Material Properties

Chapter 11
Structure of Matter

- *Matter* can be defined as anything that has mass and occupies space.

- May consist of one element alone, or elements in combinations called *compounds*.
3 States of Matter

- **Gases**: Substances that have no definite shape and no definite volume.

- **Liquids**: Substances that have no definite shape, but do have a definite volume.

- **Solids**: Substances that have a definite shape and definite volume.
Special Temperature Condition

F 11-1 Phase diagram
Properties

• Chemical properties involve the ways substances act when the amounts or nature of the substances change.

• Physical properties are related to any change in which the amounts or nature of the substances do not change.
Physical Properties of Materials

- Color
- Density
- Electrical conduction
- Magnetism
- Melting temperature
- Thermal conduction
- Thermal expansion
- Specific gravity
- Specific heat
Mechanical Properties

- Brittleness
- Compressive strength
- Creep
- Ductility
- Elastic limit
- Elasticity
- Elongation
- Endurance limit
- Fatigue failure
- Fatigue strength
- Hardness
- Impact strength
- Load
- Malleability
- Mechanical property
- Modulus of elasticity
- Notch toughness
- Physical property
- Plasticity
- Proportional limit
- Strain
- Strength
- Stress
- Tensile strength
- Toughness
- Ultimate tensile strength
- Yield point
- Yield strength
Stress-Strain Diagram

F 11-2 Ductile steel
Stress-Strain Diagram

F 11-3 Brittle material
• 1. Low carbon steel, a ductile material with a yield point
• 2. A ductile material, such as aluminum alloy, which does not have a yield point.
• 3. A brittle material, such as cast iron or concrete in compression.

Stress Strain Curves
3 Most Examined Properties

• Ductility
• Hardness
• Toughness
Ductility

• Is the property which enables a metal to be bent, twisted, drawn out, or changed in shape without breaking.
  – 3 types
    • 1. Tension
    • 2. Compression
    • 3. Shear
  – Measured by tensile strength
Hardness

• Resistance to penetration
  
  • Most tested mechanical property

• Measured by:
  – Brinell
  – Rockwell
  – Shore scleroscope (elasticity)
Brinell Hardness Test

- Measured by the diameter of the dent with a microscope
- Used on nonferrous, soft, and medium-hard steel.
- BHN ranges from 150 for soft, low carbon steel to BHN of 730+ for hardened, high carbon steel.

\[
\text{BHN} = \frac{L}{(\pi \times \frac{D}{2})(D - \sqrt{D^2-d^2})}
\]
Rockwell Hardness Test

- Based on the depth of penetration made in metal by a penetrator point under a given load.
- Rockwell-B (RB) scale uses a 1.5mm diameter ball made of hardened steel. Used for testing unhardened steel, cast iron, and nonferrous metal.
- Rockwell-C (RC) scale requires a diamond point penetrator.
- Used for testing the hardness of heat-treated or hardened steels.
- The hardness is read from either a dial or digital readout.
FIGURE 44-3  LINEAR PENETRATION—BASIS OF ROCKWELL HARDNESS TEST READINGS
Shore Scleroscope Testing

– Operates on the rebound principle

– Considered a nonmarring test

– Hardness number is read directly on a dial
Direct-reading dial on sclerooscope with equivalent Rockwell C Scale and Brinell Hardness numbers.
Toughness

• The ability to absorb energy from impact
  • Measured by:
    – Charpy test
    – Izod test
Charpy Test

139-4. Specimen mounted for Charpy impact-toughness test.
Charpy Impact Testing
Izod Test

Fig. 139-3. Specimen mounted for Izod impact-toughness test.
Izod Impact Testing
Metals

Chapter 12
Metals

• Metals generally are:
  – Solid at room temperature
  – Good conductors of heat
  – Good conductors of electricity
  – Shiny and become reflective when smooth
  – Malleable and ductile
Crystalline Structures

Body-Centered Cubic

Face-Centered Cubic

Hexagonal Close Packed
Crystalline Grain Structure

F 12-2 Growth of crystalline grains
Cooling Curve

F 12-3 Cooling curve of a pure metal
Cooling Curve

F 12-4 Cooling curve of an alloy
Type 1 Equilibrium Diagram

F 12-5 Phase diagram of an alloy
Type 2 Equilibrium Diagram

F 12-6 Phase diagram of an alloy with a eutectic point
F 12-7 Iron-carbon diagram

α = ferrite (iron)
γ = austenite
Fe₃C = cementite (iron carbide)
pearlite = mixture of α + Fe₃C

A₁ = eutectoid temperature to left of eutectoid point
A₃ = boundary between γ and α + γ
A₃,₁ = eutectoid temperature to right of eutectoid point (same as A₁)
A₂m = limit of solubility of carbon in γ
Heat Treatment Processes

- Heating and cooling of metals in a solid state without altering their chemical composition.
- Hardening
- Annealing (Softening)
Severity of Quenching
(The faster the cooling, the higher the hardness)

<table>
<thead>
<tr>
<th>Relative Severity</th>
<th>Quenching Media</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Agitated brine</td>
</tr>
<tr>
<td>1</td>
<td>Still water</td>
</tr>
<tr>
<td>0.3</td>
<td>Still oil</td>
</tr>
<tr>
<td>0.02</td>
<td>Still air</td>
</tr>
</tbody>
</table>
Heat Treatment Processes

- Heating and cooling according to a time-temperature cycle by
  - A. Heating to prescribed temperature
  - B. Holding at temperature (soaking)
  - C. Cooling at a prescribed rate of quenching in air, water, oil, or brine
Heat Treatment Improves

- Tensile Strength
- Formability
- Toughness
- Bending
- Wear Resistance
- Magnetic Property
- Machinability
- Corrosion Resistance
Heat Treatment Processes

- **Surface Hardening**
  - Carburizing
  - Cyaniding
  - Nitriding
  - Flame hardening
  - Induction hardening

- **Annealing**
  - Full annealing
  - Spheroidize annealing
  - Stress relief annealing
  - Normalizing
  - Tempering
Steel Alloy Elements

- Carbon
- Chromium
- Cobalt
- Lead
- Molybdenum
- Nickel
- Vanadium

See Table 12-2
# Steel Alloying Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>Improves hardenability, strength, and wear resistance. Reduces ductility and weldability.</td>
</tr>
<tr>
<td>Chromium</td>
<td>Improves toughness, wear and corrosion resistance, and high-temperature strength.</td>
</tr>
<tr>
<td>Cobalt</td>
<td>Improves strength and hardness at elevated temperatures.</td>
</tr>
<tr>
<td>Lead</td>
<td>Improves machinability. Causes embrittlement.</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>Improves hardenability, wear resistance, toughness, elevated temperature strength, and creep resistance.</td>
</tr>
<tr>
<td>Nickel</td>
<td>Improves strength, toughness, and corrosion resistance.</td>
</tr>
<tr>
<td>Vanadium</td>
<td>Improves strength, toughness, abrasion resistance, and hardness at elevated temperatures.</td>
</tr>
</tbody>
</table>
Characteristics of AISI-SAE Steel Series

<table>
<thead>
<tr>
<th>AISI Number</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>10XX</td>
<td>Plain carbon</td>
</tr>
<tr>
<td>13XX</td>
<td>Manganese—increases strength in as-rolled state and increases ductility after heat treatment</td>
</tr>
<tr>
<td>23XX-25XX</td>
<td>Nickel—increases tensile strength without loss of ductility</td>
</tr>
<tr>
<td>3XXX</td>
<td>Nickel/chromium—tough and ductile due to nickel, wear and corrosion due to chromium</td>
</tr>
<tr>
<td>4XXX</td>
<td>Molybdenum—significant increase in tensile strength and hardenability</td>
</tr>
<tr>
<td>5XXX</td>
<td>Chromium—high wear resistance</td>
</tr>
<tr>
<td>6XXX</td>
<td>Chromium/vanadium—high yield strength, good fatigue properties</td>
</tr>
<tr>
<td>8XXX-9XXX</td>
<td>Chromium/nickel/molybdenum—exhibits benefits of each</td>
</tr>
</tbody>
</table>
Stainless Steels

• Austenitic

• Ferritic

• Martensitic

See Table 12-4
Austenitic

- Nonmagnetic and cannot harden by heat treatment
- Hardened by cold working and has superior corrosion resistance
- Most ductile type of stainless steel
- Applications: kitchen utensils, fittings, and welded construction
Ferritic

• Magnetic and cannot harden by heat treatment
• Good corrosion resistance
• Less ductile than austenitic stainless steel
• Applications: nonstructural in corrosive environments
Martensitic

- Magnetic and are hardenable by heat treatment
- Moderate corrosion resistance
- Do not contain nickel
- Applications: valves, springs, and cutlery
Characteristics of AISI-SAE Stainless Steel Series

<table>
<thead>
<tr>
<th>AISI Number</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>2XX</td>
<td>Chromium/nickel/manganese composition, nonhardenable by heat treatment, austenitic and nonmagnetic</td>
</tr>
<tr>
<td>3XX</td>
<td>Chromium/nickel composition, nonhardenable by heat treatment, austenitic and nonmagnetic</td>
</tr>
<tr>
<td>4XX</td>
<td>Chromium composition, hardenable by heat treatment, martensitic and magnetic or nonhardenable by heat treatment, ferritic and magnetic</td>
</tr>
<tr>
<td>5XX</td>
<td>Low chromium composition, hardenable by heat treatment and martensitic</td>
</tr>
</tbody>
</table>
Cast Iron

• Contains 2%-6.67% carbon
• Very brittle
• Low-melting temperature therefore easy to pour into complex shapes
Basic Types of Cast Iron

- Gray
- White
- Malleable
- Nodular
Aluminum

- Characteristics
  - High strength to weight ratio
  - Resistance to corrosion
  - High thermal and electrical conductivity
  - Appearance
  - Machinability and formability

- Two Types
  - Wrought aluminum alloys (See table 12-5, p. 104)
  - Cast aluminum alloys (See table 12-6, p. 105)
## Aluminum Casting Alloys

<table>
<thead>
<tr>
<th>Number</th>
<th>Alloy</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1XX.X</td>
<td>Commercially pure</td>
<td>Corrosion resistant</td>
</tr>
<tr>
<td>2XX.X</td>
<td>Copper</td>
<td>High strength and ductility</td>
</tr>
<tr>
<td>3XX.X</td>
<td>Silicon</td>
<td>Good machinability (with copper or magnesium)</td>
</tr>
<tr>
<td>4XX.X</td>
<td>Silicon</td>
<td>Good castability, corrosion resistant</td>
</tr>
<tr>
<td>5XX.X</td>
<td>Magnesium</td>
<td>High strength</td>
</tr>
<tr>
<td>6XX.X</td>
<td>Unused</td>
<td></td>
</tr>
<tr>
<td>7XX.X</td>
<td>Zinc</td>
<td>High strength, excellent machinability</td>
</tr>
</tbody>
</table>
Aluminum Heat Treatment Processes

- Strain hardening (Cold Working)
- Annealing
- Solution heat treatment
- Precipitation hardening
Advantages of Plastics

- Adapting to mass production at a comparatively low cost.
- Resistance to corrosion, solvents, water, etc.
- Quiet, smooth movement with limited, if any, lubrication required.
- Qualities of an electrical and thermal insulator.
- Light mass and great range of translucent and opaque colors.
- High quality of surface finish
- Availability in solid form as powder, granules, sheets, tubes, and castings, or in liquid forms as adhesives.
Plastics

• Types
  – Thermosetting: Chemical bonding by cross-links in their molecular chain structure
    • Cannot be easily reprocessed
  – Thermoplastic: Has a linear chemical bond in its molecular structure
    • Can be reformed
Polymerization

• Polymerization: The process brings together small molecules and forces them to chemically combine with each other.

• Chemicals required for production:
  – A. Crude oil
  – B. Natural gas supply
Polymerization

F 13-1 Gas to a solid plastic
Polymer Structures
(Three Most Common)

• Homopolymers
• Copolymers
• Terpolymers
Homopolymer

- Consists of one building block or monomer.
- Most common types: polyethylene, polypropylene, polyvinyl chloride, and polystyrene
- Can be either amorphous or semicrystalline line arrangements of their molecular chains
Copolymers

- Copolymers contain two chemically different mers
- Common types: Polysytrene (PS), and polyvinyl chloride (PVC)
- Can be either amorphous or semicrystalline line arrangements of their molecular chains
Terpolymers

• Three basic mers combine to create a polymer
• Common types: Acrylic, styrene, acrylonitrile (ASA) monomers
• May have amorphous or semicrystalline arrangements
Commodity Thermoplastics Types

- Polyethylene (PE)
- Polypropylene (PP)
- Polyvinyl Chloride (PVC)
- Polystyrene (PS)
- Polyethylene Terphalate (PETE)
Engineering Thermoplastics

Properties

• Thermal, mechanical, chemical, and corrosion resistance, and usability
• Ability to sustain high mechanical loads, in harsh environments, for long periods of time
• Predictable, reliable, and polycarbonate
Most Common

• Nylon

• Acetal-Polyphenylene Oxide (PPO)

• Polycarbonate
Rubber

- Origin: Hevea Brasiliensis Tree
- Properties: Higher resilience and generates less heat than synthetic rubber
Synthetic Rubber

- Products are copolymers of a diene monomer and an additive such as styrene or acrylonitrile

- Properties: Superior to natural rubber in abrasion resistance
Four Dominate Hard Thermosets

- Phenolics
- Urea-Formaldehydes
- Epoxides
- Polyesters
Four Dominate Hard Thermosets

- Phenolics: Hard heat resistant and dark in color
- Urea-formaldehydes: Cheaper and lighter in color than phenolics
- Epoxides: Tough and high adhesion properties
- Polyesters: Forms the matrix that bonds many composite materials together
Composites

Chapter 14
Composites

- Two or more materials - a reinforcing element and a resin binder (Matrix)
  - Holds the fibers in place
  - Deforms and distributes the stress to the fibrous constituent
  - Separate components still physically identified
  - Do not chemically merge
Composite Categories

- **Laminates**: Consists of layers bonded together

- **Sandwiches**: Multiple-layer structure materials containing a low density core between thin faces of composite materials
Sandwich Construction

F 14-2 (Bakerjain and Mitchell, 1992)
Advanced Composites
Fabrication Methods

• Lamination: Flat pieces
• Filament winding: Drawing fibers through a resin bath and wound on a mandrel. Round or cylindrical objects from pressure bottles to drive shafts.
• Pultrusion: Equivalent of metal extrusion, can be used for complex parts with constant cross sections (tubing - channels).
• Resin Transfer Molding
Ceramics

• An inorganic compound containing metals, semimetals, and nonmetals
• Ionic bonds are extremely strong and stable
• Complex crystalline structure compared to metals
Ceramics Materials

- Clay based: bricks, tiles, porcelain, stoneware, and earthenware
- Glass: windowpanes, lenses, bottles, and fibers
- Cement: construction and roadways
- Abrasives and grinding wheels
- Cutting tools: tungsten carbide
Corrosion Resistance of Ceramics

<table>
<thead>
<tr>
<th></th>
<th>Hydrochloric Acid</th>
<th>Hydrofluoric Acid</th>
<th>Hot Sodium Hydroxide</th>
<th>Fused Sodium Hydroxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>A</td>
<td>D</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>Quartz</td>
<td>A</td>
<td>D</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>Aluminum oxide (99.5%)</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>Mullite</td>
<td>A</td>
<td>C</td>
<td>D</td>
<td>D</td>
</tr>
<tr>
<td>Zirconium oxide</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Silicon carbide (sintered)</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>A</td>
<td>C</td>
<td>A</td>
<td>C</td>
</tr>
<tr>
<td>Titanium diboride</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
</tbody>
</table>

Key: A: No reaction  
B: Slight reaction  
C: Appreciable attack  
D: Dissolves

(Bakerjian and Mitchell 1992)

F 15-1 (Bakerjian and Mitchell, 1992)
## Advanced Ceramic Materials Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Alumina</th>
<th>Partially Stabilized Zirconia</th>
<th>Mullite</th>
<th>Silicon Carbide</th>
<th>Silicon Nitride</th>
<th>Titanium Diboride</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, lb/in.(^3) (g/cc)</td>
<td>0.141</td>
<td>0.208</td>
<td>0.101</td>
<td>0.11</td>
<td>0.11</td>
<td>0.162</td>
</tr>
<tr>
<td></td>
<td>(3.90)</td>
<td>(5.75)</td>
<td>(2.80)</td>
<td>(3.1)</td>
<td>(3.1)</td>
<td>(4.48)</td>
</tr>
<tr>
<td>Color</td>
<td>White</td>
<td>Ivory</td>
<td>Tan</td>
<td>Black</td>
<td>Gray</td>
<td>Black</td>
</tr>
<tr>
<td>Flexural strength, ksi (MPa)</td>
<td>55</td>
<td>90</td>
<td>25</td>
<td>80</td>
<td>80</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>(379)</td>
<td>(620)</td>
<td>(172)</td>
<td>(552)</td>
<td>(552)</td>
<td>(345)</td>
</tr>
<tr>
<td>Elastic modulus, Mpsi (GPa)</td>
<td>54</td>
<td>35</td>
<td>22</td>
<td>58</td>
<td>40</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>(372)</td>
<td>(241)</td>
<td>(152)</td>
<td>(400)</td>
<td>(276)</td>
<td>(538)</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>0.20</td>
<td>0.22</td>
<td>0.19</td>
</tr>
<tr>
<td>Hardness, kg/mm(^2)</td>
<td>1,440</td>
<td>1,200</td>
<td>750</td>
<td>2,800</td>
<td>1,500</td>
<td>2,700</td>
</tr>
<tr>
<td>Fracture toughness, MPa × m(^0.5)</td>
<td>3.5</td>
<td>12</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Coefficient of thermal expansion, (10^{-6}) F (10^{-6}) C</td>
<td>4.6</td>
<td>5.7</td>
<td>2.9</td>
<td>2.4</td>
<td>1.7</td>
<td>4.6</td>
</tr>
</tbody>
</table>

F 15-2 (Bakerjian and Mitchell, 1992)