporization temperatures of either material and quenched sufficiently rapidly to achieve a supersaturated composition of one in the other. One such example is silicon and aluminum. Silicon is soluble in aluminum to about 3.0% by weight. If the melt contains up to about 11% silicon, it may be frozen into the alloy as the eutectic at the melt point. Beyond this, up to about 23%, the excess silicon freezes out as a co-continuous weblike infrastructure in the eutectic. This is known as hypereutectic alloying and requires careful preparation to preserve the maximum properties, but when properly prepared can be cast into low cost components with exceptionally high mechanical properties. One such aluminum alloy is 393.2 piston material. This material has a combination of properties not found in other aluminum alloys. Evidence of the extraordinary properties is found in the most common application, namely, automotive and truck engine components. The use as piston material requires that the CTE be as low as the cast iron cylinder, and also that after even millions of cycles the material must not display any creep or yielding. In this aspect, the material has about one half the CTE of other common aluminum alloys, and does not show any deformation after loading in cyclic fashion for millions of firings in the diesel or gasoline high performance engines or under extreme conditions in racing engines. This material has been successfully implemented into a cast optical system for the U.S. Army.¹

The casting cost is lower than HIPping costs for the powder metal composites and the temporal and thermal stability is outstanding over a very wide range of loading and temperature change. Like silicon carbide, the yield strength is the same as the ultimate strength even on the basis of microyield. This material can be plated for optical mirror performance and can also be relatively easily machined, drilled, and threaded, unlike the ceramic materials and with much less complication than the metal composites. On the other end of the same scale, aluminum can supersaturate silicon forming a high silicon, low aluminum co-continuous composite with potentially interesting applications in optics. This material is presently under study by the Ohio State University.⁵

If investment casting is used, a low cost form of HIPping (or autoclaving) is required, wherein the 393.2 aluminum silicon material is placed in a stainless steel bag and subjected to high pressure of about 14 Ksi at the solution heat treatment temperature for about 2 hr to assure the elimination of casting voids.

Although this is often called a HIPping operation, it is not to be confused with the powder metal process requiring expensive molds. The cost for the bagging process is about \$6/lb of material. This material can be cast into low cost stable optical components of lighter weight than glass or even all but the latest BeO/beryllium composites, silicon carbide or graphite epoxy composite systems. Another feature is the fact that the thermal expansion very nicely matches stainless steel, nickel phosphorus plating, and other common materials used in a complete optical system for athermalization purposes.

Cost Comparisons

A comparison of costs is difficult due to the requirement variations. However, it is always wise to consider the overall needs for the program and use the lowest cost process which satisfies those needs. The use of the graphite epoxy or metal matrices should be carefully judged by the performance drawbacks and the higher machining costs than for the cast hypereutectic aluminum alloy. Likewise, the poor microyield of the low BeO beryllium alloys may require more material to be used than is at first obvious from the engineering stiffness data, as opposed to the microyield properties required as pointed out in Chapter 4.

Added cost of HIP molds and the toxicity issues, which are very real if the beryllium must be machined, polished, or ground in any way, are also issues to be considered. As the high BeO alloys

become cost competitive and available commercially, they will be attractive lightweight options. The silicon carbide in either reaction bonded or CVD versions is probably the ultimate high end choice but will likely cost the most. Also, many shapes for optical supports and complex shapes are not readily formed in SiC by any method. If the system must be subjected to wide fluctuations in temperature and humidity, the graphite epoxy composites must be judged very carefully. Likewise, the two-phase powder or filament-filled metal composites may exhibit distortion or even fracture due to internal stresses set up by the different CTE of materials used.

The final design consideration should then be judged based on a complete assessment of system requirements and not limited to simply lightweight or high specific stiffness.

10.5 Dimensional Stability Requirements for Optical Materials

Definition of Requirements

In order to actually perform well in optical manufacturing, often many mechanical engineers have to be reoriented. A typical education in mechanical engineering may not address the issues of tolerances and material requirements needed to understand — or perhaps better put, appreciate — the true requirements to build and test a precision optical system. The units of measurement often look more like something from a physics course than their engineering courses. Indeed optical sciences are generally taught in the physics department of most universities. Some offer independent curricula in optics but omit the precision materials engineering and chemistry issues. This chapter is not intended to replace an education in these subjects but hopefully will make the reader think about the issues prior to under- (or over-) designing an optical system. Above all, 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 most commonly overlooked factor regarding thermal distortion is the fact that the components may have a temporary thermal gradient due to thermal diffusivity, which ideally is high, but in the case of glass and other common materials may not recover from temperature gradients rapidly due to poor conductivity.

The acceptable stress 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.

Material Categories for Optical Systems

An optical system designer must obey the same structural rules as any system engineer or scientist. Weight, strength, corrosion, manufacturing methods, and cost are all very important, of course. Greater emphasis must usually be placed on precision system design material choices. In particular, the extended effects of time, temperature, and loading are far more critical for an optical system than for most engineering designs.

Design Criteria for Dimensional Stability

Mechanics of deformable solids involves a knowledge of many engineering and material aspects beyond the scope of this chapter. It must suffice to briefly explain those issues at hand for the typical optical design. Five types of material behaviors regarding stress vs. strain are accepted.

Essentially two of these are to be considered for optics: first, the materials which are completely elastic over a high range of stress required for the system; second, those materials which are not elastic at high stress but behave in a plastic fashion.

All materials respond to mechanical loading by moving. The extent to which an optical component moves and, moreover, the temporal-dependent path through which it moves for a given load both during the application and also after removal of the load is extremely critical to the design performance. This movement must be determined as a function of time-dependent variables.

For the loading regime of a given material, which is completely elastic, the hysteresis or timelag effects are typically very small compared to normal loading and unloading times. However, for vibrational loading, the time-strain behavior may be important even at very low levels. The slope of the stress/strain over the exact elastic region of a loaded material is the modulus of elasticity or Young's modulus. Yield point is the stress level at which the material becomes plastic. This is a very difficult determination due to the sensitivity with respect to the measurement accuracy requirements.

For most engineering applications, a value of 0.2% plastic offset is used to determine yield strength or the maximum force per unit area at which material should be used. For optics this is totally unacceptable. A strain of no more than 1 to 20 ppm might be tolerated. No exact proportional limit for the stress and strain exists, even for the same materials, due to the sensitivity in processing to be discussed later. This is indeed true in spite of the fact that the modulus of elasticity is very nearly constant regardless of heat treatment or other material history. An example is carbon steel, which may be annealed to a very soft condition with the plastic microstrain yield occurring at a few thousand psi vs. the solution-quenched tool steel and tempered steel with the yield at 100,000 or even 200,000 psi (100 to 200 Kpsi, 700 to 1400 MN/m²). For many materials used in optics such as Al, Be, or Ti, the microyield vs. the engineering yield is equally disparaging depending on the heat treatment, alloy composition, work hardening, and thermal cycling history to be described later.

Fortunately, the microyield elastic limit and the usual engineering limit are not linearly related. A material such as aluminum 6061-T6 alloy with a 0.2% yield strength of 40 Ksi would only have a usable microyield strength of 400 psi at, say, 2.0 $\mu\epsilon$.

If this material was overaged or completely annealed, this would likely be about correct for the microyield proportional limit. In fact, for most engineering metals, which can be heat-treated to resist yielding, proper conditioning will produce values which are about 1/3 the engineering yield strength for most precision applications. If an optical system is subjected to stress levels beyond this limit, then more series quantitative results and/or testing would be required to determine the actual microyield strength.

As the design stress level approaches one third the engineering yield strength, then for critical systems a very careful material preparation and history logbook must be maintained. The preferred procedure for producing such machined optical components is to start with a larger material blank not in the solution (or quenched) state. Also, of course, this means that subsequent aging will not be performed. Unfortunately, this generally requires a very careful heat treatment monitoring procedure for proper control. If aluminum alloys containing copper (e.g., 6061 or 2024) are heated only a few degrees Celsius above the proper temperature from the initial melt condition, then the copper migrates to grain boundaries and the material cannot be properly heat-treated at all.

Many materials are also anisotropic in thermal expansion. This is particularly true in polycrystalline materials and fiber-reinforced polymer (epoxy) composites. Low expansion materials are most desirable since the effects of temperature are minimized for that component. In most cases, it is essential to have mounting components or commercial items such as lasers and mounts in the system. In this case, it is far better to achieve a match in the CTE of all the components and the wiser choice may be the selection of a higher CTE material to match a particular optical component to the system. This becomes more difficult when a particular optical item is not replaceable such as a quartz lens, for example. In this case low expansion metal pieces of Invar

(64% Fe/36% Ni by weight) or molybdenum alloys such as TZM or graphite epoxy pieces, which can be engineered to a specific CTE, may be required. The reader is referred to Chapter 4 for additional information.

Hysteresis is the strain from applied mechanical or thermal load which exhibits time dependency upon return to zero strain when the load is removed. Induced distortion is also referred to as hysteresis if the material does not return unless a load is applied in the opposite direction. Atoms of a metal or nonmetal located in an interstitial position (within the lattice structure) of the material may move from one type of lattice position to another when stress is applied. Upon removal of the load, the impurity atom may move back to the original position with a particular time dependency or history. Entire lines or rows of atoms may move similarly and are termed dislocation lines. Randomly oriented solute atoms displaced by stress may be rearranged by time and temperature which will return the strained material to the original position. This is the basis for some of the shape memory alloys such as titanium nickel dental wire alloys.

Grain boundaries can store energy after being strained by excess stress. The lowest energy level is when the grain boundaries have the nearest fit to the solidification configuration. After stressing a material to a small strain value, it may return slowly to the “best fit” of the grain boundaries. This is also true of composites with very small particles or fibers added. If the strain is less than the value required to fracture the fibers or separate the adhesion of the particles, there may be a hysteresis effect upon loading and unloading due to relaxation at the lowest possible level of energy expended. Heat treatment of other methods described later on will often permit additional relaxation.

Materials, which demonstrate a low rate return to the original configuration, are termed anelastic if the return is to the exact same position as at the start. Other forms of hysteresis include the return to the starting position by applied compressive loading following a tensile loading. This does not constitute anelastic behavior, however. If a material is stressed such that the dislocations do not return to the original position, the onset of nonreversible plastic strain is observed. If it is forced back into position as above, the disruption of grain boundaries will eventually take place and the material will generally first work harden and then subsequently may be seriously weakened. Continued cyclic stress from tensile to compressive will eventually fracture the material.

Creep is defined as the onset of low strain changes with loading. Creep or time-dependent strain beyond the elastic (or inelastic limit) occurs when a sustained load allows the slow movement of the dislocations or grain boundaries to proceed irreversibly. In a plastic material, the motion is due to the sliding of rows of whole molecules. Microcreep is defined as the time-dependent strain under a given sustained load which causes 1 ppm change in length. Thus, both the time and load must be considered. Also, this type of deformation is sensitive to the temperature with higher rates at higher loads and temperature.

Creep is more predominant in materials with low melting point and low elastic modulus of elasticity. For example, the use of tin–lead solders in any precision structure subjected to loading is to be discouraged due to the high creep susceptibility.

Stress — Internal to the Material or Intrinsic Stress

A number of issues relate directly to the stored energy in a material or as such within the structure. This stored energy will cause deformation of the structure as it is released. The above discussions relating to anelastic behavior of materials is indicative of the slow relaxation properties. The types of internal stress, sources, and manifestations which may occur will be discussed here.

The internal stresses that exist within a material in the absence of an applied external force contribute to instability when changes are made to the structure such as machining, etching, or during thermal excursions.

Two types of stresses or stored energy are commonly depicted. The first is a long-range stress and the second is termed as short-range. The long-range stress is that which is deeply imbedded in the material typically by processing steps such as welding or early stages of heat treatment involving severe quenches from high to low temperatures to freeze in the desired properties. This

stress is on an order much coarser than the grain structure of the material and is usually referred to as the residual stress. The short-range or microstructural stress is related to the types of issues which act as true material properties. The overall sum of stresses in a material must be equal to zero unless the material is moving.

The short-range stress may often be beneficial such as the pinning of dislocations as a result of the two phase alloys or metal matrix materials. The solidification of the material with different expansion rates for the composite additions will cause a local stress at the site of the particle or fiber, and will generally pin the locally surrounding material increasing the elastic modulus and yield strength properties. While the local size of the short-order stress may be small, the magnitude may be very high and even cause cracking of the material in the bulk. Any change in the long-range stress, such as by removing material from one side of a bar with a nonuniform distribution of stress, will certainly cause a distortional change. For the short-order stressed material, removal of the surface by machining or by chemical means is less likely to cause warping than in the long-range stressed material.

However, when the materials with either form of stress are heated and cooled, dimensional changes can occur. Thermal cycling will allow the material to distribute the long-range stress uniformly so long as rapid heating and cooling cycles are avoided. This occurs since the heating cycle will permit the material to flow plastically and conform to the thermal expansion mismatch of the smaller particles or the matrix addition particles. Such materials are generally "age hardenable". This means that an improvement not only in hardness but in the yield and ultimate strength will be realized along with the improvement in stability. Often for an optical system, it is required that the age-hardening steps be carried out past the point of the highest strength in order to fully relieve the internal or long-range stresses. This should be done sequentially to allow rough machining and stresses introduced during machining to be relaxed prior to final precision machining such as single-point diamond turning.

Short-range stresses can sometimes be relieved by low amplitude cyclic stress, which varies from tensile to compressive over many cycles such as by low frequency vibration. A large number of slowly applied thermal cycles including liquid nitrogen immersion with slow cooling permitted, and rapid quench in hot water in reverse of the original sequence of solution temperature (very hot) to boiling water, will also often achieve this, but it can be very cumbersome from the point of view of the manufacturing time. This process reverses the stress direction from the outside (compressive) into the interior of the material (tensile). If performed carefully the total internal stress can be reduced to nearly zero. See Section 10.5 ("Precipitation-Hardened Metals") for additional details.

Strengthening Mechanisms

Stress is typically highest in crystalline materials. This is especially true for small powder HIP and HCP materials. Beryllium is intriguing since loading in it due to acceleration or gravity is low because of the low density. Also, deformation is low due to the high elastic modulus. It is true that pure beryllium and most beryllium alloys close to pure Be have a low microyield stress. However, recent developments in hot isostatic pressing of Be + BeO have lead to more stable alloys. As explained earlier, many materials undergo a stress during cooling or heating cycles. This phenomenon has been studied and it has been shown that for stresses which arise between grains in an HCP material and the bulk material, the stress is due to a mismatch in the CTE of the different axes of the actual individual crystallite. The shear stress τ is given by:

$$\tau_{\max} = \int_{T_m}^T \frac{\bar{E}(T)\Delta\alpha(T)}{4(1+\nu)} dT$$

where $E(T)$ = average elastic modulus at temperature T

$\Delta\alpha$ = bulk CTE — (c-axis CTE)

ν = Poisson's ratio

T = temperature considered

T_m = minimum temperature

For example, when beryllium is cooled from room temperature to

4K, $\tau = 7200$ psi. Most aluminum alloys are free from this stress.

The yield strength is also related to the crystalline structure. The grain size is related to the yield strength by the Hall-Petch relationship.

$$\text{Fracture Strength} = [K(\sigma_y + \sigma_o) \times (d/r)]^{1/2}$$

where K = constant relative to a particular material

d = grain size

σ_y = yield stress considered

σ_o = Peierls stress (friction stress)

r = distance from onset of crack

The Peierls-Nabarro stress or σ_o is actually not constant for a material so much as for the method of forming the material such as heat treatment, impurity additions, and cold work which affect the dislocation density.

Heat Treatment of Optical Materials

As mentioned earlier, it is simply not possible to discuss all of the categories of materials used in optics nor how they are apt to behave to heat treatment in all cases. It is a challenge to convey with enough emphasis the more common material processing steps and perhaps a few which have many applications in optics but are less understood by the optical design community.

Precipitation-Hardened Metals

Precipitation-hardened metals form perhaps the largest category of optical structural and many mirror components. One such metal is 6061 aluminum alloy which can be heat-treated to several conditions and for which stabilization processes are fairly well defined.

This alloy is characterized by the copper content, which is just below the eutectic value such that when the alloy is cooled from a melt condition rapidly, the solution phase is retained to a degree. The rapid cooling prevents migration of significant copper into the grain boundaries but permits significant pinning and grain size reduction as mentioned above. Chapter 4 shows the effect of cooling the aluminum alloy in different liquids from the solution temperature. This effect is due not only to the ratio of the thermal conductivity of the metal to the solution, but also to the ambient temperature of the solution. The idea is to quench the solution or maximum amount of copper in solid solution, and precipitate the rest including specific addition agents in a fine dispersion, which causes many dislocations and pinning sites in the alloy. If the metal is raised even a few degrees above the solution temperature specified for a given aluminum alloy, then the copper may migrate into the grain boundaries. This will soften and weaken the metal irreversibly. Therefore, the metal is very carefully heated to solution temperature and quenched in a liquid coolant to freeze in the desired structure. The problem is that for thick sections, the cooling rate is not uniform since the temperature of coolant will increase, and of course the cooling effect reaches the interior of the alloy slowly.

Therefore, as shown in Figure 4.3 (Chapter 4), the bulk piece has different properties including residual stress. This is worse for the case of a very thick piece quenched in a liquid which starts

out cool but is rapidly heated. Two causes are known. First, the liquid quickly reaches the boiling temperature in contact with the part, and gives up additional heat due to the latent heat of vaporization and then can only transfer heat at the rate consistent with conversion from steam to vapor or 80 cal/g for water vapor compared to 454 cal/g for water to steam. So at the initial onset of the quench, the outer metal is cooled very rapidly and freezes in the desired structure. Deeper in the metal, the rate of cooling is less as described above and the grain size becomes larger with less pinning. This, in turn, causes a distribution of stress, the average of which must be zero or the material must be in motion as discussed in Chapter 4. For most practical engineering purposes, this is of no concern since the structure as a whole may meet all expectations in performance for an optical component, however, when this piece of metal is machined removing the preferential stress, the motion that occurs is not acceptable. The next step in metal preparation is the stabilization of this distributed stress to the extent possible. If the aluminum is purchased as T-6, then the entire piece has been through an “aging” process, which will lower the stresses and improve the yield and microyield properties considerably.

If the item to be machined is a mirror, then the trade-off is yield and ultimate strength for stability. Overaging is preferred if a sacrifice in maximum properties can be tolerated. An additional step is to cycle the part after all but the final machining to low and high temperatures by using liquid nitrogen and boiling cycles. This plays a similar role as the initial quench from solution temperature. The outermost metal first cools faster than the inner metal and the contraction at the surface places the outer metal in compression. This step is usually best done slowly to avoid additional strain in the same direction as before. Then the part is quickly quenched in boiling water or other quenching media of choice such as propylene glycol, and the stresses reverse causing a reversal in the strain and concurrently the stress. This serves to stabilize the metals in the opposite sense from the previous history. Therefore, the last cycle is typically cold to hot for this reason. The final optical machining is then performed.

Work-Hardened Metals

Work-hardened metals include many pure or elemental metals which only form large grain size with poor pinning due to few dislocation or impurity sites from solidification from the melt. Typical examples include copper or solid solution alloys such as brass containing a large percentage of only zinc, which is very soluble in the copper. This category of metals is seldom used for optics unless for some special property which might be desired such as very high temperature use, high thermal conductivity, or some particular corrosion behavior. These metals can be hardened, such as for brass or copper as examples. In this case, the metal is rolled sometimes at elevated temperature, until a particular reduction in cross section is achieved. This breaks down the grain size and increases the strength and yield properties considerably. The trade-off is again internal stress which, in turn, causes motion in the form of the same strain relief as before. Stabilization is similar to the aluminum alloy and some sacrifice in yield strength is generally traded for internal stress relief.

The same effect can be achieved with very low internal stress from electrodeposited copper, which has excellent thermal conductivity and relatively high strength if deposited under certain controlled conditions. Some copper optics have been formed this way, but due to high weight-to-strength ratio the issues of thermal dissipation are usually dealt with in other ways than copper optics.

Stabilization of Selected Advanced Materials

Many methods of forming components to near net shape are used for optical components as mentioned previously. Stabilization of these materials depends on the nature of the material as well as the process. HIP powder metals, CVD, or electrochemically deposited shapes (electroforms) each behave differently for different processes unique to each.

Electroformed Optics

Electroforming is the fabrication of free-standing components by the electrodeposition of a metal. Nickel and copper are the most common metals, however, many others can be utilized such as silver or gold. The requirements for an electroformed optical component are very stringent by most electroplating standards. By proper control of the chemistry and the process, in general, it is possible to deposit stress-free metal shapes with thicknesses of one or more millimeters which replicate a precision master surface. Numerous references are available regarding electroforming. A committee and dedicated symposiums meet to discuss the state of present applications. This is sponsored by the American Electroplaters and Surface Finishers Association located in Orlando, FL.

Electroformed nickel perhaps has the most intense history of stress control of electroformed materials. This is in part due to the utility and relative ease of forming free-standing shapes. Additionally, the elastic modulus of nickel is about 200 GPa (28 Mpsi) with the density at about 8.9 g/cm³. In order to accomplish fabrication of optical components, the intrinsic or internal stress must be controlled to avoid deformation of the replicate electroform. Stress in an electrodeposit is related to a number of variables. In general, the stress is caused by impurity atoms and by dislocation in the deposit. Hydrogen may cause either compressive or tensile stress and may cause relaxation over time due to the release. The hydrogen enters the metal electrochemically, also. The pressure is related to the pH and the potential at the surface. Also, the absolute rate of deposition of a metal is determined by Faraday's law, which will be defined in the next section. The absorption or uptake of hydrogen can be at pressures greater than the bond strength of the grain boundaries, causing rupture or severe hydrogen embrittlement in some cases. This is, of course, extreme and totally unacceptable in an optical component, although spontaneous in the electrodeposition of chromium, for example.

Typically nickel is plated from a sulfamate solution, which will be described in more detail later. The overall process permits a small amount of sulfur to be codeposited in parts per million, which forms a nickel sulfide striation in the grain boundaries. This in turn causes a minute compressive stress. By controlling the current density to a precise value using real-time stress monitoring, it is possible to continuously deposit zero stress nickel by controlling the diffusion ratio of nickel sulfide-forming compounds to the nickel deposit. Subsequent heat treatment is seldom required or desirable in this case.

Nickel X-ray mirrors have been formed by NASA in the U.S. and by the European team involving Italian and German cooperative efforts.^{3,4} These mirrors are of a grazing incidence Wolter I design with extremely fine internal surface finish requirements. The optical surfaces are required to have less than 1 nm rms roughness and circularity of about 1 μm/25 cm diameter.

Cast Hypereutectic Aluminum Silicon

The silicon aluminum hypereutectic mentioned earlier is a multiple-phase material and behaves to heat treatment much like other precipitation-hardenable aluminum alloys. Although the alloy is considered somewhat brittle, it has very good resistance to thermal shock and edge notches. The material can be autoclaved to eliminate casting voids by placing in a sealed stainless steel bag and heating in an autoclave at 510°C (950°F) while applying about 84 Mpa (12 Ksi) pressure. The standard solution and precipitation heat treatments should then follow prior to final machining. The stability is increased by liquid nitrogen to boiling water quenching which will not crack this material.

10.6 Chemical and Vacuum Coating Processes in Optics

The use of both chemical and vacuum coating processes as applied to optics is of paramount importance. Like other material issues, the coating processes are not always well understood by the optical designer. It does not suffice to specify a coating simply because a previous specification was used on a different system.

Vacuum Coating Processes

The most widely used and also variant methods for producing optical coatings is referred to as vacuum coating processes if indeed the parts are placed in a coating chamber from which the air is removed. The methods used depend on the material and thickness to be deposited. For single metals and some of the lower melt point alloys the simple processes are to be preferred in most cases. Common categories include the following:

Physical vapor deposition — evaporation — sputtering

- High vacuum
- Inert gas
- Reactive gas
- Ion assisted
- Bias assisted

Chemical vapor deposition — chemically induced reaction at high temperature

- Hydrogen reduction — $WF_6 + 3H_2 \rightarrow W + 6HF$
- Organometallic decomposition
- Polymerization from monomeric-evaporated material through dimer chain reactions

Evaporation is one of the more common methods used to coat optics. The material to be deposited is placed in a crucible or “boat” and typically heated either by a resistance heater or by an electron beam. The material is in a hard vacuum of 10^{-6} torr or less. This permits the vapor pressure vs. temperature to be sufficiently low to evaporate the material which then condenses on the colder surroundings forming the coating. This results in a “line of sight” deposition with a cosine-shaped cloud density distribution above the source. Better use of the material occurs when the substrate is covered by the entire “cloud”, but this is seldom possible such that surrounding parts of the chamber are also coated. A bias of DC or AC high frequency (RF) may be applied to an inert gas or in some cases a reactive gas to add additional elemental components to the deposit or to enhance the adhesion to the substrate. This also helps to confine the distribution somewhat.

Often more than one boat is used with different materials to form coatings in layers to enhance certain properties such as adhesion. For example, gold does not adhere as well to glass as chromium so the chromium is deposited first followed by the gold layer. In this case the vacuum cannot be interrupted or the chromium spontaneously oxidizes to a thickness of oxide of about 10 to 100 Å, which again is sufficient to prevent adhesion of the gold. The thickness of the deposits can be determined by the use of a quartz crystal oscillator monitor, which changes frequency of resonance with increased thickness of the deposit providing a real-time indication of the thickness. The oscillator portion of this instrument is also placed in the path of the depositing material.

Aqueous Coating Processes

Aqueous coating processes likewise are variant in nature and used for a variety of applications. The processes are by definition those performed in water, but similar processes are possible in organic solvents and even in molten salts, as briefly described in Chapter 4.

Two categories will be briefly described here. First is the issue of producing a coating by an applied current. This is usually referred to as plating when the current is negative on the part permitting transport of the metal to the substrate surface by dissociation from the anion-cation complex. The rate of deposition is governed by the metal valence and the molecular weight. The relationship is defined by Faraday’s law as:

$$\text{Grams Deposited} = \frac{MW \times \text{Time in Seconds} \times \text{Current (Ampere)}}{n \times 96,500}$$

where MW = molecular weight
 n = valence of ionic metal in solution
 $96,500$ = Faraday's constant

Often hydrogen is discharged with the metal and must be accounted for in this calculation. The efficiency is the amount of metal actually deposited vs. the predicted amount from the equation.

The coating obtained when the part (or substrate) is positive to an auxiliary electrode is an oxide formed by dissociation of the water and diffusion-controlled metal for combination which is taken from the substrate. This process is referred to as anodizing and is extensively used to produce coatings on aluminum and magnesium. The coating thickness and formation rate are less determinate than above due to the fact that the metal must diffuse through the coating as it forms. In order to maintain a coating with proper density of oxygen and metal, the rate of formation must be limited to that rate for which the metal can equilibrate to the oxide. The coatings are porous, especially when thicker than a few microns, on aluminum. The porosity can be sealed by immersion of the item in boiling water. Dyes can also be added to the process and sealed into the pores in a similar fashion. This is the basis for the black anodize process used to form some nonreflective aluminum parts for optical baffles and other nonreflecting devices.

Electroless Nickel

The second type of aqueous coating commonly applied to optical components is the electroless or autocatalytic nickel–phosphorous alloy applied to single-point diamond machined aluminum mirrors. The term electroless is actually a misnomer in that although no current is externally applied to the plating parts, current is supplied to the surface through electron transfer due to reduction of the nickel from nickel sulfate and phosphorous from hypophosphite. Other mechanisms are possible with additional metals as alloying elements or phosphorous substituted by boron reduced from borohydrates or diethylamineborane. The intrinsic or internal stress in the alloy is a direct function of the percentile of phosphorous if all additional conditions are the same. The Ni-P alloy in all compositions has significantly lower thermal expansion (or contraction) than nearly all aluminum alloys commonly used in optics such as 6061 or 2024. A commonly desired composition is the ratio of 11% phosphorous and 89% nickel which corresponds with $[Ni_3P]$, where the brackets indicate the material is more nearly amorphous than the crystalline allotrope. The plating rate is determined by the temperature and the ratio of nickel to hypophosphite or other “reducing” agent in accordance to an activation or Arrhenius rate law dependent on the specific process. The reader is referred to references on electroless nickel plating for additional chemistry detail.

If the nickel alloy is applied at neutral stress at the plating temperature of about 190°F, and the coating and substrate are subsequently cooled to room temperature, then the aluminum will contract more than the coating, placing the coating in compression. Since the part must come to equilibrium, the substrate interface with the coating is in tension. A flat aluminum plate or strip coated on one side with NiP at low stress during plating at elevated temperature will then deflect such that it becomes convex on the plated surface when cooled. If, however, the coating is the same thickness on both sides, the deformation in the coating will be distributed with linear deformation of the substrate interfacial surface and the distortion will be minimal, albeit the stored energy may be higher. Likewise, if the coating is applied at a sufficient tensile stress, then the relaxation due to lower temperature would allow the coating to come to low or zero stress at room temperature. Heat treatment can be used to relieve some of the stress by exceeding the plating temperature significantly. Permanent distortion occurring at the elevated temperature will relax more nearly to zero at room temperature in some cases. Also, as pointed out in Chapter 4, the lower phosphorous nickel alloys may change from amorphous to crystalline with a reduction in volume resulting in a better match at room temperature. This higher temperature heat treatment is not usually recommended for coated aluminum alloys due to the overaging incurred. Also, the polishing properties of the alloy may be diminished in this way.

The final stress in a plated strip mentioned above can be expressed as a function of the curvature of the strip. This procedure is commonly used to predict the behavior of a coated system. This is done in several ways and depends on whether or not the strip was permitted to bend while plating one side. The typical method of choice is for the piece to be plated on both sides without bending and subsequently stripped on one side to permit the bowing.

The stress due to CTE mismatch can then be accounted for by the ratio of the CTE values for each metal, the delta temperature, the ratio of the elastic moduli, and the overall length of the strip. The stress can be considered biaxial for simplicity with good results. This should be calculated as if the strip was still straight for best results.

Another more direct method is to use a commercially available electronic stress monitor (U.S. Patent 4, 986, 130) to measure the stress in real time. Care must be taken to account for the differential CTE in this case if the optical component is aluminum or another high expansion metal. Since the gauge is made of stainless steel, the CTE is close to the nickel phosphorous at the desired 11% phosphorous alloy such that the reading is very nearly that of the stress in the nickel phosphorous at the deposition temperature. The instrument is also used to measure stress in real time for other coating processes.

Electrolytic Deposits

The most commonly applied electrolytic coatings for optics include gold and nickel. Copper is used as a primary layer in some cases to provide a diamond-machinable surface prior to electroless nickel coating for diamond machining. Pure nickel coatings do not diamond machine well due to formation of carbides, with the very sharp diamond tool edge causing breakage and subsequent dulling of the tool. The phosphorus in the electroless version minimizes this especially in the higher phosphorous alloys. Pure nickel is used, however, for the electroformed optics described earlier and for corrosion-resistant coatings on many major components. Gold can be applied as pure gold or as an alloy. The alloys are unique to specific desired properties. The addition of copper may enhance the hardness and durability of the coating while shifting the best IR performance to longer wavelengths. This also provides for a gold coating which can be applied sufficiently thick and with adequate hardness to allow for polishing or even rework.

The gold alloys are typically plated from cyanide complexes with chelates, such as the versenes of ethylene diamine or triamine tetra- or pentaacetic acids for complexing the copper to maintain some valence two copper instead of the valence one coordination species of cyanide. Also, excess cyanide must be very carefully maintained to prevent formation of AuCN, which is insoluble and can cause roughness in the deposit. Also, cyanide is released as the gold deposits, allowing excess cyanide to accrue. This is offset by oxidation to cyanogen, C_2N_2 , which is volatile at the plating temperature and evaporates. If the free cyanide becomes excessive, then the copper is converted to monovalent copper cyanide in one or more of three possible coordination configurations which changes the plating rate and increases the deposit stress. As if this was not enough problems, the copper chelant is also oxidized at the anode, creating up to 17 breakdown products requiring frequent or continuous carbon treatment. It is evident then that both electrolytic and chronological aging of the solution must be dealt with if optical quality components are involved.

Due to these difficulties, only selected plating facilities are willing to coat expensive optical components with gold alloys. Future work in this area should include formulation of noncyanide gold alloy processes such as gold phosphite and copper complexes for improved stability. A study of the reflectance properties of a number of controlled alloy deposits would also be a viable optical undertaking.

Copper may be plated at high efficiency and with excellent quality from acid or alkaline solutions. The material can be plated with controlled stress from acid sulfate processes, with proprietary stress-reducing agents added much like nickel from the sulfamate bath. The material is easily diamond machined and as such is sometimes used for electroformed shapes to be subsequently machined. Copper, however, suffers from lower hardness and elastic modulus than nickel, while

maintaining the same density so the specific stiffness is lower. Also, the deposited copper suffers from long-term intergranular migration of the organic additives used in the sulfate processes if the deposit is used at elevated temperature. Even at room temperature, this may be manifested in surface roughness appearing over extended time in the diamond-turned copper surface if the plating process is not controlled to minimize the use of organic additives. Mild heat treatment prior to diamond machining may help stabilize the deposit in some instances.

10.7 Summary

The development of optical and electro-optical systems must necessarily involve the best design and fabrication resources available. This includes personnel, equipment, and facilities. Often this quality requirement is taken too lightly resulting in confusion or despair. This chapter cannot replace the education and experience required to differentiate between engineering and optical engineering as it applies to the manufacturing of such precision systems. The typical optical system development requires cooperation and coordination of many disciplines of engineering and science in order to establish innovative and functional devices. Modern methods involving computer-aided design and analysis must be incorporated in order to remain competitive. Rapid prototyping and extremely high precision fabrication methods must also be employed. The need to organize a development project is mandatory. The source of personnel, equipment, and materials must be established prior to proceeding in order to avoid delays and difficulties.

While no single aspect of the development of an optical system can be listed as most important, it is worth a brief review of those which may be overlooked such that personnel can be assigned to avoid problems which may otherwise arise.

Perhaps foremost is the need to develop a model using a virtual design approach. This can be used to evaluate the design with regards to material selection, mechanical and self-loading, thermal conditions, tolerance analysis, and general issues such as optical path interference or vignetting. Next it is imperative that the subtle manufacturing details be understood. This includes a working knowledge of the ultraprecision machining methods available and the requisite inspection instrumentation and methods to verify the results. Subtle issues such as out-of-plane temporary mounting surfaces can introduce sufficient distortion when an item is bolted to a tooling plate during fabrication to preclude proper operation later as an optical device. Other issues arise from the difficulties in inspection, material stabilization, or perhaps the availability of optically qualified materials. A classic example is the use of recycled materials such as aluminum alloys which may contain large quantities of iron particles and even glass chips and still meet composition specifications. While this may be acceptable for most structural applications, it wreaks havoc on diamond machining of precision optical surfaces.

References

1. Ahmad, A., Engelhaupt, D., Feng, C., Hadaway, J., and Ye Li. 1994. Design and fabrication of low-cost lightweight metal mirrors. In *Proc. Manufacturing Process Development in Photonics Conf. Redstone Arsenal, AL*.
2. Ahmad, A., Feng, C., and Sarapaka, R. 1995. Virtual prototyping: a cost-effective emerging methodology. In *SPIE Proc. Vol. 2537-39*.
3. Citterio, O., Bonelli, G., Conti, G., Mattaini, E., Santambrogio, E., Sacco, B., Lanzara, E., Bruninger, H., and Burkert, W. 1988. Optics for the X-ray imaging concentrators aboard the X-ray astronomy satellite SAX, *Appl. Opt.*, 27, 1470-1475.
4. Citterio, O., Concini, P., Mazzoleni, F., Conti, G., Cusumano, G., Sacco, B., Brauning, H., and Burkert, W. 1992. Imaging characteristics of the development model of the JET-X X-ray telescope. In *Multilayer and Grazing Incidence X-ray/EUV Optics*, Hoover, R. B., ed., pp. 150-159. *SPIE Proc. Vol. 1546*.

5. Fraser, H. and Daehn, G. Co-Continuous Ceramic Composite (C⁴) Materials, Internal Research Report. Ohio State University, Columbus.
6. Scott, S. 1991. Electroless nickel plating for enhanced gold coating: a lesson in bimetallics. In Proceedings of Metal Platings for Precision Finishing Operations Conf. Tucson, AZ.
7. Wolf, E. G. 1990. Moisture and viscoelastic effects on the dimensional stability of composites, pp. 70–75. In *SPIE Proc.* Vol. 1335.