Nachiket Kulkarni

Review of a paper

Paper title

“Advanced materials: an overview”

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ABSTRACT

Selecting an optimal material such that it can stay stable in the specified environment is a complicated and iterative method. Using of a wrong material may lead to the damage in the component or a system. This paper gives an overview of various factors to be considered to select a suitable material.

INTRODUCTION

There is wide range of materials used to fabricate optical and structural components varying from metals to alloys to non-metals. The selection must be based on a how stable the material is because they tend to fail if improperly fabricated.

The selection of material depends on various factors like optical requirement, mechanical constraints, cost, material properties, etc. It is hard to choose an optimal material and the selection process consists of

- Define parameters and specification
- Reject unsuitable materials
- Analyze strawman design
- Compare the material with respect to manufacturability and ability to meet requirements
- Perform detailed tradeoffs and iterate design to determine optimal material

This paper discusses and compares the material choices

MATERIALS

Properties and figures of merit

This section explains about primary properties to be considered while selecting a material. Material properties can be classified as physical, mechanical, thermal, optical, and crystallographic and certain aspects of fabricability. The most important factor to be considered is that these properties change with temperature.

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/dσ	Temperatures:	
Ductility	Specific heat		Softening	
Poisson's ratio	Thermal diffusivity		Annealing	
	Melting point		Stress relief	
			Recr'lization	

Figure 1: Properties considered during design of an optical system

Figure 1 shows various properties important in design of optical systems. The most common figure of merit to examine the mechanical property of the material is the specific stiffness.

Some of the figure of merits are $E/\rho^{1/2}$, $(E/\rho)^{-1}$, $\frac{\rho^3}{E}$ and $(\frac{\rho^3}{E})^{1/2}$. For comparing the resonant frequency, $E/\rho^{1/2}$ is used. More the value of the ratio, higher the frequency. $\frac{\rho}{E}$ is used for comparing the self-weight of identical geometries, Since different materials have different masses, smaller number means less deflection and stiffer the material is. Some of the material high a high value of these ratio is Be and SiC. In case of the mass being constant, $\frac{\rho^3}{E}$ provides self-weight deflection. Gr/Ep has a higher value and is better than SiC. The materials can be compared by mass when the deflection is constant using $(\frac{\rho^3}{E})^{1/2}$. This comparison doesn't account for manufacturability.

Two most important factors to examine thermal factors are thermal expansion and thermal conductivity. Most of the glasses, invars and Gr/Ep have low thermal expansion but only Gr/Ep are having stable steady state thermal distortion. The high thermal conductivity of many metals is mitigated by their high thermal expansion. The metals with lowest thermal distortions are invars with lowest expansion of metal, Mo and Si.

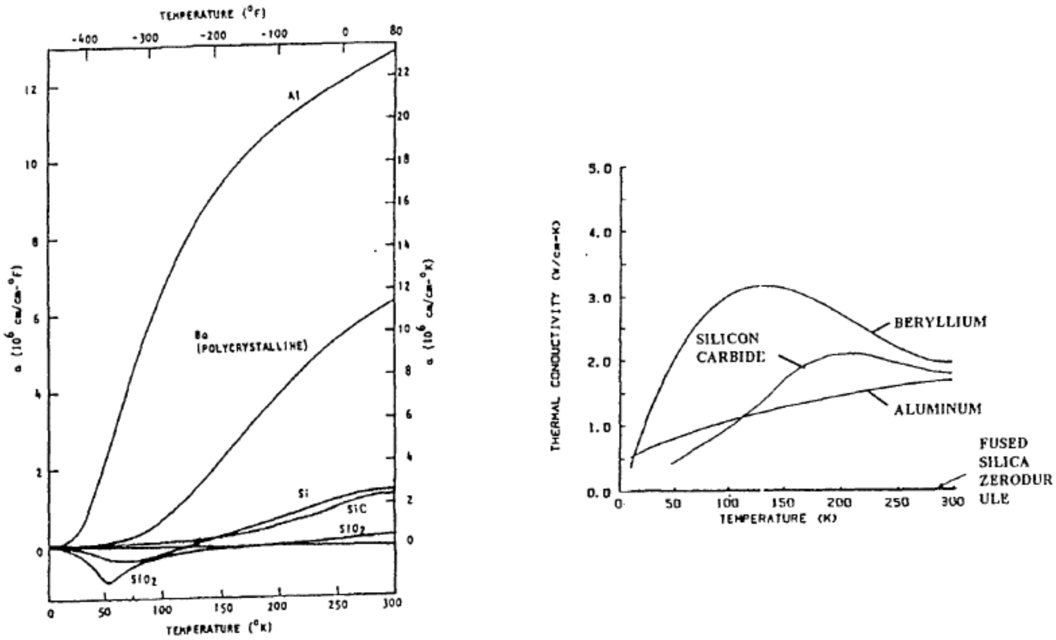

Figure 2: Temperature dependence of thermal expansion(Left) and thermal conductivity(Right)

Thermal conductivity and thermal expansion change with temperature. Figure 2 shows behavior how conductivity and expansion coefficient changes with temperature. The thermal conductivity of simple material increase to some maximum with decreasing temperature, but reaches 0 at absolute zero. Figure 1 also shows the expansion coefficient is 0 at absolute zero. It increase with temperature usually, but materials like Si and fused silica have second zero crossing at cyro-temperature. Since the change of expansion with temperature is not uniform, it is very hard to find an expansion match between dissimilar material.

Dimensional Stability

Materials change their properties because of various reasons and hence unstable. Henceforth, materials should be chosen in such a way that they are dimensionally stable with the specific change in environment. These instabilities may be due to temporal instability (change in dimension with time), thermal instability(change because of change in thermal conditions) and hysteresis instability(permanent set because of repeated loading).

The major reason for instability is inhomogeneity in the material, anisotropy where the properties vary with the direction, external forces applied and induced internal stresses. The internal stresses can be minimized using fabrication process and further reduced using thermal and non-thermal methods. Thermal methods include annealing and cryogenic stress relief method (material places in liquid nitrogen) whereas non-thermal or mechanical methods include peening. The secondary reason for the instability is the external forces. These can be controlled by effective engineering.

Fabrication Method

Near net shape (NNS)fabrication methods can be used for all materials. For the material in form of powder, hot pressing is used to fabricate. Usually pressing is in vacuum or in heated environments or using cast preforms for materials like SiC. The fabrication method for hot isostatic pressing are preferable because they provide homogenous and isotropic components. Power metallurgy is another method used to fabricate powder components.

Forging, extrusion and casting are methods used to fabricate ductile materials. Forging is where the heated metal is hit to give a specific shape. Extrusion is a process used to create objects of a fixed cross-sectional profile. A material is pushed through a die of the desired cross-section. Casting is a process where an object made by pouring molten metal or other material into a mold. Additives are added to material to enhance specific mechanical, physical or thermal property.

All the materials can be machined from solid, but in case of materials like SiC, diamond machining is tough because it creates slow shallow cuts. So NNS methods like chemical vapor deposition or hot pressing is used which provide fine grain structure and polishable. Materials are heat treated or chemically etched to remove residual stresses in the fabricated part.

COMPARISON AND SELECTION

Process of choosing a material suitable for designing an optical system is complex. Firstly, parameters and specification are defined. An example is explained which gives an outline of how material is selected. For example, three mirror material are compared for use in a system of specified deflection and that can operate at 100K. The materials are mentioned in table 3. The physical properties like modulus or density are constant. Comparing the masses by comparing denser, a Be mirror is 56% of SiC mirror and 28% of Al mirror. Considering thermal properties, SiC mirror is best in the room temperature, but at 100K, Be and SiC are comparable. Now once the thermal properties are examined, choices are made based on the system parameters like cost, schedule, weight, fabricability, etc.

This process is also complicated by the fact that there are multiple choices for each material that would affect number in table. If microyield strength was important, I-220-H might have been chosen overI-70-H Be. If mirror design is complex, then the C/SiC would have been a better choice over CVD-SiC.

MATERIALS ⇒		6061-T6 Al		I-70-H Be		CVD SiC	
PROPERTIES ⇒	Temperature	300K	100K	300K	100K	300K	100K
Young's Modulus	(GPa)	68		287		466	
Density	(g/cm^3)	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	($MPa\sqrt{m}$)	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^2/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^2 K)	0.33	0.08	0.20	0.001	0.02	0.002

Figure 3:Comparison of three material at 300K and 100K with difference in properties

CONCLUSION

This report consists of various factor to be considered to select a material properly. It doesn't give an exact method, but describes the factors that must be considered.

It is a complex method to select a material that could satisfy the requirement. Summarizing the paper, the selection process of the material includes determining requirement, strawman analysis, screening materials, performing detailed tradeoffs and iterate preceding steps to arrive a final design and suitable material. Choice of material is cast but unsuitable ones are eliminated leaving a very few in the list. Few more are eliminated, when performance goals are considered. Correct property values must be used for successful performance analysis.

Once material is widely used, fabrication methods must be chosen to minimize dimensional stability to provide stability in the system.

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