MATERIALS ENGINEERING
MT30001
3-0-0

Offered by:

Metallurgical & Materials Engineering Dept.

Instructors:

Prof. Sujoy Kumar Kar

Prof. Sumantra Mandal

Instructor's contact information

Prof. Sujoy Kumar Kar

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Phone: 03222 283258 (Office)

Office: First floor of Metallurgical & Materials Engineering Department, IIT Kharagpur

Important things for this course to be successful

- **Attend every class**
- **Participate**
- **Do not be late**
- **Please do not talk among yourself.**

Timetable

- Monday: 08:00 am – 9:55 am
- Tuesday: 12:00 pm – 12:55 pm

July 2015

Mon	Tue	Wed	Thu	Fri	Sat	Sun
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18 ✓	19 ✓	20	21	22	23	24
25 ✓	26 ✓	27	28	29	30	31

August 2015

Mon	Tue	Wed	Thu	Fri	Sat	Sun
1 ✓	2 ✓	3	4	5	6	7
8 ✓	9 ✓	10	11	12	13	14
~~15~~	16 ✓	17	18	19	20	21
22 ✓	23 ✓	24	25	26	27	28
29 ✓	30 ✓	31				

September 2015

Mon	Tue	Wed	Thu	Fri	Sat	Sun
			1	2	3	4
5 ✓	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30		

✓ : 21 class hours (i.e., First half of the course) to be taught by Prof. Sujoy Kar

Syllabus: Will email you this slide

MT30001: MATERIALS ENGINEERING (3-0-0)

Introduction: Solid Engineering Materials- their classification and characteristic properties.
Structure of solids: crystal systems/lattices, crystal structure, crystallographic planes and directions, interstitial sites, crystallinity in metals, ceramics, semiconductors and polymers, microstructures and metallography, amorphous or glassy state.
Solidification of pure metal: Homogeneous and heterogeneous nucleation processes, cooling curve, concept of supercooling, microstructure of pure metals.
Defects in solids: Point, line, planar and volume. Fundamentals of plastic deformation of metals, deformation by slip and twin, plastic deformation in polycrystalline metals, concept of cold working, preferred orientation. Annealing: Recovery, recrystallization and grain growth, hot working.
Properties of materials: Definition, units and common tests conducted to evaluate important engineering properties like physical, mechanical, chemical, electrical, magnetic, semi/super-conducting, optical, and thermal properties in engineering materials.
Concept of formation of alloys: Types of alloys, solid solutions, factors affecting solid solubility, order disorder transformation.
Binary phase diagrams: Isomorphous, eutectic, peritectic, eutectoid and peritectoid systems, effect of non equilibrium cooling, coring and homogenization.
Iron-cementite diagram: Construction and interpretation Fe-Fe_3C and Fe-Graphite diagrams. Microstructure and properties of different alloys in steel and cast iron, types of cast iron, their microstructures and typical uses.
Heat treatment: T-T-T and C-C-T diagrams, concept of heat treatments of steel - annealing, normalizing, hardening and tempering, microstructural effects brought about by these processes and their influence on mechanical properties. Effect of common alloying elements in steel, concept of hardenability, factors affecting it
Ferrous and non-ferrous alloys: Common alloy steels, stainless steel, tool steel, high speed steel, high strength low alloy steel, microalloyed steel, specifications of steels. Physical metallurgy of common non-ferrous alloys: Cu-, Al- and Ni- based alloys. Microstructures and heat treatment of common alloys of these systems
Engineering ceramics and polymers: Structure, properties and application of common engineering ceramics and polymers.
Composites: Principle, structure and application of composites.

Text Books:

1. W. D. Callister, Jr: Materials Science and Engineering- An Introduction, John Wiley and Sons, N.Y, 1985.
2. J. F. Shackelford: Introduction to Materials Science for Engineers, Mc-Millan Publishing Co., N.Y. 1992.
3. W.F. Smith: Principles of Materials Science and Engineering, Mc Graw Hill Int., 1986.
4. V. Raghavan: Materials Science and Engineering, 4th Ed., Prentice Hall of India, 1998.

Till Mid-Semester

Introduction: Solid Engineering Materials- their classification and characteristic properties. Structure of solids: crystal systems/lattices, crystal structure, crystallographic planes and directions, interstitial sites, crystallinity in metals, ceramics, semiconductors and polymers, microstructures and metallography, amorphous or glassy state.
Solidification of pure metal: Homogeneous and heterogeneous nucleation processes, cooling curve, concept of supercooling, microstructure of pure metals.
Defects in solids: Point, line, planar and volume. Fundamentals of plastic deformation of metals, deformation by slip and twin, plastic deformation in polycrystalline metals, concept of cold working, preferred orientation. Annealing: Recovery, recrystallization and grain growth, hot working.
Properties of materials: Definition, units and common tests conducted to evaluate important engineering properties like physical, mechanical, chemical, electrical, magnetic, semi/super-conducting, optical, and thermal properties in engineering materials.
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Binary phase diagrams: Isomorphous, eutectic, peritectic, eutectoid and peritectoid systems, effect of non equilibrium cooling, coring and homogenization.

Text Books:
1. W. D. Callister, Jr: Materials Science and Engineering- An Introduction, John Wiley and Sons, N.Y, 1985.

Topics to be covered in the **first half of the course**

- **Introduction, Materials Classification & Bonding** : 2 hrs. (July: 19, 25)
- **Structure of crystalline solids**: 4 hrs. (July: 25, 26; 1, 1)
- **Imperfections in solids + Microstructure**: 2 hrs. (Aug: 2, 8)
- **Deformation & Strengthening mechanisms**: 5 hrs. (Aug.: 8, 9, 16, 22, 22)
- **Phase diagrams & Phase transformations**: 5 hrs. (Aug.: 23, 29, 29; 30, 5)
- **Properties of Materials**: 4 hrs. (Sept.: 5, 6)

Text Book: **W. D. Callister, Jr: Materials Science and Engineering- An Introduction, John Wiley and Sons, N.Y.**

Students' Presentation

- Every group should have 5 people
- Maximum of 3 groups can give presentation on a particular topic (Topic will be alloted on first cum first serve basis)
- Presentation duration for a group 15 minutes
- Every member of a group has to present a few slides
- These will be part of the exam syllabus
- Attendance marks towards TA would be ignored if you give sincere effort towards this presentation
- Encourage everyone to participate.
- Send me one email for each group, by giving the names and roll numbers of the group members and the topic by this Friday (22 July 2016). Topics will be alloted on first cum first serve basis.

List of topics

1. Material for automobile applications
2. Material for aero-engine applications
3. Material for aircraft structural applications (other than the engine)
4. Material for bio applications (implants etc.)
5. Smart materials – Various applications
6. Material for IC chips/ semiconductors/ electronic materials
7. Ti alloys – Types, microstructure, applications
8. Ni based superalloys – Applications and science behind
9. Materials for applications of your imagination – Futuristic material/ Materials of science fiction
10. Material for underwater drills in Oil and gas sector
11. Material for data storage devices – Magnetic materials
12. Nano materials (Carbon nano tube etc.) – Applications
13. 3-d printing of materials

Introduction

- What are different types of Materials?
- What is Materials Science and Engineering?

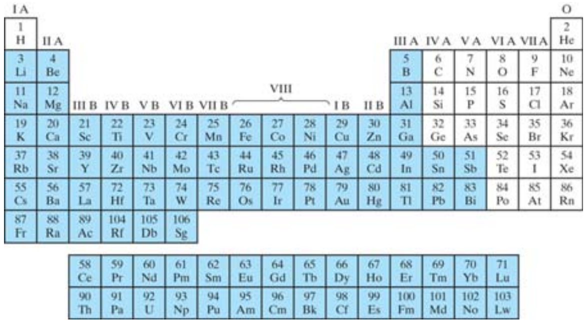
Classification of materials

- Three basic types – based on chemical makeup and atomic bonding
  - **METALS**
  - **CERAMICS/Glasses**
  - **POLYMERS**
- Combination of two or more of three basic type of materials
  - **COMPOSITES**
- Materials used in high-technology applications
  - **ADVANCED MATERIALS(Nano-materials, electronic materials)**

What type of materials are these?

Metals

Periodic Table of Elements: The Metals



Metals & Alloys

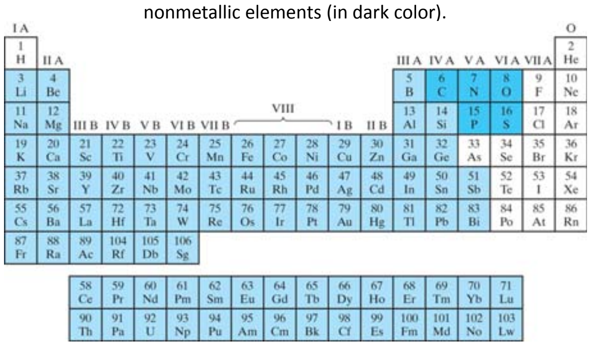
- Composed of ? (Metallic (Al/ Fe/ Cu/ Ti/ Ni) and often also some non-metallic elements (C/ O/ N)) in relatively small amounts
- **Alloys**: Substance composed of >=2 elements
- Metallic Bond: Valence electrons are detached from atoms, and spread in an 'electron sea' that "glues" the ions together.
- Characteristics:
  - Orderly arrangement of atoms: relatively dense
  - Stiff & Strong. Ductile, Resistant to fracture
  - Large number of non-localized electrons: High thermal & electrical conductivity
  - Opaque, reflective, shiny if polished.
  - Fe, Co, Ni have desirable magnetic properties

Structural Steel in Use: Howrah Bridge

What type of materials are these?

Ceramics

Periodic table: ceramic compounds are a combination of one or more metallic elements (in light color) with one or more nonmetallic elements (in dark color).



Ceramics

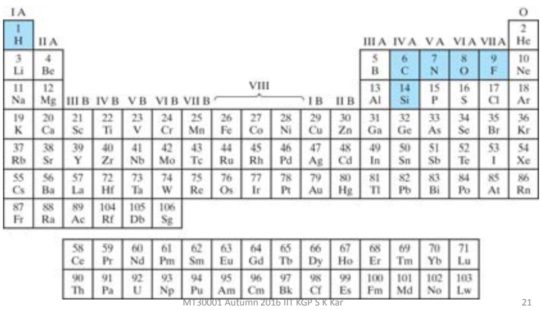
- Compounds between metallic and nonmetallic elements: Oxides, Nitrides, Carbides
- Common ceramic materials: SiO_2, Al_2O_3, SiC, Si_3N_4, Traditional ceramics: Glass, Clay (porcelain), Cement
- Ionic Bonding

- Characteristics:
  - Stiff & Strong like metals, Very Hard
  - Extremely brittle, highly susceptible to fracture
  - Insulators to heat and electricity. Resistant to high temperature and harsh environment
  - Opaque/ Translucent/ Transparent
  - Some oxide ceramics, like, Fe_3O_4 exhibit magnetic behavior

What type of materials are these?

Polymers

Periodic table with the elements associated with commercial polymers in color



Polymers

- Plastics, Rubber, Organic compound based on C, H,O, N, Si
- Common polymeric materials: PE, PVC, Nylon, PC, PS, Silicone rubber
- Covalent Bonding: Large molecular structure, Chain like in nature with backbone of carbon atoms

- Characteristics:
  - Low density
  - Low stiffness and strength (<metals/ ceramics). However, specific strength may be high.
  - Extremely ductile → good formability to complex shapes
  - Insulators to heat and electricity
  - Nonmagnetic
  - Chemically inert & unreactive to many environments
  - Soften or decompose at modest temperatures

Thoughts about these "fundamental" Materials

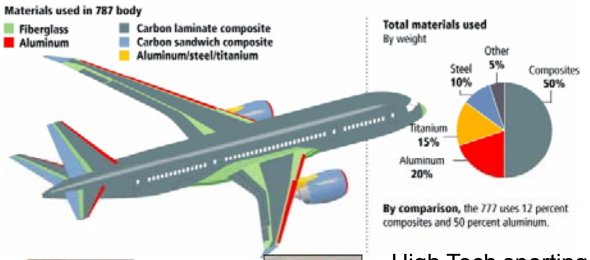
- **Metals**:
  - Strong, ductile
  - high thermal & electrical conductivity
  - opaque, reflective.
- **Ceramics**: ionic bonding (refractory) – compounds of metallic & non-metallic elements (oxides, carbides, nitrides, sulfides)
  - Brittle, glassy, elastic
  - non-conducting (insulators)
- **Polymers/plastics**: Covalent bonding → sharing of e's
  - Soft, ductile, low strength, low density
  - thermal & electrical insulators
  - Optically translucent or transparent.

Combination of good of both the worlds: Composite Materials

- Composed of 2 or more individual materials
- Naturally occurring: Wood, Bone

- Man made:
  - Fiberglass (Glass fibers (strong, stiff but brittle) embedded in polymeric material (ductile, flexible, less dense but weak)) (GFRC) ,
  - Carbon fiber reinforced polymer composite (CFRC): Used in aerospace application, bicycles, golf-club, tennis rackets, ski/ snowboards.

Composite materials

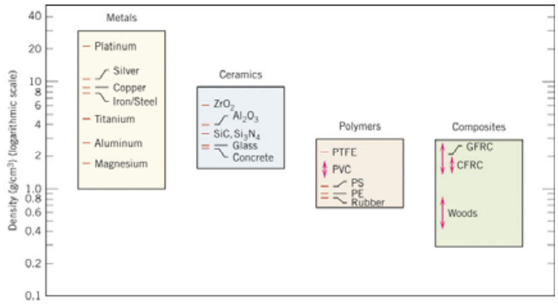


High Tech sporting
- Golf club
- Tennis rackets
- Skis/ Snowboards

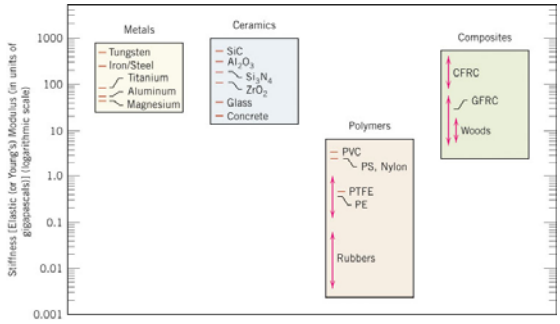
Different types of materials

- Metals
  - Steel, Cast Iron, Aluminum, Copper, Titanium, many others
- Ceramics
  - Glass, Brick, Alumina, Zirconia, SiN, SiC
- Polymers
  - Plastics, Cotton (rayon, nylon), "glue"
- Composites
  - Glass Fiber-reinforced polymers, Carbon Fiber-reinforced polymers, Metal Matrix Composites, Concrete, Wood, Bone etc.

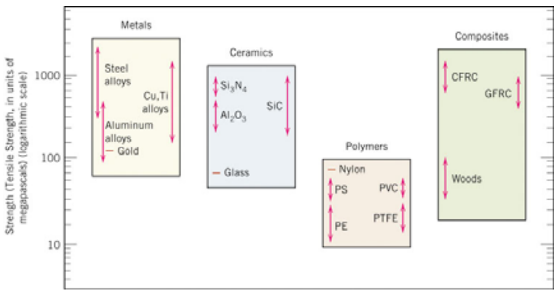
Density



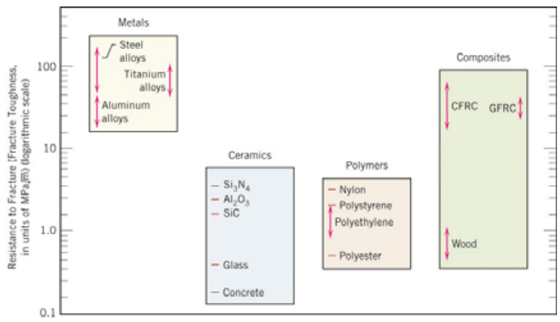
Stiffness



Strength



Fracture Toughness



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Advanced Materials

- Materials used in high-tech applications
  - High-Tech applications: Space-crafts, Air-crafts, military applications, electronic and computers (ICs), fiber optic systems, lasers, Magnetic information storage, LCDs
- Traditional materials (May be of all materials types (metals/ ceramics/ polymers)) with enhanced properties and also newly developed high performance materials
- **Semiconductors, Biomaterials, Smart materials, Nano-engineered materials**

Advanced Materials

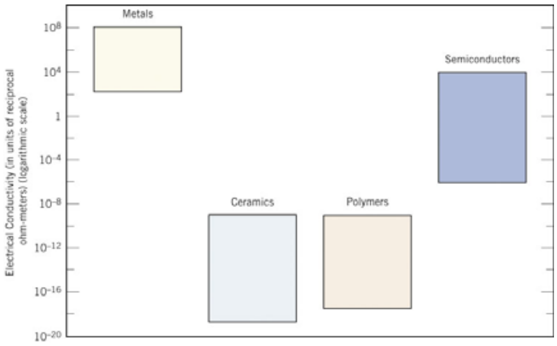
Semiconductors: intermediate electrical conductivity

- Their electrical properties depend strongly on minute proportions of contaminants.
- Examples: Si, Ge, GaAs:
- Used in IC chips

Biomaterials: employed in components Incorporated in the human body

- Must not produce toxic substance
- Must be compatible to body tissues
- Can be any of metals, ceramics, polymers and semiconductors

Electrical Conductivity



Advanced Materials

Smart Materials: Sense and respond to changes in their environment (Temperature, Electric/ Magnetic fields)

- Components of smart material (or system) include some type of sensor and an actuator

- Sensors (Detects Input Signals): Optical fibers, Piezoelectric materials, Microelectromechanical devices (MEMS)
- Actuators (Performs a responsive or adaptive function):
  - Called upon to change shape, position, natural frequency, or mechanical characteristics in response to change in temperature, electric/ magnetic fields.
  - Shape memory alloys, Piezoelectric ceramics, Magnetostrictive materials, Electro/Magneto-rheological fluids

Shape Memory Alloy

These are metals that, after having been deformed, revert back to their original shapes when temperature is changed.

Piezoelectric ceramics

Expand or contract in response to an applied electric field (or voltage); they also generate an electric field when dimensions are altered

Magnetostrictive materials

Analogous to Piezoelectric ceramics – under magnetic field

Electro/ Magneto-rheological fluids

Liquid that experience dramatic change in viscosity upon the application of electric and magnetic fields.

Demonstration for smart materials

Shape memory alloy:
https://www.youtube.com/watch?v=s62PL5vmfNw

Piezoelectric effect:
https://www.youtube.com/watch?v=LnlSSWv4qTQ

Electro-rheological fluid
https://www.youtube.com/watch?v=NOot5wxuxSg

Smart Materials

Application example: Reduce Aerodynamic noise in helicopters

Container of carbonated beverages

Property requirements:

- Barrier to the passage of CO_2
- Non toxic, Non reactive, Recyclable
- Strong
- Inexpensive
- Optically transparent
- Labels on the container
- Light weight
- Fast cool

Metal

- Barrier to the passage of CO_2
- Non toxic, Non reactive, Recyclable
- Strong
- Relatively expensive
- Opaque
- Labels on the container
- Light weight
- Fast cool

Glass (Ceramics)

- Barrier to the passage of CO_2
- Non toxic, Non reactive, Recyclable
- Strong
- Inexpensive
- Optically transparent
- Cracks and fractures easily
- Heavy

Plastics (Polymers)

- Not much impervious to the passage of CO_2
- Non toxic, Non reactive, Recyclable
- Strong
- Inexpensive
- Optically transparent
- Light weight

Summary so far

Classification of materials

- (based on chemical makeup and atomic structure):
  Metals, Ceramics, Polymers, Composites
- (based on high technology applications):
  Advanced materials: Semiconductors, Biomaterials, Smart Materials, Nano Materials
  ↓
  Shape memory alloys, Piezoelectric ceramics, Magnetostrictive materials, Electro/Magneto-rheological fluids

Processing → Structure → Properties → Performance

What is Materials Science & Engineering?

Processing → Structure → Properties → Performance

What does each of these terms mean?

Science: **Investigate the relationships**

Engineering: **Design or engineer the structure of materials that produce a set of pre-determined properties**

Clarification of the terms

Processing:
- Casting route, Powder metallurgy route, Sintering, Doping, Vapor deposition
- Thermal & Thermo-mechanical treatment (Forming): Forging, Rolling, Extrusion, Joining

Structutre: Arrangement of material's internal components

- Subatomic: 
- Atomic 
- Microscopic 
- Macroscopic 

Clarification of the terms: Properties

Magnitude and Type of materials' response to the environment and external forces.

Mechanical

Electrical

Magnetic

Thermal

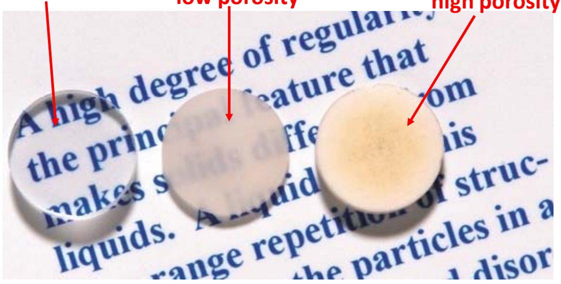
Optical

Chemical

Processing → Structure → Properties → Performance

Optical: Transmittance

single crystal **Polycrystal: low porosity** **Polycrystal: high porosity**



Why Study Materials Engineering?

Design problem involving materials:
Transmission gear, Oil refinery component, Aero-Engine components, Integrated Circuit chips

Select the right material
-In service condition
- Performance over long run
- Cost

Optimization of the properties

Familiarity with the Processing—Structure--Property relationships and the Processing techniques
→ Proficient and Confident in judicious selection of materials

The Materials Selection Process

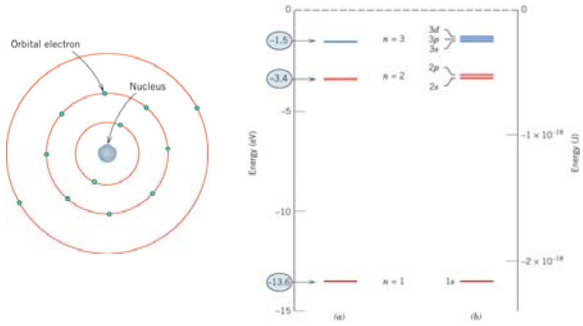
1. Pick Application ⟶ Determine required Properties
   Properties: mechanical, electrical, thermal, magnetic, optical, deteriorative.
2. Properties ⟶ Identify candidate Material(s)
   Material: structure, composition.
3. Material ⟶ Identify required Processing
   Processing: changes *structure* and overall *shape*
   ex: casting, sintering, vapor deposition, doping
   forming, joining, annealing.

Atomic Structure and Interatomic bonding

Recapitulate the following basic concepts yourself

- Electron, Proton, Neutron – Masses and charges
- Atomic mass/ weight (atomic mass unit)
- Atomic number, Avogadro number, mole
- Electrons in solids – Concepts of Classical mechanics vs. Quantum mechanics
- Bohr atomic model -- Energy levels/ states
- Wave mechanical model
- Quantum numbers – Electron states (Values of energy that are permitted for electrons)
- Pauli exclusion principle (The manner in which these states are filled with electrons) – Each electron state can hold no more than 2 electrons, which must have opposite spins
- Electronic configuration
- Ground state
- Valence electrons (that occupy the outermost shell)

Recapitulate the electronic configurations of atoms from the book



- Valence electrons determine all of the following properties
  1) Chemical (stability/ chemical reaction/ atomic bonding)
  2) Electrical
  3) Thermal
  4) Optical

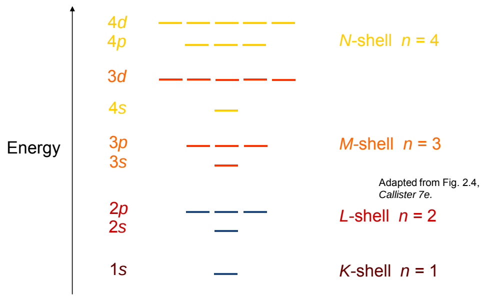
Electronic Structure

- Electrons have wavelike and particulate properties.
  - This means that electrons are in orbitals defined by a probability.
  - Each orbital at discrete energy level determined by quantum numbers.

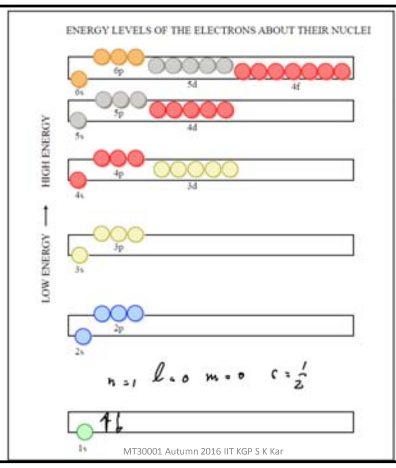
Related to	Quantum #	Designation
Position of an electron	n = principal (energy level-shell)	K, L, M, N, O (1, 2, 3, etc.)
Shape of the subshell	ℓ = subsidiary (subshell)	s, p, d, f (0, 1, 2, 3,..., n-1)
# of energy states for each subshell	m_l = magnetic	1, 3, 5, 7 ($-\ell$ to $+\ell$)
Spin moment of an electron	m_s = spin orientation	½, -½

Electron Energy States

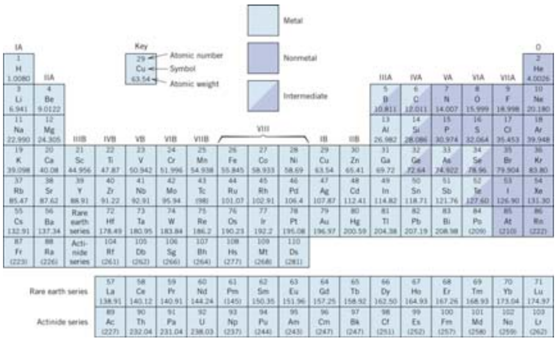
Electrons...
- have discrete energy states
- tend to occupy lowest available energy state.



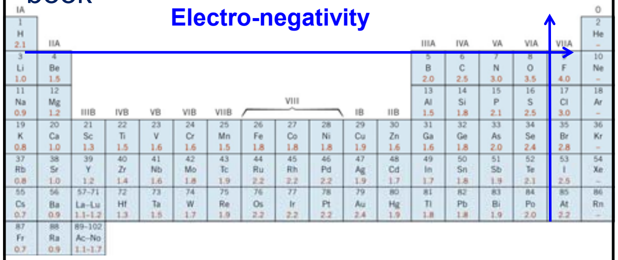
Adapted from Fig. 2.4, *Callister 7e.*



Recapitulate the Periodic Table from the book

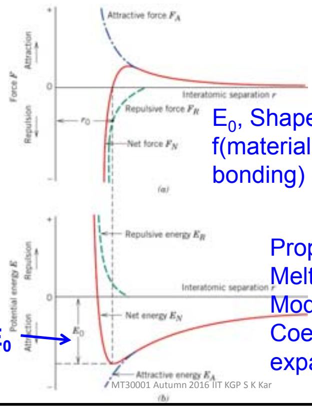


Recapitulate the Periodic Table from the book



Atoms are more likely to accept electrons if their outer shells are almost full, and if they are less "shielded" from (i.e., closer to) the nucleus

Bonding Force and Energies



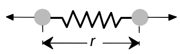
E_0, Shape of the curve = f(material, type of atomic bonding)

Properties: L/S/G; Melting Point, Modulus of elasticity, Coeff. Of thermal expansion

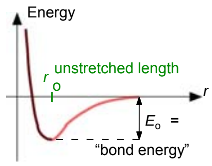
Bonding Energy: E_0

Properties From Bonding: T_m

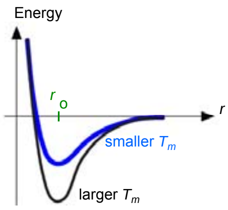
- Bond length, r



- Bond energy, E_o



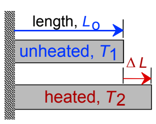
- Melting Temperature, T_m



T_m is larger if E_o is larger.

Properties From Bonding : α

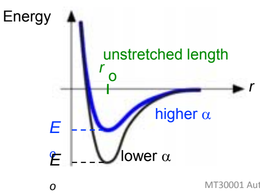
- Coefficient of thermal expansion, α



coeff. thermal expansion

$$\frac{\Delta L}{L_o} = \alpha\,(T_2 - T_1)$$

- α ~ symmetry at r_o



α is larger if E_o is smaller.

Atomic Bonding

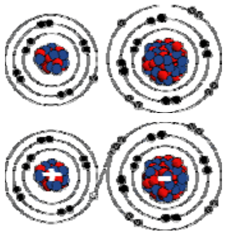
Primary

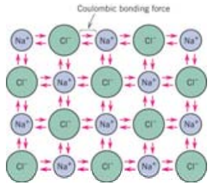
- **Covalent**
  - sharing electrons
  - strong
  - directional
- **Ionic**
  - trading of elecrons
  - electrostatic attraction
  - strong
  - non-directional
- **Metallic**
  - metal ions in sea or electrons
  - moderately strong
  - non-directional

Nature of the bonds = f (Electron structure of constituent atoms)

Atoms want to assume stable electronic structure

IONIC BONDING

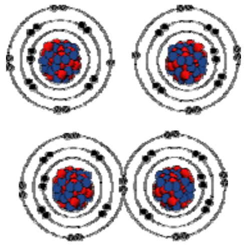


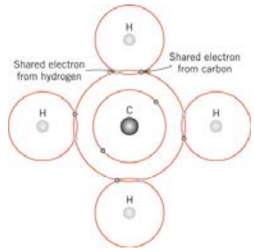


Hard, Brittle, Insulators

- **Ionic**
  - trading of elecrons
  - electrostatic Coulombic attraction
  - Strong: Large bonding energy: between 600 – 1500 kJ/mole
  - non-directional

COVALENT BONDING





- **Covalent**
  - sharing electrons
  - Strong (Diamond) or weak (Bi)
  - directional

•H_2, Cl_2, F_2
•CH_4, H_20, HNO_3, HF
•Diamond, Si, Ge
•GaAs, SiC

Primary Bonding

- Metallic Bond -- delocalized as electron cloud
- Ionic-Covalent Mixed Bonding

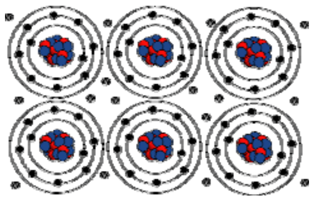
$$\%\text{ ionic character} = \left(1 - e^{-\frac{(X_A - X_B)^2}{4}}\right) \text{x } (100\ \%)$$

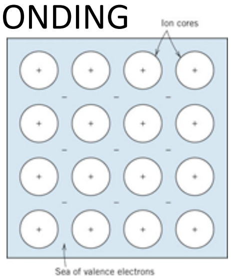
where X_A & X_B are Pauling electronegativities

Ex: MgO $\quad X_{Mg} = 1.3$, $X_O = 3.5$

$$\%\text{ ionic character} = \left(1 - e^{-\frac{(3.5-1.3)^2}{4}}\right) \text{x } (100\%) = 70.2\%\text{ ionic}$$

METALLIC BONDING





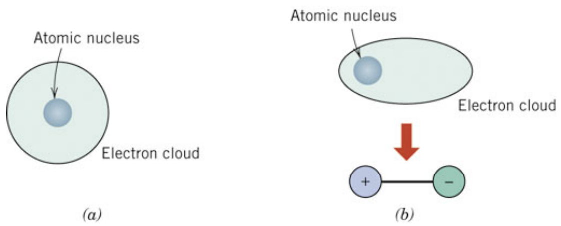
- **Metallic**
  - metal ions in sea or electrons
  - moderately strong
  - 68 kJ/mole – 850 kJ/mole
  - non-directional

•Good conductors of heat and electricity,
•Ductile behavior

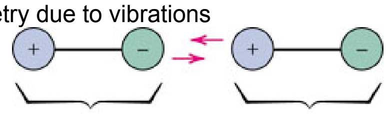
Atomic Bonding

- **Secondary,** Van der Waals
  - Arise from electrostatic attraction of electric dipole (local charge distribution)
  - Weak 10 kJ/mole
  - Effects obsceured if primary bonds are present
  - Occur between
    - Induced dipoles
    - Induced dipoles and polar molecules
    - Polar molecules (Hydrogen Bonding)

Fluctuating Induced Dipole bonds

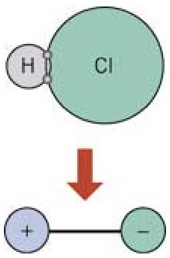


Instantaneous Short lived distortion of electrical symmetry due to vibrations



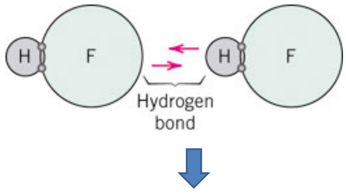
Atomic or molecular dipoles

Polar Molecule - Induced Dipole bonds



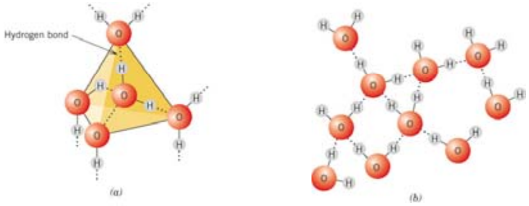
INTERMOLECULAR BONDING

Permanent Dipole bonds



Low molecular weight , However MP and BP very high

Water: Volume expansion upon freezing!!



Summary so far

- **What is Materials Science and Engineering about?**
- **Subatomic (electronic) structure,**
- **Periodic table,**
- **Bond energy,**
- **Inter-atomic/molecular bonding = f (electronic str.),**
  - **Primary**
    - **Metallic**
    - **Ionic**
    - **Covalent**
  - **Secondary**
- **Effects of sub-atomic structure and bonding on properties**

Questions

1. If you are given plots of interatomic force vs. interatomic distance for two different metal systems, then how would you determine which metal has higher stiffness among the two from the plots?

2. Why are metals electrically conductive while ceramics are not?

3. How is bond energy related to coefficient of thermal expansion?

4. How many valence electrons are there for Boron?