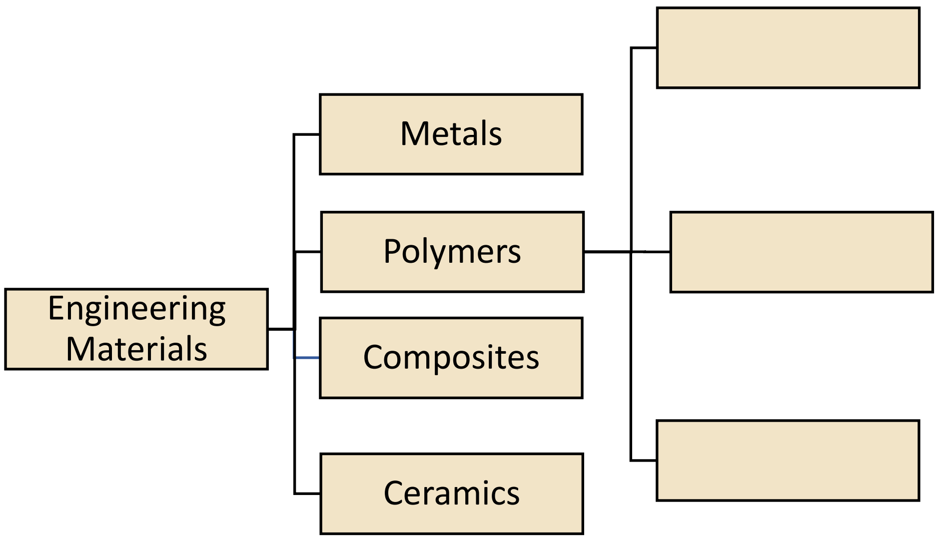
Mechanics In Design and Manufacturing

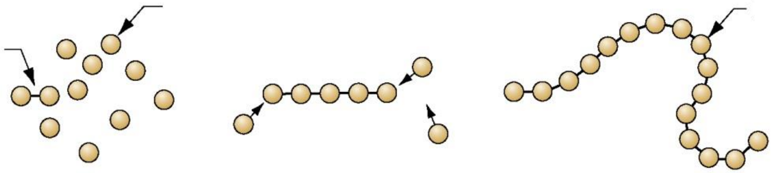
- Polymers Properties and Processing

Materials



Engineering Materials
Metals
Polymers
Composites
Ceramics

What is a Polymer?

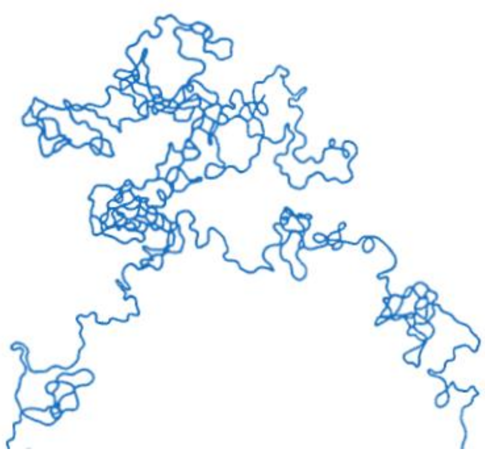


Groover 6th ed.

- Compound consisting of long-chain molecules, each molecule made up of repeating units connected together

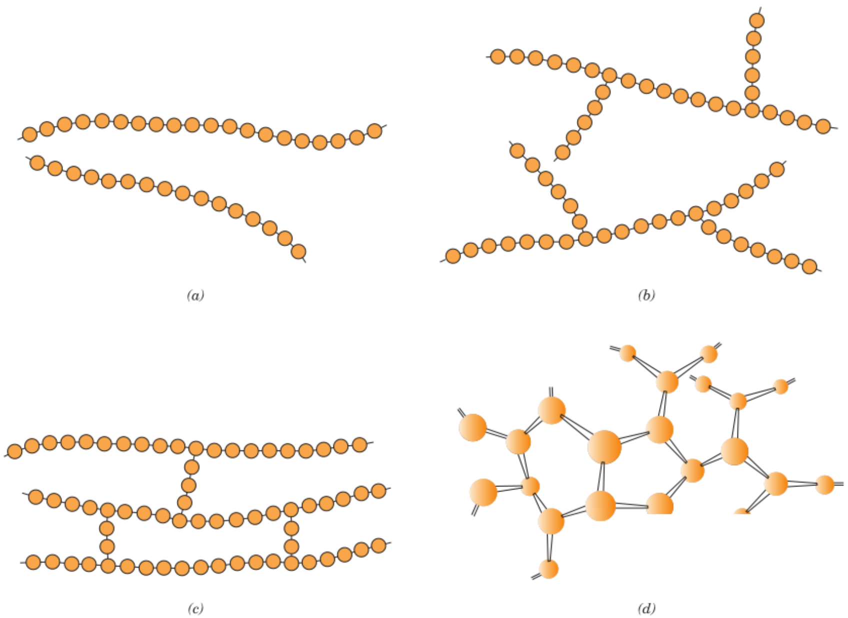
- 2 Types
  - Example:

- Molecular weight

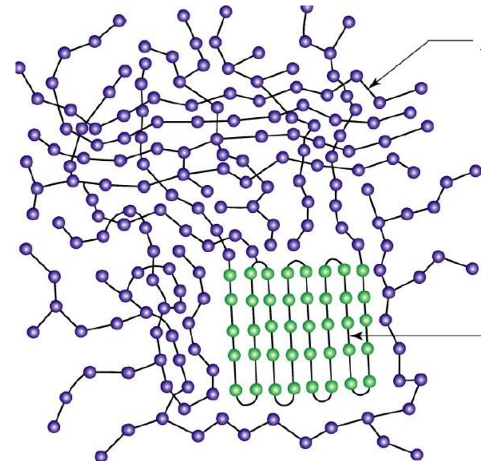


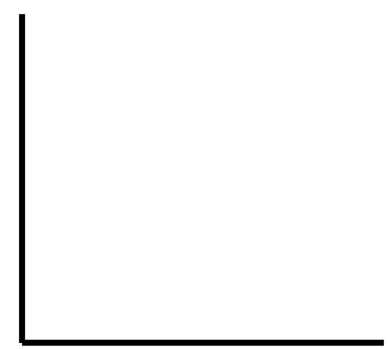
L. R. G. Treloar, The Physics of Rubber Elasticity, 2nd edition, Oxford University Press, Oxford, 1958, p. 47.

Structure



Callister 8e.



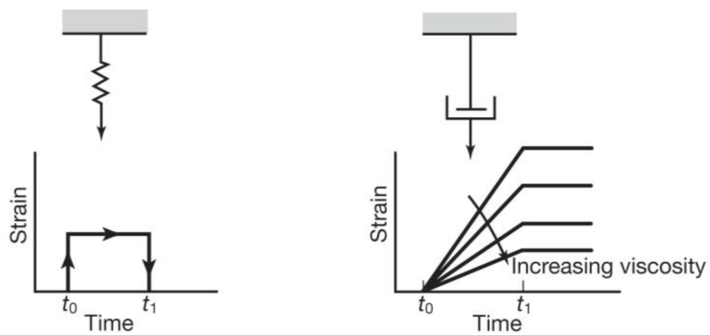


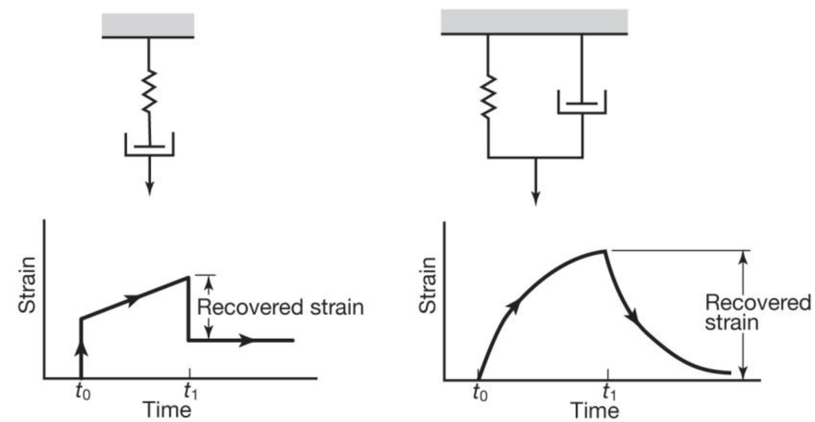
Blends/Additives

- Blending

- Fillers
- Plasticizer
- Flame retardants
- Stabilizers
- Lubricants

Viscoelastic behavior





Behavior

- Typical stress strain curve

- Glass transition temperature

Table 15.2 Melting and Glass Transition Temperatures for Some of the More Common Polymeric Materials

Material	*Glass Transition Temperature* [°C (°F)]	*Melting Temperature* [°C (°F)]
Polyethylene (low density)	−110 (−165)	115 (240)
Polytetrafluoroethylene	−97 (−140)	327 (620)
Polyethylene (high density)	−90 (−130)	137 (279)
Polypropylene	−18 (0)	175 (347)
Nylon 6,6	57 (135)	265 (510)
Poly(ethylene terephthalate) (PET)	69 (155)	265 (510)
Poly(vinyl chloride)	87 (190)	212 (415)
Polystyrene	100 (212)	240 (465)
Polycarbonate	150 (300)	265 (510)

Adapted from *Callister 8e*.

Physical Properties

<u>High</u>

<u>Low</u>

<u>Other Properties</u>

Table 15.1 Room-Temperature Mechanical Characteristics of Some of the More Common Polymers

Material	*Specific Gravity*	*Tensile Modulus [GPa (ksi)]*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Elongation at Break (%)*
Polyethylene (low density)	0.917–0.932	0.17–0.28 (25–41)	8.3–31.4 (1.2–4.55)	9.0–14.5 (1.3–2.1)	100–650
Polyethylene (high density)	0.952–0.965	1.06–1.09 (155–158)	22.1–31.0 (3.2–4.5)	26.2–33.1 (3.8–4.8)	10–1200
Poly(vinyl chloride)	1.30–1.58	2.4–4.1 (350–600)	40.7–51.7 (5.9–7.5)	40.7–44.8 (5.9–6.5)	40–80
Polytetrafluoroethylene	2.14–2.20	0.40–0.55 (58–80)	20.7–34.5 (3.0–5.0)	13.8–15.2 (2.0–2.2)	200–400
Polypropylene	0.90–0.91	1.14–1.55 (165–225)	31–41.4 (4.5–6.0)	31.0–37.2 (4.5–5.4)	100–600
Polystyrene	1.04–1.05	2.28–3.28 (330–475)	35.9–51.7 (5.2–7.5)	25.0–69.0 (3.63–10.0)	1.2–2.5
Poly(methyl methacrylate)	1.17–1.20	2.24–3.24 (325–470)	48.3–72.4 (7.0–10.5)	53.8–73.1 (7.8–10.6)	2.0–5.5
Phenol-formaldehyde	1.24–1.32	2.76–4.83 (400–700)	34.5–62.1 (5.0–9.0)	—	1.5–2.0
Nylon 6,6	1.13–1.15	1.58–3.80 (230–550)	75.9–94.5 (11.0–13.7)	44.8–82.8 (6.5–12)	15–300
Polyester (PET)	1.29–1.40	2.8–4.1 (400–600)	48.3–72.4 (7.0–10.5)	59.3 (8.6)	30–300
Polycarbonate	1.20	2.38 (345)	62.8–72.4 (9.1–10.5)	62.1 (9.0)	110–150

Source: *Modern Plastics Encyclopedia '96*. Copyright 1995, The McGraw-Hill Companies. Reprinted with permission.

Adapted from *Callister 8e.*

Failure of Polymers

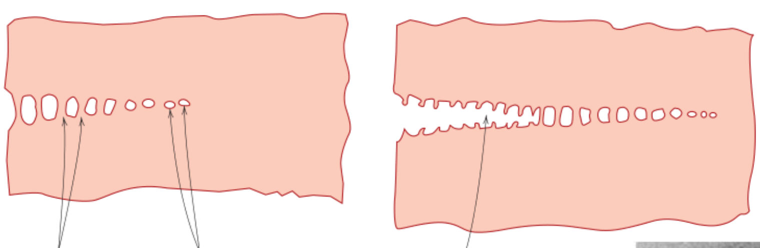
- Failure modes

Table 8.1 Room-Temperature Yield Strength and Plane Strain Fracture Toughness Data for Selected Engineering Materials

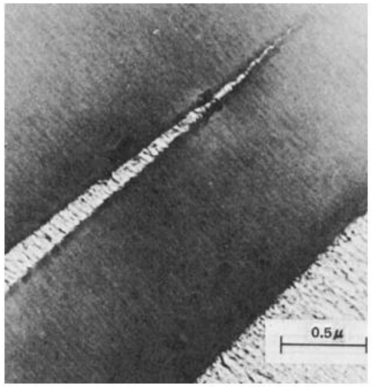
	Yield Strength		K_{Ic}	
Material	*MPa*	*ksi*	$MPa\sqrt{m}$	$ksi\sqrt{in.}$
Metals				
Aluminum alloy[a] (7075-T651)	495	72	24	22
Aluminum alloy[a] (2024-T3)	345	50	44	40
Titanium alloy[a] (Ti-6Al-4V)	910	132	55	50
Alloy steel[a] (4340 tempered @ 260°C)	1640	238	50.0	45.8
Alloy steel[a] (4340 tempered @ 425°C)	1420	206	87.4	80.0
Ceramics				
Concrete	—	—	0.2–1.4	0.18–1.27
Soda-lime glass	—	—	0.7–0.8	0.64–0.73
Aluminum oxide	—	—	2.7–5.0	2.5–4.6
Polymers				
Polystyrene (PS)	25.0–69.0	3.63–10.0	0.7–1.1	0.64–1.0
Poly(methyl methacrylate) (PMMA)	53.8–73.1	7.8–10.6	0.7–1.6	0.64–1.5
Polycarbonate (PC)	62.1	9.0	2.2	2.0

[a] **Source:** Reprinted with permission, *Advanced Materials and Processes,* ASM International, © 1990.

Adapted from *Callister 8e.*



Adapted from *Callister 8e.*



Applications

TABLE 10.3 General recommendations for plastic products.

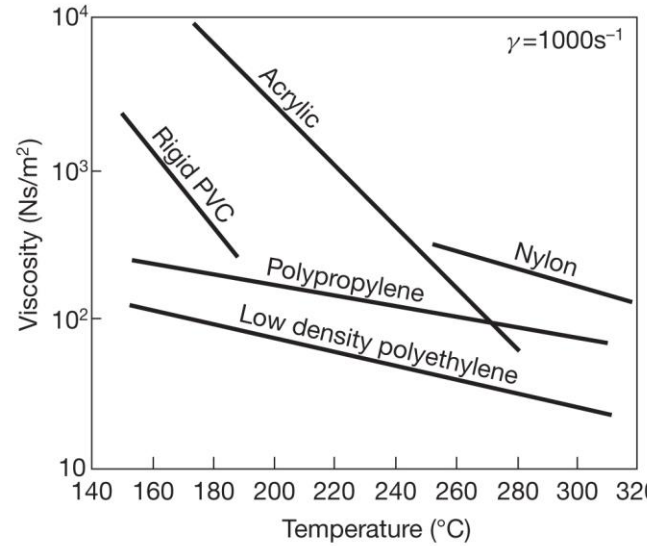
Design requirement	Typical applications	Plastics
Mechanical strength	Gears, cams, rollers, valves, fan blades, impellers, pistons	Acetals, nylon, phenolics, polycarbonates, polyesters, polypropylenes, epoxies, polyimides
Wear resistance	Gears, wear strips and liners, bearings, bushings, roller-skate wheels	Acetals, nylon, phenolics, polyimides, polyurethane, ultrahigh-molecular-weight polyethylene
Friction		
High	Tires, nonskid surfaces, footwear, 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, polypropylenes, 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

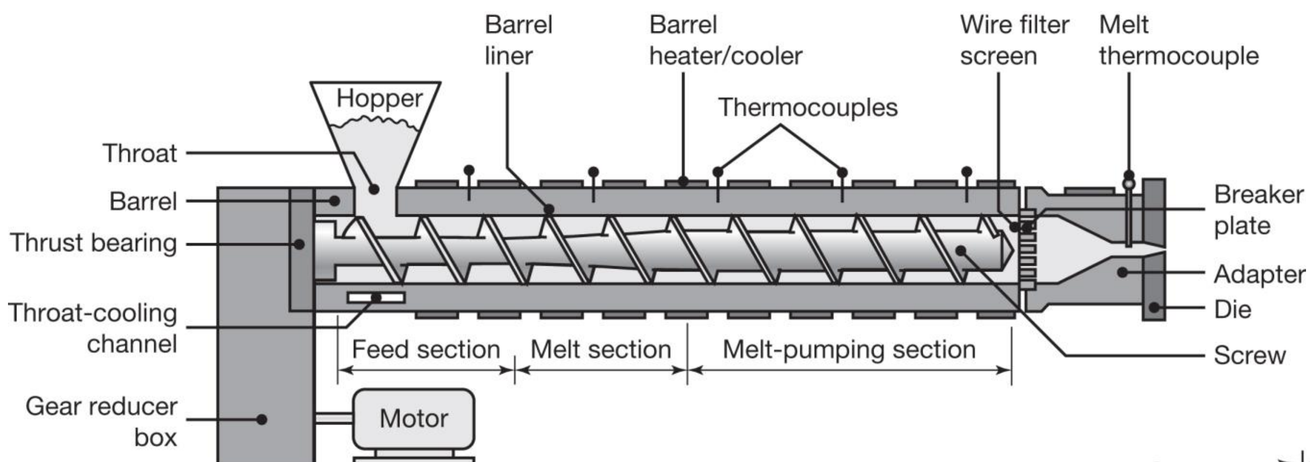
Mechanics In Design and Manufacturing

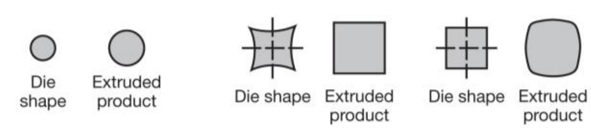
+ Polymer Processing

Processing Basics

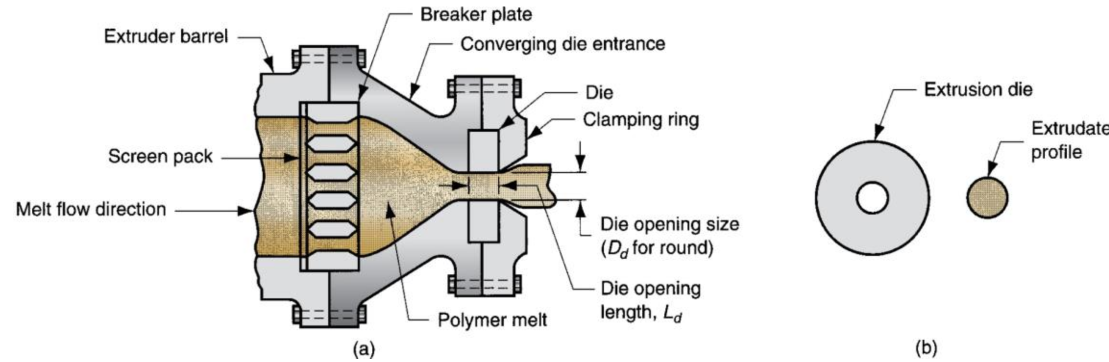
- Viscosity/Temperature

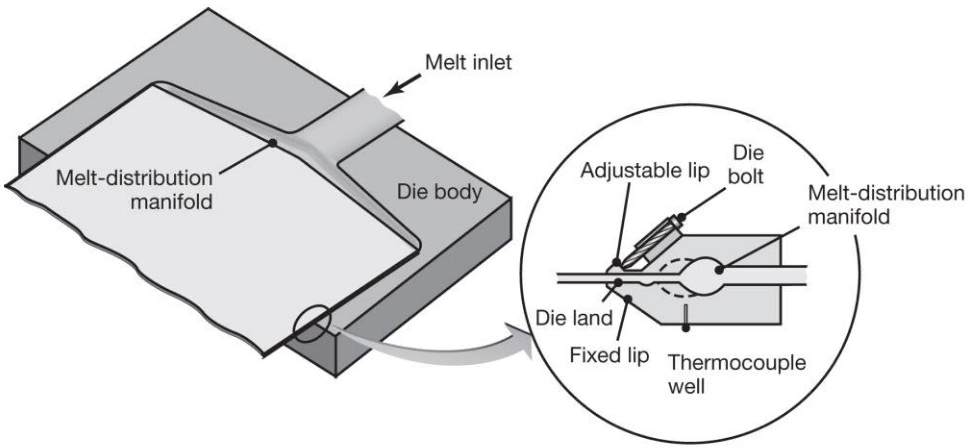


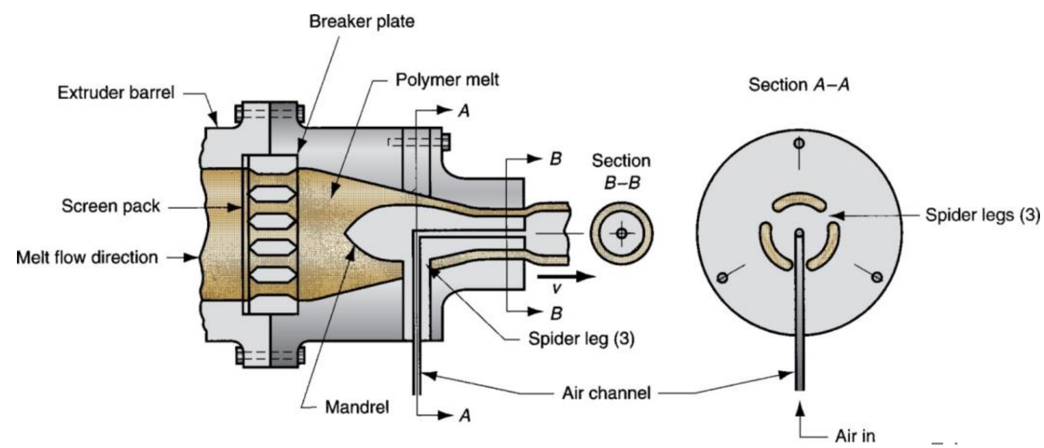




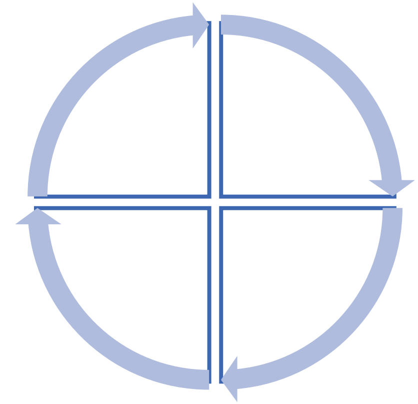
Extrusion, etc.

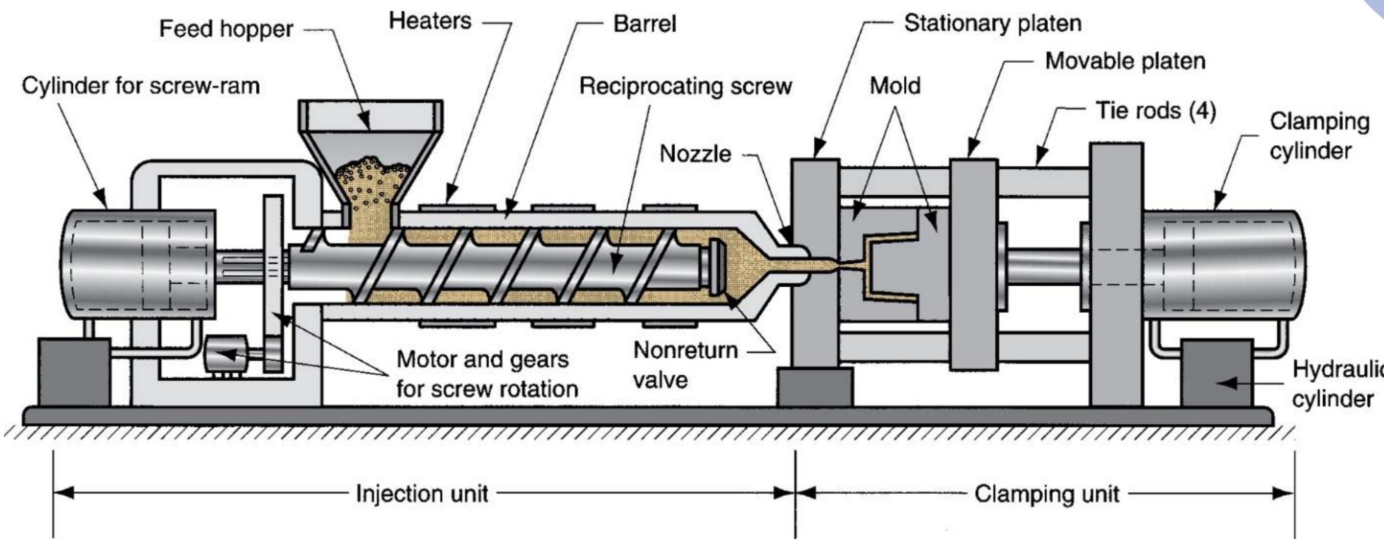


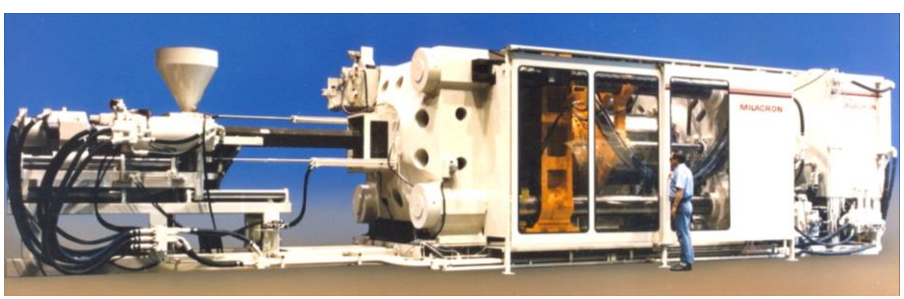


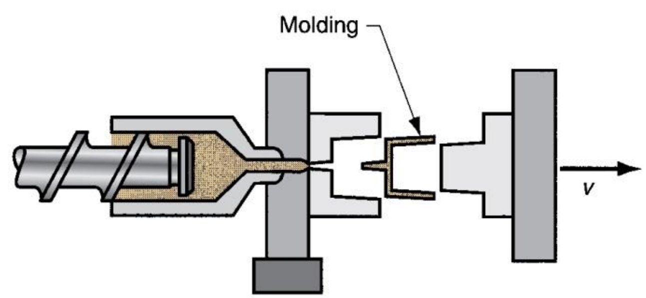


Injection Molding Press

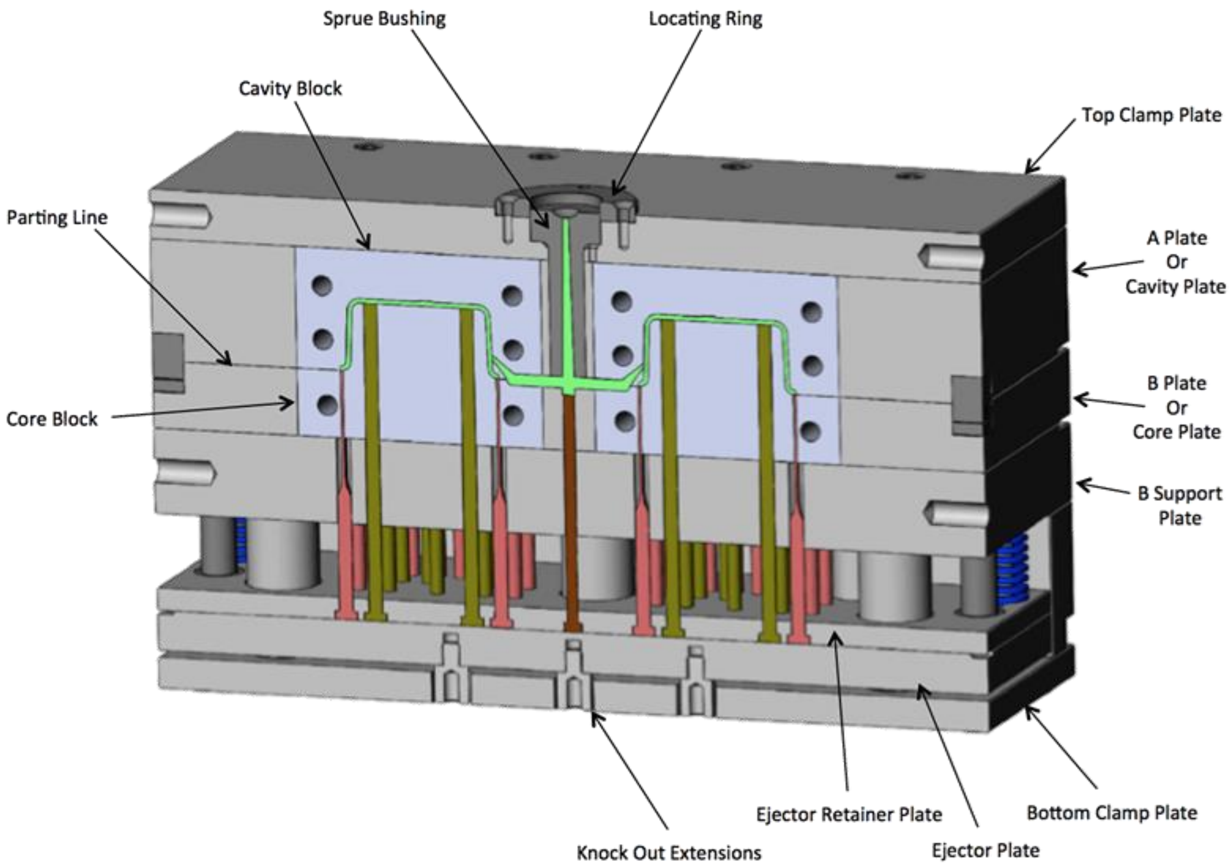


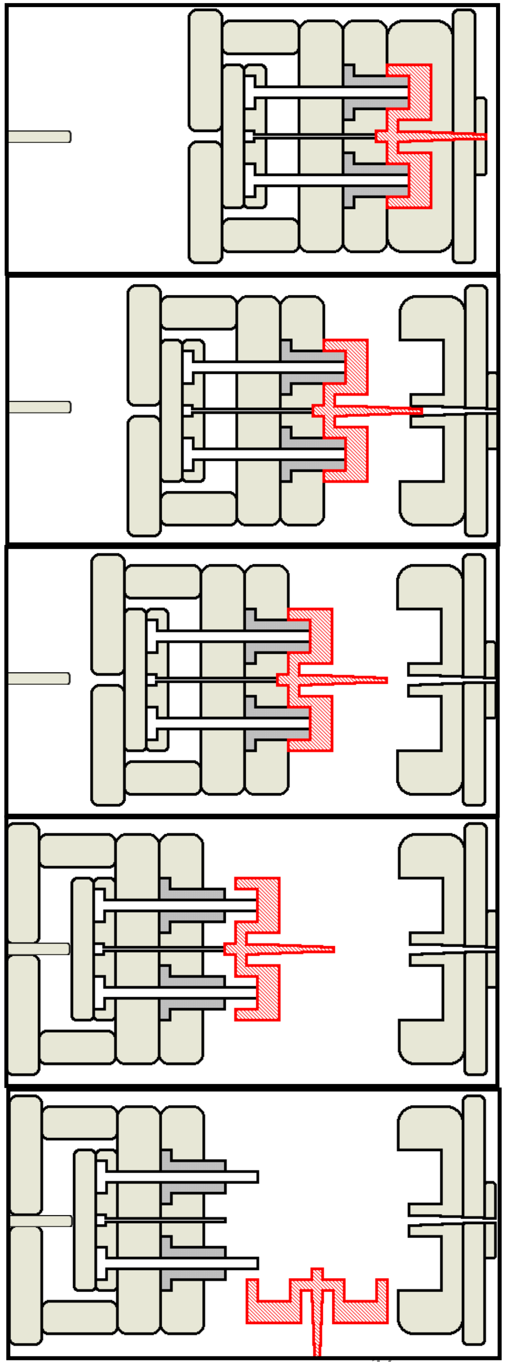




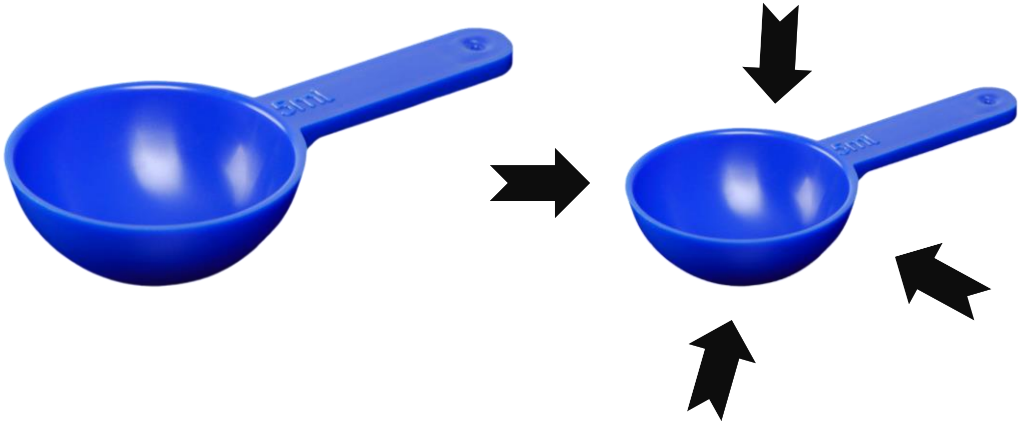


Molds


Sprue Bushing
Locating Ring
Cavity Block
Top Clamp Plate
Parting Line
A Plate Or Cavity Plate
Core Block
B Plate Or Core Plate
B Support Plate
Ejector Retainer Plate
Bottom Clamp Plate
Knock Out Extensions
Ejector Plate



Shrink Rate



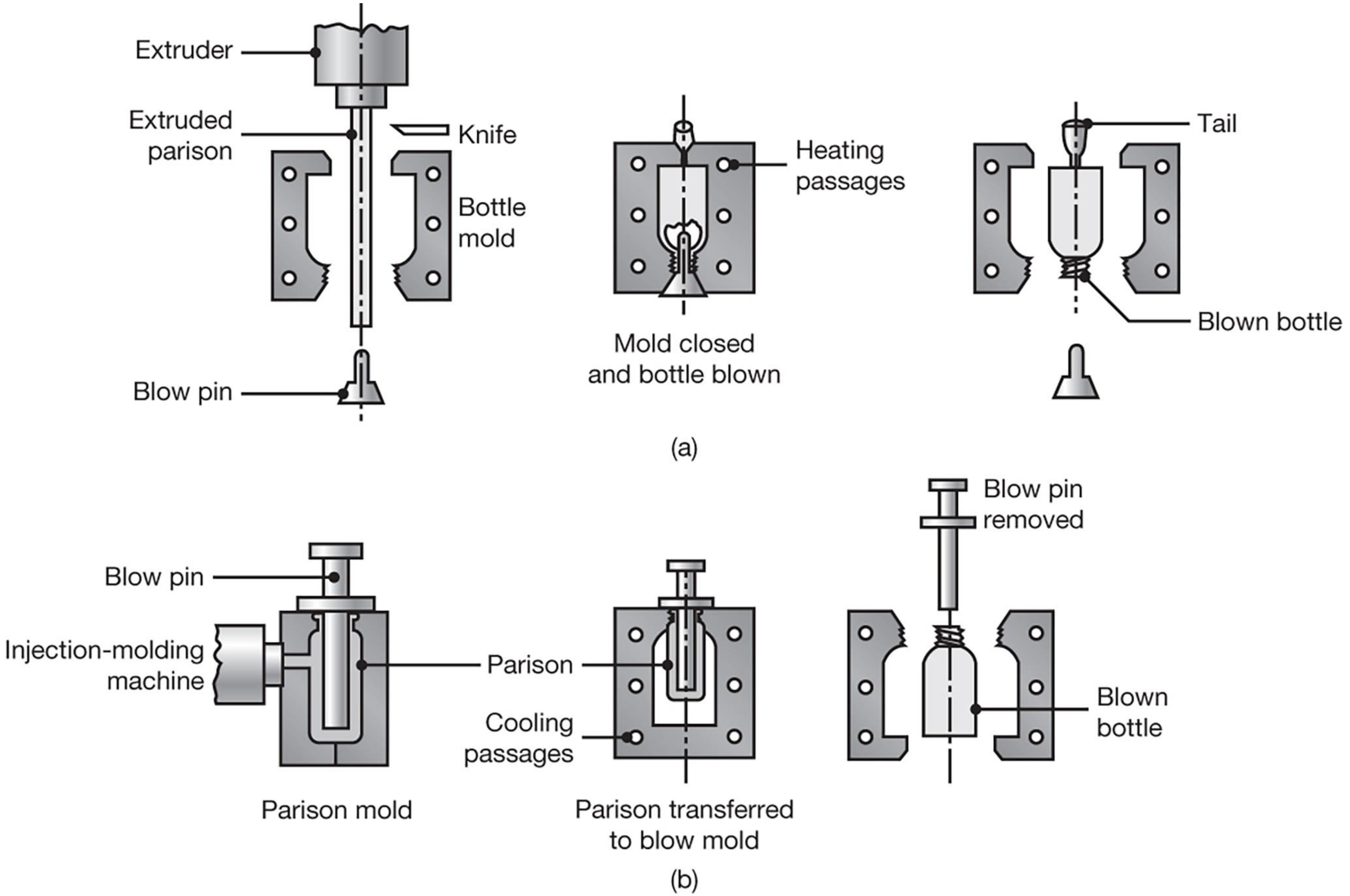
- Polymers have high thermal expansion coefficients, so significant shrinkage occurs during solidification and cooling in mold.

Thermoplastic	Shrinkage (mm/mm)
ABS	0.006
Nylon-6,6	0.020
Polycarbonate	0.007
Polyethylene	0.025
Polystyrene	0.004
PVC	0.005

Injection Mold Parts

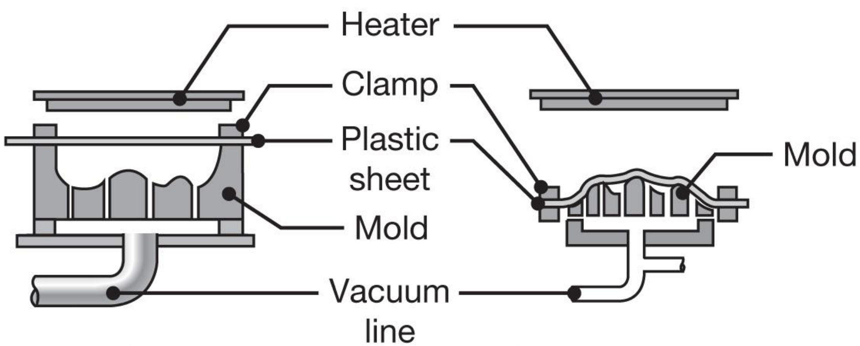
- Insert Molding

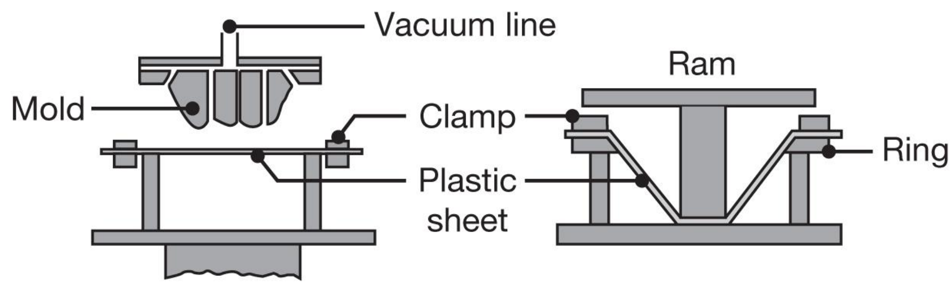
Blow Molding



https://youtu.be/FvzkIpYReD4

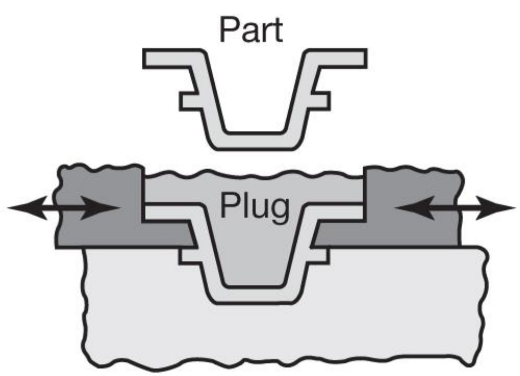
Vacuum/Thermo Forming

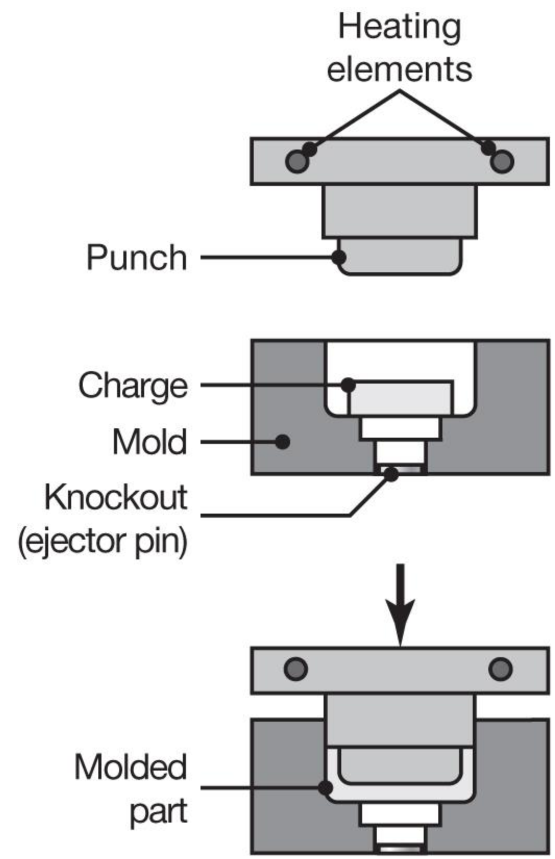




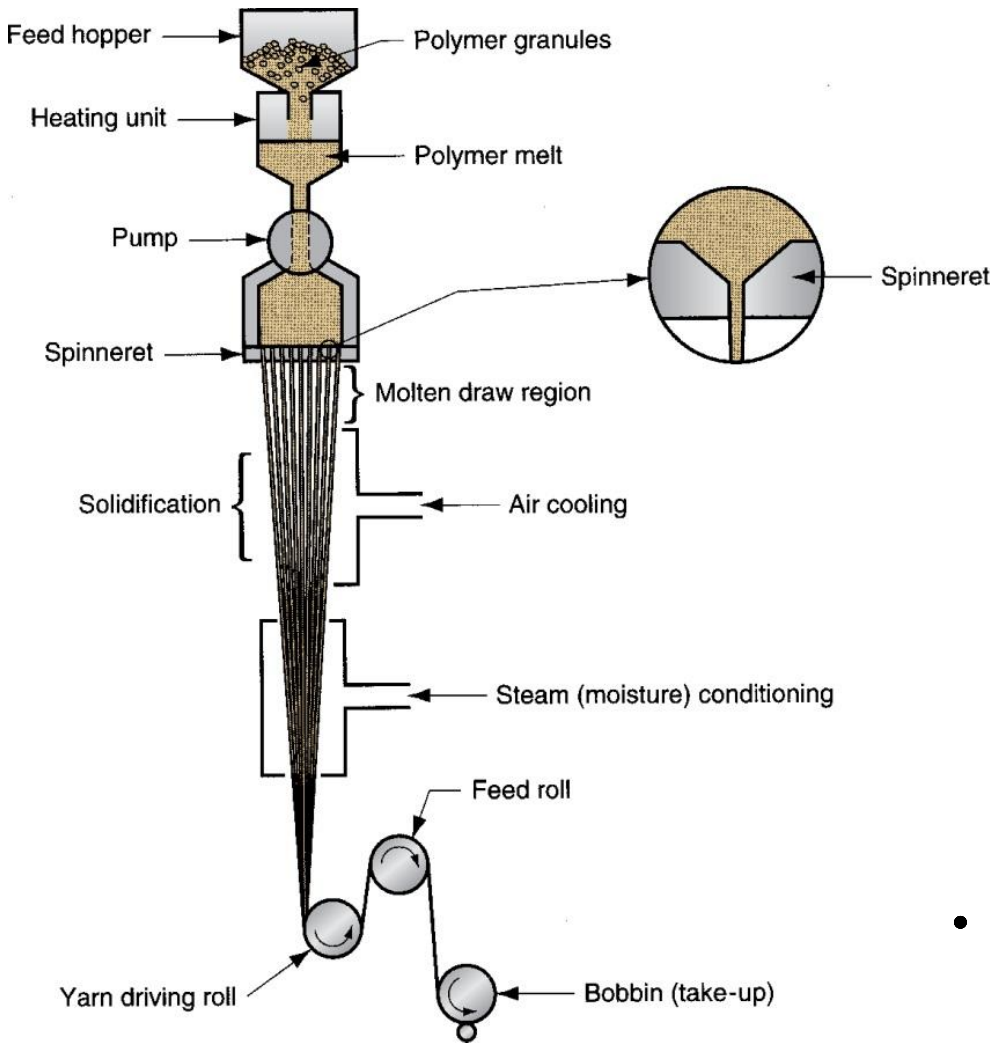
https://www.youtube.com/watch?v=bsdNZFMplyM

Compression Molding





Melt Spinning



- [Melt Spinning]

MechanicsIn Design and Manufacturing

+ Polymer DFM

Injection Molding

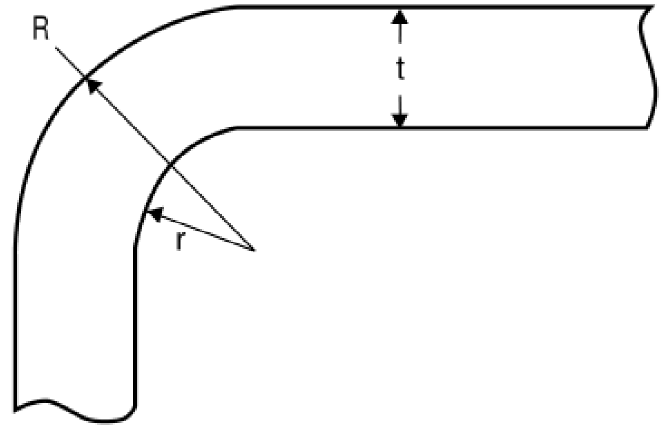
- Strengths

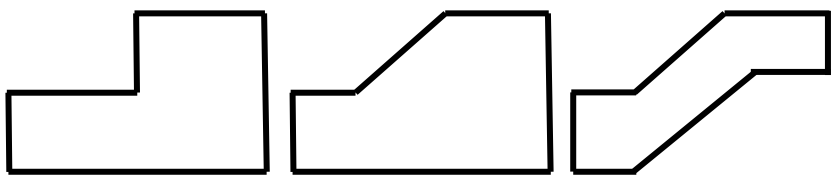
- Weaknesses

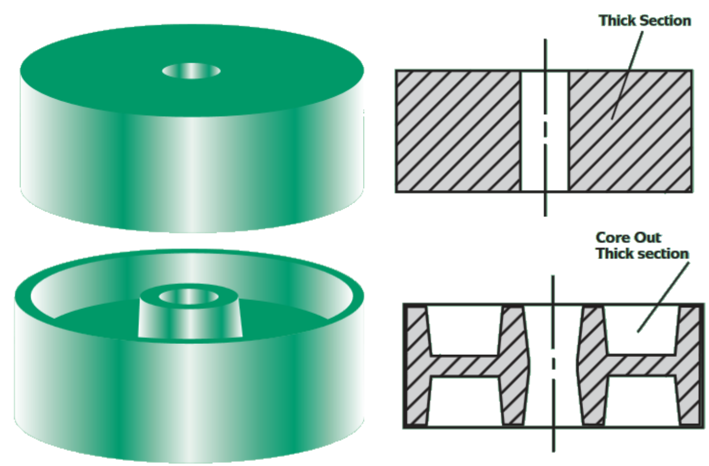
Wall thickness and radii

- Less than 5mm
- Avoid variation in thickness to simplify flow patterns

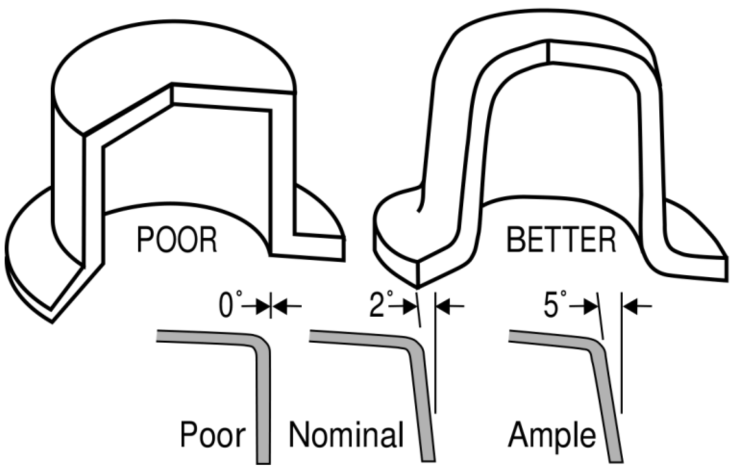
- Avoid abrupt changes in wall thickness -> use gradual transitions if you have to

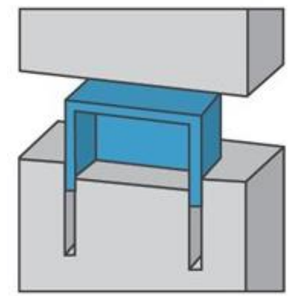


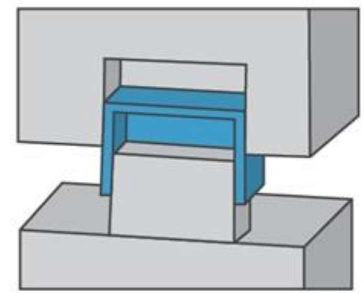


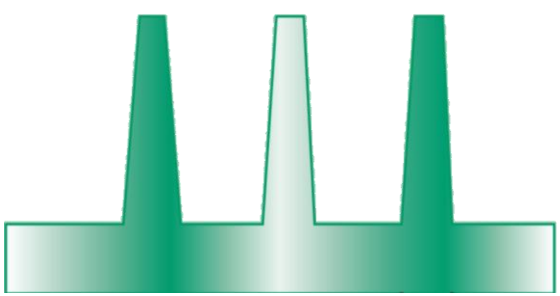


Draft and Ribs

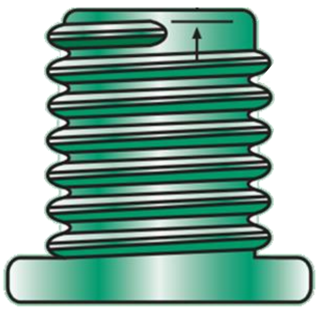




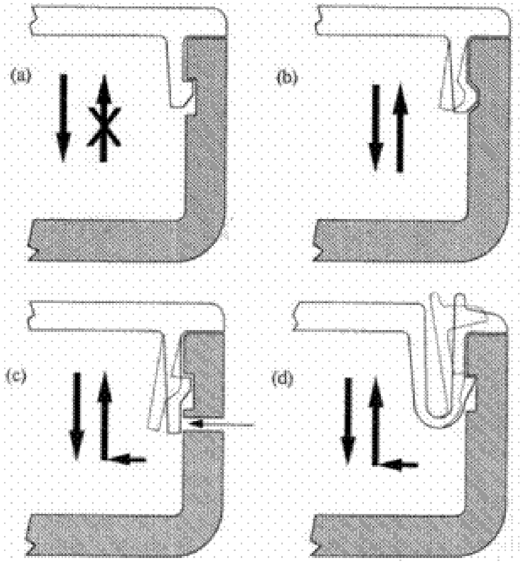




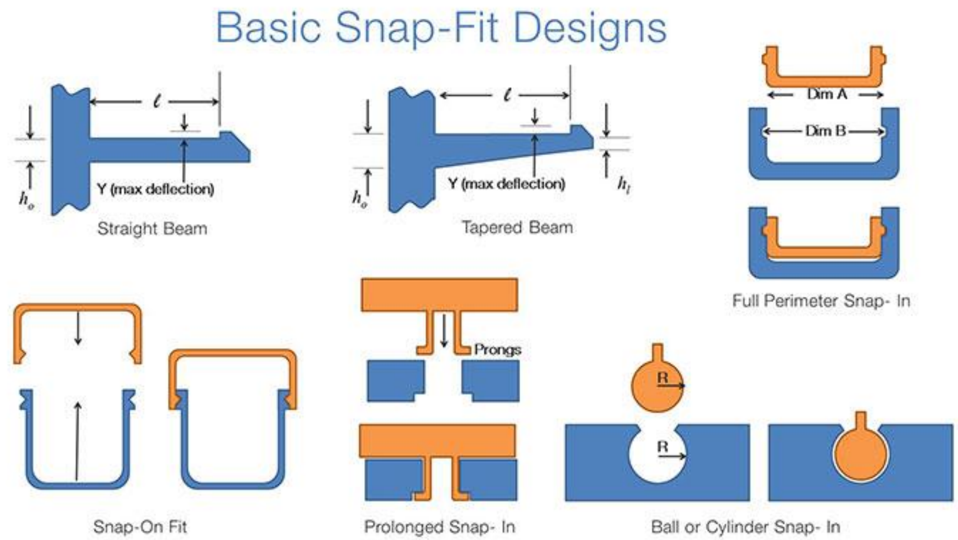
Threads and Fasteners



Snaps and Slide tools



Tres, Designing Plastic Parts for Assembly 2nd, Revised Edition.



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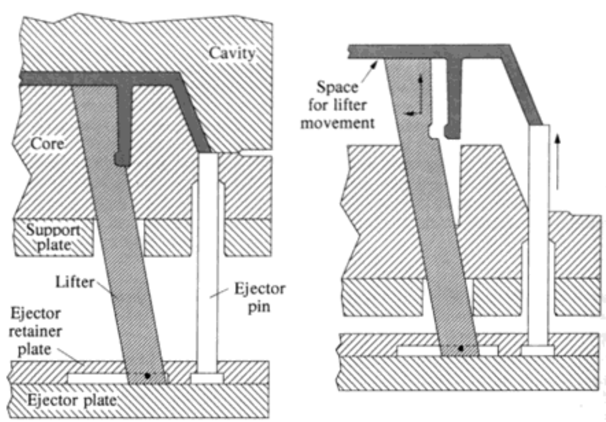

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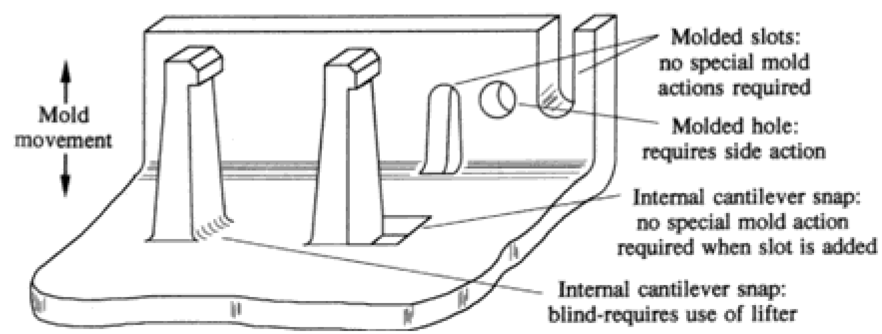
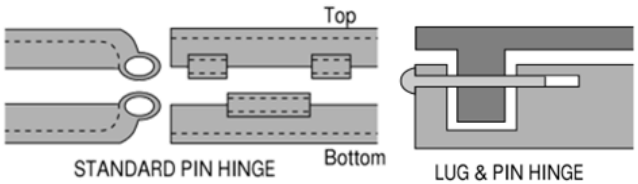
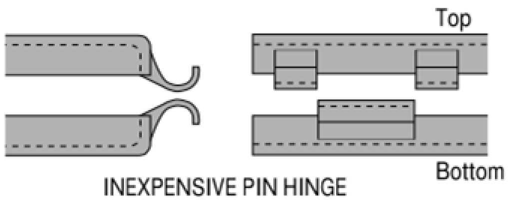
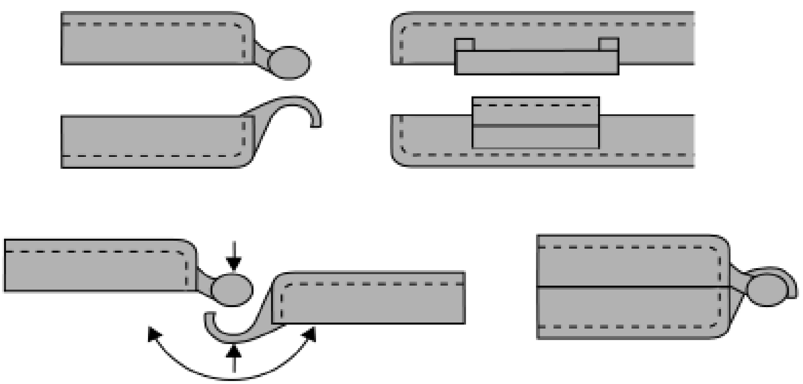


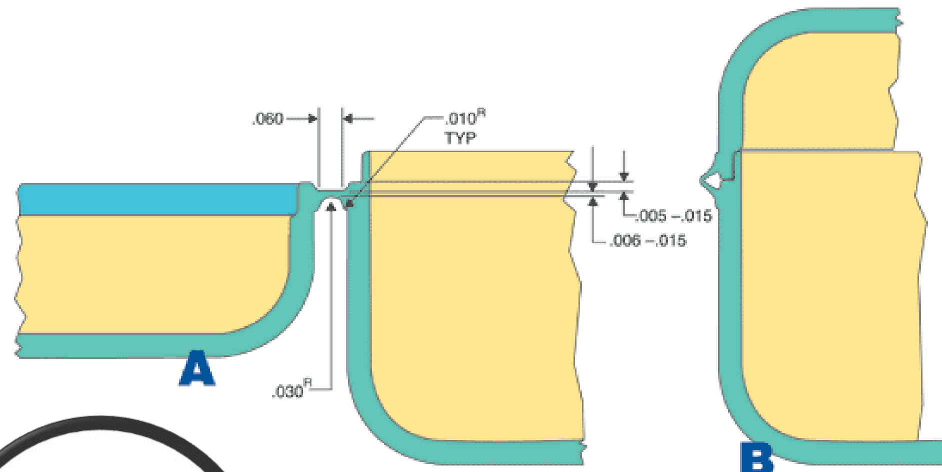
Tres, Designing Plastic Parts for Assembly 2nd, Revised Edition.

Hinges

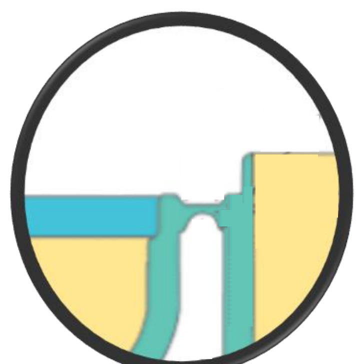








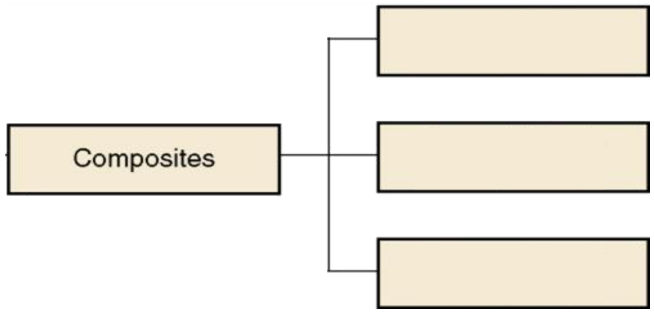
Beal, *Plastics Today* (2002)

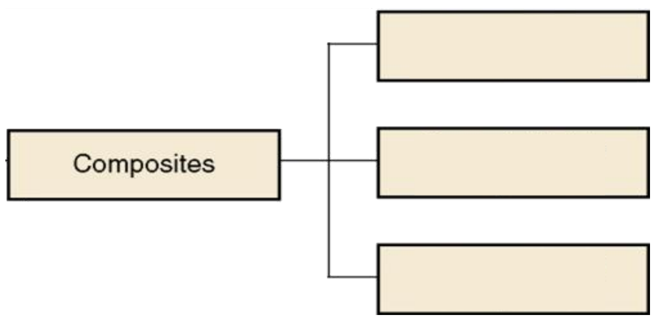


Mechanics In Design and Manufacturing

- Composites Properties and Behavior

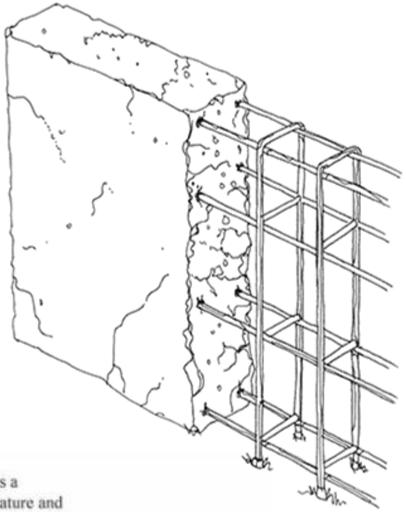
Materials

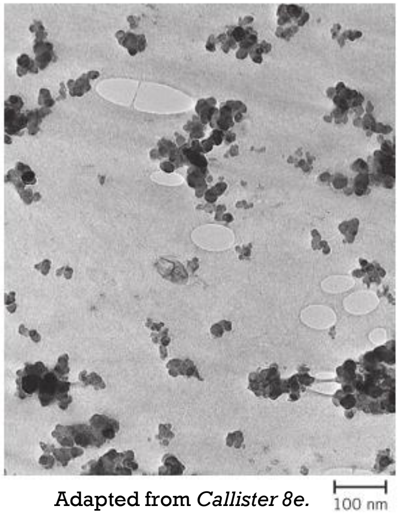




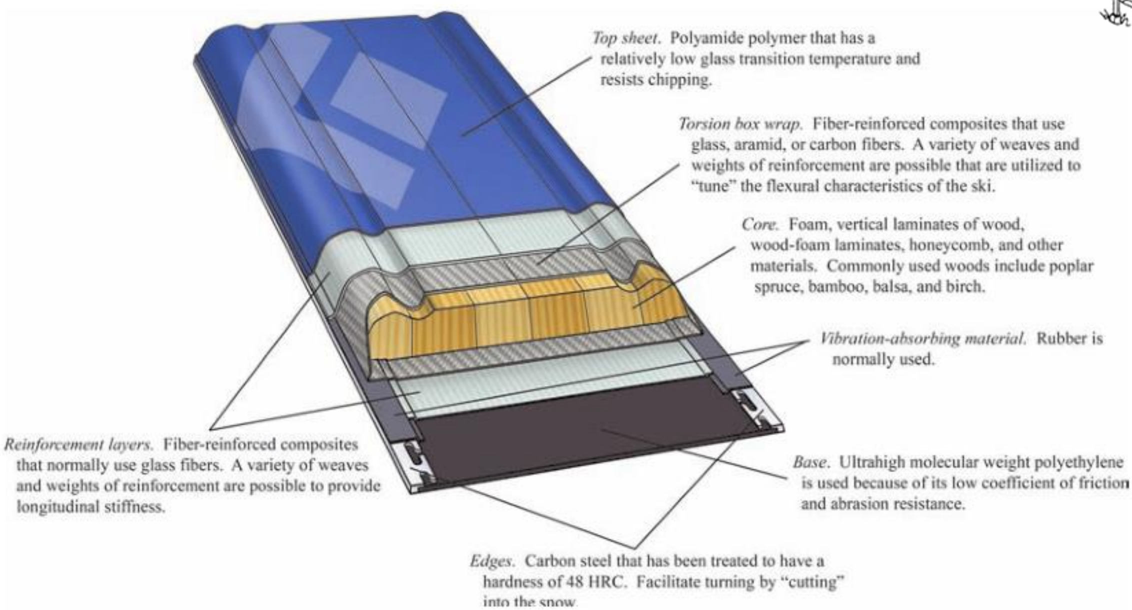
What is a Composite?

- A material system that is composed of two or more physically distinct phases that together have different properties from its constituents.

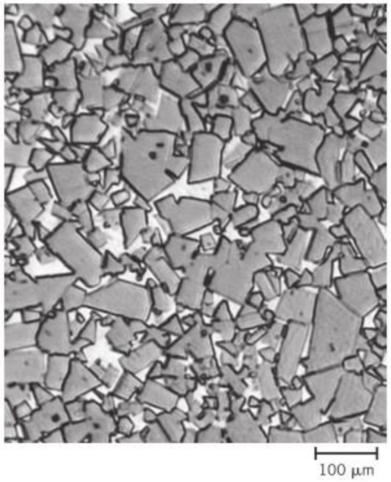




Adapted from *Callister 8e.*



Adapted from *Callister 8e.*



Adapted from *Callister 8e.*

Physical Properties

<u>High</u>

<u>Low</u>

<u>Other Properties</u>

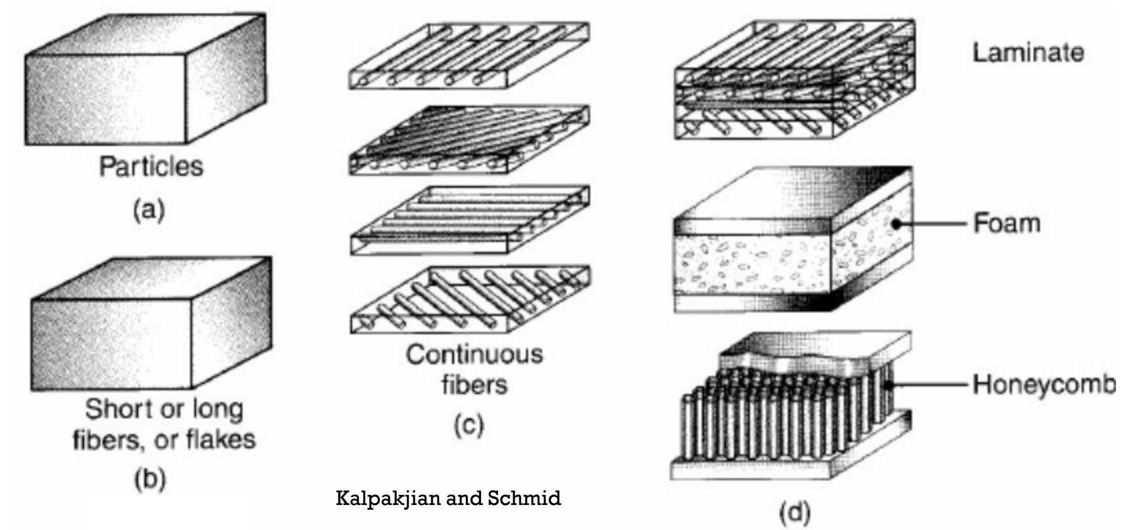
TABLE 10.4 Typical properties of reinforcing fibers.

Type	Tensile strength (MPa)	Elastic modulus (GPa)	Density (kg/m^3)	Relative cost
Boron	3500	380	2380	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	2920	70.5	1440	High
49	3000	112.4	1440	High
129	3200	85	1440	High
Nextel				
312	1700	150	2700	High
610	2770	328	3960	High
Spectra				
900	2270	64	970	High
1000	2670	90	970	High
2000	3240	115	970	High
Alumina (Al_2O_3)	1900	380	3900	High
Silicon carbide	3500	400	3200	High

Note: These properties vary significantly depending on the material and method of preparation.

Structure

- Macrostructure can vary widely depending on the constituents and desired properties

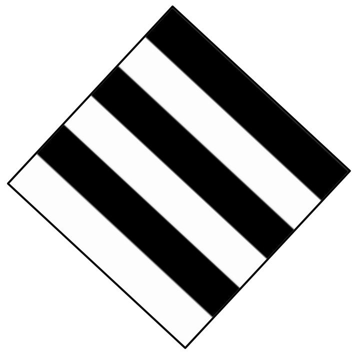


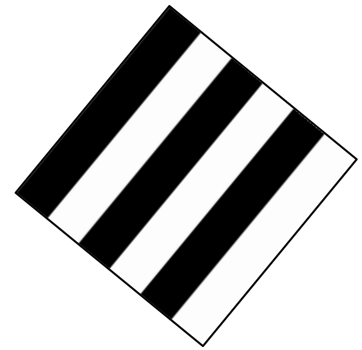
Kalpakjian and Schmid

Large

Small

General Material Models

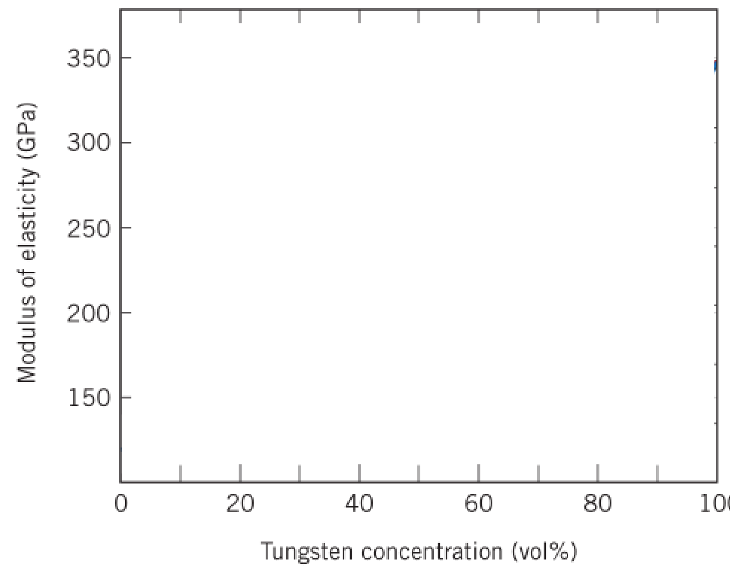




Particle Reinforced Composites

- Equal Strain Model:

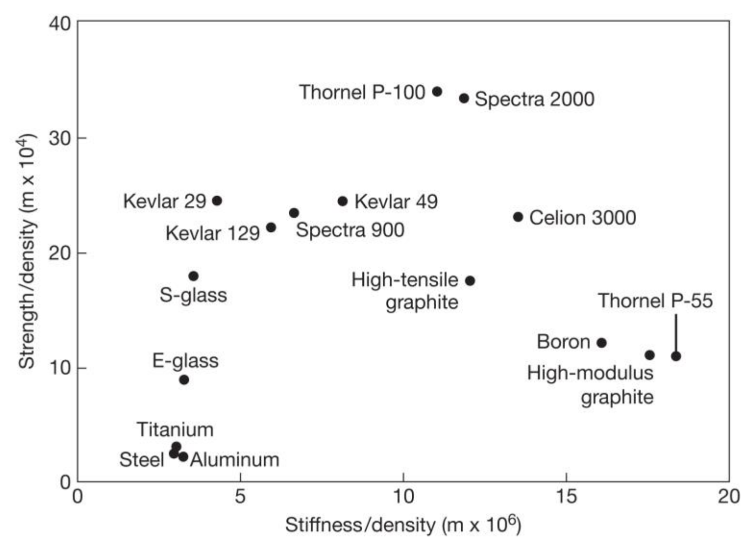
- Equal Stress Model:



Fiber Reinforced Composites

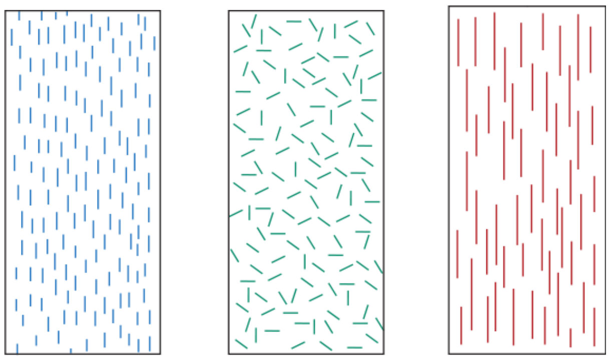
TABLE 10.5 Types and general characteristics of reinforced plastics and metal-matrix and ceramic-matrix composites.

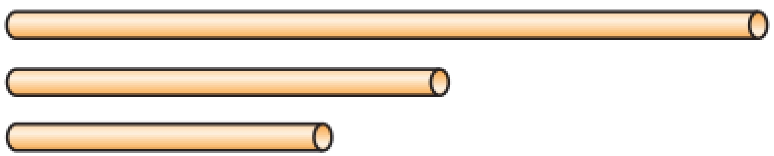
Material	Characteristics
Fiber	
Glass	High strength, low stiffness, high density; E (calcium aluminoborosilicate) and S (magnesia-aluminosilicate) types are commonly used; lowest cost
Graphite	Available typically as high modulus or high strength; less dense than glass; low cost
Boron	High strength and stiffness; has tungsten filament at its center (coaxial); highest density; highest cost
Aramids (Kevlar)	Highest strength-to-weight ratio of all fibers; high cost
Other	Nylon, silicon carbide, silicon nitride, aluminum oxide, boron carbide, boron nitride, tantalum carbide, steel, tungsten, and molybdenum; see Chapters 3, 8, 9, and 10
Matrix	
Thermosets	Epoxy and polyester, with the former most commonly used; others are phenolics, fluorocarbons, polyethersulfone, silicon, and polyimides
Thermoplastics	Polyetheretherketone; tougher than thermosets, but lower resistance to temperature
Metals	Aluminum, aluminum-lithium alloy, magnesium, and titanium; fibers used are graphite, aluminum oxide, silicon carbide, and boron
Ceramics	Silicon carbide, silicon nitride, aluminum oxide, and mullite; fibers used are various ceramics



Fiber Length/Bonding

Adapted from *Callister 8e.*





Mechanics In Design and Manufacturing

- Composite Mechanics: Stress-Strain Relationships and Failure Models

Stress-Strain Relationships

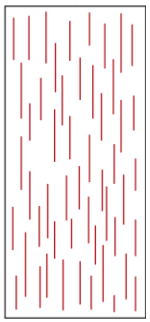
Hooke's law (3-D)

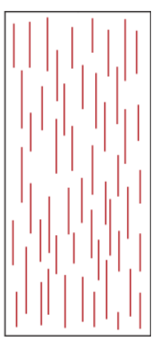
General Stress Strain Relationship

$$
\left\{ \phantom{\begin{matrix} \sigma \\ \\ \\ \\ \\ \\ \\ \\ \end{matrix}} \right\} = \begin{pmatrix}
C_{1111} & C_{1122} & C_{1133} & C_{1123} & C_{1131} & C_{1112} & C_{1132} & C_{1113} & C_{1121} \\
C_{2211} & C_{2222} & C_{2233} & C_{2223} & C_{2231} & C_{2212} & C_{2232} & C_{2213} & C_{2221} \\
 & & & & & & & & \\
 & & & & & & & & \\
 & & & & & & & & \\
 & & & & & & & & \\
 & & & & & & & & \\
C_{2111} & C_{2122} & C_{2133} & C_{2123} & C_{2131} & C_{2112} & C_{2132} & C_{2113} & C_{2121}
\end{pmatrix} \left\{ \phantom{\begin{matrix} \varepsilon \\ \\ \\ \\ \\ \\ \\ \\ \end{matrix}} \right\}
$$

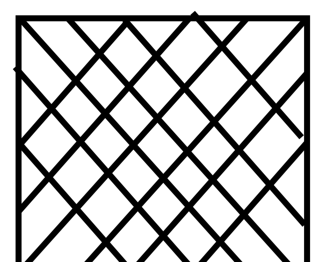
$$
\left\{ \phantom{\begin{matrix} \sigma \\ \\ \\ \end{matrix}} \right\} = \begin{pmatrix} & & \\ & & \\ & & \end{pmatrix} \left\{ \phantom{\begin{matrix} \varepsilon \\ \\ \\ \end{matrix}} \right\}
$$

Elastic Modulus for Long Fiber Composites



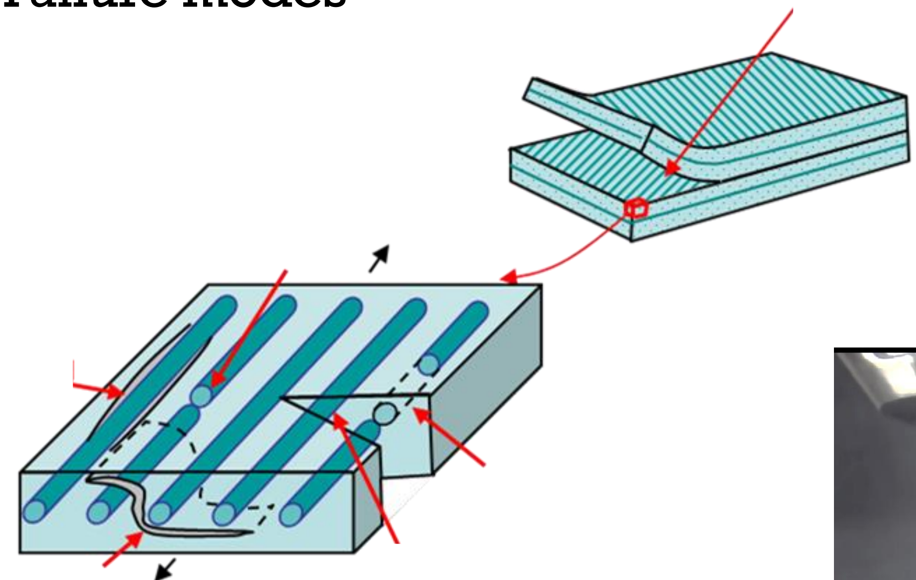


Material	E_1 Msi (GPa)	E_2 Msi (GPa)	G_{12} Msi (GPa)	ν_{12}	v_f
T300/934 graphite/epoxy	19.0 (131)	1.5 (10.3)	1.0 (6.9)	0.22	0.65
AS/3501 graphite/epoxy	20.0 (138)	1.3 (9.0)	1.0 (6.9)	0.3	0.65
p-100/ERL 1962 pitch graphite/epoxy	68.0 (468.9)	0.9 (6.2)	0.81 (5.58)	0.31	0.62
Kevlar® 49/934 aramid/epoxy	11.0 (75.8)	0.8 (5.5)	0.33 (2.3)	0.34	0.65
Scotchply® 1002 E-glass/epoxy	5.6 (38.6)	1.2 (8.27)	0.6 (4.14)	0.26	0.45
Boron/5505 boron/epoxy	29.6 (204.0)	2.68 (18.5)	0.81 (5.59)	0.23	0.5
Spectra® 900/826 polyethylene/epoxy	4.45 (30.7)	0.51 (3.52)	0.21 (1.45)	0.32	0.65
E-glass/470-36 E-glass/vinylester	3.54 (24.4)	1.0 (6.87)	0.42 (2.89)	0.32	0.30

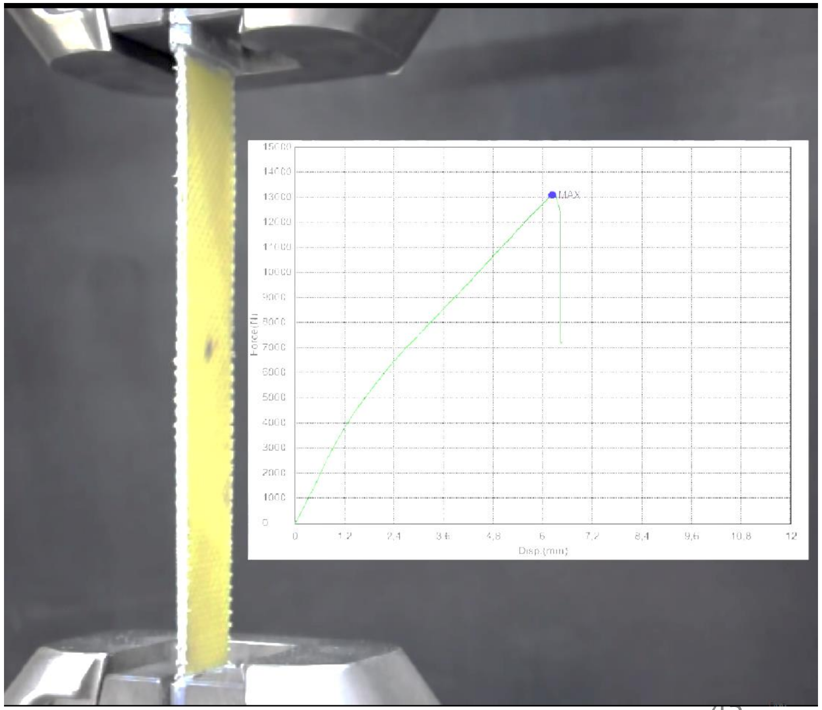


Failure of Fiber Composites

- Failure modes

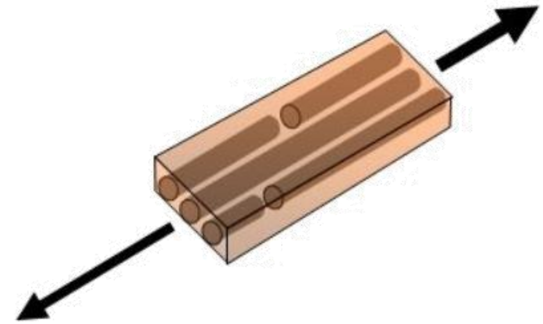


http://www.ltas-cm3.ulg.ac.be/FractureMechanics/overview_P3.html#PictureI49



https://www.youtube.com/watch?v=zJ4rTNeZlJs

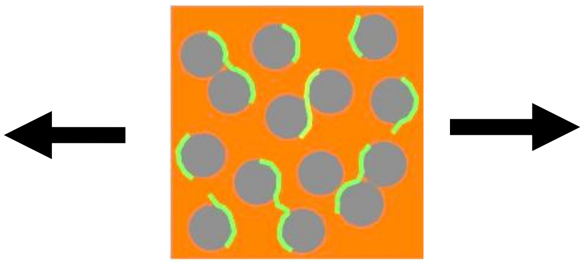
Longitudinal Strength

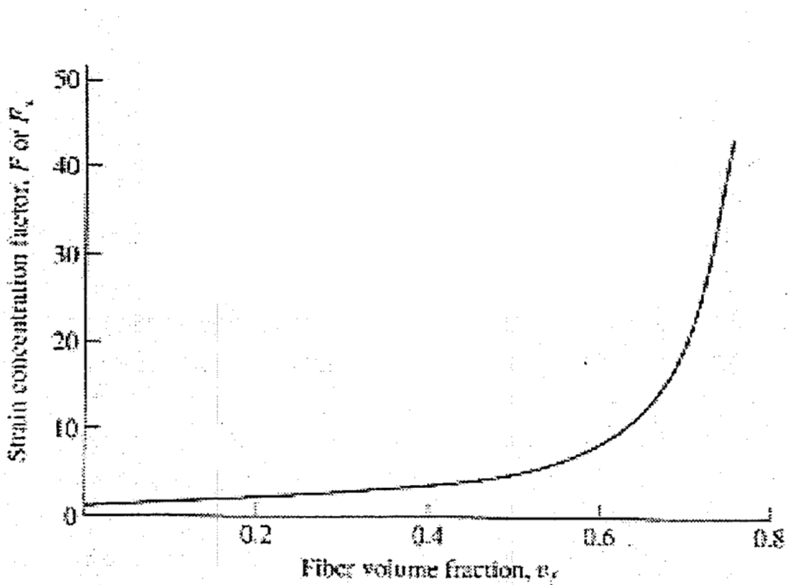


Typical values of lamina strengths for several composites

Material	$S_L^{(+)}$ ksi(MPa)	$S_L^{(-)}$ ksi(Mpa)	$S_T^{(+)}$ ksi(Mpa)	$S_T^{(-)}$ ksi(Mpa)	S_{LT} ksi(Mpa)
Boron/5505 boron/epoxy $v_f = 0.5$ (*)	230 (1586)	360 (2482)	9.1 (62.7)	35.0 (241)	12.0 (82.7)
AS/3501 graphite/epoxy $v_f = 0.6$ (*)	210 (1448)	170 (1172)	7.0 (48.3)	36.0 (248)	9.0 (62.1)
T300/5208 graphite/epoxy $v_f = 0.6$ (*)	210 (1448)	210 (1448)	6.5 (44.8)	36.0 (248)	9.0 (62.1)
Kevlar 49/epoxy aramid/epoxy $v_f = 0.6$ (*)	200 (1379)	40 (276)	4.0 (27.6)	9.4 (64.8)	8.7 (60.0)
Scotchply 1002 E-glass/epoxy $v_f = 0.45$ (*)	160 (1103)	90 (621)	4.0 (27.6)	20.0 (138)	12.0 (82.7)
E-glass/470-36 E-glass/vinylester $v_f = 0.30$ (*)	85 (584)	116 (803)	6.2 (43)	27.1 (187)	9.3 (64.0)

Transverse Strength





- Best Model

- Stress-strain relationships for transverse loading are often non-linear