Office hours

Monday, 3.00 – 4.00 PM
Tuesday, 5.00 – 6.00 PM

Instructor: Prof. Alexander Mukasyan
Office: 210 Stinson-Remick Hall
TA’s OFFICE HOURS

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Michael Humbert  
mhumbert@nd.edu

5:30-7:30 p.m. each Wednesday

- Location: 101  DBRT: 9/10; 9/24; 10/8; 10/15;
- Location: 140  DBRT: 9/17;
- Location: 138  DBRT: 10/1; 10/29

November & December - TBA
Remember: Materials “Drive” our Society!

- Ages of “Man” we survive based on the materials we control

  - the Stone Age (>10,000 BC) – naturally occurring materials
    - Special rocks, skins, wood, ceramics and glasses, natural polymers and composites
  - the Bronze Age, (4000 BC-1000 BC)
    - Casting and forging
  - the Iron Age, (1000 BC-1620 AD)
    - High Temperature furnaces; Cast iron technology (1620's) established the dominance of metals in engineering;
  - Steel Age (1859 and up)
    - High Strength Alloys
  - Non-Ferrous and Polymer Age (light (1940's) and special alloys)
    - Aluminum, Titanium and Nickel (super-alloys) – aerospace
    - Silicon – Information
    - Plastics and Composites – food preservation, housing, aerospace and higher speeds
  - Exotic Materials Age?
    - Nano-Material and bio-Materials – they are coming and then…
3000-800 BC transition from stone to bronze for tools & arts

Turkey, 3000-2000 B.C.

N. Afghanistan, 2200-1800 B.C.

Bronze:
Cu + Sn
$T_m$ 950°C

Turkey, 3000-2000 B.C.
Bronze age: not only bronze but also gold and silver.

Why not iron?

More complex process,

Higher temperature $> \sim 1200^\circ C$

Reduction of ore with charcoal

Obtaining charcoal

Iron is harder than bronze, keeping its cutting edge.
Centuries of Materials Science

‘Knowledge’ transferred from father to son, master to apprentice.

The art of materials

Combination of tough and hard

Damasascener sword

1100-1700
Meanwhile demands of society on materials grew:

Bigger, larger, faster ....

But materials science was still largely empirical.
Factories, commerce, travel … placed ever increasing demands on iron

The “Firth of Forth” Bridge, 2.5 km.  Built from 1883-1890.

The era of steam …

Fundamental knowledge of iron & steel?
Construction of the Eiffel tower.

World exhibition 1889.
Materials science became a real science due to the development of modern analysis and imaging techniques.

Modern analysis and imaging techniques become possible due to developments in the materials science …..
Radiation went straight through a closed, black carton, hitting a fluorescent screen.

Wilhelm Conrad Röntgen

Discovered the ‘Röntgen’ rays in 1895. Named these ‘X-rays’.

Nobel prize 1901
Sir William Henry Bragg:

He saw the shortcomings of the Von Laue method.

His solution: rotating single crystal.

The most important thing in science is not so much to obtain new facts as to discover new ways of thinking about them.

Bragg’s law

\[ 2d \sin \theta = n \lambda \]
• **1931** Max Knoll and Ernst Ruska build first electron microscope

• **1933** Ruska develops an EM with higher resolution than an optical microscope

• **1937** The first scanning electron microscope is built

• **1939** Siemens brings the first commercial EM on the market

• **1965** First commercial SEM (Oatley)
Impact of high resolution microscopic images.

Tremendous depth of sharpness!

Beyond our imagination
Gold on Carbon: Record Resolution <0.6 nm

Magnification x1,600,000

Resolution 0.58 nm

Magnification x1,000,000
We can see atoms!
History – the evolution of materials
Classification of Materials
**Metals and Alloys:** Valence electrons are detached from atoms, and spread in an 'electron sea' that "glues" the ions together (metallic bonding). Strong, ductile, with high electrical and heat conductivity. **Examples:** Al, Cu, Ni, Ti, steels and etc.

**Ceramics:** Atoms behave like either positive or negative ions, and are bound by Coulomb forces (ionic bonding). They are usually combinations of metals or non-metals with oxygen, nitrogen or carbon (oxides: Al$_2$O$_3$, SiO$_2$; nitrides: TiN, Si$_3$N$_4$; and carbides: TiC, SiC). Hard, brittle, insulators. **More examples:** glass, porcelain.

**Composites:** Consist of more than one material type. Producing properties not found in any single material. **Examples:** concrete, fiberglass, carbon-carbon-composite Kevlar-fiber composites.

**Polymers:** Are bound by covalent forces (electrons are shared between atoms) and also by weak van der Waals forces (secondary bonding), and usually based on C and H. They decompose at moderate temperatures (100 – 400 °C), and are lightweight. **Examples:** plastics, rubber.
Classification of Materials (Metals)

• Metals can be further classified as Ferrous & Non-Ferrous, some examples include:

<table>
<thead>
<tr>
<th>Ferrous</th>
<th>Non-Ferrous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steels</td>
<td>Aluminium</td>
</tr>
<tr>
<td>Stainless Steels</td>
<td>Copper</td>
</tr>
<tr>
<td>High Speed Steels</td>
<td>Brass</td>
</tr>
<tr>
<td>Cast Irons</td>
<td>Titanium</td>
</tr>
</tbody>
</table>
Classification of Materials (Ceramics)

- Ceramics are compounds of metallic and non-metallic elements, examples include;

- Oxides (alumina – insulation and abrasives, zirconia – dies for metal extrusion and abrasives)
- Carbides (tungsten-carbide tools)
- Nitrides (cubic boron nitride, 2nd in hardness to diamond)
Classification of Materials (Plastics)

- Plastics can be further classified as:
  - Thermoplastic
  - Thermoset
  - Elastomers

<table>
<thead>
<tr>
<th>Thermoplastics</th>
<th>Thermosets</th>
<th>Elastomers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylcs</td>
<td>Epoxy resins</td>
<td>Rubbers</td>
</tr>
<tr>
<td>Nylons</td>
<td>Phenolic</td>
<td>Silicons</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyesters</td>
<td>Polyurethanes</td>
</tr>
<tr>
<td>Polyethylene</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Classification of Materials (Composites)

- A composite is a combination of two or more chemically distinct materials whose physical characteristics are superior to its constituents acting independently.
- Because of their high strength/stiffness to weight ratio they are widely used in the:
  - Aerospace industry
  - Offshore structures
  - Boats
  - Sporting goods
The Materials Science Mantra:

The properties of a material depend upon its composition and microstructure.

The microstructure of a material depends upon its composition and the processing that it undergoes.
Structure
Q1: What is materials’ composition?

- Composition: the chemical make up of a material!
- Examples: C – carbon; BN- boron nitride; $\text{La}_{0.6}\text{Sr}_{0.4}\text{Fe}_{0.7}\text{Ni}_{0.3}\text{O}_3$ – lanthanum-based perovskite

Q2: What are materials’ properties?

- **Mechanical Properties** describe how well a material withstands applied forces, including tensile or compressive, impact, cycling or fatigue at room or high temperature
- **Physical properties** describe material characteristics such as color, elasticity, electrical and thermal conductivity, magnetism and optical behavior that generally are not significantly influenced by forces acting on a material.
Q3: Can materials have same composition but possess different properties?

• Answer: Yes !!!
• Examples: C – carbon can be in different modifications, e.g. graphite, diamond, Bucky ball.

Graphite, is a **black**, lustrous solid that is **completely opaque**.

Pure diamonds are **clear** and **colorless**.

In solution buckminsterfullerene deep **red color** is revealed.
Q4: Why it could be so?

The properties are defined by *material structure*!

*Material structure* describes the arrangement of atoms or ions in material and profoundly influences the material properties.
Scale of Structure Organization

Units:
- micrometer = $10^{-6} \text{m} = 1\mu\text{m}$
- nanometer = $10^{-9} \text{m} = 1\text{nm}$
- Angstrom = $10^{-10} \text{m} = 1\text{Å}$

- A hair is ~ 100 $\mu$m
- A diameter of single wall carbon nanotube ~ 2 nm
- A size of H$_2$ molecule ~ 2.5 Å
Properties
**Stress** - force per unit area; **Strain** – change of dimension divided by original dimension; If the strain goes away after the stress is removed – **elastic** strain; If the strain remains – **plastic** strain; During elastic deformation stress and strain are linearly related with the slope known as **Young’s modulus**; A level of stress needed to initiate plastic deformation is called **yield strength**; The maximum percent of deformation is a measure of the material **ductility**.
FIGURE 4.5

The diagram illustrates the relationship between Young's modulus ($E$) and strength ($\sigma_f$) for various materials, including metals, ceramics, composites, polymers, and nontechnical ceramics. The graph uses a logarithmic scale for both axes to accommodate the wide range of values for modulus and strength. The legend highlights different materials and categories, such as metals, technical ceramics, composites, polymers, and nontechnical ceramics. The design guidelines are indicated by dashed lines, with notes on yield before buckling and buckling before yield. The graph also includes a yield strain formula ($\sigma_f/E = 10^{-4}$) for reference.
Strength - Density

Metals and polymers: yield strength, $\sigma_y$
Ceramics, glasses: modulus of rupture, MOR
Elastomers: tensile tear strength, $\sigma_t$
Composites: tensile failure, $\sigma_t$

Guide lines for minimum mass design
Optimized selection using charts

Young's modulus - Density

Search area

Results

<table>
<thead>
<tr>
<th>Material</th>
<th>Index $E^{1/2}/\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material 1</td>
<td>2230</td>
</tr>
<tr>
<td>Material 2</td>
<td>2100</td>
</tr>
<tr>
<td>Material 3</td>
<td>1950</td>
</tr>
<tr>
<td>etc...</td>
<td></td>
</tr>
</tbody>
</table>

Material selection process:

1. Identify the material with the highest $E^{1/2}/\rho$ index.
2. Rank materials by $E^{1/2}/\rho$ index.
3. Select the top-ranked material.

$E = M\rho^{1/2}$

$E^{1/3} = M\rho^{1/3}$

$E/\rho = M$
Structure-Properties Relation
STRUCTURE–PROPERTY RELATIONS

Macro-Scale Structure
Engine Block
≡ upto 1 meter

Performance Criteria
- Power generated
- Efficiency
- Durability
- Cost

Microstructure
- Grains
≡ 1 – 10 millimeters

Properties affected
- High cycle fatigue
- Ductility

Microstructure
- Dendrites & Phases
≡ 50 – 500 micrometers

Properties affected
- Yield strength
- Ultimate tensile strength
- High cycle fatigue
- Low cycle fatigue
- Thermal Growth
- Ductility

Nano-structure
- Precipitates
≡ 3-100 nanometers

Properties affected
- Yield strength
- Ultimate tensile strength
- Low cycle fatigue
- Ductility

Atomic-scale structure
≡ 1-100 Angstroms

Property affected
- Young’s modulus
- Thermal Growth
• Properties depend on structure
  ex: hardness vs structure of steel

• Processing can change structure
  ex: structure vs cooling rate of steel
• Electrical Resistivity of Copper:

- Adding “impurity” atoms to Cu increases resistivity.
- Deforming Cu increases resistivity.
• Space Shuttle Tiles:
  - Silica fiber insulation offers low heat conduction.

• Thermal Conductivity of Copper:
  - It decreases when you add zinc!
**OPTICAL**

- **Transmittance:**
  -- Aluminum oxide may be transparent, translucent, or opaque depending on the material structure.

  - Single crystal
  - Polycrystalline:
    - Low porosity
    - High porosity
“Synthesis”: how materials are made from chemicals.

Examples:
- Reaction Sintering (RS)
- Chemical Vapor Deposition (CVD)
- Combustion Synthesis (CS)

“Processing”: how materials are shaped into useful components to cause changes in their properties.

Examples: metal casting, cold work.

Composition, atomic, crystalline and microstructures define material properties, but also processing does!
What is MSE?
WHAT IS MATERIALS SCIENCE & ENGINEERING (MSE)?

Materials Science: relations between synthesis/processing parameters and material composition/structure and its properties

Materials Engineering: material transformation to useful devices

MSE Tetrahedron

- Performance or Properties to Cost Ratio
- Composition
- Structure
- Synthesis and Processing
- Processing ➔ Structure ➔ Properties ➔ Performance
Conclusion

- **MSE** an interdisciplinary field of science concerned with *inventing new* and improving previously known materials by developing a *deeper* understanding of the *microstructure-composition-synthesis-processing* relationship.