Nonmetallic Materials: Plastics, Elastomers, Ceramics, and Composites

Chapter 9

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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

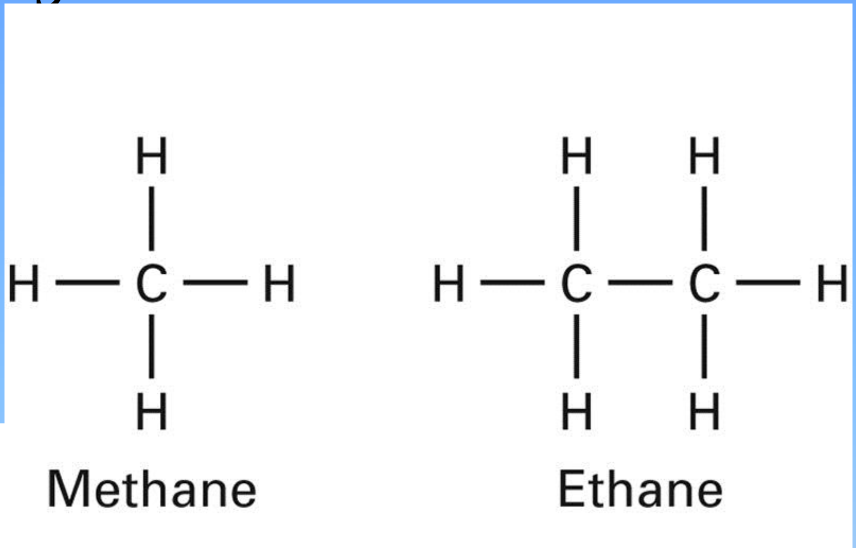
- Plastics are engineered materials
  - Large molecules that are composed of smaller molecules
  - Made from natural or synthetic resins and compounds
  - Can be molded, extruded, cast, or used for coatings
  - Low density, low tooling costs, good corrosion resistance, low cost
  - Plastics are very 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.



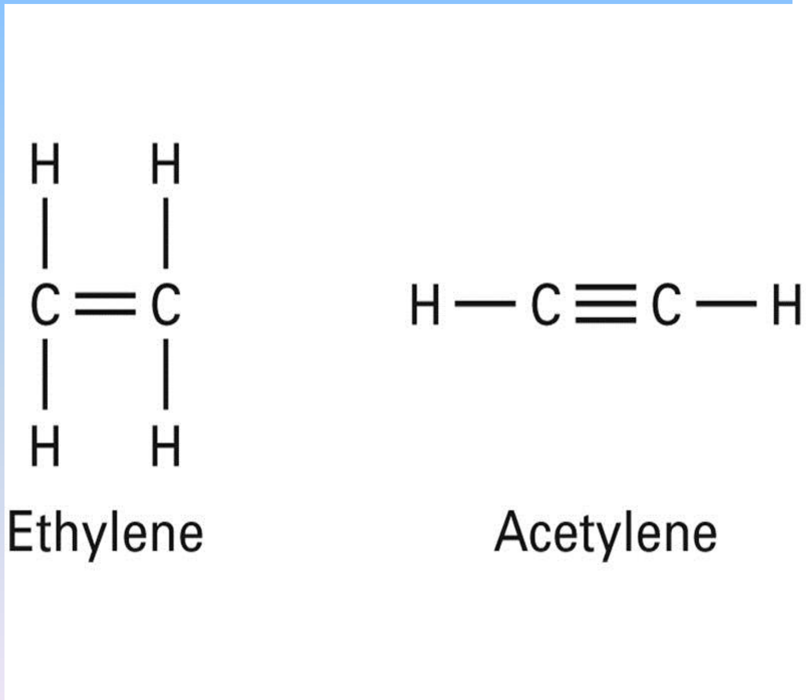


Figure 8-2 (Left) Double and Triple covalent bonds exist between the carbon atoms in unsaturated ethylene and acetylene molecules.

Isomers

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

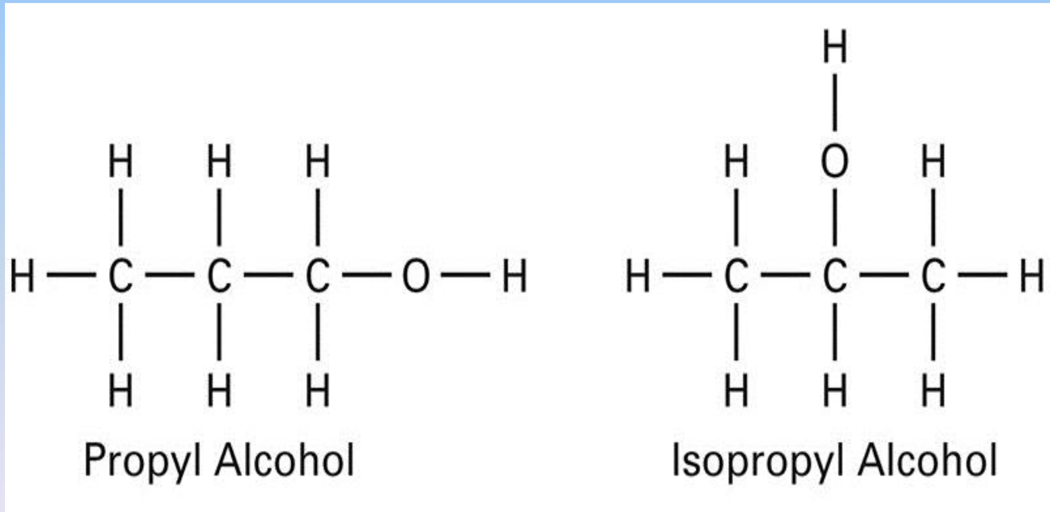


Figure 8-3 Linking of eight hydrogen, one oxygen, and three carbon atoms to form two isomers: propyl alcohol and isopropyl alcohol.

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

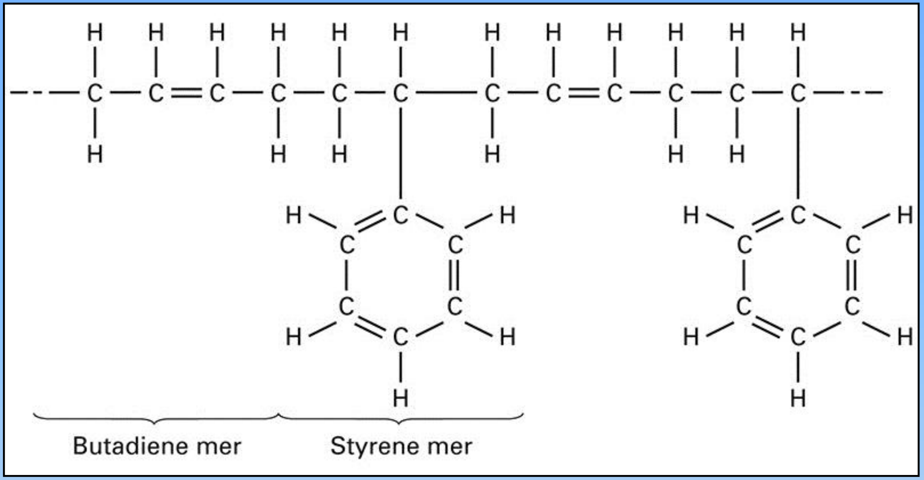
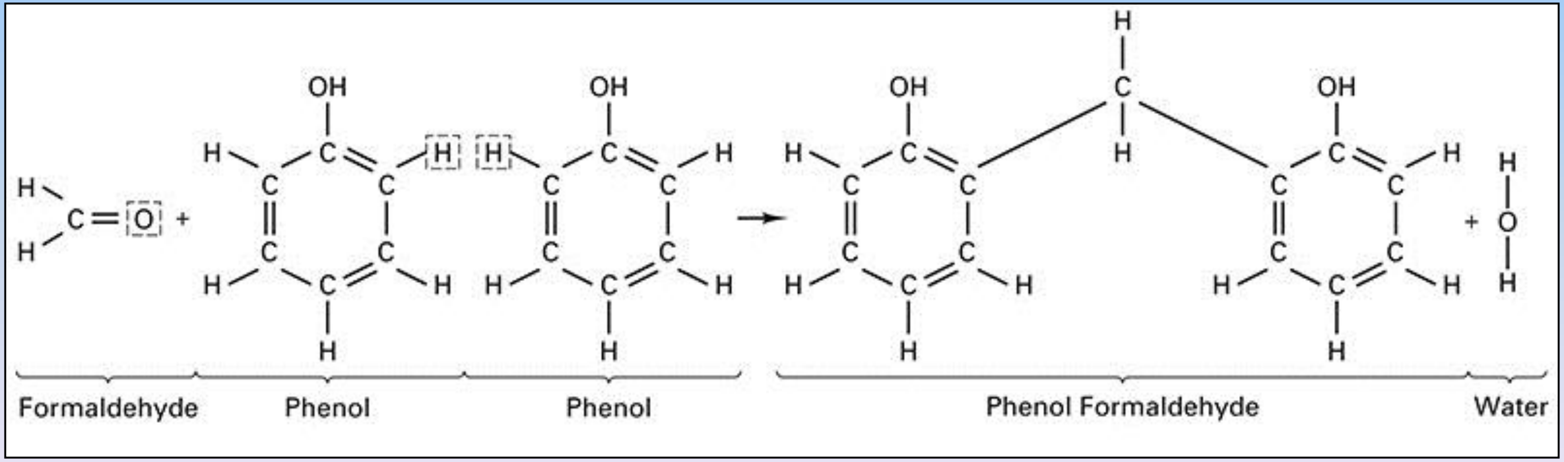


Figure 8-6 (Below) The formation of phenol-formaldehyde by condensation polymerization



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 can not 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 8-2 Additive Agents in Plastics and Their Purpose

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

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

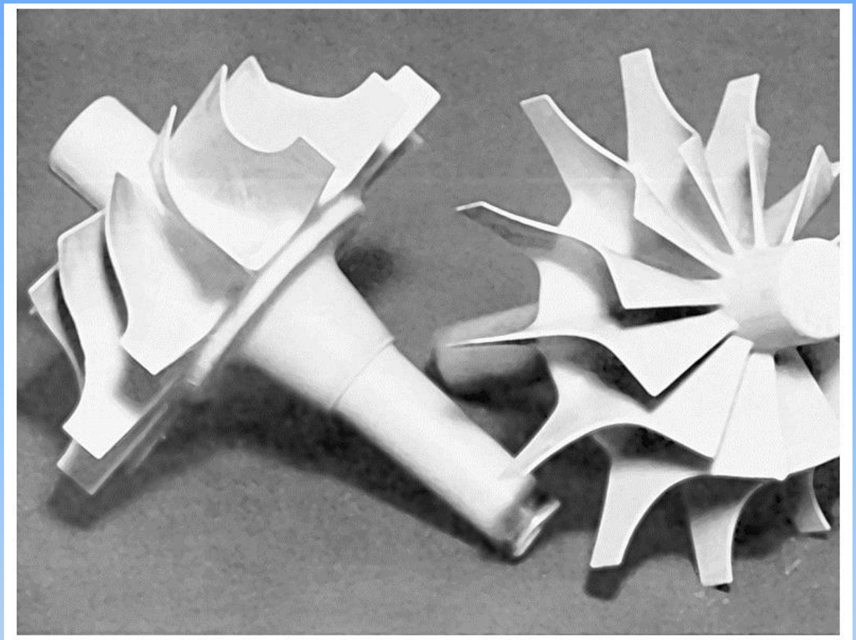


Figure 8-8 Gas-turbine rotors made of silicon nitride. The lightweight material (one-half the weight of stainless steel) offers strength at elevated temperature as well as excellent resistance to corrosion and thermal shock. (Courtesy of Wesgo Division, GTE, Hayward, CA.)

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

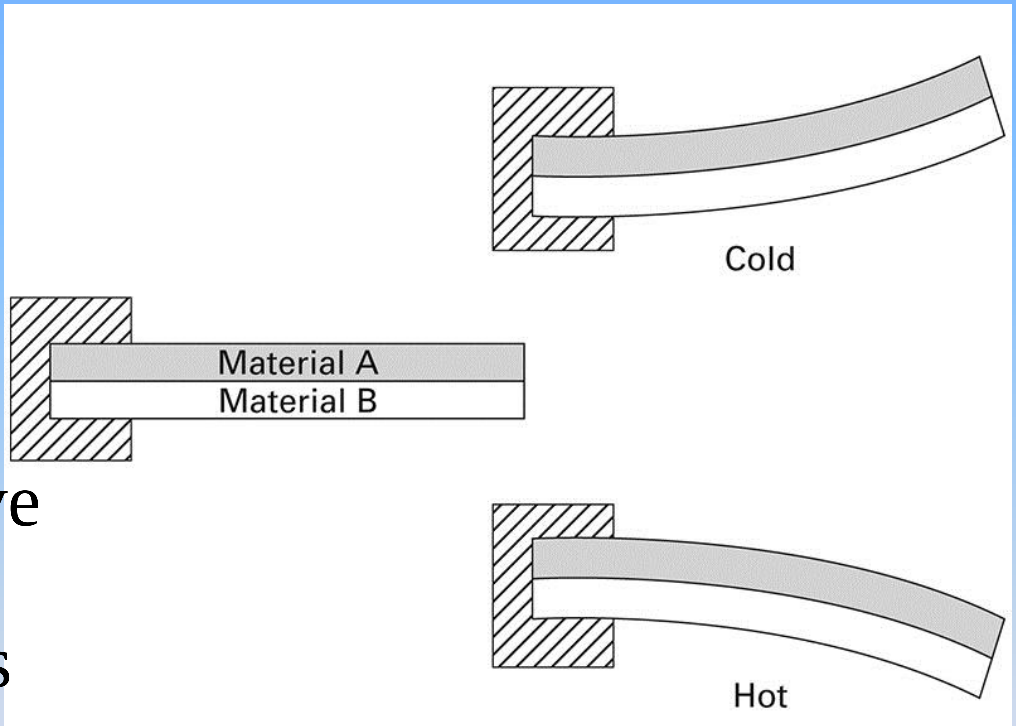


Figure 8-11 Schematic of a bimetallic strip where material A has the greater coefficient of thermal expansion.

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

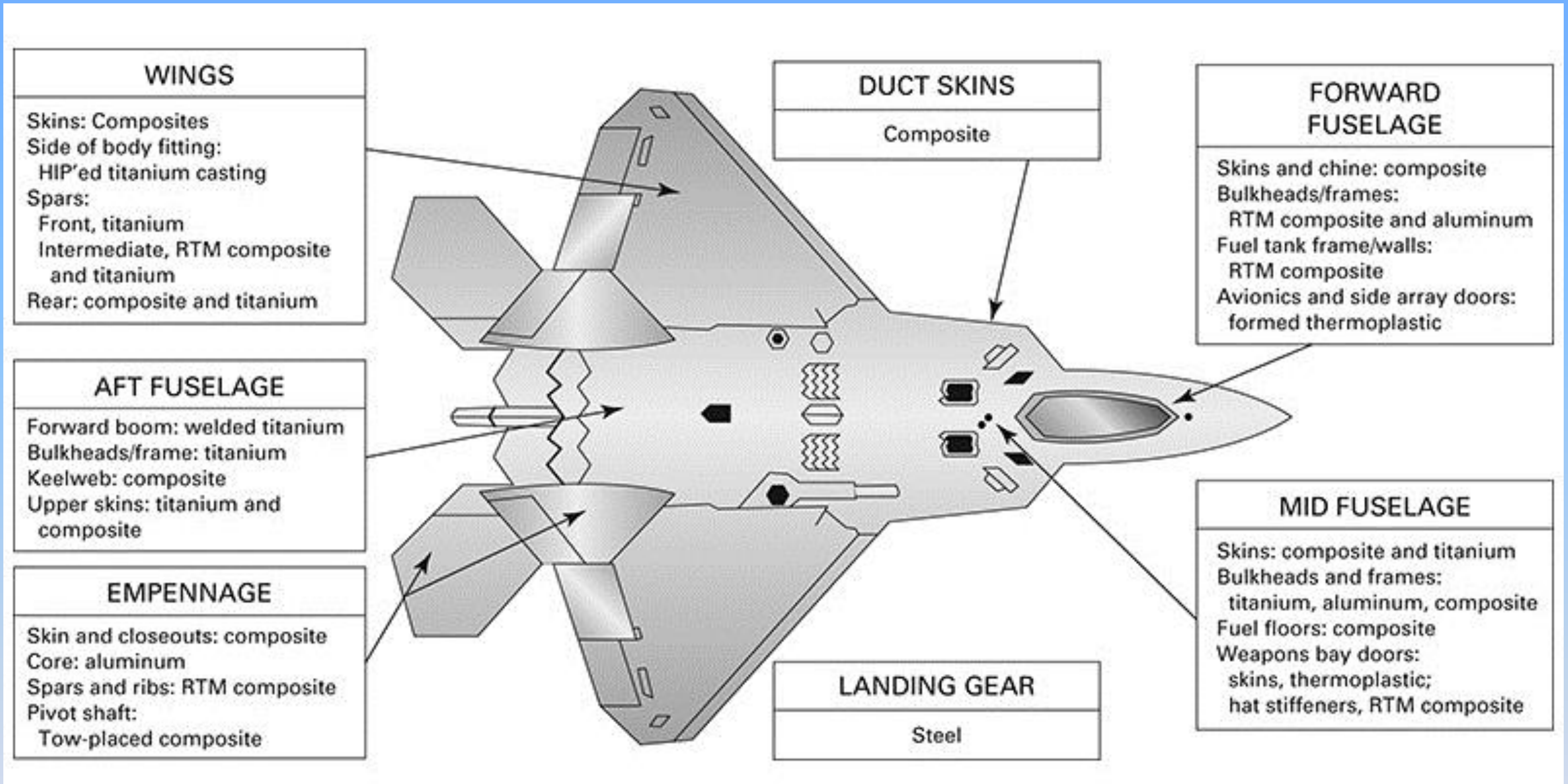


Figure 8-13 Schematic diagram showing the materials used in the various sections of the F-22 Raptor fighter airplane (Reprinted with permission of ASM International, Metals Park, OH.)

Areas of Application

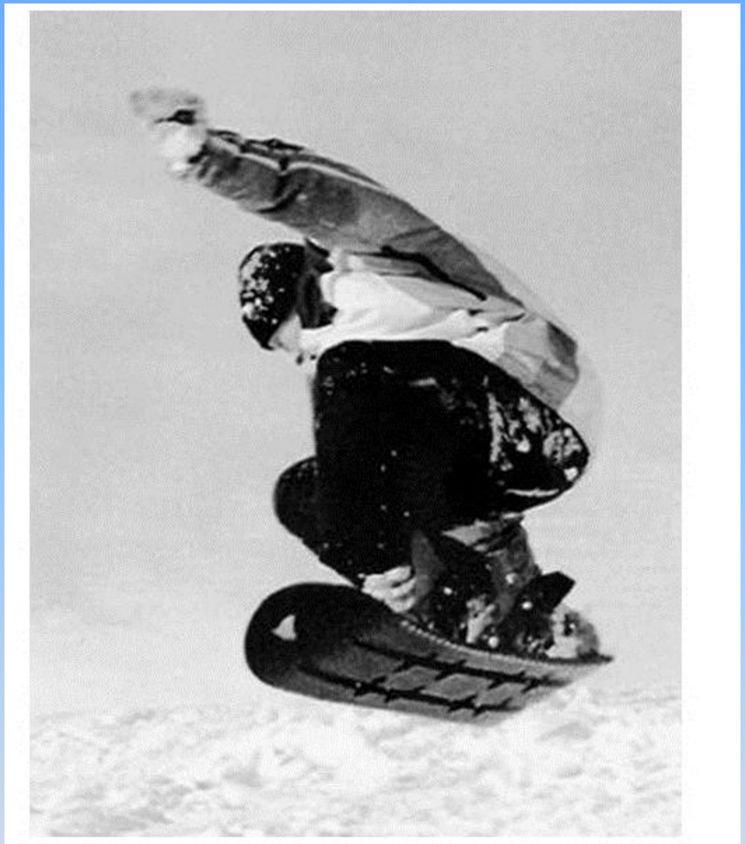


Figure 8-14 Composite materials are often used in sporting goods to improve performance through light weight, high stiffness, and high strength, and also to provide attractive styling. (Left) A composite material snowboard; (right) composites being used in a fishing rod, water ski, and tennis racquet.

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