Unified Engineering

Lecture M21 12/2/2003

Materials Selection
Objective

• Aim to provide coherent overview of material selection
  – Materials (and structural configurations and processes) should be selected for applications based on measurable criteria
Key Ideas

• It is possible to compare the suitability of materials for a given application according to quantifiable performance metrics based on material properties
  – Properties (such as Young’s modulus, density, strength) quantify material performance

• Some materials properties are more invariant than others
  – Role of scale, role of manufacturing, microstructure
  – Fiber composite allow flexibility
  – Important to know what you can change - or not!
Central Problem - Interaction of Function, Material, Process and Shape

Function
Transmits loads, heat
resonates, contains pressure
stores energy etc.
At minimum weight, cost, size,
or maximum efficiency,
safety etc.
(rest of Unified)

Material

Shape

Process
References

- Ashby and Jones, Engineering Materials I, Chapter 6
- Design of a structural element is specified by three parameters, or groups of parameters (performance indices):
  - Functional requirements (F), Geometry (G) and Material Properties (M)
- We can quantify the interdependence if we can specify performance, \( p \), as a function of F, G and M:
  \[ p = f(F, G, M) \]
- We can simplify further if the three groups of parameters are separable, i.e:
  \[ p = f_1(F) \cdot f_2(G) \cdot f_3(M) \]
Ex: Lightweight stiff rod - tensile load

Material, modulus E, density $\rho$ - note these are a property of the material, and cannot be independently selected

- Mass of rod given by
  \[ m = \rho AL \]

- Stiffness of rod, given by
  \[ k = \frac{P}{\delta} = \frac{AE}{L} \]

- Combining, by eliminating free variable, A:
  \[ m = \frac{kL^2 \rho}{E} = k \cdot L^2 \cdot \frac{\rho}{E} \]

Choose material with low $\rho/E$ ratio!!!
MATERIAL SELECTION FOR A MICROMECHANICAL RESONATOR

Fatigue test device
(Courtesy of Stuart Brown. Used with permission.)
Example 2 - High f Beam Resonator

\[ \delta = A_0 \sin \omega t \]

\[ L \]

Material, modulus \( E \), density \( \rho \)

\[ I = \frac{\pi r^4}{4} \]

- **Natural (resonant) frequency, \( f \)**

\[
f \propto \sqrt{\frac{EI}{ML^3}} \Rightarrow \beta_1 \sqrt{\frac{Er^2}{\rho L^4}} = \beta_2 \sqrt{\frac{E}{\rho}} \cdot \frac{r}{L^2} \quad \beta_n = f(B.C \ s)
\]

- For high frequency resonator select high \( E/\rho \)

- Note frequency \( f \propto \frac{1}{L} \) for given \( \frac{r}{L} \) implies scale effect

*Choose material with low \( \rho/E \) ratio,*

*MEMS allow high frequencies*
MODULUS - DENSITY RATIOS OF SOME MEMS MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, $\rho$, Kg/m$^3$</th>
<th>Modulus, E, GPa</th>
<th>$E/\rho$ GN/kg-m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon</td>
<td>2330</td>
<td>165</td>
<td>72</td>
</tr>
<tr>
<td>Silicon Oxide</td>
<td>2200</td>
<td>73</td>
<td>36</td>
</tr>
<tr>
<td>Silicon Nitride</td>
<td>3300</td>
<td>304</td>
<td>92</td>
</tr>
<tr>
<td>Nickel</td>
<td>8900</td>
<td>207</td>
<td>23</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2710</td>
<td>69</td>
<td>25</td>
</tr>
<tr>
<td>Aluminum Oxide</td>
<td>3970</td>
<td>393</td>
<td>99</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>3300</td>
<td>430</td>
<td>130</td>
</tr>
<tr>
<td>Diamond</td>
<td>3510</td>
<td>1035</td>
<td>295</td>
</tr>
</tbody>
</table>

*Silicon performs well, diamond, SiC and SiN significantly better*
The elastic deflection of a telescope mirror (shown as a flat disc), under its own weight.
(Adapted from Ashby.)

\[
d \approx \frac{0.67}{\pi} \frac{mg a^2}{Et^3}
\]

\[
m = \pi a^2 t \rho
\]

\[
m = \left( \frac{0.67/g}{\delta} \right)^{1/2} \pi a^4 \left( \frac{\rho^3}{E} \right)^{1/2}
\]

\[
M = \frac{\rho^3}{E}
\]
Example 3 - Telescope Mirror

- Choose materials with high

\[ M = \frac{\rho^3}{E} \]

The distortion of the mirror under its own weight can be corrected by applying forces to the back surface. (Adapted from Ashby.)
Note contours of equal performance
STRENGTH-MODULUS PROPERTY MAP

Might also want
Deflection at
minimum force -
polymers would
appear more
attractive
STRENGTH-DENSITY MAP

Ashby
CTE-THERMAL CONDUCTIVITY

[Diagram of CTE and thermal conductivity with various materials plotted across the graph.]
CTE-MODULUS MAP

Determines thermal stress, thermal buckling limits for thin tethers,
also
Feasibility of thermal actuation

Ashby
SUMMARY

- Aimed to provide coherent overview of material selection
  - Materials (and structural configurations and processes) should be selected for applications based on measurable criteria
  - Often combinations of material properties
- Material properties group according to class of material
  - Metal, ceramic, polymers
  - Engineered materials (composites, foams)
  - Natural materials (wood, bone, etc)