MATERIALS SELECTION

- ME 481 Senior Design I
- Fall 2020
Why Should I Care?

- The designer of any product, other than software must get involved with material selection.
- Only occasionally will the exact grade of material be specified by the customer.
- Even then the designer must understand the material to be able to design the product.
- Material selection is critical part of almost all engineering designs.

ME 481 Fall 2020 – Mehrdad Nejhad, Trevor Sorensen, Zac Trimble, Z-Song, Bardia Konh
Why Should I Care? (Cont.)

- Not stiff enough (need bigger $E$)  
  
  Young’s modulus

- Not strong enough (need bigger $\sigma_y$)

  Yield strength

- Not tough enough (need bigger $K_{ic}$)

  Fracture toughness

- Too heavy (need lower $\rho$)

  Density

All OK!

Why Should I Care? - Evolution of Materials

DATE

10000BC 5000BC 0 1000 1500 1800 1900 1940 1960 1980 2000 2010 2020

Polymers & elastomers
- Gold
- Copper
- Bronze
- Iron
- Cast Iron
- Steels
- Alloy Steels
- Light Alloys
- Super Alloys
- Titanium
- Zirconium
- etc.

Composites
- Straw-Brick
- Paper
- Glass
- Bakelite
- PE
- PMMA
- Acrylics
- Epoxies
- Compounds

Ceramics & glasses
- Stone
- Flint
- Pottery
- Refractories
- Portland Cement
- Fused Silica
- Cermets
- Pyro-Ceramics

Metals
- Development Slow:
  - Mostly Quality
  - Control and Processing

Glassy Metals
- Al-Lithium Alloys
- Dual Phase Steels
- Microalloyed Steels
- New Super Alloys

High Temperature Polymers
- High Modulus Polymers
- Ceramic Composites
- Metal-Matrix Composites
- FRP
- C/C

Tough Engineering Ceramics
- Al₂O₃, Si₃N₄, PSZ etc.
Role of Materials Selection in Design

- Materials selection is a key step for a successful design
- A large number of materials to select from
- Discovery of new and advanced materials

Function
- Mechanical Properties
- Failure Mode
- Manufacturability
- Cost
- Environmental Considerations

- An ability to select materials that best meet requirements of a design
- Access to information and tools for comparison and selection
~ 40,000 Metallic alloys
~ 40,000 nonmetallic engineering materials

- Improper choice of materials can lead to:
  1. Short service life
  2. Higher cost

- Material selection should be based on:
  1. Property requirements
  2. Material processing

The Material Selection Process

1. Analysis of the materials requirements; determine the condition of service and environment.
2. Identification and screening of alternative materials; use Concept Evaluation Matrix or Decision Matrix (use lower or upper limits to eliminate some).
3. Selection of the BEST candidate; use iterations.
4. Development of design data; determine the key material properties for the critical service condition(s).
Introduction & Background

Introduction & Background

* Economics of Materials:

> Material selection process comes down to a trade-off between performance and cost.

- A high performance is needed in aerospace and defense industry (with minimum cost).
- A low cost product is needed for household appliances (with maximum performance).

## Introduction & Background

### Property characteristics of material classes

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<tr>
<th>Metals</th>
<th>Ceramics</th>
<th>Polymers</th>
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<td>High thermal conductivity</td>
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<td>Temperature sensitive</td>
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### Introduction & Background

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<tr>
<th>Failure mode</th>
<th>Ultimate tensile strength</th>
<th>Yield strength</th>
<th>Compressive yield strength</th>
<th>Shear yield strength</th>
<th>Fatigue properties</th>
<th>Ductility</th>
<th>Impact energy</th>
<th>Transition temperature</th>
<th>Modulus of elasticity</th>
<th>Creep rate</th>
<th>$K_I$</th>
<th>$K_{ISCC}$</th>
<th>Electrochemical potential</th>
<th>Hardness</th>
<th>Coefficient of expansion</th>
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*Shaded block at intersection of material property and failure mode indicates that a particular material property is influential in controlling a particular failure mode.*

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### Material performance characteristics

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Mechanical properties</th>
<th>Thermal properties</th>
<th>Chemical properties</th>
<th>Fabrication properties</th>
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<td>Crystal structure</td>
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<td>Conductivity</td>
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<td>Tension</td>
<td>Coef. of expansion</td>
<td>Corrosion and degradation</td>
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Where Do I Start?

- **Textbooks**
  - Good for general information
  - Some have tables of properties
  - Not good for detailed specifications and properties
  - A useful first point of call

- **Databooks** (e.g., ASM’s Books on Metals)
  - One of the quickest sources of detailed information
  - Usually contain grades and specifications as well as properties
  - Small and perfectly formed – pocketbooks
  - Easy to navigate around

- **Manufacturer’s literature**
  - Variable in quality and usefulness
  - Often only cover their products
  - Usually do not compare materials
  - Can be biased
  - Good for final selection before ordering

- **Internet Sites**
  - Can be a real minefield
  - Lots of poorly presented information
  - Google searches bring up lots of rubbish
  - Hard to find technical information
  - Best to use non-commercial sites

Outline
- Material property
- Material selection
- Sustainability
Material Properties

Physical
- Density
- Melting point
- Vapor pressure
- Viscosity
- Porosity
- Permeability
- Reflectivity
- Transparency
- Optical properties
- Dimensional stability

Chemical
- Corrosion
- Oxidation
- Thermal stability
- Biological stability
- Stress Corrosion
- ....

Electrical
- Conductivity
- Dielectric constant
- Coersive force
- Hysteresis

Thermal
- Conductivity
- Specific Heat
- Thermal expansion
- Emissivity

Mechanical
- Hardness
- Elastic constants
- Yield strength
- Ultimate strength
- Fatigue
- Fracture Toughness
- Creep
- Damping
- Wear resistance
- Spalling
- Ballistic performance
- .......

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Material Selection Process

“The interaction between function, material, shape and process lies at the heart of the material selection process.”

-- M. Ashby

Ashby Methodology

- **Translation**: Express design requirements as objectives & constraints
- **Screening**: Eliminate materials that cannot do the job
- **Ranking**: Find the materials that do the job best
- **Supporting information**: Explore pedigrees of top-ranked candidates
“Express design requirements as objectives and constraints”

Using design requirements, analyze four items:

1. **Function**: What does the component do?
2. **Objective**: What essential conditions must be met?
3. **Constraints**: What is to be maximized or minimized?
4. **Free variables**: Which design variables are free?
Translation Example – Light Strong Tie

1. Function: Support a tension load
2. Objective: **Minimize mass** \( m = A L \rho \Rightarrow A = m / L \rho \)
3. Constraints: Length specified, Carry load \( F \), w/o failure: \( F / A < \sigma_y \)
4. Free variables: Cross-section area, Material:

\[
F / A = F L \rho / m < \sigma_y \\
\Rightarrow \quad m \geq (F)(L) \left( \frac{\rho}{\sigma_y} \right)
\]

OR Maximize Material Index \( \left( \frac{\sigma_y}{\rho} \right) \)

Adapted from J. Gregory and R. Kirchain
Translation Example – Heat Sink for Power Electronics

1. **Function:** Heat Sink
2. **Objective:** Maximize heat transfer
3. **Constraints:**
   - Max service temp: $T > 200 \, ^\circ C$
   - Electrical insulator: $R > 10^{20} \mu \Omega \, cm$
   - Thermal conduct: $\lambda > 100 \frac{W}{m \, K}$
   - Not heavy: $\rho < 3,000 \frac{kg}{m^3}$
4. **Free variables:** Material and some Geometry
Material Selection Process – Screening

“Eliminate materials that cannot do the job”

Need effective way of evaluating large range of material classes and properties

Bar Chart for Single Property Screening

Material Property Chart for Double Property Screening

Adapted from J. Gregory and R. Kirchain
Screening Example – Heat Sink for Power Electronics

- Translation
- Screening
- Ranking
- Supporting information

Max service temp > 200°C

Adapted from J. Gregory and R. Kirchain
Screening Example – Heat Sink for Power Electronics

- Electrical insulator: \( R > 10^{20} \mu \Omega \text{ cm} \)
- Thermal conduct: T-conduct. \( \lambda > 100 \text{ W/m K} \)

Adapted from J. Gregory and R. Kirchain
“Find the materials that do the job best”
What if multiple materials are selected after screening?
Which one is best?
What if there are multiple material parameters for evaluation?

Use Material Index

Adapted from J. Gregory and R. Kirchain
Ranking Example – Overhead Transmission Cable

**1. Function:** Transmit electricity

**2. Objective:**

Minimize electrical resistance

**1. Constraints:**

- Length L and section A are specified
- Must not fail under wind or ice-load → Required tensile strength > 80 MPa

**2. Free variables:** Material

| Screen on strength, Rank on resistivity |

Adapted from J. Gregory and R. Kirchain

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https://eeguides.blogspot.com
Screening on strength eliminates polymers, some ceramics

Ranking on resistivity selects Al and Cu alloys

Adapted from J. Gregory and R. Kirchain
Material Selection Process – Supporting Information

Young's modulus

http://www-materials.eng.cam.ac.uk/mpsite/properties/default.html
Strength and Specific Strength

http://www-materials.eng.cam.ac.uk/mpsite/properties/default.html
Material Selection Process – Supporting Information

Toughness

http://www-materials.eng.cam.ac.uk/mpsite/properties/default.html
Material Selection Process – Supporting Information

Translation  Screening  Ranking  Supporting Information

Elongation

http://www-materials.eng.cam.ac.uk/mpsite/properties/default.html
Material Selection Process – Supporting Information

Density

http://www-materials.eng.cam.ac.uk/mpsite/properties/default.html
Material Selection Process – Supporting Information

Maximum Service Temperature

http://www-materials.eng.cam.ac.uk/mpsite/properties/default.html
Materials Selection by Material Index
Recall tensile load example:
Tension load, strength limited

- Maximize material index:
  \[ M = \frac{\sigma}{\rho} \]
- In log space:
  \[ \log \sigma = \log \rho + \log M \]
- This is a set of lines with slope = 1
- Materials above line are candidates

Adapted from J. Gregory and R. Kirchain
Optimize Materials Selection Using Material Index

Optimize Matyerials Selection Using Material Index

Material Indices & Property Charts

Stiffness

Example:
Stiff beam
- Maximize: $M = E^{1/2}/\rho$
- In log space:
  $\log E = 2 (\log \rho + \log M)$
- This is a set of lines with slope=2
- Candidates change with objective

Adapted from J. Gregory and R. Kirchain
Optimize Materials Selection Using Material Index

Optimize Materials Selection Using Material Index

Adapted from J. Gregory and R. Kirchain

Adapted from J. Gregory and R. Kirchain
Specific Strength $\frac{\sigma_y}{\rho}$

Specific Stiffness $\frac{E}{\rho}$
Sustainable Engineering
Sustainability means developing engineering products and manufacturing processes that do NOT consume irreplaceable/recyclable resources. -- ASME

Ways to go Green:
- Recyclable materials (e.g., aluminum, steel, rubber, thermoplastics)
- High-yielding biomaterials (e.g., bamboo)
- Non-toxic materials and processes

Additional Resource:
- Autodesk Sustainability Workshop
  (https://www.autodesk.com/sustainability/sustainable-design-education)

Adapted from Dr. Chad Ulven
Material affects design based on
  - Geometric specifics
  - Loading requirements
  - Design constraints
  - Performance objective
  - Environmental conditions

Effects can be assessed analytically
Keep candidate set large as long as is feasible
Materials charts give quick overview; software can be used to more accurately find options (e.g., Granta)
Resources for Materials Properties Data-base: “MATDAT.com” or “MATWEB.com” etc.
Finally remember that strategic considerations can alter best choice