

## Advanced materials: an overview

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### ABSTRACT

Optical systems come in many shapes and sizes. Each system must perform in an environment that imposes unique constraints when combined with the operating system dynamics and other requirements. These constraints make the choice of materials a not so simple task.

An overview of the available choices in advanced materials, with an emphasis on system compatibility and dimensional stability, is presented. Materials covered include: metals, glasses and glass ceramics, composites including metal and polymer matrix materials, and plated nickel and aluminum coatings. Refractive materials have not been included, the emphasis being on mirror systems. Properties comparisons are made and fabrication methods briefly discussed. There is never a material that meets all the requirements for a particular application. This paper, together with the others in this volume, provides guidelines for selecting the most suitable material or combination of materials for almost any optical system.

**Keywords:** materials, mirror materials, optical systems, beryllium, aluminum, silicon carbide, material properties, fabrication methods, dimensional stability, electroless nickel, electroplated aluminum

### 1. INTRODUCTION

There are many materials to choose from when considering the optical and structural components in systems designs. Metals and ceramics such as aluminum (Al), beryllium (Be) and silicon carbide (SiC) are used for both mirrors and structures, and can provide athermalized systems when all components are fabricated from the same material. Glass and glass-ceramic mirrors such as fused silica, ULE™ fused silica, borosilicate glass and Zerodur® are typically supported and metered by graphite/epoxy (Gr/Ep) and invar for space systems, or Al, invar and steel for ground based systems. Many otherwise desirable mirror materials can not be polished to an acceptable optical finish but are used with appropriate coatings such as silicon (Si), electroless nickel (EN) or other electroplated material suitable for diamond turning. There are many other available materials that can and are being used, particularly in non-traditional optical systems such as high energy lasers and synchrotron beam lines.

Dimensional instability is a critical factor in many optical systems and must be considered in the selection of materials and fabrication processes. While all materials can be unstable if improperly fabricated, careful preparation of a manufacturing plan that incorporates low stress processes and stress relief treatments will yield stable systems.

The factors that determine the materials choices include system optical requirements, imposed mechanical constraints, material properties and manufacturing methods, end-use environmental considerations and of course, cost and schedule. It is clear that the choice is not simple, and material selection processes usually consist of the following steps:

1. Determine end-use parameters and specifications,
2. Screen materials by properties, rejecting unsuitable ones,
3. Establish and analyze a strawman design,
4. Compare candidate materials with respect to fabrication methods and ability to meet system requirements and
5. Perform detailed tradeoffs and iterate design to determine optimum material and fabrication process combination.

Depending on the complexity of the system and scope of the program, the selection process may be more or less elaborate. The following sections discuss and compare the materials choices. Other papers in this conference furnish details of some advanced applications and for many of the materials for use in these optical systems.

## 2. MATERIALS

The emphasis in this paper is on advanced materials or materials for demanding applications. The more traditional mirror and structural materials are included for comparison. Selected properties and figures of merit that may not be as familiar as density and elastic modulus are defined and their importance discussed.

### 2.1 Properties and figures of merit

Material properties can be categorized as physical, mechanical, thermal, optical and crystallographic, and certain aspects of fabricability can also be categorized as properties. A number of important properties in each of these categories are listed in Table 1. A critical factor to consider in obtaining material properties is that almost all properties change as a function of temperature, and the dependency is rarely linear.

Table 2 lists some physical and mechanical properties of important materials used in optical systems.. Mirror and structural materials are included along with two coating materials, EN and electroplated Al. These two materials, along with polycrystalline Si are important coating materials that can be diamond turned and are often used as polishable coatings on mirror substrates that are more difficult to polish.

Since fracture and yield strengths of most materials used in optical systems are not critical and readily obtainable, they are not listed.. Density and Young's modulus are shown and are used in Table 3 in various combinations described below to compare self-weight deflection and mass. Poisson's ratio relates strain in orthogonal directions in a component under uniaxial load. For brittle materials like glasses and ceramics, fracture toughness is most important, it being a measure of the energy necessary to propagate cracks. Microyield strength, the stress to cause one ppm of permanent deformation, is very important, particularly in the stressed areas around attachment points.

**Table 1. Properties important in the design of optical systems**

Mechanical	Physical/ Thermal	Optical	Crystallographic	Fabricable
Young's modulus	Density	Reflectivity	Crystalline or amorphous	Castability
Fracture strength	Electrical conductivity	Absorptivity	Crystal structure	Machinability
Yield strength	Vapor pressure	Transmissivity	Crystallographic texture	Forgability
Microyield strength	Neutron cross-section	Refractive index	Phases present	Platability
Creep strength	X-ray absorption	Extinction coefficient	Grain size	Polishability
Fatigue strength	Corrosion potential	dn/dT	Voids	
Fracture toughness	Thermal expansion	dn/dλ	Inclusions	
Hardness	Thermal conductivity	dn/dc	Temperatures: Softening	
Ductility	Specific heat		Annealing	
Poisson's ratio	Thermal diffusivity		Stress relief	
	Melting point		Recr'lization	

From a mechanical standpoint, there is no clear winner. While Be and Gr/Ep have the lowest density, they do not have very high microyield strength (many properties that are direction dependent in Gr/Ep are not shown). Molybdenum (Mo) and the SiC's have high modulus, but not low density. Most of the high microyield strength materials have high density.

The use of Table 3 can help when determining the right material in a mass and/or deflection critical application. The specific stiffness,  $E/\rho$ , is a figure of merit used to compare materials – and it is usually used incorrectly. In the table, a number of figures of merit are listed and each has a use when comparing specific features of a design<sup>1</sup>.

For comparing resonant frequency of a design for various materials,  $(E/\rho)^{1/2}$  is the correct term and the larger the number, the higher the frequency. Beryllium and the pure SiC's clearly are superior in this category.

Use  $\rho/E$  for comparing the self weight deflection of identical geometries, or equal thickness plates, but remember that in this case, each component will have a different mass. In this case, a smaller number indicates less deflection and a stiffer material and again, Be and the SiC's have the lowest numbers.

**Table 2. Physical and mechanical properties**

Property	$\rho$ Density	E Young's modulus	$\nu$ Poisson's ratio	$K_{Ic}$ Fracture toughness	MYS Microyield strength
Units	g/cm <sup>3</sup>	GPa	-	MPa m <sup>1/2</sup>	MPa
Preferred	small	large	small	large	large
Fused Silica	2.19	72	0.17	<1.0	-
ULE	2.21	67	0.17	1.0	-
Zerodur	2.53	91	0.24	1.5	-
Al 6061-T6	2.70	68	0.33	22	240
MMC 30% SiC	2.91	117	0.29	<10	>200
Be I-70-H	1.85	287	0.043	11	30
Be I-220-H	1.85	287	0.043	12	70
Cu OFC	8.94	117	0.343	-	12
Cu Glidcop	8.84	130	0.33	-	>250
Invar 36	8.05	141	0.259	-	70
Super Invar	8.13	148	0.26	-	75
Molybdenum	10.21	324	0.293	-	280
Silicon	2.33	131	0.42	1.0	-
SiC HP alpha	3.2	455	0.14	5.2	-
SiC CVD beta	3.21	466	0.21	3.4	-
SiC RB 30% Si	2.89	330	0.24	2.5	-
C/SiC	2.65	260	0.25	6.5	-
SS 304	8.00	193	0.27	-	>300
SS 416	7.8	215	0.283	-	>300
SS 17-4PH	7.8	200	0.28	53	>300
Ti 6Al4V	4.43	114	0.31	-	>150
Electroless Ni 12%P	7.9	140	0.41	-	-
Electroplated Al	2.70	69	0.33	-	-
Gr/Ep GY70x30	1.78	93	-	-	-

Table 3. Structural figures of merit (arbitrary units)

Figure Of Merit	$(E/\rho)^{1/2}$	$\rho/E$	$\rho^3/E$	$(\rho^3/E)^{1/2}$
Compares	Resonant frequency	Deflection	Deflection	Mass
Constant	Geometry	Thickness	Mass	Deflection
Independent variable	Mass	Mass	Thickness	Thickness
Preferred	large	small	small	small
Fused Silica	5.7	3.04	1.46	1.21
ULE	5.5	3.30	1.61	1.27
Zerodur	6.0	2.78	1.78	1.33
Al 6061-T6	5.0	3.97	2.89	1.70
MMC 30% SiC	6.3	2.49	2.11	1.45
Be I-70-H	12.5	0.64	0.22	0.47
Be I-220-H	12.5	0.64	0.22	0.47
Cu OFC	3.6	7.64	61.1	7.81
Cu Glidcop	3.8	6.80	53.1	7.29
Invar 36	4.2	5.71	37.0	6.08
Super Invar	4.3	5.49	36.3	6.03
Molybdenum	5.6	3.15	32.8	5.73
Silicon	7.5	1.78	0.97	0.98
SiC HP alpha	11.9	0.70	0.72	0.85
SiC CVD beta	12.0	0.69	0.71	0.84
SiC RB 30% Si	10.7	0.88	0.73	0.86
C/SiC	9.9	1.02	0.72	0.85
SS 304	4.9	4.15	26.5	5.15
SS 416	5.2	3.63	22.1	4.70
SS 17-4PH	5.1	3.90	23.7	4.87
Ti 6Al4V	5.1	3.89	7.63	2.76
Gr/Ep GY70x30	7.2	1.91	0.61	0.78

If the mass is made equal and the thickness is independent, then  $\rho^3/E$  provides a comparison of self-weight deflections. For this case, the difference between Be and SiC is larger and Gr/Ep appears better than SiC while Si is almost as good as SiC. The comparison becomes even more favorable for Be when deflection is fixed and mass is compared using the term  $(\rho^3/E)^{1/2}$ . A Be component would have only 56% of the mass of the best SiC. A cautionary note is required here because these comparisons do not take into account the manufacturability of the various materials, i.e., how thin a wall can be fabricated.

Table 4 lists thermal properties and figures of merit for these same materials. The low expansion glasses, invars and Gr/Ep have the lowest thermal expansion, but when combined with their thermal conductivities, only the Gr/Ep is a standout performer for steady state thermal distortion. The high thermal conductivity of many metals is mitigated by their high thermal expansions. The metals with the lowest thermal distortions are the invars with the lowest expansion of the metals, Mo and Si. The SiC's, with low expansion combined with high conductivity give them exceptionally low thermal distortion, second only to the Gr/Ep.

In high flux systems with cooled mirrors, expansion is the primary parameter to avoid thermal mapping of the beam footprint. In this case invar, or better yet super invar, is the choice among metals since it can be made with thermal expansion much closer to zero than the nominal value given in the table.

But clearly, if the temperature changes, all bets are off because, as shown in Figure 1, thermal expansion and thermal conductivity change dramatically with temperature. This kind of thermal behavior is typical for all materials and points up the need for careful study of properties in designing an optical system that will operate in a thermal environment other than room temperature.

The thermal conductivity of most simple materials (not highly alloyed) increases to some maximum with decreasing temperature, but then approaches zero at absolute zero. In general, conductivity decreases with increasing temperature. Thermal expansion and specific heat also go to zero at 0 K, but Figure 1 shows that some materials like Si and fused silica have a zero crossing for thermal expansion, becoming negative at cryo temperatures. The curves also show that it can be very difficult to find a thermal expansion match between dissimilar materials over a wide temperature range. More complete properties data as a function of temperature for these and other materials are available in the literature<sup>2</sup>

Figure 2 shows the thermal expansion coefficients for a number of low expansion materials<sup>3</sup>. Note the range for the invars and the variation at cryo temperatures for the various forms of vitreous SiO<sub>2</sub>. Zerodur has been shown<sup>3-5</sup> to have a dimensional and thermal expansion change when cooled in the range of 320°C to 130°C at a rate other than the original manufacturer's annealing rate. A modified material, Zerodur M, is stable in this temperature range, but has a different expansion coefficient, as shown in the figure.

Table 4. Thermal properties and figures of merit

Property	Coefficient of Thermal Expansion	Thermal Conductivity	Specific Heat	Thermal Diffusivity	Distortion Coefficients	
					Steady State	Transient
	$\alpha$	k	$C_p$	D	$\alpha/k$	$\alpha/D$
units	$10^{-6}/K$	W/m K	W s/kg K	$10^{-6}m^2/s$	mm/W	$s/m^2 K$
preferred	small	large	large	large	small	small
Fused Silica	0.5	1.4	750	0.85	0.36	0.59
ULE	0.03	1.31	766	0.78	0.02	0.04
Zerodur	0.05	1.64	821	0.77	0.03	0.07
Al 6061-T6	22.5	167	896	69	0.13	0.33
MMC 30% SiC	12.4	123	870	57	0.10	0.22
Be I-70-H	11.4	216	1,925	57.2	0.05	0.20
Be I-220-H	11.4	216	1,925	57.2	0.05	0.20
Cu OFC	16.5	391	385	115.5	0.04	0.14
Cu Glidcop	18.4	365	380	108.7	0.05	0.17
Invar 36	1.0	10.4	515	2.6	0.10	0.38
Super Invar	0.3	10.5	515	2.5	0.03	0.12
Molybdenum	5.0	140	247	55.5	0.04	0.09
Silicon	2.6	137	710	83	0.02	0.03
SiC HP alpha	2.4	155	650	74.5	0.02	0.03
SiC CVD beta	2.2	300	733	128	0.01	0.02
SiC RB 30% Si	2.5	155	670	80	0.01	0.03
C/SiC	2.0	198	700	74.2	0.01	0.03
SS 304	14.7	16.2	500	4.1	0.91	3.68
SS 416	8.5	24.9	460	6.9	0.34	1.23
SS 17-4PH	10.4	22.2	460	6.2	0.47	1.68
Ti 6Al4V	8.8	7.3	560	2.9	1.21	3.03
Electroless Ni 12%P	14.0	5.0	-	-	2.8	-
Electroplated Al	22.7	234	900	96.3	0.10	0.24
Gr/Ep GY70x30	0.02	35.0	-	-	0.00	-

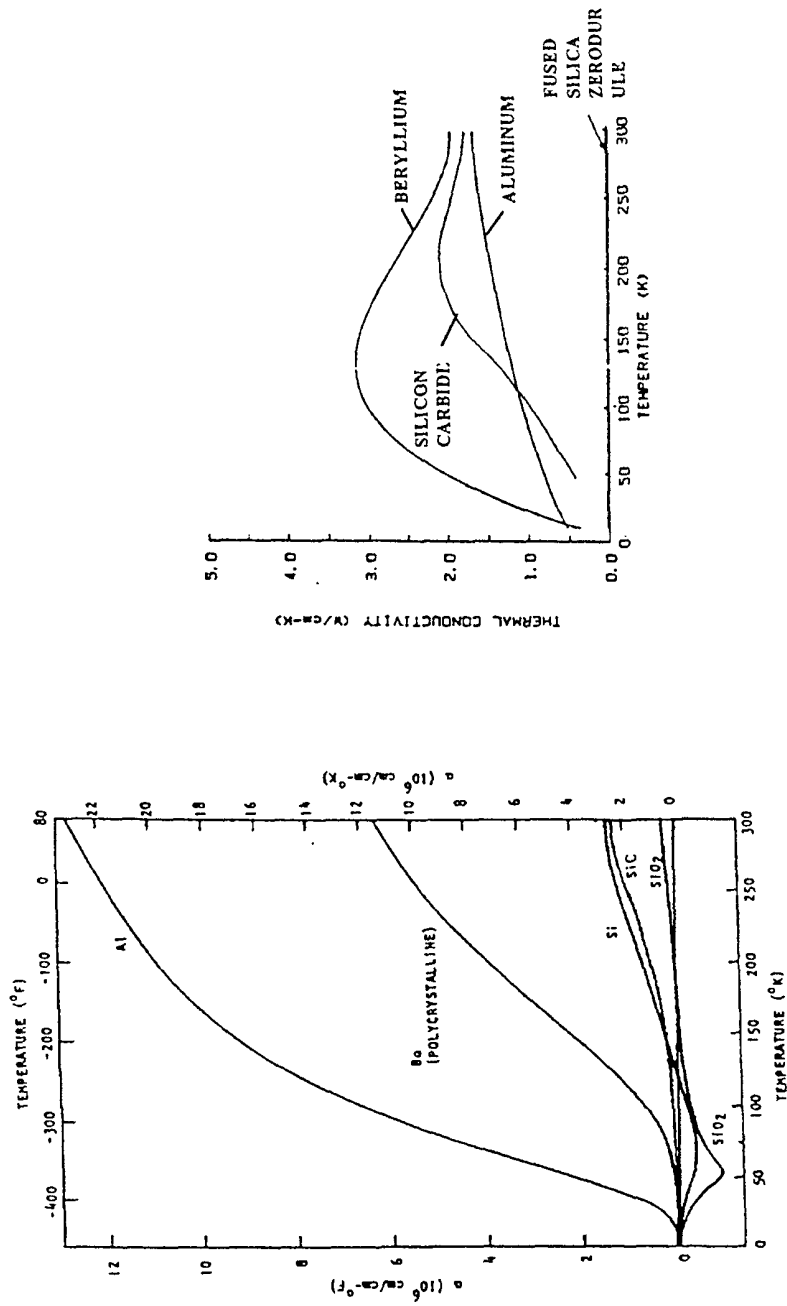


Figure 1. Temperature dependence of thermal expansion and thermal conductivity



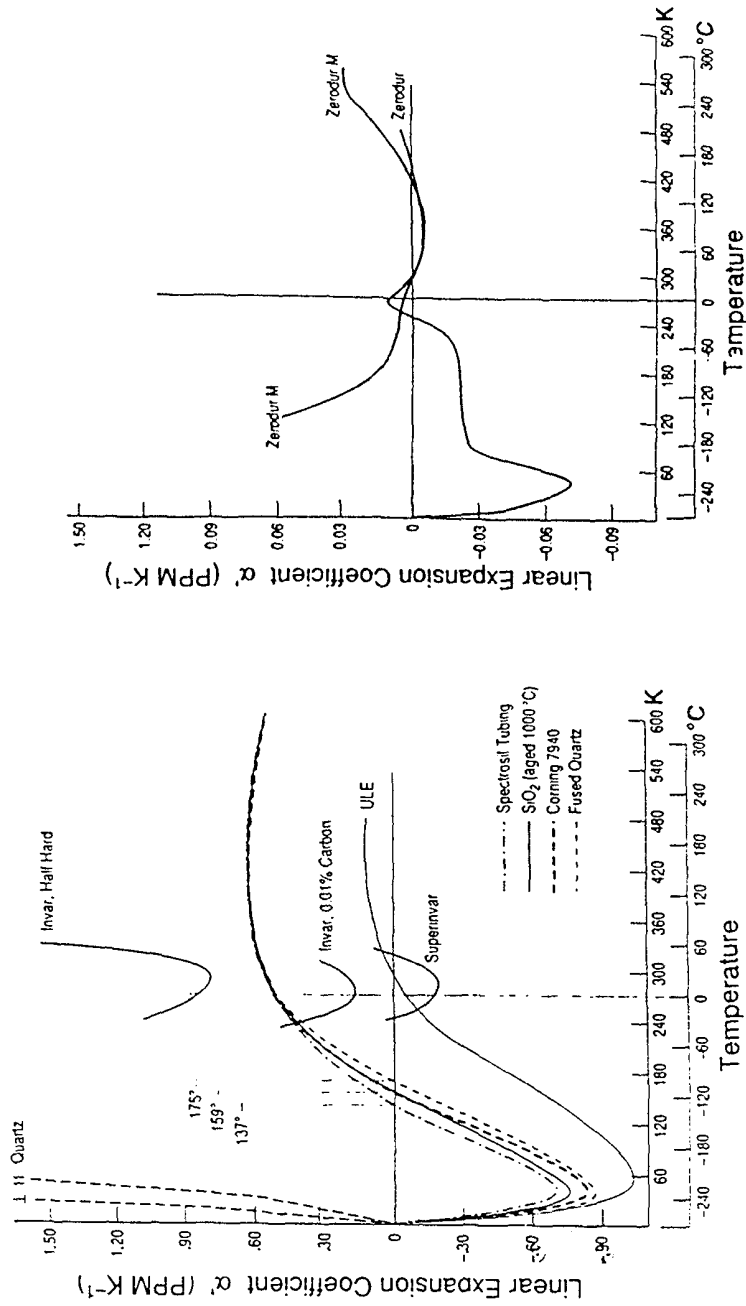
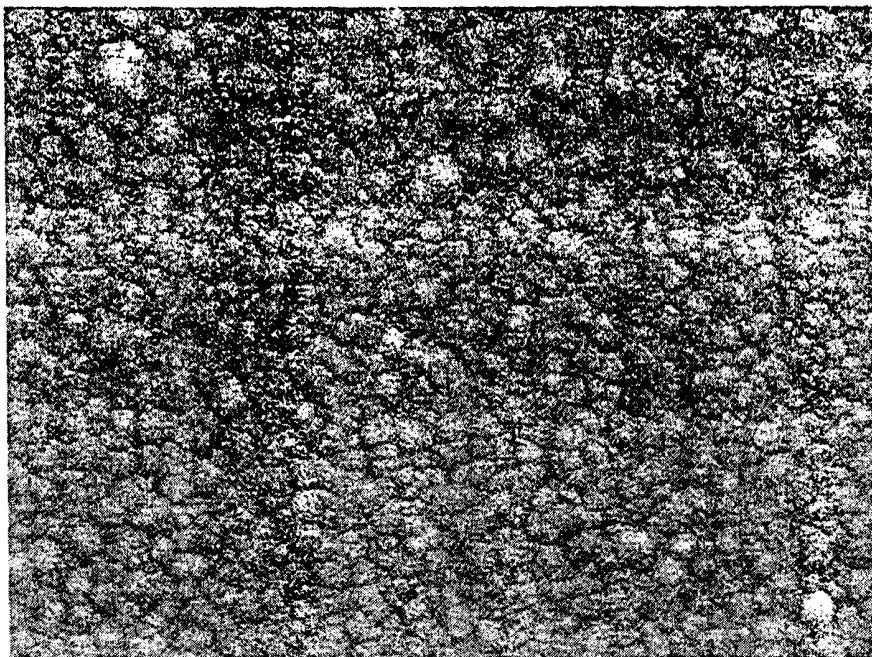


Figure 2. Temperature dependence of thermal expansion of some low expansion materials<sup>3</sup>

Two materials listed in the tables that are not covered elsewhere in these proceedings are C/SiC and electroplated Al. C/SiC is a carbon fiber reinforced SiC<sup>6</sup> produced by IABG<sup>7</sup> and DBA<sup>8</sup>. It is a quasi-ductile composite ceramic with a nominal composition of 50-60% SiC, 20-30% Si and 10-20% C. The fabrication process utilizes a starting material of short fiber, randomly oriented carbon felt that is machined to shape and infiltrated without shrinkage with pyrolytic carbon and liquid Si that partly react to form SiC. The material is fully dense, but requires a mirror surface coating/cladding of Si, SiC or glass to provide a low roughness, easily polished surface. Current facilities can produce components up to three meters in diameter.

Electrodeposited Al is now available from AlumiPlate<sup>9</sup> utilizing a newer process than that used in past years. It can be used for coating mirrors and is diamond turnable to low roughness surfaces. It can be plated on a number of materials with a very fine grain structure as shown in Figure 3. Several Al mirrors have been successfully fabricated and the potential for this new coating material is currently untapped. It may open the door to lower cost and to the possibility of utilizing new materials such as AlBeMet<sup>10</sup> for mirror applications.



**Figure 3. SEM micrograph of a 25µm thick electroplated Al coating on copper<sup>9</sup>.  
(Magnification = 1400x)**

## **2.2 Dimensional Stability**

Many aspects of materials have to be considered in addition to the properties described above. Foremost among these is the dimensional stability of the material<sup>11</sup>,

both the inherent stability of the basis material and the instabilities that can be attributed to fabrication methods. These instabilities fall in three classes:

- Temporal instability where a component changes figure and/or dimensions with time in a constant environment,
- Thermal instability where the component can be different at another temperature, but always returns to its original shape at the starting measurement conditions, and
- Thermal/mechanical cycling, or hysteresis instability where the component undergoes a permanent shape change as a result of thermal and/or mechanical loading such as repeated use at an elevated temperature or mechanical vibration.

Thermal instability in the basic material can be from one or more of the following sources:

- Inhomogeneity, the random variation of properties in the material,
- Anisotropy, the systematic, directionally preferred variation of the properties and/or
- Internal stress on a microscale between phases or grains of an anisotropic material.

These can be mitigated by careful preparation and selection of the methods used to prepare the basic material, as discussed in the next section, but once they are present in a component there is nothing that can be done to eliminate, or even reduce their effects.

The major source of instability in precision components is residual stress induced by the fabrication processes. This is the source of most temporal and hysteresis instability and this source can be minimized in the fabrication processes and further reduced to insignificance by careful and frequent stress relief processes such as chemical etching, heat treatment (annealing) and thermal cycling. Evidence of such successful processing is given in several other papers in this conference<sup>12-14</sup> as well as the open literature<sup>15-19</sup>.

The third major source of instability is the external forces applied by attachments, fabrication and use environments and/or in-process handling. By effective engineering analysis and design, along with the choice of a strong and stiff enough material, resulting moments and stresses can be minimized. It can be noted that in most cases, the in-process loads are greater than the loads applied in operation and should be considered in component as well as system design.

### 2.3 Fabrication Methods

Near-net-shape (nns) fabrication methods can be used in some form for virtually all materials. Since Be, SiC and the metal matrix composites start out as powders, they can be formed by hot pressing, usually in a vacuum (VHP), hot isostatic pressing (HIP) or as cast preforms in the case of SiC. The HIP process is preferred to VHP for Be since it provides more homogeneous and isotropic components. Lightweight, hollow components can be formed to nns through the use of soluble formers<sup>20</sup>. More recent developments at Brush Wellman<sup>21</sup> indicate that new methods for obtaining net-shape Be components are forthcoming.

For the ductile metals, forging and extrusion are two options, and most metals can be cast. Reaction bonded SiC is usually formed by casting a preform that is fired and infiltrated with Si. Higher SiC proportions are obtained by adding reactive carbon at some stage of the process that reacts with the Si to form additional SiC. Silicon contents can range from 60% to as low as 6%, although the lower Si materials are not as readily formable. The use of C/SiC allows the components to be easily machined to virtually any configuration before infiltration to obtain a net-shape component.

All of the materials can be machined from solid, but the various forms of SiC require diamond machining with relatively slow shallow cuts, so near net shape fabrication of preforms is highly recommended. Two such methods include chemical vapor deposition (CVD) of pure cubic (beta) SiC or hot pressing of nns preforms of almost pure hexagonal (alpha) SiC. Both can be very fine grained and polishable to low scatter. Machining of Be requires special equipment to collect respirable Be dust since it can be toxic if inhaled<sup>22</sup>.

Machining processes generally cause damage and residual stress in the surface of components and heavy machining forces can also impart bulk residual stresses. The stresses can be tensile or compressive depending on the machining method and are always accompanied by a change in dimensions and/or shape. The damaged material and stresses can be removed with chemical etching followed by annealing or other significant heat treatment, but be aware that the distortions will be removed in the process so that there will be a resulting shape change. Thermal cycling can be used to reduce residual stress from less damaging processes such as loose abrasive grinding (lapping) and polishing. Further discussions of residual stress, its reduction in and after fabrication and thermal cycling as stress reduction methods are contained in a number of sources<sup>11,23-27</sup> and should be consulted.

### 3. COMPARISONS AND SELECTION

The process of choosing the most appropriate materials for an optical system is complex and iterative. After first defining the end-use parameters, the materials are initially screened and suitable candidates chosen. A strawman structural design is then analyzed to narrow the materials choices and refine the design. Fabrication methods can then be considered with respect to the candidate materials, component shapes and cost and schedule. A semi-quantitative screening of room temperature properties and available forms will narrow the choices. A matrix can then be constructed showing the room and use temperature properties similar to that shown in Table 5.

In this example, three typical mirror materials are compared for use in a system with specified deflection and operating at 100 K. There are little changes in modulus or density in this temperature range for all materials and the mechanical properties of the brittle ceramic SiC also are temperature insensitive. For this example, and based strictly on the numbers in the table, a Be mirror will be 56% of the mass of a SiC mirror and 28% of the Al mirror. From a thermal performance perspective, the SiC mirror is clearly the best choice at room temperature, but at 100 K, Be and SiC are comparable. Not shown in the table are the total contractions for these materials from 300 K to 100 K, and that would clearly favor SiC. Choices would then have to be made that would depend on system parameters such as the role of weight, system performance,

MATERIALS ⇒	⇒ Temperature	6061-T6 Al		I-70-H Be		CVD SiC	
		300K	100K	300K	100K	300K	100K
Young's Modulus (GPa)		68		287		466	
Density (g/cm <sup>3</sup> )		2.70		1.85		3.21	
Mass figure of merit for equal deflection		1.70		0.47		0.84	
Fracture Strength (MPa)		310	414	410	385	595	
Microyield Strength (MPa)		240	>280	30	28	N/A	
Fracture Toughness (MPa√m)		22	-	11	-	3.4	
Thermal Expansion (ppm/K)		22.5	12.5	11.4	0.7	2.2	0.5
Thermal Conductivity (W/m K)		167	213	216	268	300	179
Specific Heat (W s/g K)		0.90	0.48	1.92	0.18	0.73	0.23
Thermal Diffusivity (cm <sup>2</sup> /s)		0.69	1.64	0.57	8.05	1.28	2.42
Steady State Distortion (μm/W)		0.13	0.06	0.05	0.003	0.01	0.003
Transient Distortion (s/m <sup>2</sup> K)		0.33	0.08	0.20	0.001	0.02	0.002

Table 5. Comparison of three mirror materials at 300K and 100K showing the great differences in properties and figures of merit at the two temperatures.

of the system design with respect to fabricability of each material, cost and schedule. This process is also complicated by the fact that there are multiple choices for each material that would affect the numbers in the table. If MYS were critical, I-220-H might have been chosen over I-70-H Be. If mirror design is too complex to be formed in CVD SiC, C/SiC or RB SiC might have been chosen. These changes could easily change the ultimate material choice.

The process is then iterated to refine the design and compare the short list of materials and their ability to meet end-use parameters. Detailed tradeoffs can then be performed to determine the optimum combination of design, material and fabrication processes that cost-effectively meet the end use parameters with an acceptable schedule.

#### 4. CONCLUSIONS

Selection of materials for optical systems is a complex and iterative process. It requires a logical selection process that incorporates as a minimum the following sequence of steps:

- Determine end-use parameters and a strawman system design,
- Screen materials by properties, eliminating unsuitable ones
- Perform detailed tradeoffs to determine optimum material/fabrication process combinations. And
- Iterate the preceding steps to arrive a final design and suitable materials.

The material choices are vast, but unsuitable ones can usually be eliminated leaving a few families of candidate materials. When performance goals at the system operating environment are taken into account, some other materials may also be eliminated. Use of the correct property values is critical to the successful performance of the particular system design. While property data at room temperature are readily available, those at higher and lower temperatures are not as readily available but must be obtained if critical performance goals are to be achieved.

Once the system is designed and materials chosen, fabrication methods must be chosen to minimize dimensional instability to provide a stable system that meets requirements in the environment for the predicted lifetime of the system.

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