CH 8 & 11

Importance of Materials in Manufacturing

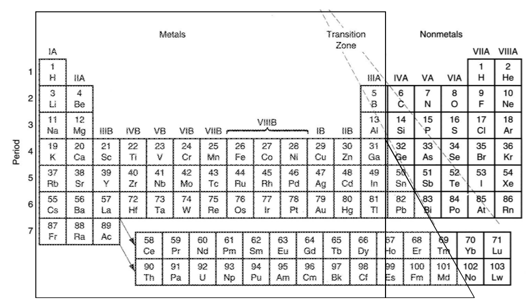
- Manufacturing is a transformation process
  - It is the material that is transformed
  - And it is the behavior of the material when subjected to the forces, temperatures, and other parameters of the process that determines the success of the operation

Element Groupings

The elements can be grouped into families and relationships established between and within the families by means of the Periodic Table

- Metals occupy the left and center portions of the table
- Nonmetals are on right
- Between them is a transition zone containing *metalloids* or *semi-metals*

Periodic Table



Periodic Table of Elements. Atomic number and symbol are listed for the 103 elements.

Structures of Matter

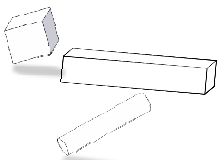
- Matter
  - Defined as anything that has mass and occupies space
    - Gas
    - Liquid
    - Solid
  - Stand alone element
  - Compound
    - Elements in combination with one another

Structures of Matter

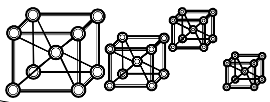
- Gases
  - No definite shape
  - No definite volume
    - Vapors
      - Expand and compress
  - Solutions
    - Mixtures of gases
    - *Miscible* – capable of being mixed
- Liquids
  - No definite shape
  - But has definite volume
  - Solutions
    - Mixtures of liquids
    - miscible
    - Oil and Water (*immiscible*) form a heterogeneous mixture

Structures of Matter

- Solids
  - Definite shape
  - Definite volume

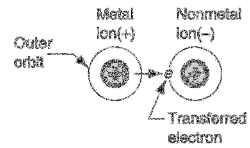


- Crystalline Structure
  - Atoms in a solid arranged in orderly geometric patterns



Ionic Bonding

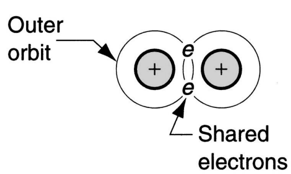
Atoms of one element give up their outer electron(s), which are in turn attracted to atoms of some other element to increase electron count in the outermost shell to eight



(a) Ionic

Covalent Bonding

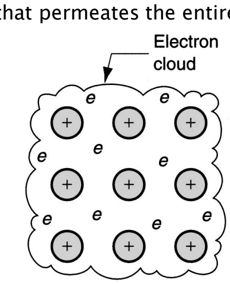
Electrons are shared (as opposed to transferred) between atoms in their outermost shells to achieve a stable set of eight



(b) Covalent

Metallic Bonding

Sharing of outer shell electrons by all atoms to form a general electron cloud that permeates the entire block



(c) Metallic

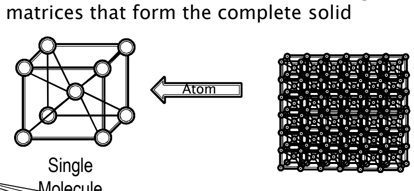
Crystalline Structure

Structure in which atoms are located at regular and recurring positions in three dimensions

- *Unit cell* – basic geometric grouping of atoms that is repeated
- The pattern may be replicated millions of times within a given crystal
- Characteristic structure of virtually all metals, as well as many ceramics and some polymers

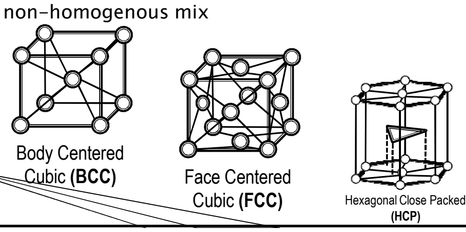
Metallurgic Properties

- From the broad spectrum:
  - materials are a matrix of microscopic balls that form the larger solid
  - each matrix of atoms then falls into organized matrices that form the complete solid



Metallurgic Properties

- Material properties are a function of multiple factors
  - Chemistry determines what atoms are available to make up the structure
  - Must be noted that the atoms are dispersed in a non-homogenous mix



Crystal Structures for Common Metals

Room temperature crystal structures for some of the common metals:

- Body-centered cubic (BCC)
  - Chromium, Iron, Molybdenum, Tungsten
- Face-centered cubic (FCC)
  - Aluminum, Copper, Gold, Lead, Silver, Nickel
- Hexagonal close-packed (HCP)
  - Magnesium, Titanium, Zinc

Temperature

- Different temperatures
  - Same material may change to form different structures (lower energy requirement)
- IRON
  - Forms **bcc** structure (alpha) below 912° C (1674° F) and above 1394° C (2541° F)
  - Forms **fcc** structure (gamma) between 912° C and 1394° C

Point Defects

Imperfections in crystal structure involving either a single atom or a few number of atoms

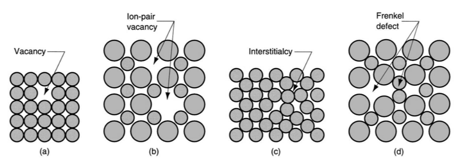


Figure 2.9 Point defects: (a) vacancy, (b) ion-pair vacancy, (c) interstitialcy, (d) displaced ion (Frenkel Defect).

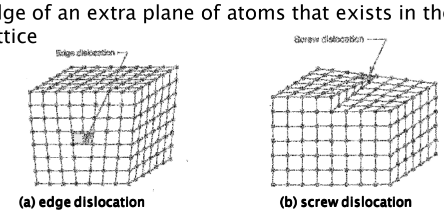
Line Defects

Connected group of point defects that forms a line in the lattice structure

- Most important line defect is a *dislocation*, which can take two forms:
  - Edge dislocation
  - Screw dislocation

Edge & Screw Dislocation

Edge of an extra plane of atoms that exists in the lattice



Spiral within the lattice structure wrapped around an imperfection line

Surface Defects

Imperfections that extend in two directions to form a boundary

- Examples:
  - External: the surface of a crystalline object is an interruption in the lattice structure
  -
  - Internal: grain boundaries are internal surface interruptions

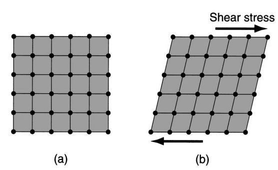
Deformation and Strength

- **Elastic deformation**
  - Returns to original shape when a force is removed
- **Plastic (permanent) deformation**
  - Does not return to original shape when force is removed

Elastic Strain

When a crystal experiences a gradually increasing stress, it first deforms *elastically*

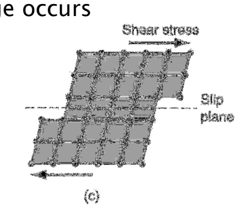
- If force is removed lattice structure returns to its original shape



Deformation of a crystal structure: (a) original lattice: (b) elastic deformation, with no permanent change in positions of atoms.

Plastic Strain

If stress is higher than forces holding atoms in their lattice positions, a permanent shape change occurs



Deformation of a crystal structure: (c) plastic deformation (*slip*), in which atoms in the lattice are forced to move to new "homes".

Stress-Strain Relationships

Three types of static stresses to which materials can be subjected:

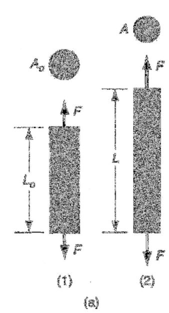
1. Tensile – tend to stretch the material
2. Compressive – tend to squeeze it
3. Shear – tend to cause adjacent portions of material to slide against each other

- Stress-strain curve – basic relationship that describes mechanical properties for all three types

Tensile Test

Most common test for studying stress-strain relationship, especially metals

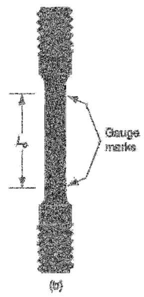
In the test, a force pulls the material, elongating it and reducing its diameter



Tensile test: (a) tensile force applied in (1) and (2) resulting elongation of material

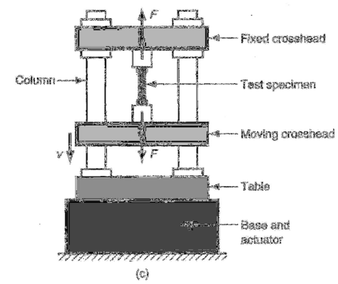
Tensile Test Specimen

ASTM (American Society for Testing and Materials) specifies preparation of test specimen



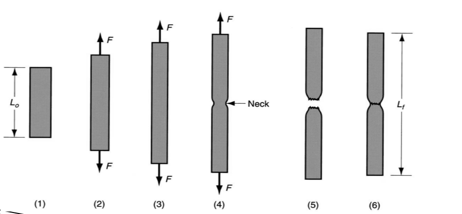
Tensile test:
(b) typical test specimen

Tensile Test Setup



Tensile Test Sequence

Typical progress of a tensile test: (1) beginning of test, no load; (2) uniform elongation and reduction of cross-sectional area; (3) continued elongation, maximum load reached; (4) necking begins, load begins to decrease; and (5) fracture. If pieces are put back together as in (6), final length can be measured.

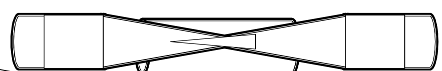


Metallurgic Terminology

- **<u>% of Elongation</u>** $= \dfrac{Lf - Lo}{Lo} x100$

- **L_f – final length** (in. [mm])
- **L_o – original gage length (in. [mm])**

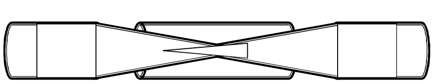
Ability of a material to plastically strain without fracture
Ductility measure = elongation EL



Metallurgic Terminology

- **<u>% of Reduction in Area</u>** $= \dfrac{Ao - Af}{Ao} x100$

- **A_o – original cross-sectional area** (in.^{2} [mm^2])
- **A_f – original gage length** (in.^{2} [mm^2])



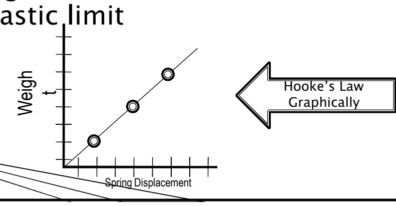
Two Regions of Stress-Strain Curve

The two regions indicate two distinct forms of behavior:

1. Elastic region – prior to yielding of the material
2. Plastic region – after yielding of the material

Metallurgic Terminology

- **Hooke's Law** –
  - approximation that states that the extension of a spring is in direct proportion with the load added to it as long as this load does not exceed the elastic limit

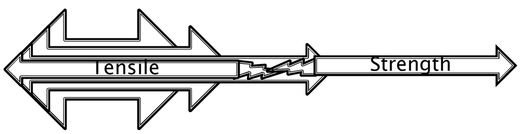


Metallurgic Terminology

- **Stress** –
  - the load, or amount of force, applied per unit area
- **Strain** –
  - Physical effect of stress
    - Evidenced by stretching or other deformation of the material
- **Yield Strength/ Point** –
  - Point where the material will continue to elongate without increase in the force applied and the stress level at which permanent deformation results

Metallurgic Terminology

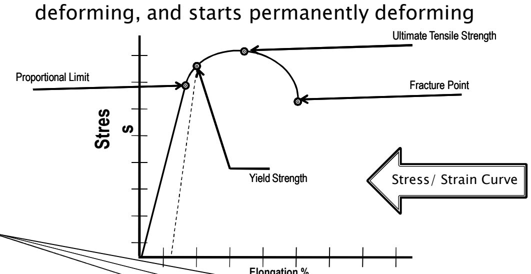
- **Tensile Strength** –
  - the maximum tensile load that can be applied before a material fractures by being pulled apart



- **Ultimate Tensile Strength** –
  - Maximum pulling force to which the material can be subjected without failure

Metallurgic Terminology

- **Yield Strength** –
  - The load at which the material stops elastically deforming, and starts permanently deforming



Metallurgic Terminology

- **Modulus of Elasticity (*E*)**–
  - Indicator of stiffness of a material

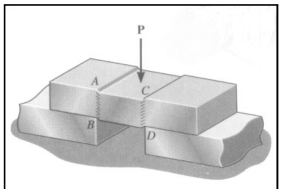
$$E = \frac{Stress}{Strain} = \frac{\sigma}{\varepsilon}$$

Strain Hardening in Stress-Strain Curve

- Note that true stress increases continuously in the plastic region until necking
  - In the engineering stress-strain curve, the significance of this was lost because stress was based on an incorrect area value
- It means that the metal is becoming stronger as strain increases
  - This is the property called *strain hardening*

Slip Planes

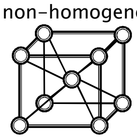
- Slipping one plane of atoms over an adjacent plane
- **Shear Stress**
  - Applied shearing force over the cross sectional area being sheared

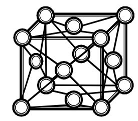


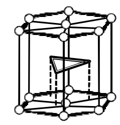
(a)

Metallurgic Properties

- Material properties are a function of multiple factors
  - Chemistry determines what atoms are available to make up the structure
  - Must be noted that the atoms are dispersed in a non-homogenous mix


Body Centered Cubic **(BCC)**


Face Centered Cubic **(FCC)**

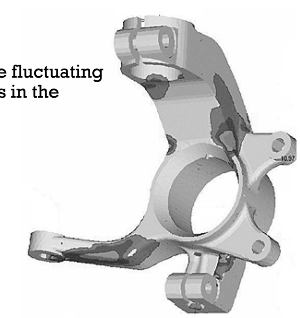

Hexagonal Close Packed **(HCP)**

Slip Systems

- **BCC**
  - 48 possible slip systems
  - High probability that external shear stress will cause a slip
  - Generally have good strength and moderate ductility
- **FCC**
  - 12 possible slip systems
  - Moderate probability of slip
  - Generally have moderate strength and good ductility
- **HCP**
  - 3 possible slip systems
  - Low probability of slip (elevated temperatures increase number of systems)
  - Material is generally brittle at room temperature

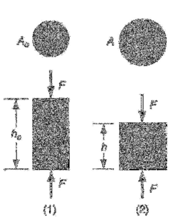
Fatigue

Fatigue
- Failure due to excessive fluctuating forces that cause cracks in the material



Compression Test

Applies a load that squeezes the ends of a cylindrical specimen between two platens

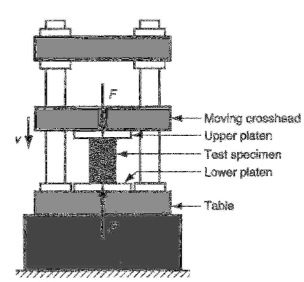


(a)

Compression test:

(a) compression force applied to test piece in (1) and (2) resulting change in height.

Compression Test Setup



(b)

Testing of Brittle Materials

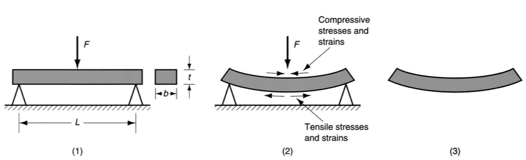
- Brittle materials do not flex
- They deform elastically until fracture
  - Failure occurs because tensile strength of outer fibers of specimen are exceeded
  - Failure type: *cleavage* - common with ceramics and metals at low temperatures, in which separation rather than slip occurs along certain crystallographic planes

Testing of Brittle Materials

- Hard brittle materials (e.g., ceramics) possess elasticity but little or no plasticity
- Often tested by a *bending test* (also called *flexure test*)
  - Specimen of rectangular cross-section is positioned between two supports, and a load is applied at its center

Bending Test

Figure 3.10 Bending of a rectangular cross-section results in both tensile and compressive stresses in the material: (1) initial loading; (2) highly stressed and strained specimen; and (3) bent part.



Mechanical Properties in Design and Manufacturing

Mechanical properties determine a material's behavior when subjected to mechanical stresses

- Properties include elastic modulus, ductility, hardness, and various measures of strength

- *Dilemma: mechanical properties desirable to the designer, such as high strength, usually make manufacturing more difficult*
  - The manufacturing engineer should appreciate the design viewpoint
  - And the designer should be aware of the manufacturing viewpoint

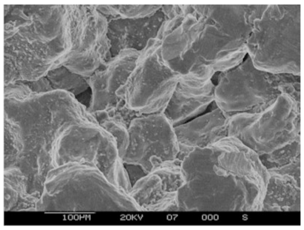
Metallurgic Properties

- If solids were made of single well organized molecules they would be significantly stronger
- Unfortunately, small *deformations* and *cracks* **weaken** materials which result in numerous engineering problems
- Solids usually fail because cracks form, and then quickly propagate through solids.
  - The chemistry and non-homogenous structure that can slow or stop these cracks as well as the composition determines how stiff the material is

Grains and Grain Boundaries in Metals

- How do polycrystalline structures form?
  - As a block of metal cools from the molten state and begins to solidify, individual crystals nucleate at random positions and orientations throughout the liquid
  - These crystals grow and finally interfere with each other, forming at their interface a surface defect - a *grain boundary*
  - Grain boundaries are transition zones, perhaps only a few atoms thick

Failures and Fractures



Transgranular
- Crack propagates *through* the grain

Intergranular fracture
- Crack propagates *along* the grain boundary

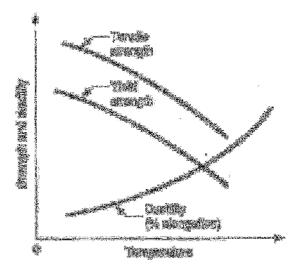
Metallurgic Terminology

- **Brittleness** –
  - the tendency of a material to break before it undergoes plastic deformation
- *Plastic Deformation –*
  - Deforming a material under the action of a force/load and not returning to its original shape once the force/load is removed
  - **Creep** – slow deformation of a material under prolonged stress over time

Metallurgic Terminology

- **Ductility** –
  - the ability of certain materials to be plastically deformed without fracture/failure
    - *Failure – can mean cracking or even surface blemishes depending on the application*
- **Elasticity** –
  - The ability to deform and return to the un-deformed shape
    - Hooke's law

Effect of Temperature on Properties



General effect of temperature on strength and ductility.

Metallurgic Terminology

- **Hardness** –
  - the resistance to deformation and forced penetration
- **Malleablility** –
  - the ability of a material to take a new shape when hammered or rolled without rupturing
- **Toughness** –
  - The ability to withstand cracking, as opposed to brittleness, or shock of a rapidly applied load
- **Machinability** –
  - How easy the material can be machined

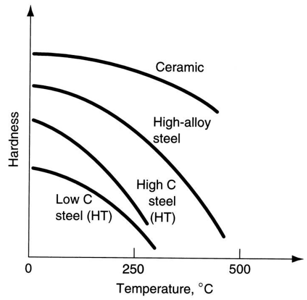
Hardness

Resistance to permanent indentation

- Good hardness generally means material is resistant to scratching and wear
- Most tooling used in manufacturing must be hard for scratch and wear resistance

Hot Hardness

Ability of a material to retain hardness at elevated temperatures



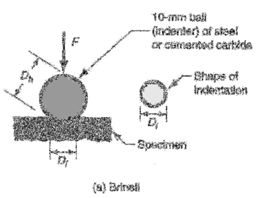
Hardness Tests

- Commonly used for assessing material properties because they are quick and convenient
- Variety of testing methods are appropriate due to differences in hardness among different materials
- Most well-known hardness tests are *Brinell* and *Rockwell*
- Other test methods are also available, such as Vickers, Knoop, Scleroscope, and durometer

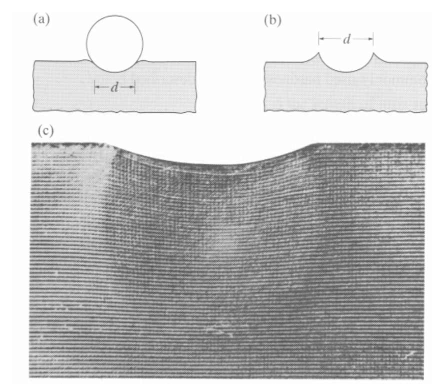
Brinell Hardness Test

Widely used for testing metals and nonmetals of low to medium hardness

A hard ball is pressed into specimen surface with a load of 500, 1500, or 3000 kg



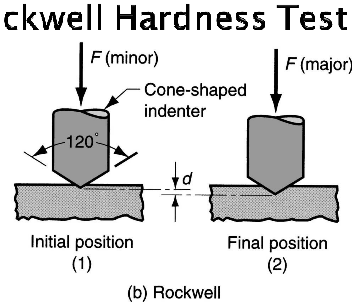
Hardness testing methods: (a) Brinell



Rockwell Hardness Test

- Another widely used test
- A cone shaped indenter is pressed into specimen using a minor load of 10 kg, thus seating indenter in material
- Then, a major load of 150 kg is applied, causing indenter to penetrate beyond its initial position
- Additional penetration distance *d* is converted into a Rockwell hardness reading by the testing machine

Rockwell Hardness Test



Hardness testing methods: (b) Rockwell: (1) initial minor load and (2) major load.

Summary: Characteristics of Metals

- Crystalline structures in the solid state, almost without exception
- BCC, FCC, or HCP unit cells
- Atoms held together by metallic bonding
- Properties: high strength and hardness, high electrical and thermal conductivity
- FCC metals are generally ductile