Structure, Properties and Processing of Plastics and Reinforced Plastics

(Chap10 in Kalpakjian and Schmid)

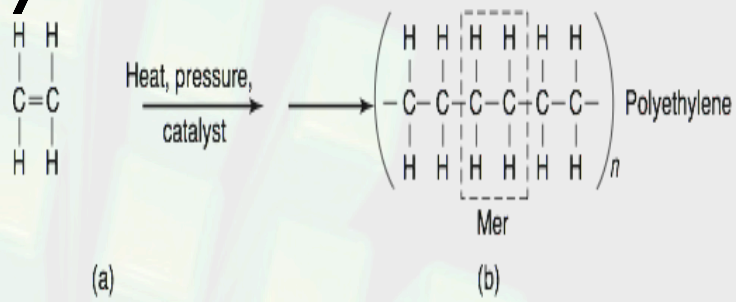
Objectives

- Thermoplastics, thermosets, elastomers, and reinforced plastics
  - Structure
  - Property
  - Applications
  - Processing

Introduction

- Plastics ~ polymers
- Plastics are engineered materials
  - Large molecules composed of smaller molecules
  - Made from natural or synthetic resins and compounds
  - Low density, low tooling costs, good corrosion resistance, low cost
  - Can be molded, extruded, cast, or used for coatings
  - Plastics are very versatile materials and are used more than steel, aluminum, and copper combined in the United States
  - Used as food and beverage containers, packaging, signs, housewares, foams, paints, toys, etc
  - An important group: reinforced plastics (composites)

Molecular Structure of Polymers



- **Hydrocarbons**
  - C_nH_{2n+2}
  - Covalent bonding
  - Double or triple covalent bonds may also be present
- **Monomer**
  - Smallest repeating unit

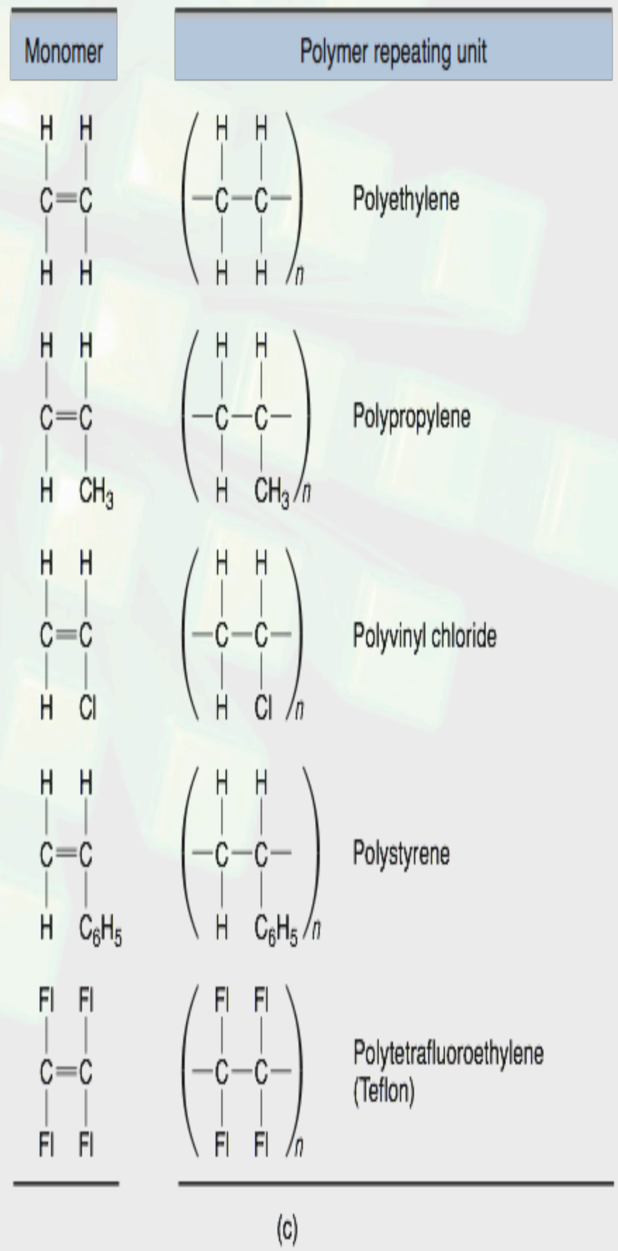


FIGURE 10.1 Basic structure of some polymer molecules: (a) ethylene molecule; (b) polyethylene, a linear chain of many ethylene molecules; (c) molecular structure of various polymers. These molecules are examples of the basic building blocks for plastics.

Characteristics of Polymers

- Molecular weight

  Sum of the molecular weight of the mers in polymer chain

- Bonding
  - Primary bonds: covalent
  - Secondary bonds: van der Waals , hydrogen bonds, ionic bonds…
- Arrangement of the polymer chains
  - Linear polymer
  - Branched polymer
  - Cross-linked polymer (thermosets) and network polymers (3 active covalent bonds)

Effect of Molecular Weight

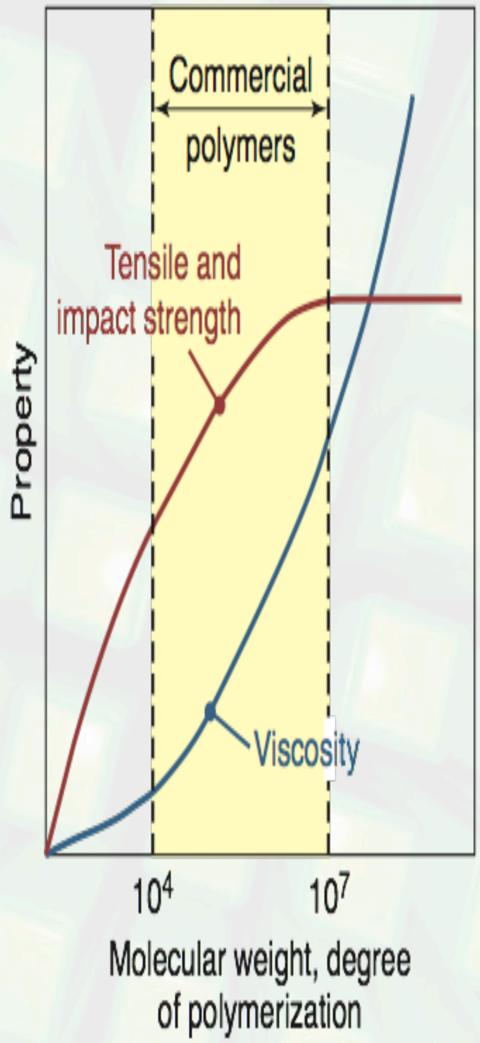


FIGURE 10.2 Effect of molecular weight and degree of polymerization on the strength and viscosity of polymers.

Arrangement of Polymer Chains

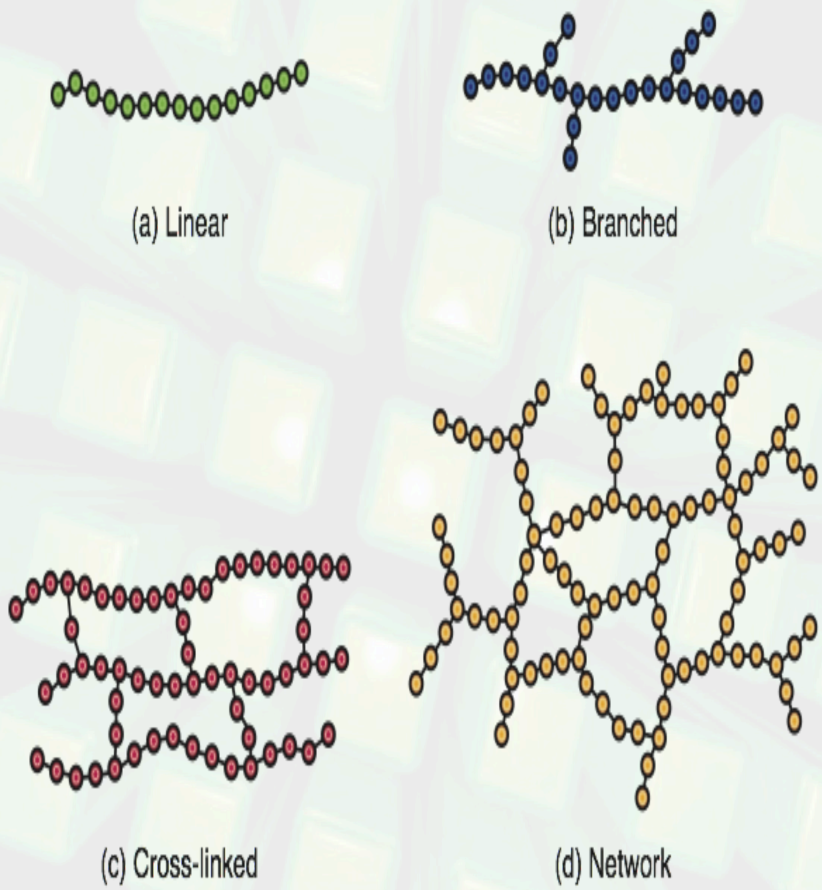


FIGURE 10.3 Schematic illustration of polymer chains. (a) Linear structure; thermoplastics such as acrylics, nylons, polyethylene, and polyvinyl chloride have linear structures. (b) Branched structure, such as polyethylene. (c) Cross-linked structure; many rubbers and elastomers have this structure. Vulcanization of rubber produces this structure. (d) Network structure, which is basically highly cross-linked; examples include thermosetting plastics such as epoxies and phenolics.

Crystallinity

- Polymer can be partially crystalline
- Orderly arrangement of molecules in crystalline region (**crystallite**)
- The higher the crystallinity, the harder, stiffer, and less ductile the polymer
  - Can never be 100% crystalline
- Linear polymer is easier to crystallize than branched
- Color:
  - Opaque for crystalline
  - Transparent for amorphous

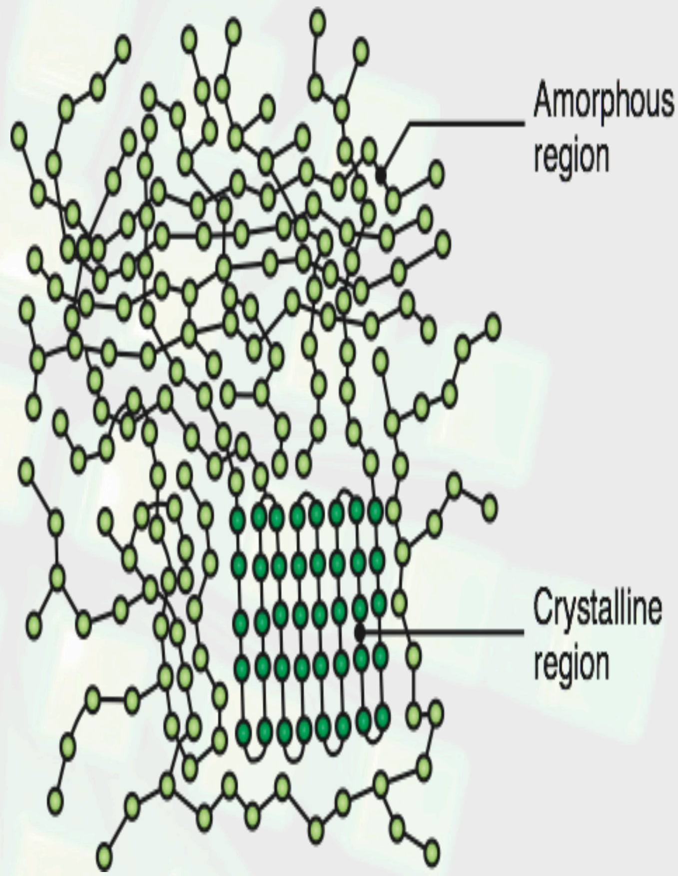


FIGURE 10.5 Amorphous and crystalline regions in a polymer.

Effect of Temperature, Crystallinity, Crosslinking

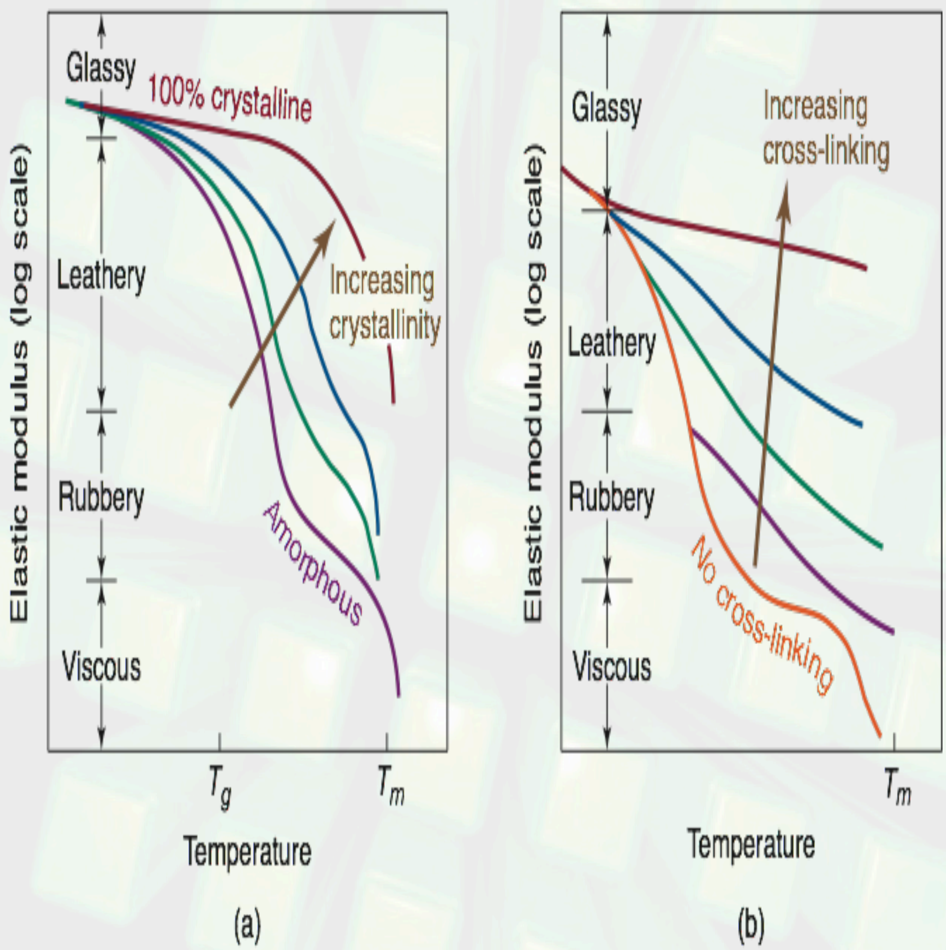


FIGURE 10.4 Behavior of polymers as a function of temperature and (a) degree of crystallinity and (b) cross-linking. The combined elastic and viscous behavior of polymers is known as viscoelasticity.

Glass-Transition Temperature

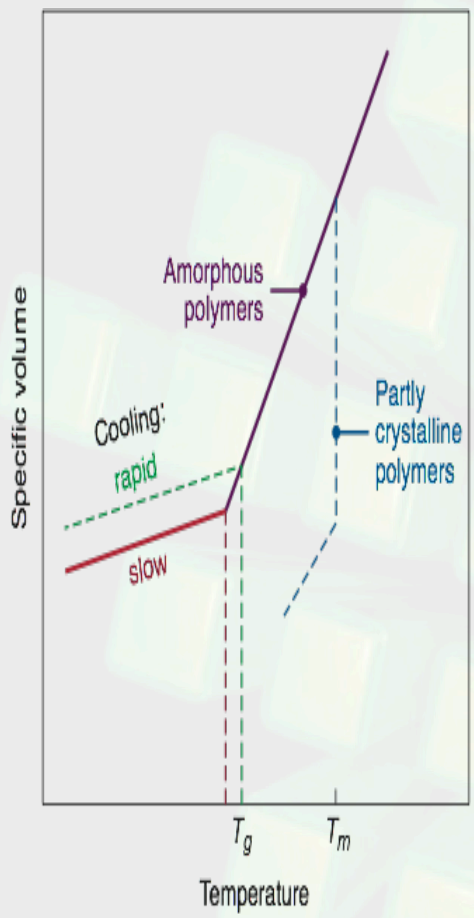


FIGURE 10.6 Specific volume of polymers as a function of temperature. Amorphous polymers, such as acrylic and polycarbonate, have a glass-transition temperature, T_g, but do not have a specific melting point, T_m. Partly crystalline polymers, such as polyethylene and nylons, contract sharply at their melting points during cooling.

Material	T_g (°C)	T_m (°C)
Nylon 6,6	57	265
Polycarbonate	150	265
Polyester	73	265
Polyethylene		
High density	-90	137
Low density	-110	115
Polymethylmethacrylate	105	–
Polypropylene	-14	176
Polystyrene	100	239
Polytetrafluoroethylene (Teflon)	-90	327
Polyvinyl chloride	87	212
Rubber	-73	–

TABLE 10.2 Glass-Transition and Melting Temperatures of Selected Polymers

Polymer Additives

- Fillers
  - Improve strength, stiffness, and toughness
  - Reduce shrinkage and weight
  - Common fillers: wood flour, silica flour, clay, powdered mica
- Plasticizers
  - Added in small amounts to reduce viscosity
- Stabilizers and antioxidants
  - Retard the effects of heat, light, and oxidation
- Colorant (organic dyes or inorganic pigments)
- Flame retardants
- Lubricants
  - Reduce friction
  - Improve moldability
  - Facilitates part removal

Thermoplastics and Thermosets

- Thermoplastics and thermosets are classified based on their response to heat
  - Internal bonding is covalent (primary)
  - Intermolecular bonds are *van* der Waal forces (secondary)
  - Secondary bond is much weaker than primary
  - Secondary bonds determine the overall strength of polymers
  - Heat treatment for thermoplastics is reversible, for thermosets irreversible

Thermoplastics

- Contain molecules of different lengths
- Above the melting temperature, the material can be poured and cast or molded; once cooled, returns to original strength and harness (reversible)
- Application of a force deforms the material both elastically and plastically
  - Plastic deformation occurs by adjacent chains slipping past one another
- Common thermoplastics
  - Polyethylene (PE)
  - Polypropylene (PP)
  - Polystyrene (PS)
  - Polyvinyl Chloride (PVC)

Thermosets

- Highly cross-linked
- Three-dimensional framework connected by covalent bonds (one giant molecule)
- Typically produced by condensation polymerization
    - Elevated temperatures produce an irreversible reaction
    - Once set, subsequent heating will not soften the material
    - At substantially high temperature, burns up, degrade or char

Properties of Thermosets

- Significantly stronger and more rigid than thermoplastics
- Able to resist higher temperatures
- Greater dimensional stability
- Lower ductility
- Strength and hardness are not affected by temperature and strain rate
- Poorer impact properties
- Heating changes their structure permanently
- The setting time is very important because it can not be repeated

Elastomers

- Elastomer ~ Rubber
- Rubbers are amorphous polymers with
  - Low Tg
  - Ability to undergo large elastic deformation
  - Soft
  - Low elastic modulus
- Characteristics
  - Hardness increase with cross-linking
  - Compression hysteresis
- Can be thermosets or thermoplastics

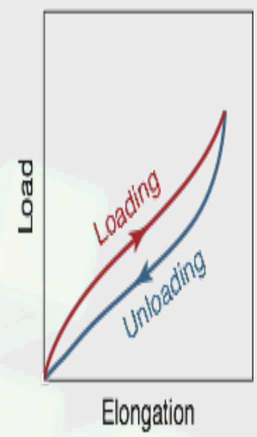


FIGURE 10.14 Typical load-elongation curve for elastomers. The area within the clockwise loop, indicating loading and unloading paths, is the hysteresis loss. Hysteresis gives rubbers the capacity to dissipate energy, damp vibration, and absorb shock loading, as in automobile tires and vibration dampeners for machinery.

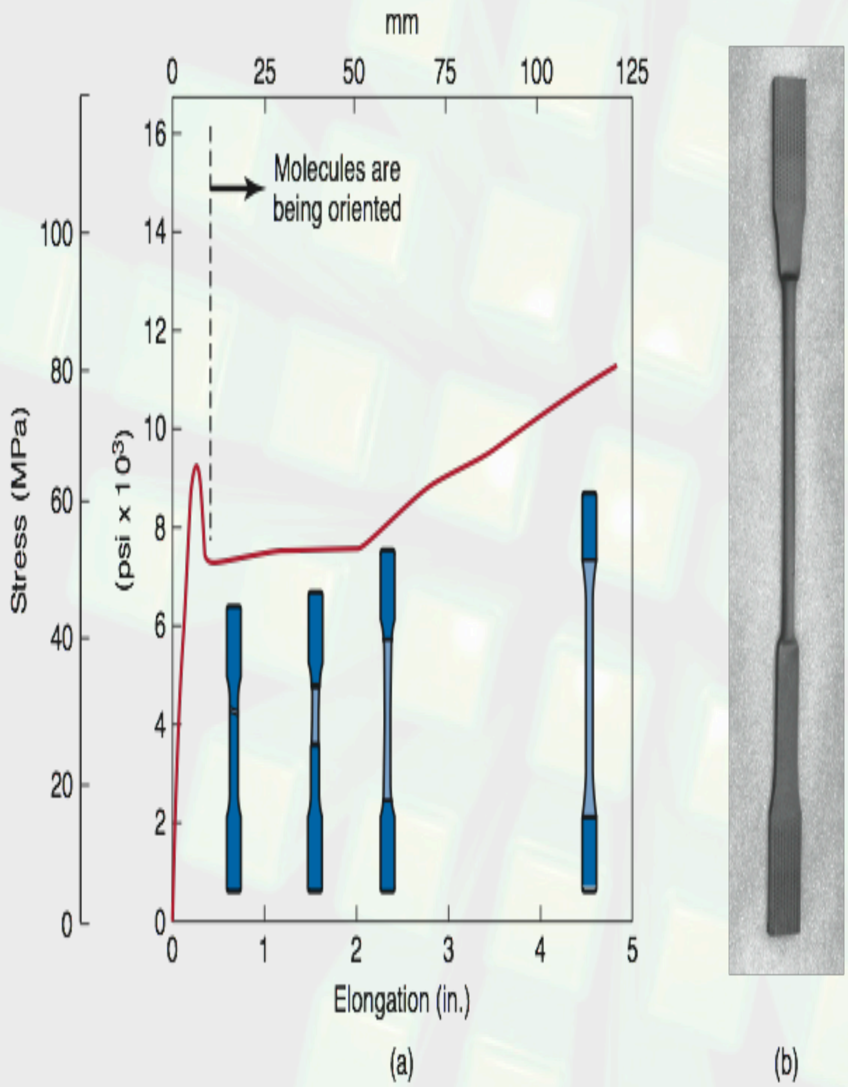
Summary

- What is polymer/plastics
- Structure of polymers: mer vs polymer
- Characteristics of polymers
- Thermoplastics vs thermosets
  - Difference
  - Characteristics
- Elastomers

Behavior of Thermoplastics

- Temperature effect
- Large elongation and orientation under tension
- Strain rate effect
- Viscoelasticity

Thermoplastic Behavior in Tension

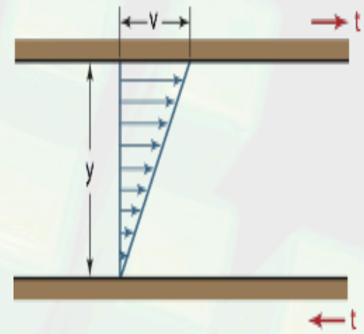


- Large elongation without necking
- Orientation of molecules along stretching direction

FIGURE 10.13 (a) Load-elongation curve for polycarbonate, a thermoplastic. (b) High-density polyethylene tension-test specimen, showing uniform elongation (the long, narrow region in the specimen).

Viscosity of Melted Polymers

- Measure of resistance of the polymer molecules in sliding along each other
- Depends on
  - Temperature
  - Pressure
  - Polymer structure
  - Molecular weight



$$\tau = \eta \left(\frac{dv}{dy} \right) = \eta \dot{\gamma}$$

$$log\eta = 12 - \frac{17.5\Delta T}{52 + \Delta T}$$

$$\Delta T = T - T_g$$

Viscosity of Melted Polymers

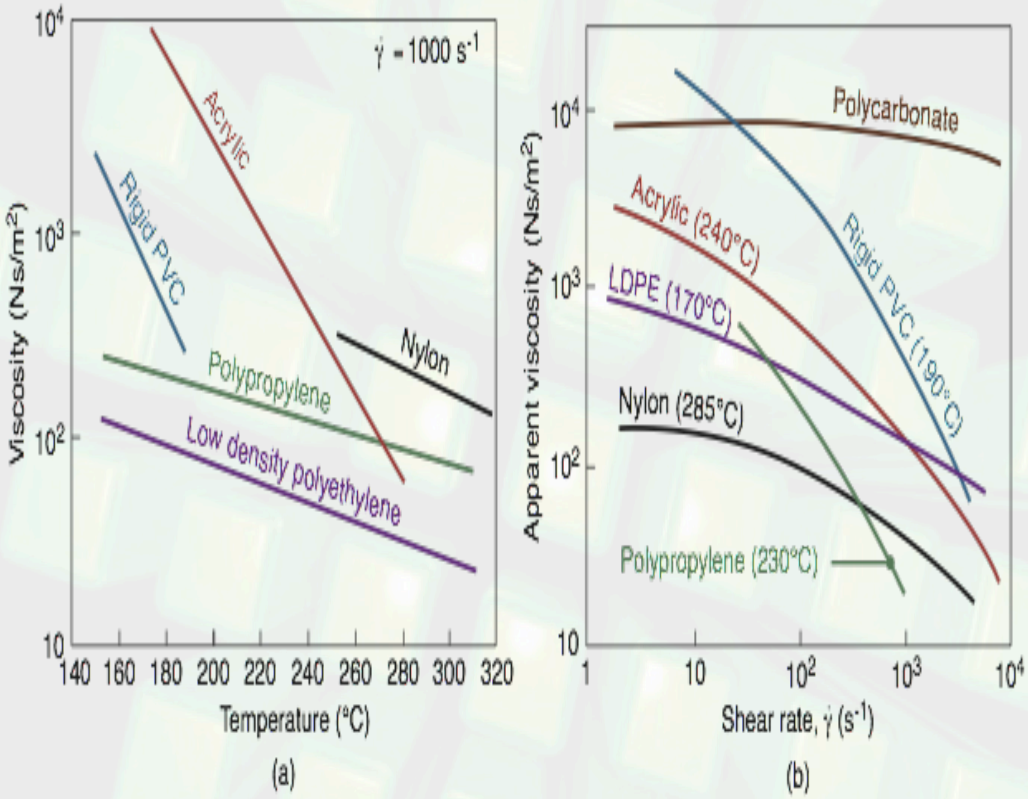


FIGURE 10.12 Viscosity of some thermoplastics as a function of (a) temperature and (b) shear rate. *Source:* After D.H. Morton-Jones.

Reinforced Plastics

- Composites
  - Combination of two or more chemically distinct and insoluble phases whose properties and structural performances are superior to the constituents acting independently
  - Types of Composites
    - Polymer matrix (reinforced plastics)
    - Metal matrix
- Properties of composites depend on:
  - Properties of individual components
  - Relative amounts
  - Size, shape, and distribution
  - Orientation
  - Degree of bonding

Applications of Reinforced Plastics

- Aerospace, automotive, marine, and construction industries.….
- Example: Boeing 787 Dreamliner
  - 50% carbon-fiber composite (CFRP), in the fuselage, wings, tail, and interior components (100% of the skin, 80% by volume)
  - 20% aluminum, primarily on the wing and tail leading edges
  - 15% titanium, primarily in the engines
  - 10% steel
  - 5% other materials

Reinforced Plastics

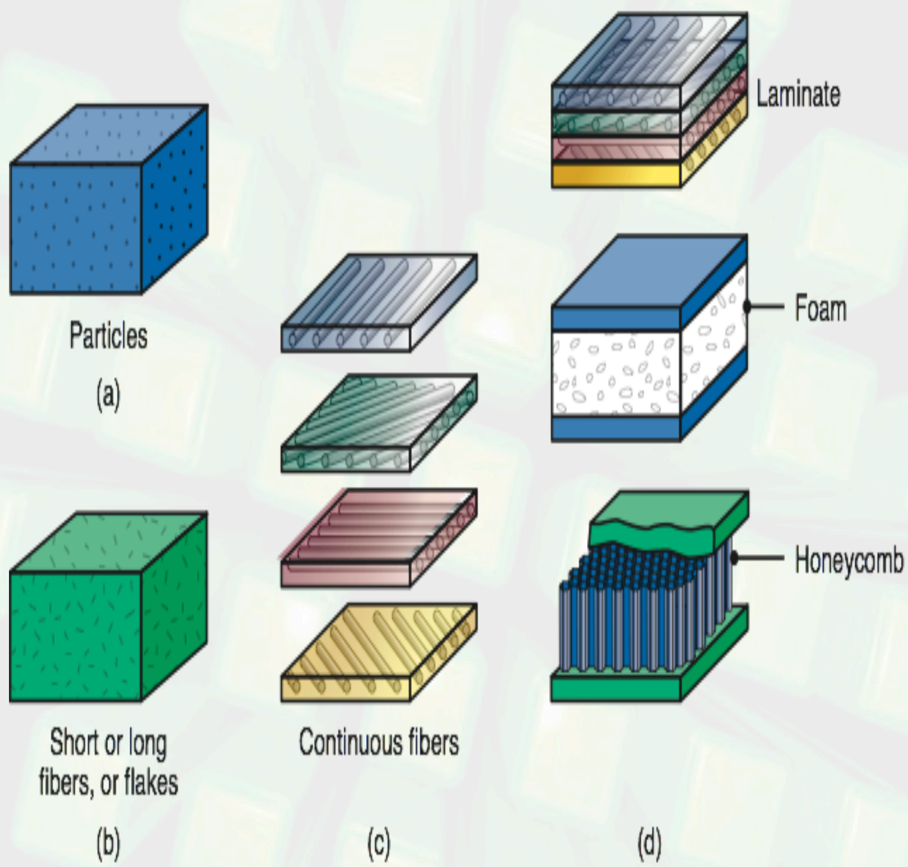


FIGURE 10.15 Schematic illustration of types of reinforcing plastics. (a) Matrix with particles; (b) matrix with short or long fibers or flakes; (c) continuous fibers; and (d) and (e) laminate or sandwich composite structures using a foam or honeycomb core (see also Fig. 7.48 on making of honeycombs).

Matrix Materials

- Common matrix
  - Usually thermosets
    - Epoxy (80% of all reinforced plastics)
    - Polyester (less expensive)
    - Polyimides (for high temperature)
  - Thermoplastics
    - PEEK (polyetheretherketone) – high stiffness, low T resistance
- Matrix functions
  - Support and transfer load to the fibers
  - Protect fibers against physical damage and environment
  - Reduce propagation of cracks by virtue of ductility and toughness

Reinforcing Fibers

- Common reinforcing fibers
  - Polymer (Kevlar (Aramid), Spectra (PE)
  - Glass: S and E
  - Graphite (carbon)
  - Boron: CVD on W
- Fiber Length
  - Short fiber (L/d=20-60)
  - Long fiber (L/d= 200-500)

Properties of Reinforcing Fibers

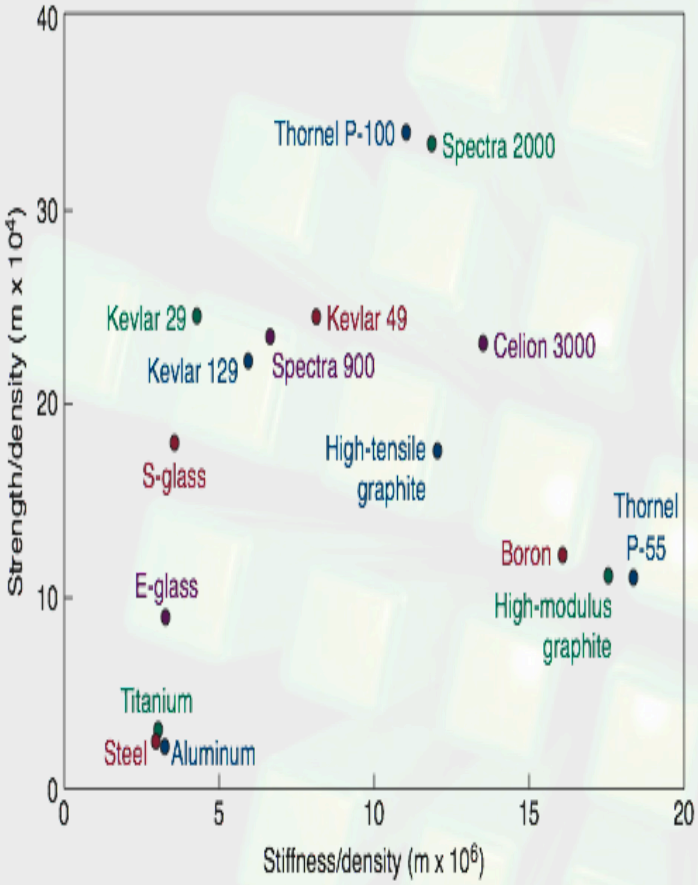


FIGURE 10.16 Specific tensile strength (ratio of tensile strength-to-density) and specific tensile modulus (ratio of modulus of elasticity-to-density) for various fibers used in reinforced plastics. Note the wide range of specific strength and stiffness available.

Type	Tensile Strength (MPa)	Elastic Modulus (GPa)	Density (kg/m^3)	Relative Cost
Boron	3500	380	2600	Highest
Carbon				
High strength	3000	275	1900	Low
High modulus	2000	415	1900	Low
Glass				
E type	3500	73	2480	Lowest
S type	4600	85	2540	Lowest
Kevlar				
29	2800	62	1440	High
49	2800	117	1440	High
129	3200	85	1440	High
Nextel				
312	1630	135	2700	High
610	2770	328	3960	High
Spectra				
900	2270	64	970	High
1000	2670	90	970	High

Note: These properties vary significantly, depending on the material and method of preparation. Strain to failure for these fibers is typically in the range of 1.5% to 5.5%.

TABLE 10.4 Typical properties of reinforcing fibers.

Effect of Fibers

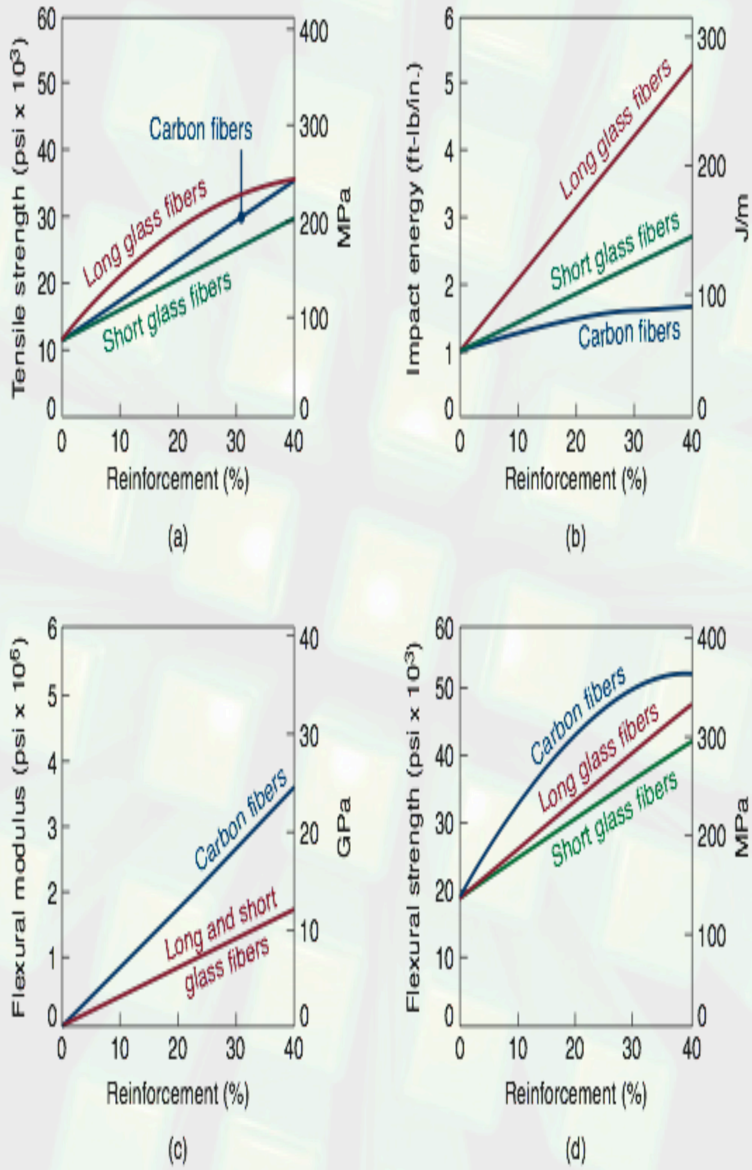


FIGURE 10.19 Effect of the percentage of reinforcing fibers and fiber length on the mechanical properties of reinforced nylon. Note the significant improvement with increasing percentage of fiber reinforcement. *Source:* Courtesy of Wilson Fiberfill International.

Strength and Fracture of Composites

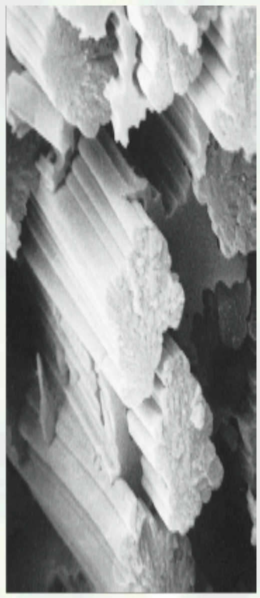


FIGURE 10.20 (a) Fracture surface of **glass-fiber-reinforced epoxy** composite. The fibers are 10 μm (400 μin.) in diameter and have random orientation. (b) Fracture surface of a **graphite-fiber-reinforced epoxy** composite. The fibers are 9-11 μm in diameter. Note that the fibers are in bundles and are all aligned in the same direction.

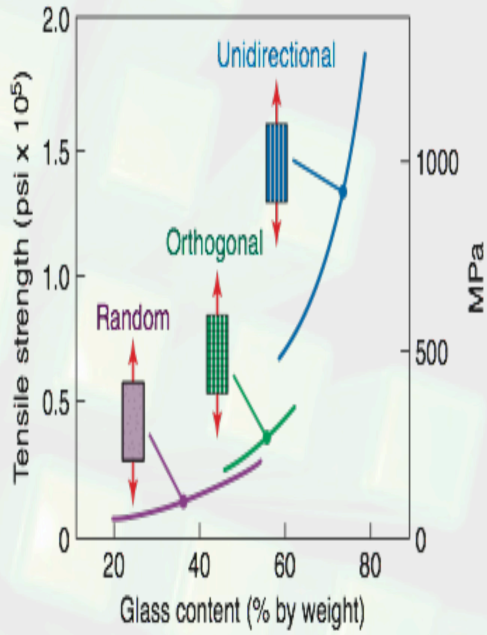


FIGURE 10.21 Tensile strength of glass-reinforced polyester as a function of fiber content and fiber direction in the matrix. *Source:* After R.M. Ogorkiewicz.

Properties of Fiber-reinforced Composites

- Rule of Mixtures

  - Longitudinal direction

  - O

$$E_c = xE_f + (1-x)E_m$$

$$E_c = \frac{E_f E_m}{xE_m + (1-x)E_f}$$

x- volume fraction of fiber

Example

Assume that a graphite-epoxy-reinforced plastic with longitudinal fibers contains 20% graphite fibers, which have a strength of 2500 MPa, and elastic modulus of 300 GPa,. The strength of the epoxy matrix is 120 MPa, and it has an elastic modulus of 100 GPa.

Calculate:

a) The elastic modulus of the composite in the fiber direction

b) The fraction of load supported by the fiber if the load is applied in the fiber direction

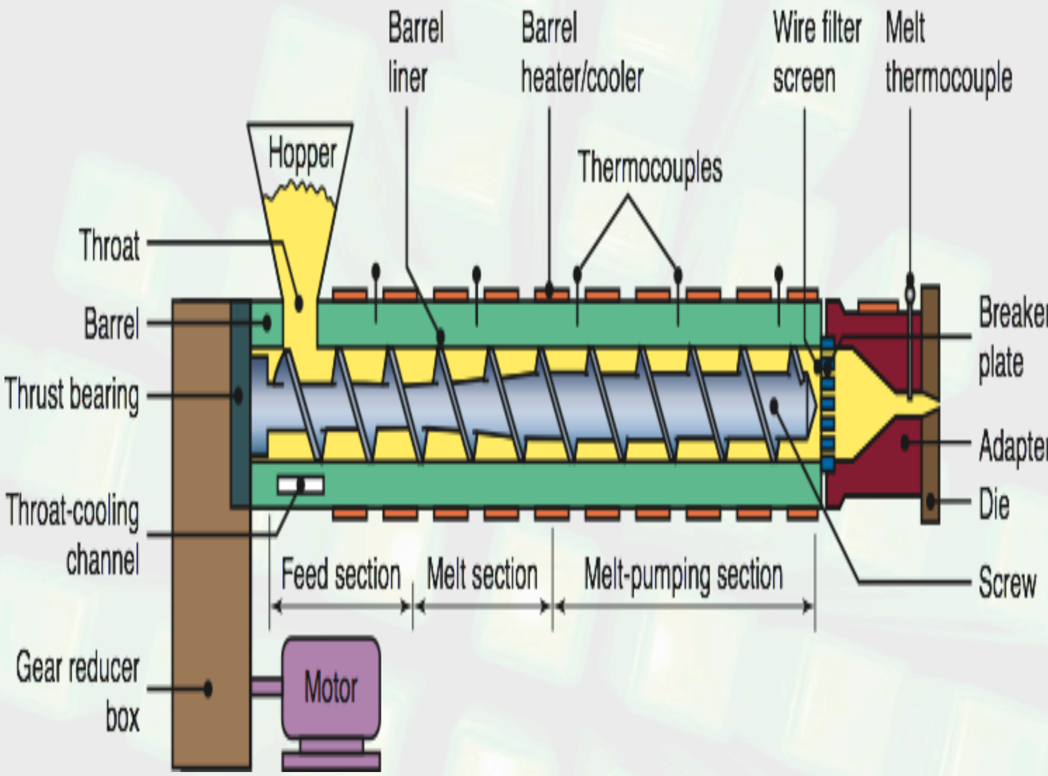
Processing Techniques

- Plastics
  - Extrusion
  - Injection molding
  - Blow molding
  - Thermoforming
- Reinforced plastics
  - Impregnation
  - Molding processes
  - Filament winding, pultrusion, pulforming

Extrusion

- Accounts for largest production volume
- Produce long and uniform, solid and hollow parts
  - Bars, tubes, sheets and films
- Mostly for thermoplastics
- High production rates, low tooling cost

Extrusion



- Hopper: feed raw materials (pellets, granules, powders)
- Screw: blends and conveys pellets down the barrel
  - Three sections: feed, melt (transition), melt-pumping
- Internal friction, shear stress & heater heats and liquefies pellets

Important Extrusion Parameters

- Process control parameters
  - Temperature
  - Back pressure
  - Screw speed
  - Injection rate
  - Cooling after extrusion: air or water cool
- Typical geometric parameters
  - D = 1 ~ 8 in.
  - L/D=5~30
- Difference from metal extrusion: screw

Injection Molding

- 3-D complex shapes

  Cups, containers, housing, knobs, electrical components
- ~hot-chamber die casting

- Delivery of plastic
  - ❑ Hydraulic plunger
  - ❑ Rotating screw
- Shape
  - ❑ Split-die chamber

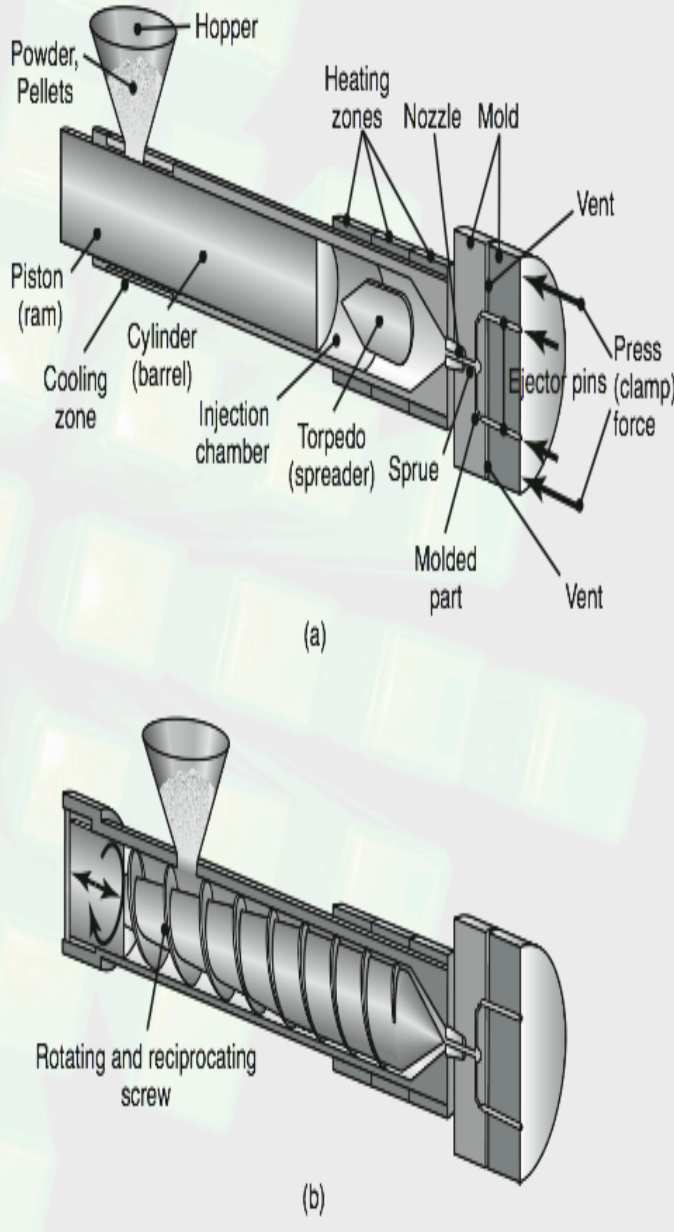


FIGURE 10.27 Injection molding with (a) a **plunger** and (b) a **reciprocating rotating screw**.

Mold Features

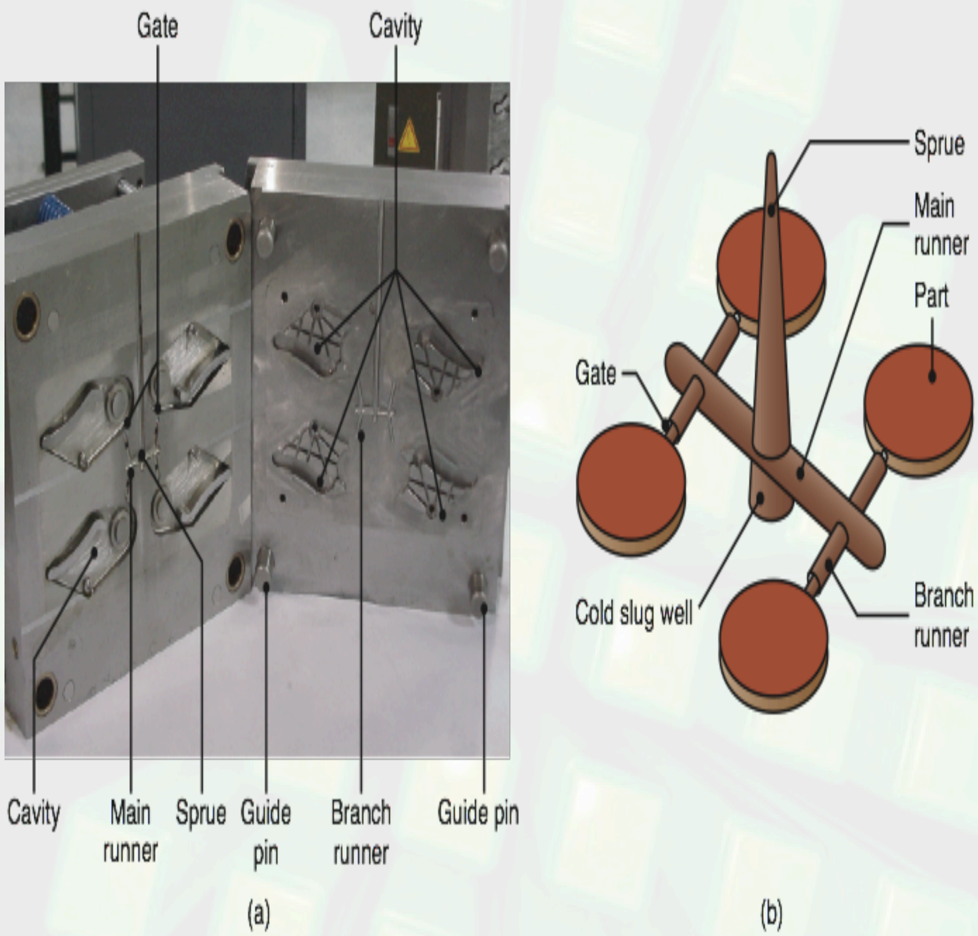
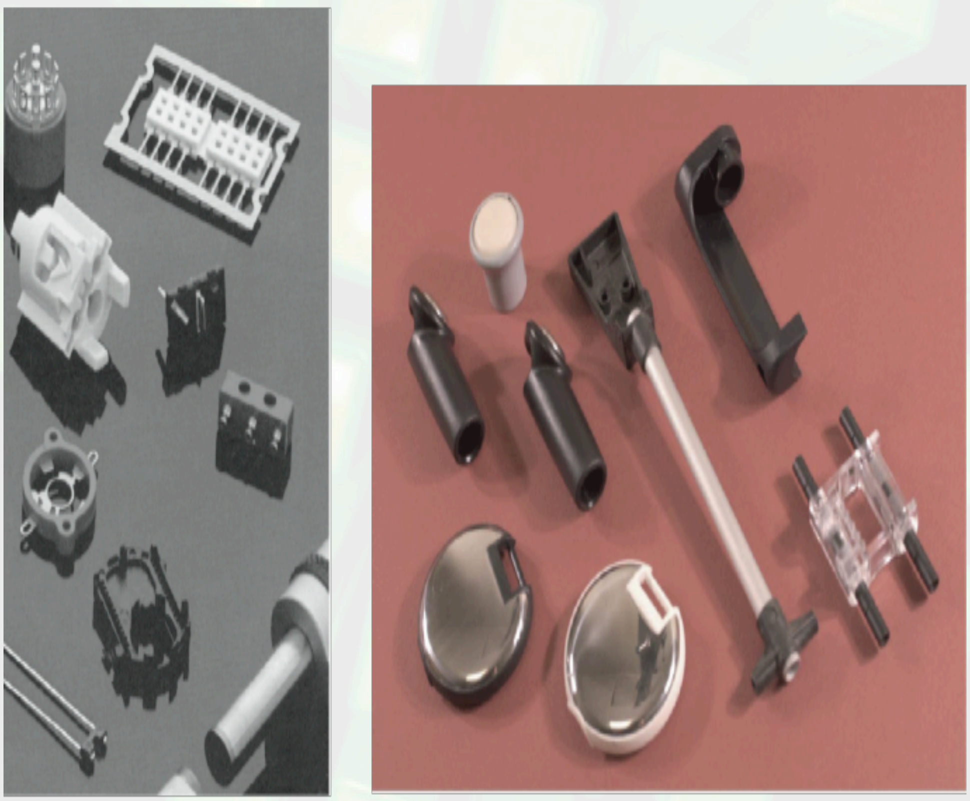


FIGURE 10.28 Illustration of mold features for injection molding. (a) Two-plate mold, with important features identified; (b) injection molding of four parts, showing details and the volume of material involved. *Source:* Courtesy of Tooling Molds West, Inc.

Insert Molding

Metal components can be placed in the mold cavity (insert) to be integrated in the injection molded product



(a) (b)

FIGURE 10.30 Products made by insert injection molding. Metallic components are embedded in these parts during molding. *Source:* (a) Courtesy of Plainfield Molding, Inc., and (b) Courtesy of Rayco Mold and Mfg. LLC.

Blow Molding

- An extruded or injection-molded tubular piece (parison) is expanded by internal pressure (hot air)
- Typical products
  - Beverage bottles
  - Hollow containers

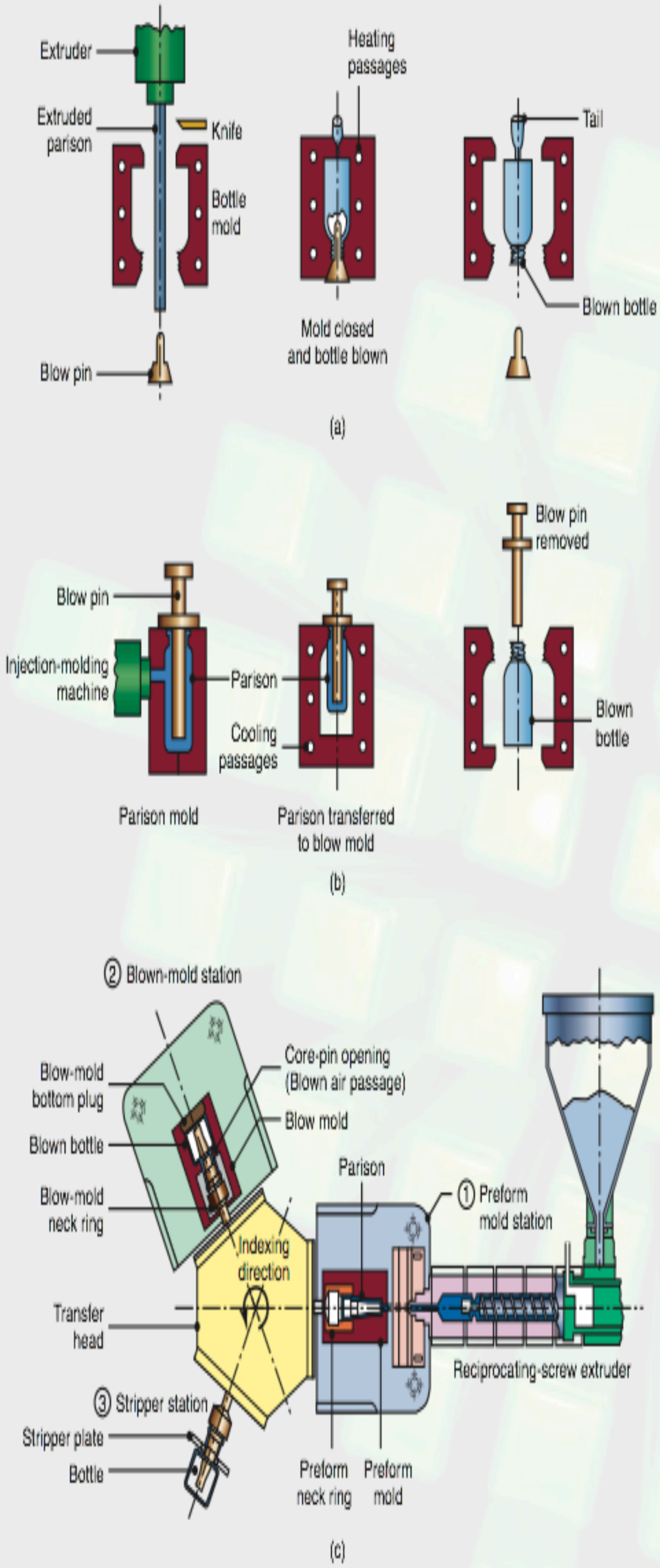


FIGURE 10.32 Schematic illustrations of (a) **extrusion blow molding** (b) **injection blow molding**; (c) three-station injection-blow-molding machine.

Thermoforming

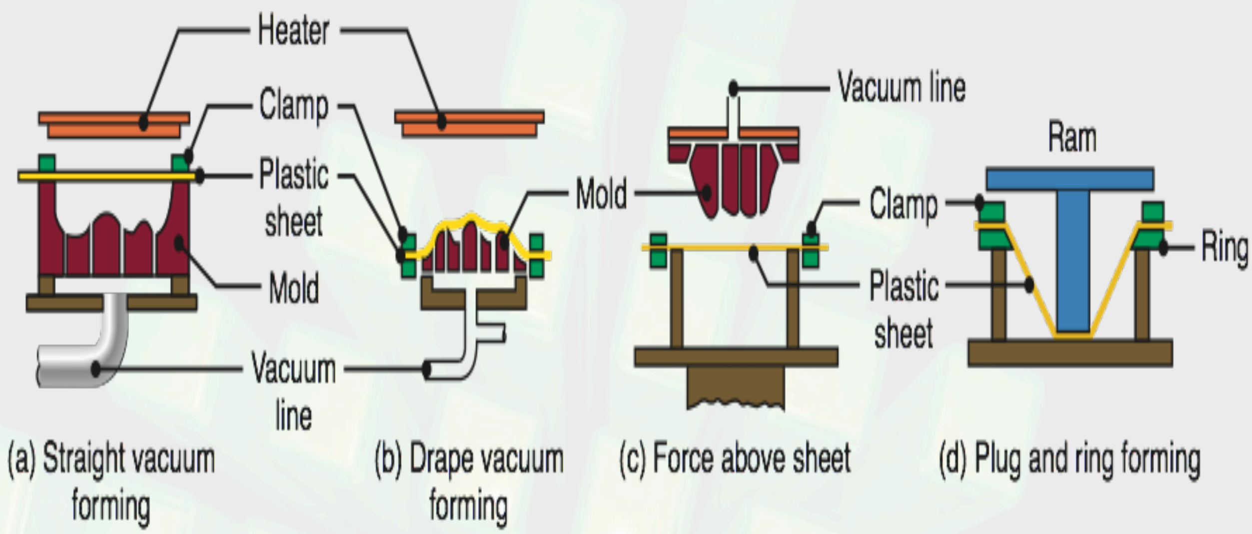


FIGURE 10.35 Various thermoforming processes for thermoplastic sheet. These processes are commonly used in making advertising signs, cookie and candy trays, panels for shower stalls, and packaging.

- Forming thermoplastic sheet or film over a mold through applied heat and pressure or vacuum
- Procedure
  - Sheet is heated to sag point (softening, but below T_m)
  - Placed on mold, apply vacuum or pressure
  - Not applicable to parts with holes
  - Hollow parts can be made with twin sheets

Processing of Reinforced Plastics

- Impregnation
- Molding

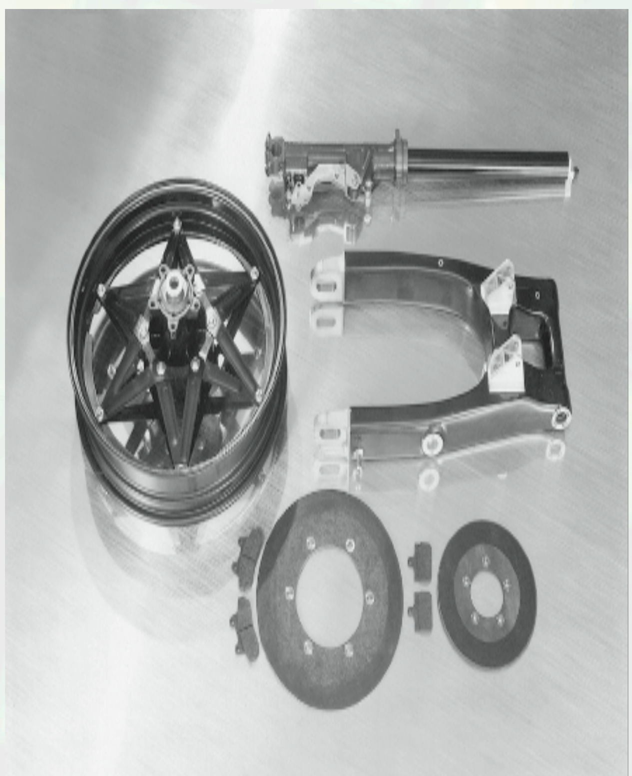


FIGURE 10.39 Reinforced-plastic components for a Honda motorcycle. The parts shown are front and rear forks, a rear swing arm, a wheel, and brake disks.

Impregnation of Fibers

- Surface treatment of reinforcing fibers (sizing)
- Partially cured sheets are referred to as:
  - Prepregs
  - Sheet-molding compounds (SMC)
  - Bulk-molding compounds (BMC)
  - Thick-molding compounds (TMC)

Manufacture of Prepregs and SMCs

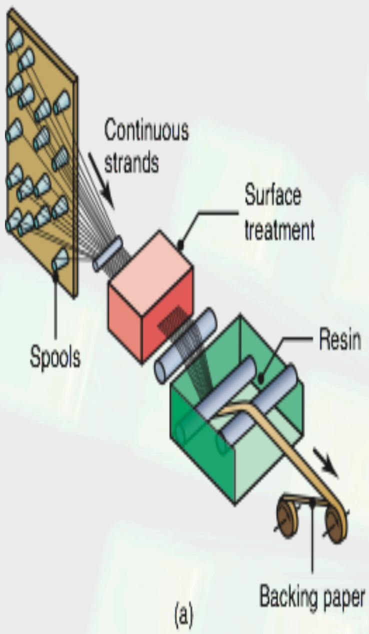
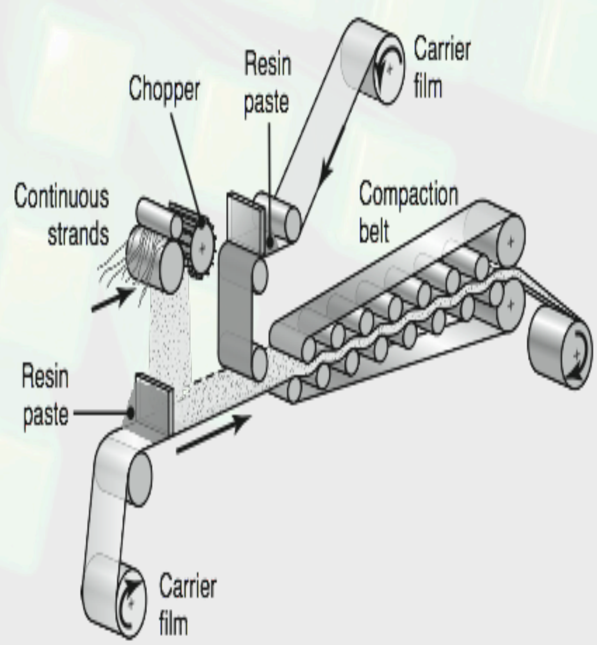


FIGURE 10.40 (a) Manufacturing process for polymer-matrix composite. *Source:* After T.-W. Chou, R.L. McCullough, and R.B. Pipes. (b) Boron-epoxy **prepreg** tape. *Source:* Textron Systems.

FIGURE 10.41 Manufacturing process for producing reinforced-plastic sheets. The sheet is still viscous at this stage and can later be shaped into various products. *Source:* After T.-W. Chou, R. L. McCullough, and R. B. Pipes. **Example of SMC**



Vacuum and Pressure Molding

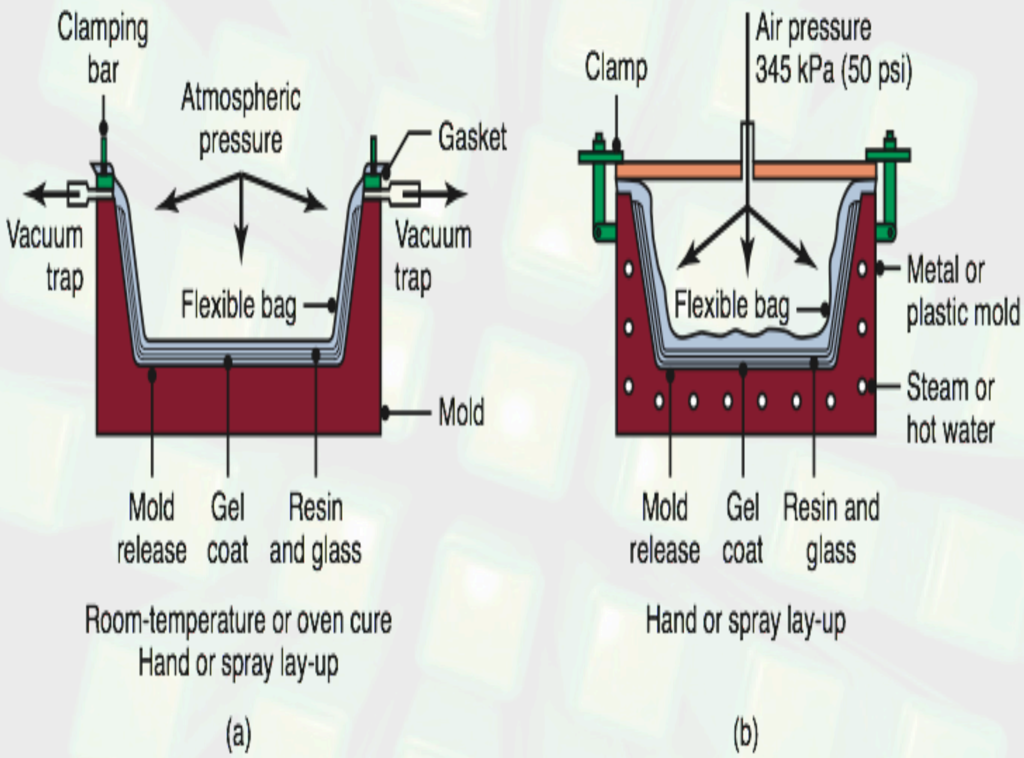


FIGURE 10.42 (a) Vacuum-bag forming. (b) Pressure-bag forming. *Source:* After T. H. Meister.

Contact-Mold (Open Mold) Processing

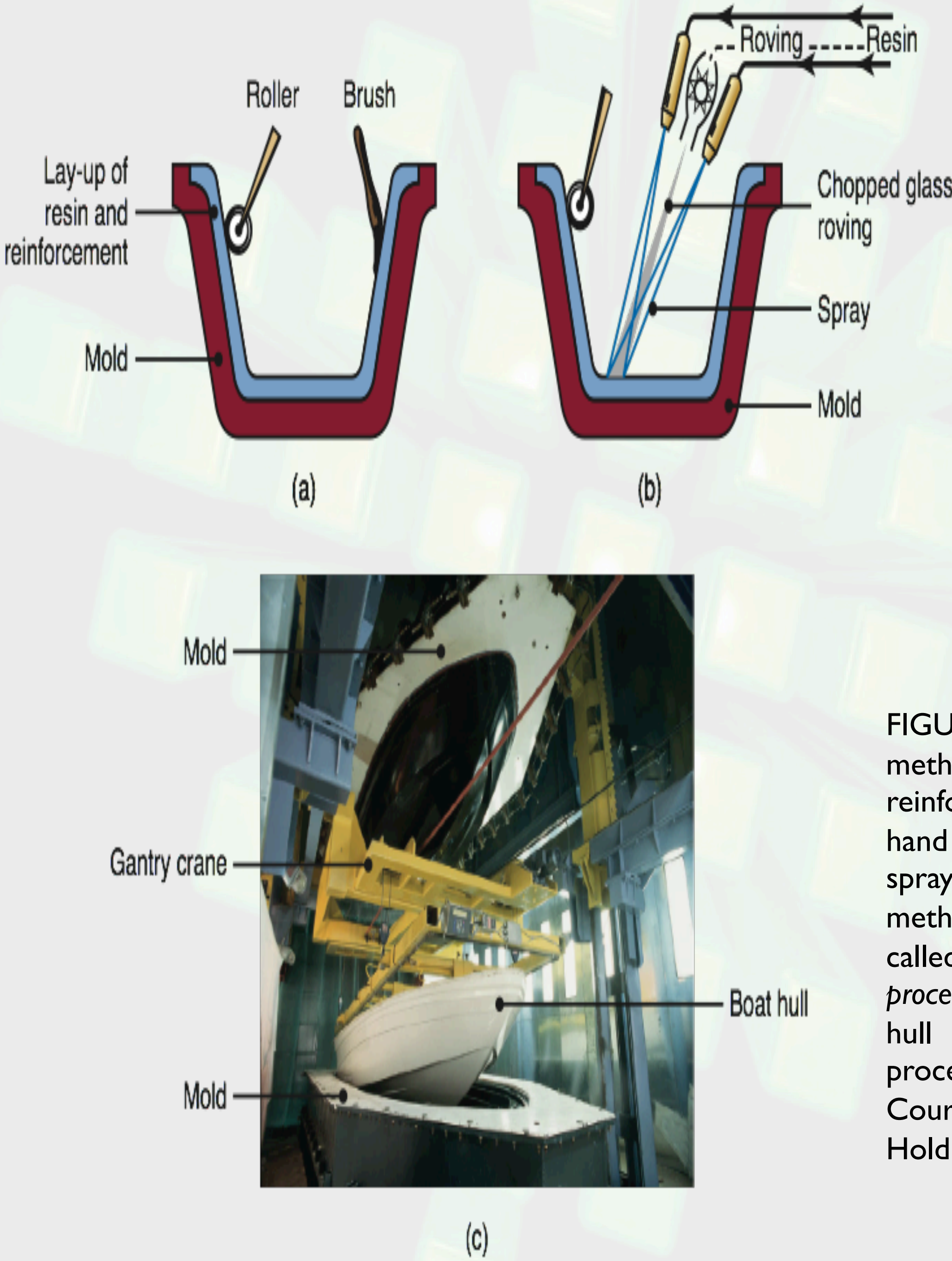
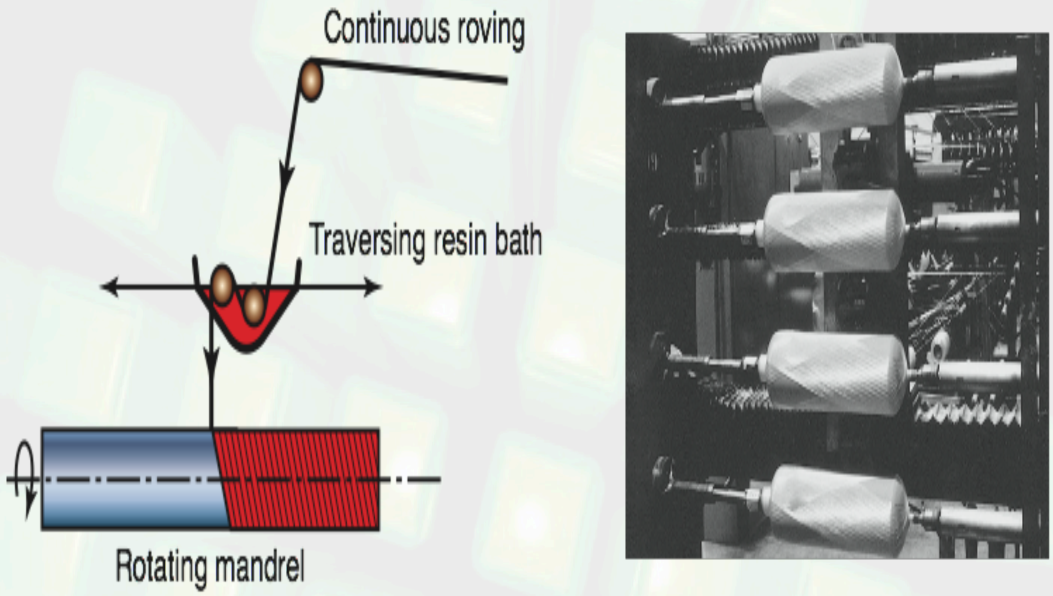


FIGURE 10.43 Manual methods of processing reinforced plastics: (a) hand lay-up and (b) spray-up. These methods are also called *open-mold processing*. (c) A boat hull made by these processes. *Source:* Courtesy of Genmar Holdings, Inc.

Reinforcement is impregnated with resin at time of molding

Filament Winding



(a) (b)

FIGURE 10.44 (a) Schematic illustration of the filament-winding process. (b) Fiberglass being wound over aluminum liners for slide-raft inflation vessels for the Boeing 767 aircraft. *Source:* Advanced Technical Products Group, Inc., Lincoln Composites.

Pultrusion

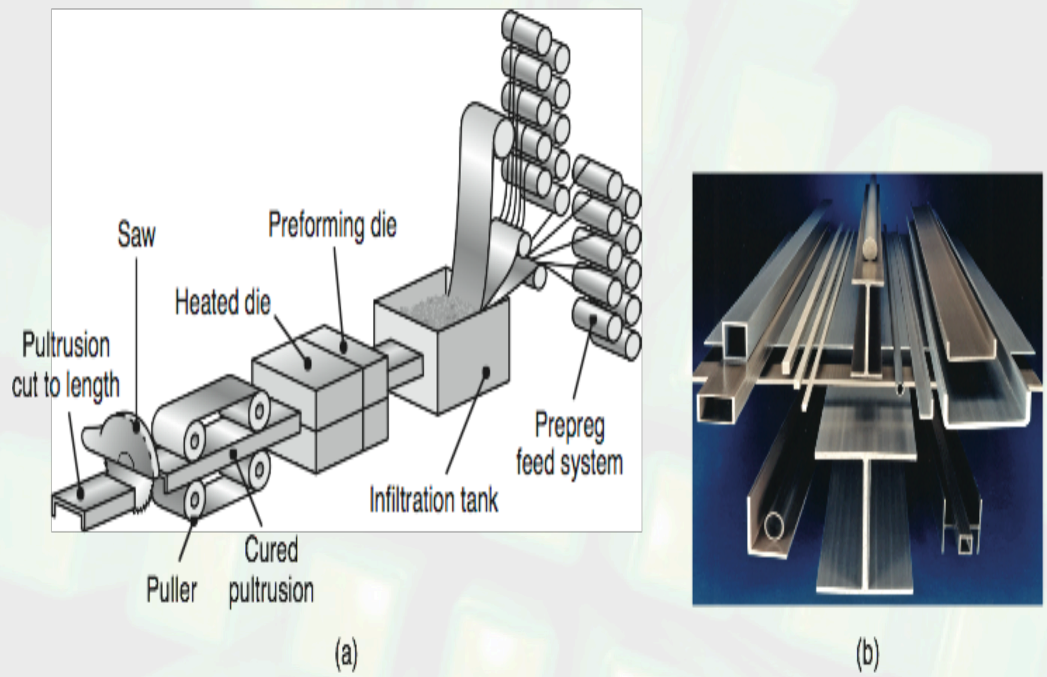


FIGURE 10.45 (a) Schematic illustration of the pultrusion process. (b) Examples of parts made by pultrusion. *Source:* Courtesy of Strongwell Corporation.

Summary

- Processing of plastics
  - Extrusion
  - Injection molding
  - Blow molding
  - Thermoforming
- Processing of reinforced plastics
  - Impregnation
  - Molding
    - Compression molding
    - Vacuum bag molding
    - Contact molding
    - …
  - Other techniques
    - Filament winding, pultrusion, pulforming

Composite Material Microstructure

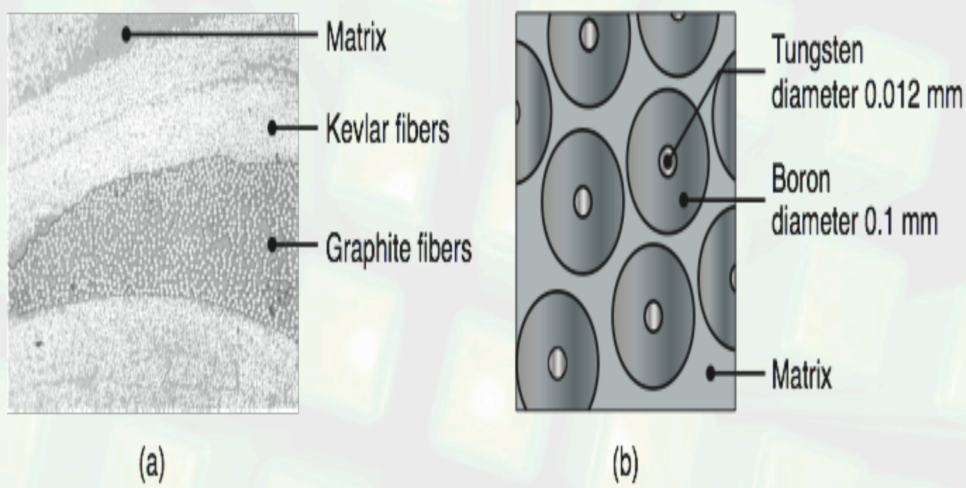


FIGURE 10.18 (a) Cross-section of a tennis racket, showing graphite and aramid (Kevlar) reinforcing fibers. *Source:* After J. Dvorak and F. Garrett. (b) Cross-section of boron-fiber-reinforced composite material.

Applications for Plastics

Design Requirement	Typical Applications	Plastics
Mechanical strength	Gears, cams, rollers, valves, fan blades, impellers, pistons.	Acetals, nylon, phenolics, polycarbonates, polyesters, polypropylenes, epoxies, polyimides.
Wear resistance	Gears, wear strips and liners, bearings, bushings, roller-skate wheels.	Acetals, nylon, phenolics, polyimides, polyurethane, ultrahigh-molecular-weight polyethylene.
Frictional properties		
High	Tires, nonskid surfaces, footware, flooring.	Elastomers, rubbers.
Low	Sliding surfaces, artificial joints.	Fluorocarbons, polyesters, polyethylene, polyimides.
Electrical resistance	All types of electrical components and equipment, appliances, electrical fixtures.	Polymethylmethacrylate, ABS, fluorocarbons, nylon, polycarbonate, polyester, polypropylenes, ureas, phenolics, silicones, rubbers.
Chemical resistance	Containers for chemicals, laboratory equipment, components for chemical industry, food and beverage containers.	Acetals, ABS, epoxies, polymethylmethacrylate, fluorocarbons, nylon, polycarbonate, polyester, polypropylene, ureas, silicones.
Heat resistance	Appliances, cookware, electrical components.	Fluorocarbons, polyimides, silicones, acetals, polysulfones, phenolics, epoxies.
Functional and decorative features	Handles, knobs, camera and battery cases, trim moldings, pipe fittings.	ABS, acrylics, cellulosics, phenolics, polyethylenes, polpropylenes, polystyrenes, polyvinyl chloride.
Functional and transparent features	Lenses, goggles, safety glazing, signs, food-processing equipment	Acrylics, polycarbonates, polystyrenes, polysulfones. laboratory hardware.
Housings and hollow shapes	Power tools, housings, sport helmets, telephone cases.	ABS, cellulosics, phenolics, polycarbonates, polyethylenes, polypropylene, polystyrenes.

TABLE 10.3 General recommendations for plastic products.