Models and Materials Program:
A Brief Introduction to
Materials Science and Engineering

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History of Materials Science & Engineering

- materials closely connected our culture
- the development and advancement of societies are dependent on the available materials and their use
- early civilizations designated by level of materials development

![Diagram of materials timeline]

- initially natural materials
- develop techniques to produce materials with superior qualities (heat treatments and addition of other substances)

MATERIALS SELECTION!
Materials Science and Engineering

- **structure**
  - arrangement of internal components
  - subatomic
  - atomic
  - microscopic
  - macroscopic (bulk)

- **properties**
  - material characteristic
  - response to external stimulus
  - mechanical, electrical, thermal, magnetic, optical, deteriorative

- **performance**
  - behavior in a particular application

- **processing**
  - method of preparing material

- **characterization**
  - structure

July 24, 2007
Models & Materials
Classification of Materials

Metals
- good conductors of electricity and heat
- lustrous appearance
- susceptible to corrosion
- strong, but deformable

Ceramics & Glasses
- thermally and electrically insulating
- resistant to high temperatures and harsh environments
- hard, but brittle

Polymers
- very large molecules
- low density, low weight
- maybe extremely flexible

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Classification of Materials: A Few Additional Categories

**Biomaterials**
- implanted in human body
- compatible with body tissues

**Semiconductors**
- electrical properties between conductors and insulators
- electrical properties can be precisely controlled

**Composites**
- consist of more than one material type
- designed to display a combination of properties of each component

- hip replacement
- Intel Pentium 4
- fiberglass surfboards
Why study materials?

- applied scientists or engineers must make material choices
- materials selection
  - in-service performance
  - deterioration
  - economics

BUT…really, everyone makes material choices!

aluminum  |  glass  |  plastic
Choice of Medium

medium: wood
“Wood is a natural material that ties the indoors to the outdoors when it is used...A project is a creative 3 dimensional design process...You don't need a huge shop space or heavy duty metal working machine tools.”
– George J. Haberer

medium: pastels
“I love this rather dirty, dusty medium. Most important factor is that I keep the work behind my bedroom door and in the trunk of my car. Where could I have put all the canvases???”
– Jacqueline M. Haberer
structure

processing

performance

properties
Levels of Structure

STRUCTURE (length scale)

Sub-atomic

< 0.2 nm
**Metals**

**Metallic Bond**
- one, two, or three valence electrons
- valence electrons free to drift through the entire material forming a “sea of electrons” surrounding net positive ionic cores
- non-directional bond

**Properties**
- good conductors of electricity and heat
- lustrous appearance
- susceptible to corrosion
- strong, but deformable
Ceramics and Glasses

Ionic Bond
- composed of metallic and non-metallic elements
- metallic elements give up valence electrons to non-metallic elements
- all atoms have filled “inert gas” configuration
- ionic solid
- non-directional bond

Coulombic bonding force

Ceramics & Glasses
- thermally and electrically insulating
- resistant to high temperatures and harsh environments
- hard, but brittle
Polymers

Covalent Bond
- electrons are shared between adjacent atoms, each contributing at least one electron
- shared electrons belong to both atoms
- directional bond

Polymers
- very large molecules
- low density, light weight materials
- maybe extremely flexible
Levels of Structure

STRUCTURE (length scale)

Sub-atomic
< 0.2 nm
1 nm = ?

Atomic
0.2-10 nm
Atomic Arrangement: Ordered vs. Disordered

Crystalline:
atoms are arranged in a 3D, periodic array giving the material “long range order”

- stacking can effect properties (i.e. ductility)
- anisotropic materials

Non-crystalline or amorphous:
atoms only have short-range, nearest neighbor order

- viscous materials (generally complex formulas) or rapid cooling
- isotropic materials
Levels of Structure

**STRUCTURE** (length scale)

- **Sub-atomic**: < 0.2 nm
  - 1 nm = ?
- **Atomic**: 0.2-10 nm
- **Microscopic**: 1-1000 μm
Microstructure

Single Crystal
- the periodic arrangement of atoms extends throughout the entire sample
- difficult to grow, environment must be tightly controlled
- anisotropic materials

Polycrystalline
- many small crystals or grains
- small crystals misoriented with respect to one another
- several crystals are initiated and grow towards each other
- anisotropic or isotropic materials
Levels of Structure

STRUCTURE (length scale)

Sub-atomic
< 0.2 nm
1 nm = ?

Atomic
0.2-10 nm

Microscopic
1-1000 μm

Bulk
> 1 mm
**Bulk Properties**

**Mechanical:**
- elastic modulus
- shear modulus
- hardness

**Electrical:**
- conductivity
- resistivity
- capacitance

**Optical:**
- reflectivity
- absorbance
- emission

**Thermal:**
- thermal expansion
- heat capacity
- thermal conductivity
In actuality, crystals are NOT perfect. There are defects! In metals, strength is determined by how easily defects can move!
Aluminum Oxide ($\text{Al}_2\text{O}_3$)

- Single-crystal (transparent)
- Polycrystalline, fully dense (translucent)
- Polycrystalline, 5% porosity (opaque)
Optical Microscopy

- light is used to study the microstructure
- opaque materials use reflected light, where as transparent materials can use reflected or transmitted light
Electron Microscopy

- beams of electrons are used for imaging
- electrons are accelerated across large voltages
- a high velocity electron has a wavelength of about 0.003 nm
- the electron beam is focused and images are formed using magnetic lenses
- reflection and transmission imaging are both possible

**Scanning Electron Microscopy (SEM)**
- an electron beam scans the surface and the reflected (backscattered) electrons are collected
- sample must be electrically conductive
- material surface is observed
- 200,000x magnification possible

**Transmission Electron Microscopy (TEM)**
- an electron beam passes through the material
- thin samples
- details of internal microstructure observed
- 1,000,000x magnification possible
Scanning Probe Microscopy (SPM)

- 3D topographical map of material surface
- probe brought into close proximity of material surface
- probe rastered across the surface experiencing deflection in response to interactions with the material surface
- useful with many different types of materials

Animation of SPM on epitaxial silicon.

SPM image of a butterfly wing.

SPM image of silica coated gold nanoparticles.

SPM image of 70 nm photoresist lines.
**X-ray Diffraction**

- x-rays are a form of light that has high energy and short wavelength
- when x-rays strike a material a portion of them are scattered in all directions
- if the atoms in the material is crystalline or well-ordered constructive interference can order

\[ 2d \sin \theta = n\lambda \]  

\[ \text{Bragg's Law} \]
Clay

- aluminosilicate: combination of alumina (Al$_2$O$_3$) and silica (SiO$_2$) that bind water
- melting temperature of alumina > silica
- layered crystalline structure: kaolinite (Al$_2$Si$_2$O$_5$(OH)$_4$)
- water fits between layers
- “clay” has three main ingredients:
  1. clay
  2. quartz (cheap filler material)
  3. flux (lowers melting temperature)

Forming:
- hydroplastic forming
- slipcasting

Drying:
- shrinkage
- material becomes brittle
Clay (cont.)

Firing:
- firing temperature, 900-1400°C (1650-2550°F)
- permanent physical and chemical changes
- fuses or melts over large temperature range
- desired shaped is retained
- shrinkage due to removal of bound water

Sintering:
- bonds start to form between particles
- particles are fused into a very porous solid
- melting has not yet occurred

Vitrification:
- flux lowers quartz melting temperature
- quartz particles begin to melt and pull silica out of clay matrix
- silicates form increasing the viscosity of the melt
- remaining “alumina rich” clay particles have higher melting temperature
- final structure: alumina rich particles in silicate glass matrix
Polymer Clay (Sculpey, FIMO)

- polyvinyl chloride (PVC)
- long chain or high molecular weight polymer
- thermoplastic: polymer that melts to a liquid when heated and freezes to a brittle, glassy state when cooled
- as-purchased a plasticizer is added to keep clay malleable
- heating the clay decomposes the plasticizer hardening the clay

without plasticizer: polymer clay is brittle at room temperature

with plasticizer: polymer clay is malleable at room temperature
- the plasticizer acts as a lubricant putting space between chains and allowing them to slide passed each other
Metal Foil Embossing

- polycrystalline metal sheet
- relatively isotropic in-plane
- ductile material
- embossing process: plastic or non-recoverable, permanent deformation
- during embossing bonds are broken with original neighboring atoms and reformed with new neighbors
- yield strength: stress required to produce a very slight deformation
- metals a can generally only support 0.5% elongation before plastic deformation occurs
- materials choice important

<table>
<thead>
<tr>
<th>Metal Alloy</th>
<th>Yield Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>35</td>
</tr>
<tr>
<td>Copper</td>
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<tr>
<td>Iron</td>
<td>130</td>
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<tr>
<td>Steel</td>
<td>180</td>
</tr>
<tr>
<td>Titanium</td>
<td>450</td>
</tr>
</tbody>
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Summary

structure

processing

properties

performance

metal
ceramic
polymer
wood
pastels