CHAPTER 15

Polymer II
Characteristics, Applications and Processing
ISSUES TO ADDRESS...

• What are the tensile properties of polymers and how are they affected by basic microstructural features?

• Hardening, anisotropy, and annealing in polymers.

• How does the elevated temperature mechanical response of polymers compare to ceramics and metals?

• What are the primary polymer processing methods?
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1. Introduction

• There are several reasons why an engineer should know something about the characteristics, applications, and processing of polymeric materials.

• Polymers are used in a wide variety of applications, such as construction materials and microelectronics processing.

• Thus, most engineers will be required to work with polymers at some point in their careers.

• Understanding the mechanisms by which polymers elastically and plastically deform allows one to alter and control their moduli of elasticity and strengths.

• Also, additives may be incorporated into polymeric materials to modify a host of properties, including strength, abrasion resistance, toughness, thermal stability, stiffness, deteriorability, color, and flammability.
2. Stress-Strain Behavior

- On the basis of stress–strain behavior, polymers fall within three general classifications (Figure 15.1): brittle (curve A), plastic (curve B), and highly elastic (curve C).

- Polymers are neither as strong nor as stiff as metals. However, their high flexibilities, low densities, and resistance to corrosion make them the materials of choice for many applications.

- The mechanical properties of polymers are sensitive to changes in temperature and strain rate. With either rising temperature or decreasing strain rate, modulus of elasticity diminishes, tensile strength decreases, and ductility increases.
• Fracture strengths of polymers ~ 10% of those for metals
• Deformation strains for polymers > 1000%
  – for most metals, deformation strains < 10%
<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Gravity</th>
<th>Tensile Modulus [GPa (ksi)]</th>
<th>Tensile Strength [MPa (ksi)]</th>
<th>Yield Strength [MPa (ksi)]</th>
<th>Elongation at Break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene (low density)</td>
<td>0.917–0.932</td>
<td>0.17–0.28</td>
<td>8.3–31.4</td>
<td>9.0–14.5</td>
<td>100–650</td>
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<tr>
<td></td>
<td>(25–41)</td>
<td>(1.2–4.55)</td>
<td>(3.8–4.8)</td>
<td>(1.3–2.1)</td>
<td></td>
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<tr>
<td>Polyethylene (high density)</td>
<td>0.952–0.965</td>
<td>1.06–1.09</td>
<td>22.1–31.0</td>
<td>26.2–33.1</td>
<td>10–1200</td>
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<tr>
<td></td>
<td>(155–158)</td>
<td>(3.2–4.5)</td>
<td>(3.8–4.8)</td>
<td>(3.8–4.8)</td>
<td></td>
</tr>
<tr>
<td>Poly(vinyl chloride)</td>
<td>1.30–1.58</td>
<td>2.4–4.1</td>
<td>40.7–51.7</td>
<td>40.7–44.8</td>
<td>40–80</td>
</tr>
<tr>
<td></td>
<td>(350–600)</td>
<td>(5.9–7.5)</td>
<td>(5.9–6.5)</td>
<td>(5.9–6.5)</td>
<td></td>
</tr>
<tr>
<td>Polytetrafluoroethylene</td>
<td>2.14–2.20</td>
<td>0.40–0.55</td>
<td>20.7–34.5</td>
<td>13.8–15.2</td>
<td>200–400</td>
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<tr>
<td></td>
<td>(58–80)</td>
<td>(3.0–5.0)</td>
<td>(2.0–2.2)</td>
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<td>Polypropylene</td>
<td>0.90–0.91</td>
<td>1.14–1.55</td>
<td>31–41.4</td>
<td>31.0–37.2</td>
<td>100–600</td>
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<td></td>
<td>(165–225)</td>
<td>(4.5–6.0)</td>
<td>(4.5–5.4)</td>
<td></td>
<td></td>
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<tr>
<td>Polystyrene</td>
<td>1.04–1.05</td>
<td>2.28–3.28</td>
<td>35.9–51.7</td>
<td>25.0–69.0</td>
<td>1.2–2.5</td>
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<tr>
<td></td>
<td>(330–475)</td>
<td>(5.2–7.5)</td>
<td>(3.63–10.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poly(methyl methacrylate)</td>
<td>1.17–1.20</td>
<td>2.24–3.24</td>
<td>48.3–72.4</td>
<td>53.8–73.1</td>
<td>2.0–5.5</td>
</tr>
<tr>
<td></td>
<td>(325–470)</td>
<td>(7.0–10.5)</td>
<td>(7.8–10.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenol-formaldehyde</td>
<td>1.24–1.32</td>
<td>2.76–4.83</td>
<td>34.5–62.1</td>
<td>—</td>
<td>1.5–2.0</td>
</tr>
<tr>
<td></td>
<td>(400–700)</td>
<td>(5.0–9.0)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Nylon 6,6</td>
<td>1.13–1.15</td>
<td>1.58–3.80</td>
<td>75.9–94.5</td>
<td>44.8–82.8</td>
<td>15–300</td>
</tr>
<tr>
<td></td>
<td>(230–550)</td>
<td>(11.0–13.7)</td>
<td>(6.5–12)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyester (PET)</td>
<td>1.29–1.40</td>
<td>2.8–4.1</td>
<td>48.3–72.4</td>
<td>59.3</td>
<td>30–300</td>
</tr>
<tr>
<td></td>
<td>(400–600)</td>
<td>(7.0–10.5)</td>
<td>(8.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>1.20</td>
<td>2.38</td>
<td>62.8–72.4</td>
<td>62.1</td>
<td>110–150</td>
</tr>
<tr>
<td></td>
<td>(345)</td>
<td>(9.1–10.5)</td>
<td>(9.0)</td>
<td></td>
<td></td>
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</tbody>
</table>

Influence of $T$ and Strain Rate on Thermoplastics

- Decreasing $T$...
  - increases $E$
  - increases $TS$
  - decreases $\%EL$
- Increasing strain rate...
  - same effects as decreasing $T$.

Adapted from Fig. 15.3, Callister & Rethwisch 8e. (Fig. 15.3 is from T.S. Carswell and J.K. Nason, 'Effect of Environmental Conditions on the Mechanical Properties of Organic Plastics", Symposium on Plastics, American Society for Testing and Materials, Philadelphia, PA, 1944.)
Mechanisms of Deformation—Brittle Crosslinked and Network Polymers

Stress-strain curves adapted from Fig. 15.1, Callister & Rethwisch 8e.

Initial | Near Failure
aligned, crosslinked polymer

Initial | Near Failure
network polymer
3. Macroscopic deformation

Tensile strain-stress curve for a semicrystalline polymer.
4. Viscoelastic Deformation

- Viscoelastic mechanical behavior, being intermediate between totally elastic and totally viscous, is displayed by a number of polymeric materials.
- This behavior is characterized by the relaxation modulus, a time-dependent modulus of elasticity.
- Magnitude of the relaxation modulus is very sensitive to temperature. Glassy, leathery, rubbery, and viscous flow regions may be identified on a plot of logarithm of relaxation modulus versus temperature (Figure 15.7).
- The logarithm of relaxation modulus versus temperature behavior will depend on molecular configuration—degree of crystallinity, presence of crosslinking, and so on. (Figure 15.8).
(a). load-time; (b)-(d) strain-time

(a) Load vs. Time
(b) Totally elastic
(c) Viscoelastic
(d) Viscous
• **Stress relaxation test:**
  -- strain in tension to $\varepsilon_o$ and hold.
  -- observe decrease in stress with time.

• **Relaxation modulus:**

$$E_r(t) = \frac{\sigma(t)}{\varepsilon_o}$$

- **Representative $T_g$ values ($^\circ$C):**
  - PE (low density) - 110
  - PE (high density) - 90
  - PVC + 87
  - PS +100
  - PC +150

- **There is a large decrease in $E_r$ for $T > T_g$:**

  Adapted from Fig. 15.7, Callister & Rethwisch 8e. (Fig. 15.7 is from A.V. Tobolsky, Properties and Structures of Polymers, John Wiley and Sons, Inc., 1960.)

- **Selected values from Table 15.2, Callister & Rethwisch 8e.**
5. Fracture of polymers

• Fracture strengths of polymeric materials are low relative to metals and ceramics.
• Both brittle and ductile fracture modes are possible.
• Some thermoplastic materials experience a ductile-to-brittle transition with a lowering of temperature, an increase in strain rate, and/or an alteration of specimen thickness or geometry.
• In some thermoplastics, the crack-formation process may be preceded by crazing; crazes are regions of localized deformation and the presence of microvoids (Figure 15.9).
• Crazing can lead to an increase in ductility and toughness of the material.
Craze formation prior to cracking

– during crazing, plastic deformation of spherulites
– and formation of microvoids and fibrillar bridges

Adapted from Fig. 15.9, Callister & Rethwisch 8e.
Fracture of Polymers

- **Thermosetting plastics** → Primarily **brittle** mode.
- **Thermoplastics** → **ductile or brittle depending on the temperature**.

Figure 7.52  craze in PMMA

6. Miscellaneous Mechanical Characteristics

- Impact strength
- Fatigue
- Tear strength
- Hardness
7. Deformation of semicrystalline polymers

• During the elastic deformation of a semicrystalline polymer having a spherulitic structure that is stressed in tension, the molecules in amorphous regions elongate in the stress direction (Figure 15.12).

• The tensile plastic deformation of spherulitic polymers occurs in several stages as both amorphous tie chains and chain-folded block segments (which separate from the ribbonlike lamellae) become oriented with the tensile axis (Figure 15.13).

• Also, during deformation the shapes of spherulites are altered (for moderate deformations); relatively large degrees of deformation lead to a complete destruction of the spherulites to form highly aligned structures.
Mechanisms of Deformation — Semicrystalline (Plastic) Polymers

- Brittle failure
- Plastic failure
- Onset of necking
- Unload/reload
- Crystalline block segments separate
- Fibrillar structure near failure
- Amorphous regions elongate
- Crystalline regions align
- Undeformed structure

σ (MPa)

ε
Elastic Deformation of a semicrystalline polymer
Plastic deformation

- **Molecular weight**
  - \( \text{TS} = \text{TS}_\infty - \left( \frac{A}{M_n} \right) \)

- **Degree of crystallinity**
  - TS increases with crystallinity

- **Predeformation by drawing**
  - Analog to strain hardening

- **Heat-treating**
  - Improve crystallinity
Predeformation by Drawing

- **Drawing**...(ex: monofilament fishline)
  - stretches the polymer prior to use
  - aligns chains in the stretching direction
- **Results of drawing:**
  - increases the elastic modulus ($E$) in the stretching direction
  - increases the tensile strength ($TS$) in the stretching direction
  - decreases ductility (%$EL$)
- **Annealing after drawing...**
  - decreases chain alignment
  - reverses effects of drawing (reduces $E$ and $TS$, enhances %$EL$)
- Contrast to effects of **cold working** in metals!

Adapted from Fig. 15.13, *Callister & Rethwisch 8e.* (Fig. 15.13 is from J.M. Schultz, *Polymer Materials Science*, Prentice-Hall, Inc., 1974, pp. 500-501.)
9. Mechanisms of Deformation—Elastomers

- Compare elastic behavior of elastomers with the:
  -- brittle behavior (of aligned, crosslinked & network polymers), and
  -- plastic behavior (of semicrystalline polymers)
  (as shown on previous slides)

Stress-strain curves adapted from Fig. 15.1, *Callister & Rethwisch 8e*. Inset figures along elastomer curve (green) adapted from Fig. 15.15, *Callister & Rethwisch 8e*. (Fig. 15.15 is from Z.D. Jastrzebski, *The Nature and Properties of Engineering Materials*, 3rd ed., John Wiley and Sons, 1987.)

- Initial: amorphous chains are kinked, cross-linked.
- Deformation is reversible (elastic)!
- Final: chains are straighter, still cross-linked.
Elastomers (Rubbers)

- **Natural rubber**: Produced from latex of *Hevea Brasiliensis* tree.

  \[
  \begin{array}{c}
  \text{H} \\
  \text{C} \\
  \text{H}
  \end{array}
  \begin{array}{c}
  \text{CH}_3 \\
  \text{C} \\
  \text{CH}_2
  \end{array}
  \begin{array}{c}
  \text{H} \\
  \text{C} \\
  \text{H}
  \end{array}
  \text{Polyisoprene}
  \]

- **Vulcanization**: Heating rubber with sulfur and lead carbonate.
  - Increases tensile strength.
  - Restricts molecular movement by **crosslinking** of molecules.

Figure 7.41
10. Crystallization

- During the crystallization of a polymer, randomly oriented molecules in the liquid phase transform into **chain-folded crystallites** that have ordered and aligned molecular structures.
  - Nucleation and growth process
- Avrami equation
  - Fraction of crystallization \( y = 1 - \exp(-kt^n) \)
- 100% crystallinity is impossible
11-12. Melting and glass transition temperatures

- **Melting** The melting of crystalline regions of a polymer corresponds to the transformation of a solid material, having an ordered structure of aligned molecular chains, to a viscous liquid in which the structure is highly random.

- **The Glass Transition** The glass transition occurs in amorphous regions of polymers. Upon cooling, this phenomenon corresponds to the gradual transformation from a liquid to a rubbery material, and finally to a rigid solid. With decreasing temperature there is a reduction in the motion of large segments of molecular chains.
13. Melting & Glass Transition Temperatures

Adapted from Fig. 15.18, *Callister & Rethwisch 8e.*
14. Factors that influence melting and glass transition temp.

- The magnitudes of $T_m$ and $T_g$ increase with increasing chain stiffness;
- stiffness is enhanced by the presence of chain double bonds and side groups that are either bulky or polar.
- At low molecular weights $T_m$ and $T_g$ increase with increasing $M$. 
15. Plastics: Thermoplastics vs. Thermosets

- **Thermoplastics:**
  - little crosslinking
  - ductile
  - soften w/heat
  - polyethylene
  - polypropylene
  - polycarbonate
  - polystyrene

- **Thermosets:**
  - significant crosslinking (10 to 50% of repeat units)
  - hard and brittle
  - do NOT soften w/heat
  - vulcanized rubber, epoxies,
    polyester resin, phenolic resin
**Table 15.3** Trade Names, Characteristics, and Typical Applications for a Number of Plastic Materials

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Trade Names</th>
<th>Major Application Characteristics</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylonitrile-butadiene-styrene (ABS)</td>
<td>Abson</td>
<td>Outstanding strength and toughness, resistant to heat distortion; good electrical properties; flammable and soluble in some organic solvents</td>
<td>Refrigerator linings, lawn and garden equipment, toys, highway safety devices</td>
</tr>
<tr>
<td></td>
<td>Cycolac</td>
<td></td>
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<td></td>
<td>Kralastic</td>
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<td></td>
<td>Lustran</td>
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<td></td>
<td>Novodur</td>
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<td></td>
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<tr>
<td></td>
<td>Tybrene</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material Type</td>
<td>Trade Names</td>
<td>Major Application Characteristics</td>
<td>Typical Applications</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------------</td>
<td>----------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>Polyesters (PET or PETE)</td>
<td>Celanar, Dacron, Eastapak, Hylar, Melinex, Mylar, Petra</td>
<td>One of the toughest of plastic films; excellent fatigue and tear strength, and resistance to humidity, acids, greases, oils, and solvents</td>
<td>Magnetic recording tapes, clothing, automotive tire cords, beverage containers</td>
</tr>
<tr>
<td>Epoxies</td>
<td>Araldite, Epikote, Epon, Epi-rez, Lekutherm, Lytex</td>
<td>Excellent combination of mechanical properties and corrosion resistance; dimensionally stable; good adhesion; relatively inexpensive; good electrical properties</td>
<td>Electrical moldings, sinks, adhesives, protective coatings, used with fiberglass laminates</td>
</tr>
<tr>
<td>Phenolics</td>
<td>Bakelite, Amberol, Arofene, Durite, Resinox</td>
<td>Excellent thermal stability to over 150°C (300°F); may be compounded with a large number of resins, fillers, etc.; inexpensive</td>
<td>Motor housings, telephones, auto distributors, electrical fixtures</td>
</tr>
<tr>
<td>Polyesters</td>
<td>Aropol, Baygal, Derakane, Laminac, Selectron</td>
<td>Excellent electrical properties and low cost; can be formulated for room- or high-temperature use; often fiber reinforced</td>
<td>Helmets, fiberglass boats, auto body components, chairs, fans</td>
</tr>
</tbody>
</table>

**Thermosetting Polymers**

16. Elastomers

- Table 15.4 lists properties and applications of common elastomers; these properties are typical and, of course, depend on the degree of vulcanization and on whether any reinforcement is used.
- Natural rubber is still used to a large degree because it has an outstanding combination of desirable properties.
- However, the most important synthetic elastomer is SBR, which is used predominantly in automobile tires, reinforced with carbon black.
- NBR, which is highly resistant to degradation and swelling, is another common synthetic elastomer.
<table>
<thead>
<tr>
<th>Chemical Type</th>
<th>Trade (Common) Names</th>
<th>Elongation (%)</th>
<th>Useful Temperature Range [°C (°F)]</th>
<th>Major Application Characteristics</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural polyisoprene</td>
<td>Natural rubber (NR)</td>
<td>500-760</td>
<td>-60 to 120 (-75 to 250)</td>
<td>Excellent physical properties; good resistance to cutting, gouging, and abrasion; low heat, ozone, and oil resistance; good electrical properties</td>
<td>Pneumatic tires and tubes; heels and soles; gaskets</td>
</tr>
<tr>
<td>Styrene-butadiene</td>
<td>GRS, Buna S (SBR)</td>
<td>450-500</td>
<td>-60 to 120 (-75 to 250)</td>
<td>Good physical properties; excellent abrasion resistance; not oil, ozone, or weather resistant; electrical properties good, but not outstanding</td>
<td>Same as natural rubber</td>
</tr>
<tr>
<td>copolymer</td>
<td></td>
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</tr>
<tr>
<td>Acrylonitrile-</td>
<td>Buna A, Nitrile (NBR)</td>
<td>400-600</td>
<td>-50 to 150 (-60 to 300)</td>
<td>Excellent resistance to vegetable, animal, and petroleum oils; poor low-temperature properties; electrical properties not outstanding</td>
<td>Gasoline, chemical, and oil hose; seals and O-rings; heels and soles</td>
</tr>
<tr>
<td>butadiene copolymer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloroprene</td>
<td>Neoprene (CR)</td>
<td>100-800</td>
<td>-50 to 105 (-60 to 225)</td>
<td>Excellent ozone, heat, and weathering resistance; good oil resistance; excellent flame resistance; not as good in electrical applications as natural rubber</td>
<td>Wire and cable; chemical tank linings; belts, seals, hoses, and gaskets</td>
</tr>
<tr>
<td>Polysiloxane</td>
<td>Silicone (VMQ)</td>
<td>100-800</td>
<td>-115 to 315 (-175 to 600)</td>
<td>Excellent resistance to high and low temperatures; low strength; excellent electrical properties</td>
<td>High- and low-temperature insulation; seals, diaphragms; tubing for food and medical uses</td>
</tr>
</tbody>
</table>

**Sources:** Adapted from C. A. Harper (Editor), *Handbook of Plastics and Elastomers*. Copyright © 1975 by McGraw-Hill Book Company, reproduced with permission; and Materials Engineering's *Materials Selector*, copyright Penton/IPC.
Fibers - length/diameter > 100

- Primary use is in textiles.
- Fiber characteristics:
  - high tensile strengths
  - high degrees of crystallinity
  - structures containing polar groups

- Formed by spinning
  - extrude polymer through a spinneret (a die containing many small orifices)
  - the spun fibers are drawn under tension
  - leads to highly aligned chains - fibrillar structure
18. Polymer Types – Miscellaneous

- **Coatings** – thin polymer films applied to surfaces – i.e., paints, varnishes
  - protects from corrosion/degredation
  - decorative – improves appearance
  - can provide electrical insulation

- **Adhesives** – bonds two solid materials (*adherands*)
  - bonding types:
    1. Secondary – van der Waals forces
    2. Mechanical – penetration into pores/crevices

- **Films** – produced by blown film extrusion

- **Foams** – gas bubbles incorporated into plastic
Ultrahigh Molecular Weight Polyethylene (UHMWPE)

- Molecular weight ca. $4 \times 10^6$ g/mol
- Outstanding properties
  - high impact strength
  - resistance to wear/abrasion
  - low coefficient of friction
  - self-lubricating surface
- Important applications
  - bullet-proof vests
  - golf ball covers
  - hip implants (acetabular cup)
Advanced Polymers

Thermoplastic Elastomers

Styrene-butadiene block copolymer

Fig. 15.22, Callister & Rethwisch 8e. (Fig. 15.22 adapted from the Science and Engineering of Materials, 5th Ed., D.R. Askeland and P.P. Phule, Thomson Learning, 2006.)
20. Polymer Formation

• There are two types of polymerization

• Addition (or chain) polymerization
  – Monomer units are attached one at a time in chainlike fashion to form a linear molecule.

• Condensation (step) polymerization
  – Involve stepwise intermolecular chemical reactions that may include more than a single molecular species.
Addition (Chain) Polymerization

- **Initiation**

  \[ R\cdot + CH=CH \rightarrow R-CH=CH \cdot \]

- **Propagation**

  \[ R-CH=CH \cdot + CH=CH \rightarrow R-CH=CH-CH=CH \cdot \]

- **Termination**

  \[ R-CH=CH-CH=CH \cdot + CH=CH-CH=CH-R \rightarrow \]

  \[ \text{Disproportionation} \quad \text{Combination} \]
Condensation (Step) Polymerization

\[ \text{hexamethylene diamine} + \text{adipic acid} \rightarrow \text{nylon-6,6} + \text{H}_2\text{O} \]
21. Polymer Additives

Improve mechanical properties, processability, durability, etc.

- **Fillers**
  - Added to improve tensile strength & abrasion resistance, toughness & decrease cost
  - ex: carbon black, silica gel, wood flour, glass, limestone, talc, etc.

- **Plasticizers**
  - Added to reduce the glass transition temperature \( T_g \) below room temperature
  - Presence of plasticizer transforms brittle polymer to a ductile one
  - Commonly added to PVC - otherwise it is brittle
Polymer Additives (cont.)

- **Stabilizers**
  - Antioxidants
  - UV protectants
- **Lubricants**
  - Added to allow easier processing
  - polymer “slides” through dies easier
  - ex: sodium stearate
- **Colorants**
  - Dyes and pigments
- **Flame Retardants**
  - Substances containing chlorine, fluorine, and boron
22. Processing of Plastics

- **Thermoplastic**
  - can be reversibly cooled & reheated, i.e. recycled
  - heat until soft, shape as desired, then cool
  - ex: polyethylene, polypropylene, polystyrene.

- **Thermoset**
  - when heated forms a molecular network (chemical reaction)
  - degrades (doesn’t melt) when heated
  - a prepolymer molded into desired shape, then chemical reaction occurs
  - ex: urethane, epoxy
23. Forming techniques for plastics, fibers and films

- Fabrication of plastic polymers is usually accomplished by shaping the material in molten form at an elevated temperature, using at least one of several different molding techniques—compression (Figure 15.23), transfer, injection (Figure 15.24), and blow. Extrusion (Figure 15.25) and casting are also possible.

- Some fibers are spun from a viscous melt or solution, after which they are plastically elongated during a drawing operation, which improves the mechanical strength.

- Films are formed by extrusion and blowing (Figure 15.26) or by calendering.
Processing Plastics – Compression Molding

Thermoplastics and thermosets

- polymer and additives placed in mold cavity
- mold heated and pressure applied
- fluid polymer assumes shape of mold
Thermoplastics and some thermosets

- When ram retracts, plastic pellets drop from hopper into barrel.
- Ram forces plastic into the heating chamber (around the spreader) where the plastic melts as it moves forward.
- Molten plastic is forced under pressure (injected) into the mold cavity where it assumes the shape of the mold.
Processing Plastics – Extrusion

thermoplastics

- plastic pellets drop from hopper onto the turning screw
- plastic pellets melt as the turning screw pushes them forward by the heaters
- molten polymer is forced under pressure through the shaping die to form the final product (extrudate)
• Limitations of polymers:
  -- $E, \sigma_y, K_c, T_{\text{application}}$ are generally small.
  -- Deformation is often time and temperature dependent.
• Thermoplastics (PE, PS, PP, PC):
  -- Smaller $E, \sigma_y, T_{\text{application}}$
  -- Larger $K_c$
  -- Easier to form and recycle
• Elastomers (rubber):
  -- Large reversible strains!
• Thermosets (epoxies, polyesters):
  -- Larger $E, \sigma_y, T_{\text{application}}$
  -- Smaller $K_c$

Table 15.3 Callister & Rethwisch 8e:

Good overview of applications and trade names of polymers.
Summary II

• Polymer Processing
  -- compression and injection molding, extrusion, blown film extrusion
• Polymer melting and glass transition temperatures
• Polymer applications
  -- elastomers  -- fibers
  -- coatings    -- adhesives
  -- films      -- foams
  -- advanced polymeric materials
Plastics Recycling

**PET** Polyethylene Terephthalate
Two-liter beverage bottles, mouthwash bottles, boil-in-bag pouches.

**HDPE** High Density Polyethylene
Milk jugs, trash bags, detergent bottles.

**PVC** Polyvinyl Chloride
Cooking oil bottles, packaging around meat.

**LDPE** Low Density Polyethylene
Grocery bags, produce bags, food wrap, bread bags.

**PP** Polypropylene
Yogurt containers, shampoo bottles, straws, margarine tubs, diapers.

**PS** Polystyrene
Hot beverage cups, take-home boxes, egg cartons, meat trays, cd cases.

**OTHER**
All other types of plastics or packaging made from more than one type of plastic.

PLASTICS PRODUCED/PLASTICS RECYCLED

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount Produced</th>
<th>Amount Recycled</th>
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</thead>
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<tr>
<td>PETE</td>
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<td>350</td>
</tr>
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<td>1230</td>
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<td>30</td>
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<tr>
<td>OTHER</td>
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</tr>
</tbody>
</table>

In thousands of tons

Action to save the earth

• 3R
  – Reduce
  – Reuse
  – Recycle

• 5R
  – Refuse
  – Respect
台灣已經「過度『塑化』」。」李俊璋認為，某些攤販不想洗盤子，就在盤子外面套一層塑膠袋，「塑膠袋耐熱是保證『不變形』，不代表『不溶出』塑化劑！」他也不建議用塑膠奶瓶幫小孩泡牛奶，萬一洗瓶子刮傷內壁，下次泡就溶出更多。要吃便利商店的微波食品，最好買回家倒在盤子裡，「用那種容器我不敢吃！」李俊璋強調，他不是希望政府「全部禁掉(塑膠)」。他举例，化妝品、保養品的定香劑可用天然產物取代，就應該禁用塑化劑；器皿方面，政府應對所有常用塑化劑訂定溶出標準，作「正面列表」，告訴廠商什麼能用。