Nonmetallic Materials: Plastics, Elastomers, Ceramics, and Composites

Chapter 9
9.1 Introduction

• Wood has been a key engineering material throughout human history
  – Ways to manufacture specific types of woods are well established
• Stone, rock, and clay are also historically important construction materials
• Plastics, elastomers, ceramics, and composites have become important materials
  – Can be manufactured so that a wide range of properties may be obtained
9.2 Plastics

- Plastics are engineered materials
  - Large molecules that are composed of smaller molecules
  - Made from natural or synthetic resins and compounds
  - Can be molded, extruded, cast, or used for coatings
  - Low density, low tooling costs, good corrosion resistance, low cost
  - Plastics are very versatile materials and are used more than steel, aluminum, and copper combined in the United States
  - Used in applications such as cars, artificial organs, shower curtains, contact lenses, computers, etc.
Molecular Structure of Plastics

• Hydrocarbons
  – \( C_nH_{2n+2} \)
  – Covalent bonding
  – When no additional atoms can be added to the chain, the molecule is said to be saturated
  – Double or triple covalent bonds may also be present
  – Common hydrocarbons
    • Ethylene and acetylene
    • Unsaturated- do not have the maximum number of hydrogen atoms

• Polymerization
  – Small molecules link to form larger molecules with the same constituent atoms
Examples of Hydrocarbons

**Figure 8-1** (Right) The linking of carbon and hydrogen to form methane and ethane molecules. Each dash represents a shared electron pair or covalent bond.

**Figure 8-2** (Left) Double and Triple covalent bonds exist between the carbon atoms in unsaturated ethylene and acetylene molecules.
Isomers

• The same type and kind of atoms can arrange themselves in multiple configurations
• Different structures have different engineering properties

Figure 8-3 Linking of eight hydrogen, one oxygen, and three carbon atoms to form two isomers: propyl alcohol and isopropyl alcohol.
Forming Molecules by Polymerization

- Molecules can be linked by addition or condensation methods
- Monomers are the basic building blocks
- Monomers can be linked together to produce polymers
- Increasing the chain length increases toughness, creep resistance, melting temperature, melt viscosity, and difficulty in processing
- Copolymers are similar to alloys in metals when two monomers are combined
- Condensation polymerization occurs when a polymer is formed plus byproducts (such as water)
Copolymerization and Condensation Polymerization

Figure 8-5 (Right) Addition of Polymerization with two kinds of mers- here, the copolymerization of butadiene and styrene

Figure 8-6 (Below) The formation of phenol-formaldehyde by condensation polymerization
Thermosetting and Thermoplastics

• Thermosets and thermoplastics are classified based on their response to heat
  – Internal bonding is covalent
  – Intermolecular bonds are van der Walls forces

• Linear polymers are typically flexible and tough
  – Soften with increasing temperature
  – Slide over each other in molding processes
Thermoplastics

• Contain molecules of different lengths
• Do not have a definite melting temperature
• Above the melting temperature, the material can be poured and cast
  – Additionally, injection molding
• Application of a force deforms the material both elastically and plastically
  – Plastic deformation occurs by adjacent fibers and chains slipping past one another
Thermoplastics

• If cooled below the melting temperature, thermoplastics crystallize
  – Polymer becomes stiffer, harder, less ductile, and more resistant to solvents and heat

• Common thermoplastics
  – Polyethylene (PE)
  – Polypropylene (PP)
  – Polystyrene (PS)
  – Polyvinyl Chloride (PVC)
Thermosets

• Highly cross-linked
• Three-dimensional framework connected by covalent bonds
• Typically produced by condensation polymerization
  – Elevated temperatures produce an irreversible reaction
  – Once set, subsequent heating will not soften the material
Thermosets

- Significantly stronger and more rigid than thermoplastics
- Able to resist higher temperatures
- Greater dimensional stability
- Lower ductility
- Poorer impact properties
- Heating changes their structure permanently
- The setting time is very important because it cannot be repeated
Properties and Applications of Plastics

- Light weight
- Corrosion resistance
- Electrical resistance
- Low thermal conductivity
- Variety of optical properties
- Formability
- Surface finish
- Low cost
- Low energy content
Plastics vs. Metals

- Unless they are in the form of composites, plastics do not have strength properties close to the engineering metals.
- Inferior dimensional stability to metals.
- Coefficient of thermal expansion is higher for plastics.
- Good corrosion resistance.
- UV and radiation can alter plastics’ properties.
- Plastics are difficult to repair.
Applications of Plastics

- Almost any color material is possible with plastics
- Used in packaging and containers
- Household appliances, clock cases, exteriors of electronic products
- Cushioning materials
- Rigid foams are used in sheet metals for compressive strength
- Gears, lenses, safety helmets and unbreakable windows
Common Types or Families of Plastics

- Table 8-1 lists common properties of plastics
- Thermoplastics
  - ABS
  - Nylon
  - Polyethylene
  - Polypropylene
  - Polystyrene
  - Polyvinyl Chloride
  - Vinyl
- Thermosets
  - Epoxies
  - Polyesters
  - Silicones
Additive Agents in Plastics

• Additional materials may be added to plastics for the following purposes
  – Impart or improve properties
  – Reduce cost
  – Improve moldability
  – Adds color

• Classified as fillers, reinforcements, plasticizers, lubricants, coloring agents, stabilizers, antioxidants, and flame retardants
Additives

• Fillers
  – Improve strength, stiffness, and toughness
  – Reduce shrinkage and weight
  – Common fillers: wood flour, cloth fibers, macerated cloth, glass fibers, mica, calcium carbonate

• Coloring agents
  – Dyes are soluble and pigments are insoluble

• Plasticizers
  – Added in small amounts to reduce viscosity
Additives

• Lubricants
  – Improve moldability
  – Facilitates part removal
• Stabilizers and antioxidants
  – Retard the effects of heat, light, and oxidation
• Antimicrobial
  – Long-term protection from bacteria and fungus
• Fibers
  – Increase strength and stiffness
Summary of Additives

<table>
<thead>
<tr>
<th>Type</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fillers</td>
<td>Enhance mechanical properties, reduce shrinkage, reduce weight, or provide bulk</td>
</tr>
<tr>
<td>Plasticizer</td>
<td>Increase flexibility, improve flow during molding, reduce elastic modulus</td>
</tr>
<tr>
<td>Lubricant</td>
<td>Improve moldability and extraction from molds</td>
</tr>
<tr>
<td>Coloring agents (dyes and pigments)</td>
<td>Impart color</td>
</tr>
<tr>
<td>Stabilizers</td>
<td>Retard degradation due to heat or light</td>
</tr>
<tr>
<td>Antioxidants</td>
<td>Retard degradation due to oxidation</td>
</tr>
<tr>
<td>Flame retardants</td>
<td>Reduce flammability</td>
</tr>
</tbody>
</table>
Additional Plastics

• Oriented plastics
  – Processing aligns the molecules in parallel give the material higher strength
  – May be stretched, rolled, or extruded
  – If thermoplastics are heated, molecules tend to revert back to their original orientation (viscoelastic memory)

• Engineering plastics
  – Enhanced impact and stress resistance
  – High rigidity, superior electrical resistance, excellent processing properties
  – Polyamides, polyacetals, polyketones, etc.
Additional Plastics

• Plastics as adhesives
  – May be used to bond metals to nonmetals
  – Hot-melt glues
  – Two-part epoxies

• Plastics for tooling
  – Jigs, forming-dies

• Foamed plastics
  – Incorporate gases in their structure
  – Cushioning in upholstery and automobile seats
  – Flotation devices, insulation, disposable food trays

• Polymer coatings
  – Enhance appearance and provide corrosion resistance
Additional Considerations

• Plastics have replaced many other materials
  – Glass with transparent plastics
  – Copper and brass piping with PVC
• Due to weight concerns in automobiles, plastics have replaced many components
• Recycling of plastics
  – Materials must be sorted based on resin type, fillers, and color
  – Packaging is the largest usage for plastics
  • PET, HDPE, PE, PS
8.3 Elastomers

• Linear polymers that have large amounts of plastic deformation
  – Return to their original shape when the load is removed

• Cross-linking restricts the viscous deformation; retains the elastic response

• Rubber
  – Natural and synthetic
  – Charles Goodyear discovered vulcanization
  – Natural rubbers have good flexibility, good electrical insulation, low internal friction, and resistance to most inorganic acids, salts, and alkalis
  – Poor resistance to oil, gasoline, and other petroleum products
Artificial Elastomers

- Natural rubbers are expensive, so many artificial or synthetic rubbers have been developed.
- Can be classified as thermoplastics or thermosets.
- Thermosets are formed using vulcanization.
- Thermoplastics are formed using injection molding, extrusion, blow molding, etc.
Selection of an Elastomer

• Used in applications that require
  – Shock absorption
  – Noise and vibration control
  – Sealing
  – Corrosion resistance
  – Abrasion protection
  – Friction
  – Insulation
  – Waterproofing
  – Table 8-5 lists common elastomers
8.4 Ceramics

- Traditional materials
  - Brick, pottery

- Typical properties
  - High temperature usage
  - Hard and brittle
  - High melting point
  - Low thermal expansion
  - Good creep resistance
  - High compressive strength
Nature and Structure of Ceramics

• Compounds of metallic and nonmetallic elements
• Primary bonds have high strength
  – High melting temperatures
  – High rigidity
  – High compressive strength
• Noncrystalline structures are possible
  – Amorphous condition is observed in glasses
• Both crystalline and noncrystalline ceramics are brittle
• Clay and whiteware are commonly used ceramics
Special Ceramics

- **Refractory materials**
  - Ceramics that have been designed to provide mechanical or chemical properties at high temperatures
  - Three categories
    - Acidic, basic, and neutral

- **Abrasives**
  - Ceramics have high hardness
  - Can be used in grinding applications
  - Diamond and cubic boron nitride are superabrasives

- **Ceramics may be used for electrical and magnetic applications**
  - Dielectric, piezoelectric, and ferroelectric properties
Special Ceramics

• Glasses
  – Soft and moldable when hot; easily shaped
  – Strong in compression but brittle and weak in tension
  – Excellent corrosion resistance

• Cermets are combinations of metals and ceramics
  – Crucibles, nozzles, aircraft brakes

• Cements
  – Plaster of paris

• Ceramic coatings
  – Enamels, porcelains, glazes
Ceramics for Mechanical Applications

- Ceramics have strong ionic or covalent bonds
  - Most ceramics have small cracks, pores, and impurities
  - Act as mechanical stress concentration points

- Advanced ceramics
  - Alumina
  - Silicon carbide
  - Sialon
  - Zirconia

- Advanced ceramics may be used as cutting tools
Advanced Ceramics

Figure 8-8 Gas-turbine rotors made of silicon nitride. The lightweight material (one-half the weight of stainless steel) offers strength at elevated temperature as well as excellent resistance to corrosion and thermal shock. (Courtesy of Wesgo Division, GTE, Hayward, CA.)

Figure 8-9 A variety of components manufactured from silicon nitride, including an exhaust valve and turbine blade. (Courtesy of Wesgo Division, GTE, Hayward, CA.)
8.5 Composite Materials

• Nonuniform solid consisting of two or more different materials
  – Mechanically or metallurgically bonded
  – Each of the constituent materials maintains its identity

• Properties depend on:
  – Properties of individual components
  – Relative amounts
  – Size, shape, and distribution
  – Orientation
  – Degree of bonding
Laminar or Layered Composites

- Distinct layers of materials
- Layers are bonded together
- Typical example is plywood
- Bimetallic strips have two metals with different coefficients of thermal expansion
- Sandwich materials

*Figure 8-11* Schematic of a bimetallic strip where material A has the greater coefficient of thermal expansion.
Particular Composites

- Consist of discrete particles of one material in a matrix of another material
  - Concrete
- Dispersion strengthened materials have a small amount of hard, brittle particles in a soft, metal matrix
- True particulate composites have large amount of coarse particles
- Metal-matrix composites
Fiber-Reinforced Composites

• Discontinuous thin fibers of one material are embedded in a matrix
  – Wood and bamboo are naturally occurring fiber composites
  – Bricks of straw and mud
  – Automobile tires
    • Fibers of nylon, rayon, Kevlar, or steel to reinforce the rubber
    – Glass fibers
    – Graphite
    – Ceramic fibers, metal wires, whiskers
  • Common objective is high strength and lightweight
    – Orientation of the fibers is important
Properties of Fiber-Reinforced Composites

- Table 8-7 and Table 8-8 list properties of common fiber-reinforced materials
- Advanced fiber-reinforced composites
  - Organic or resin matrix composites
    - Sports equipment, light-weight armor, low-temperature aerospace applications
  - Metal-matrix composites
    - Nonflammable, do not absorb water or gases, corrosion resistance
  - Carbon-carbon composites
    - High temperature applications
  - Ceramic-matrix composites
    - High temperature strength, stiffness, and environmental stability
Composites

• Hybrid composites
  – Two or more fibers
    • Alternate layers of fibers
    • Mixed strands in the same layer
    • Combination of mixed strands and alternating layers
    • Selected placements
    • Fibers are stitched together
Design and Fabrication

- Select the component materials
- Determine the relative amounts of each component
- Determine the size, shape, distribution, and orientation
- Select the proper fabrication method
  - Compression molding
  - Filament winding
  - Pultrusion
  - Cloth lamination
- Composites may be tailored to specific applications
Practical Applications

• Manufacturing with composites is labor intensive
• Defects
  – Delamination voids
  – Missing layers
  – Contamination
  – Fiber breakage
  – Improperly cured resin
• Areas of application
  – Aerospace
  – Sporting equipment
  – Automobiles
  – Boat hulls
  – Pipes
Areas of Application

Figure 8-13 Schematic diagram showing the materials used in the various sections of the F-22 Raptor fighter airplane (Reprinted with permission of ASM International, Metals Park, OH.)
Areas of Application

Figure 8-14 Composite materials are often used in sporting goods to improve performance through light weight, high stiffness, and high strength, and also to provide attractive styling. (Left) A composite material snowboard; (right) composites being used in a fishing rod, water ski, and tennis racquet.
Summary

• Plastics, ceramics, and composites are nonmetallic materials that are commonly used.

• Additives are used in plastics to produce desired properties

• Composite’s properties depend on the way in which the materials are combined and their orientation

• Ceramics are ideal for high temperature applications