Materials Science and Engineering
Interdisciplinary with HUGE potential

Christine Broadbridge, Ph. D.
Center for Research on Interface Structures and Phenomena
an NSF-funded Materials Research Science & Engineering Center (MRSEC)
Yale University • Southern CT State University

Materials and Manufacturing Teacher Institute 2014
Introduction

What is materials science*?

- A branch of science that focuses on materials; interdisciplinary field impacting the physical, life & engineering sciences.

- Relationship of material properties to its structure, performance and processing.

What is a materials scientist?

- A person who uses his/her knowledge of science and engineering to exploit structure - property relationships for practical use.

- Goal: Take raw materials & make finished products

*Materia**ls Science and Engineering [MSE]
Materials Science and Engineering

- **Processing**
  - Synthesis, fabrication & manufacturing

- **Characterization**
  - Materials testing & imaging

- **Structure**
  - Crystal structure, atomic structure (i.e. bonding)

- **Properties**
  - Chemical & Physical

  - Reliable & cost-efficient
What are Materials?

Classification of materials:

- **Metals** (Al, Ni, Cu, etc. // good conductors)
- **Ceramics/Glasses** ($\text{Al}_2\text{O}_3$, glass // good insulators)
- **Polymers** (plastic, rubber, proteins // synthetic, natural)
- **Composites** (combination of 1-3; i.e. carbon fiber)

**Advanced materials**, i.e. semiconductors, biomaterials, smart materials, and nano-engineered materials

**Materials engineering** – fabrication and application of new materials
The impact of Materials Science

• Materials have defined the progression of humankind: **Stone Age, Bronze Age, Iron Age**
• Today’s age: **Silicon Age, Information Age**

**metals** • **ceramics** • **semiconductors** • **polymers**
**composites** • **smart materials**

New generation of materials created by pushing the boundaries of science/innovation
What do Materials Scientists do?

• Investigate how materials are made, figure out how they can be changed and improved, and engineer entirely new materials.

Materials science is an interdisciplinary field with many applications.
What is structure?
Atomic Structure - $10^{-10}$ m

- Pertains to atom electron structure and atomic arrangement
- Atom length scale
  - Includes electron structure – **atomic bonding**
    - ionic
    - covalent
    - metallic
    - secondary bonding (Van der Waals)
  - Atomic ordering – **crystal structure**
    - Crystalline
    - Polycrystalline
    - Amorphous
  - Long range (metals), short range (glass)
What is a property?

- A material’s response to an external stimuli – physical and chemical
  - Mechanical
  - Electrical
  - Chemical
  - Optical
  - Magnetic

Optical: Stimuli = light [EM radiation]

https://colour-yourlife.co.uk
Structure/Property Relationships

Atomic Structure

- Periodic Table – general trends
**Structure/Property Relationships**

**Crystal structure and bonding**

- **Graphite**
  - One of the softest natural materials, graphite is used in pencil lead.
  - Graphite is a good conductor of electricity.
  - Graphite is also used in medicine to absorb poisons and toxins.

- **Buckyball**
  - The form of a buckyball closely resembles a soccer ball.
  - Buckyballs are named after the architect Buckminster Fuller.
  - Buckyballs have potential uses in medicine and may help fight cancer.

- **Diamond**
  - Formed at high pressures, diamond is one of the hardest known natural materials.
  - Diamonds are sometimes used in drill bits to make them very hard.
  - Diamonds are excellent electrical insulators.

- **Carbon Nanotube**
  - A single human hair is 50,000 times wider than a carbon nanotube.
  - Carbon nanotubes are useful in electronics and optics.
  - Carbon nanotubes are extremely strong and conduct electricity well.
Length Scales of Materials Science

- Atomic – < 10^{-10} m
- Nano – 10^{-9} m
- Micro – 10^{-6} m
- Macro – > 10^{-3} m
Nano Structure - $10^{-9}$ m

• Length scale that pertains to clusters of atoms that make up small particles or material features

• Show interesting properties because of large surface area to volume ratio
  – More atoms on surface compared to bulk atoms
  – Optical, magnetic, mechanical and electrical properties change

• How to conceptualize? Your finger nail grows $\sim 1$nm every second
Microstructure – $10^{-6}$

- Larger features composed of either nanostructured materials or periodic arrangements of atoms known as crystals
- Features are visible with high magnification in light microscope.
  - Grains, inclusions other or micro-features that make up material
  - These features are traditionally altered to improve material performance
  - Human hair is ~100 microns in diameter
Macrostructure – $10^{-3}$ m

- Macrostructure pertains to collective features on microstructure level
- Grain flow, cracks, porosity are all examples of macrostructure features
- Some features can be observed with the naked eye
Classes of Materials

- metals
- polymers
- ceramics/glasses
- composites
Metals

• Metals consist of alkaline, alkaline earth, metalloids and transition metals and are typically crystalline
• Metal alloys are mixtures of two or more metal and nonmetal elements (for example, aluminum and copper, Cu-Ni alloy, steel)

• Bonding: Metallic
  – No particular sharing or donating occurs. Electron cloud is formed (that is, free electrons)
  – Strong bonds with no hybridization or directionality

• Properties:
  – Electrically conductive (free electrons)
  – Thermally conductive
  – High strength – large capacity to carry load over x-section area (stress)
  – Ductile – endure large amounts of deformation before breaking.
  – Magnetic – permanent, temporary
  – Medium melting point
Metal Applications

• Electrical wire: aluminum, copper, silver
• Heat transfer fins: aluminum, silver
• Plumbing: copper
• Construction beams (bridges, sky scrapers, rebar, etc.): steel (Fe-C alloys)
• Cars: steel (Fe-C alloys)
• Consumer goods:
  – soup cans
  – appliances (stainless steel sheet metal)
  – utensils
  – tools
  – Many, many, many more...
• MSE used to = metallurgy [study of metals]
Polymers

- Polymers consist of various hydro-carbon (organic elements) with select additives to create specific properties
- Polymers are typically disordered (amorphous) strands of hydrocarbon molecules.
- **Bonding**: Covalent-Secondary Bonding Forces
- **Properties**:
  - ductile: can be stretched up to 1000% of original length
  - lightweight: Low densities
  - medium strength: Depending on additives
  - chemical stability: inert to corrosive environments
  - low melting point
  - disposal can be a concern for the environment
Polymer Applications

• Car tires: vulcanized polymer (added sulfur)
• Ziploc bags
• Food storage containers
• Plumbing: polyvinyl chloride (PVC)
• Kevlar
• Aerospace and energy applications: Teflon
• **Consumer goods:**
  – calculator casings
  – TV consuls
  – shoe soles
  – cell phone casings
  – Elmer’s Glue (adhesives)
  – contact lenses
  – Many, many. many more...
Ceramics

• Consist of metal and non metal elements
• Typically a mixture of elements in the form of a chemical compound, for example $\text{Al}_2\text{O}_3$ or glass
• Different types: crystalline and amorphous ceramics
• Bonding: covalent – ionic
  – Typically covalent. In some cases highly direction covalent bonding
  – Ionic in case of $\text{SiO}_2$ glasses
• Properties:
  – wear resistant (hard)
  – chemical stability: corrosion resistant
  – high temperature strength: strength retention at very high temperatures
  – high melting points
  – good insulators (dielectrics)
  – adhesives
  – good optical properties
Ceramic/glass Applications

• Window glass: $\text{Al}_2\text{O}_3 – \text{SiO}_2 – \text{MgO} – \text{CaO}$
• Aerospace, energy and automotive industry
  – heat shield tiles
  – engine components
  – reactor vessel and furnace linings
• Consumer products:
  – pottery
  – dishes (fine china, plates, bowls)
  – glassware (cups, mugs, etc.)
  – eye glass lenses
  – Ceramic braces
Composites

• A mixture of two different materials to create a new material with combined properties

• Types of composites:
  – Particulate reinforced – discontinuous type with low aspect ratio
  – Whisker/rod reinforced - discontinuous type with high aspect ratio
  – Fiber reinforced - continuous type with high aspect ratio (naturally)
  – Laminated composites - layered structures (surf boards, skate boards)

• Bonding: depends on type of composite (strong-covalent, medium-solid solution, weak-tertiary phase layer)

• Properties: Depends on composites
  – High melting points with improved high temperature strength: ceramic-ceramic
  – High strength and ductile with improved wear resistance: metal-ceramic
  – High strength and ductile: polymer-polymer
Composites: Applications

• Wood: naturally occurring biological material consists of very strong fibers imbedded in a soft matrix
• Plywood: laminated wood for buildings
• Concrete: basements, bridges, sidewalks
• Fiberglass: boats
• Carbon fiber resins: bicycle frames
• Composite decking
Other advanced materials

• **Semiconductors** – ceramics
  – computer chips
  – memory storage devices
  – solar cells
  – image screens

• **Nanomaterials** – ceramics, metals, polymers
  – gold nanoshells
  – quantum dots
  – ferrofluids
  – medical devices
How do we test materials?

Materials Characterization

We use mechanical, chemical and imaging methods

- **Mechanical testing** gives strength, ductility and toughness material information
  - tensile tests
  - bend tests
  - compressive tests
  - fracture testing

- **Chemical testing** tells us about composition and chemical stability
  - x-ray diffraction and fluorescence – composition testing
  - corrosion testing

- **Microscopy** is more of a way to view atomic, nano and microstructures, and gives us insight to structure property relationships
  - light optical microscope – microstructure
  - scanning electron microscope – microstructure and nano structure
  - transmission electron microscope – nanostucture and atomic structure
  - scanning tunneling electron microscope – atomic structures
Mechanical Testing

universal testing machines
Imaging Methods

Scanning Electron Microscope

Transmission Electron Microscope

Atomic Force Microscope

Optical (Light) Microscope
Optical Microscopy

biology and forensics

resolution $\sim 1 \mu m$

Hoffman modulation contrast microscopy [pollen]
Scanning Electron Microscopy [SEM] Analysis

Resolution < 10 nm
Powers of ten ~ from macro to nano

1 nm to 100 nm

• A human hair is about 100,000 nm in diameter

• A smoke particle is about 1,000 nm

• A Virus is 3 – 50 nm

• DNA is about 1 – 2 nm in diameter

• 10 Hydrogen atoms is 1 nm

Provide as many examples as possible for students
Nanotechnology

Control & manipulation of matter [1-100nm]
Unique phenomenon enable novel applications

C_{60} buckyball
fullerene

C nanotube
cylindrical fullerene
[photovoltaic, solar cell]

Quantum dots
Nanosize semiconductors
[DVD, video games]
Innovations In Development or Under Investigation

- **Health Care**
  - Chemical and biological sensors, drugs and delivery devices, prosthetics and biosensors

- **Technology**
  - Better data storage and computation

- **Environment**
  - Clean energy, clean air

Thin layers of gold are used in tiny medical devices

Carbon nanotubes can be used for H fuel storage

Possible entry point for nanomedical device
Examples of current commercial products

- Cosmetics (skin care products)
- Tennis balls which last longer
- Wrinkle free fabrics, “nano-fabrics”
- Sunscreen with transparent zinc-oxide

The possibilities are limitless...
Potential Impacts

How might Materials Science and Engineering enhance K-12 education?
For Discussion -- MSE Connections to the NAE Frameworks

SCIENCE AND ENGINEERING PRACTICES FOR K-12 SCIENCE CLASSROOMS

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information
CORE AND COMPONENT IDEAS IN THE PHYSICAL SCIENCES

Core Idea PS1: Matter and Its Interactions
PS1.B: Chemical Reactions
PS1.C: Nuclear Processes

Core Idea PS2: Motion and Stability: Forces and Interactions
PS2.A: Forces and Motion
PS2.B: Types of Interactions
PS2.C: Stability and Instability in Physical Systems

Core Idea PS3: Energy
PS3.A: Definitions of Energy
PS3.B: Conservation of Energy and Energy Transfer
PS3.C: Relationship Between Energy and Forces
PS3.D: Energy in Chemical Processes and Everyday Life

Core Idea PS4: Waves and Their Applications in Technologies for Information Transfer
PS4.A: Wave Properties
PS4.B: Electromagnetic Radiation
PS4.C: Information Technologies and Instrumentation
Summary

Materials Science & Engineering

- A branch of science that focuses on materials; interdisciplinary field composed of physical, life and engineering sciences.
- Relationship of material properties to its structure, performance and processing.
- Interdisciplinary field with huge potential for synergies with the National Academies Frameworks, Next Generation Science Standards & Common Core.