Chapter 15: Characteristics, Applications, and Processing of Polymers

Chapter Notes

15.1 Introduction

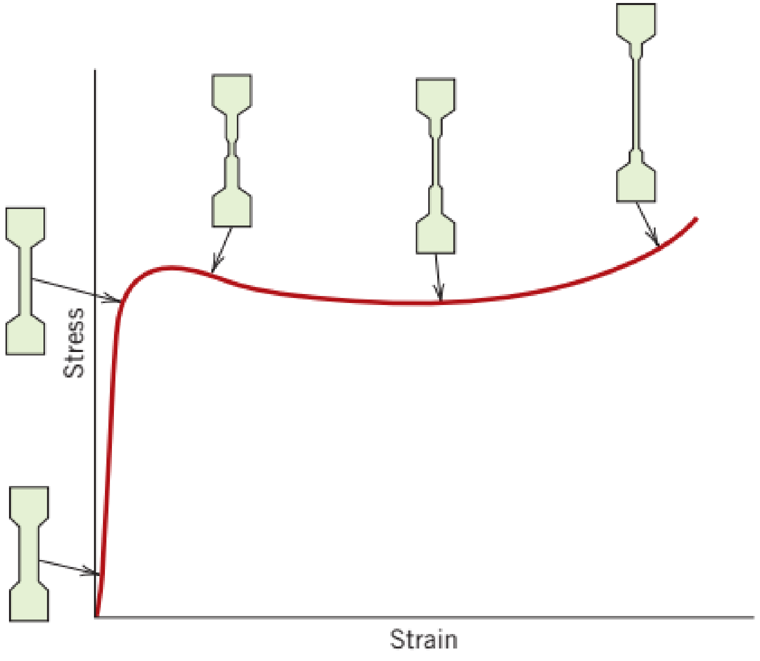
- Mechanical Behavior of Polymers
- Mechanisms of Deformation and for Strengthening of Polymers
- Crystallization, Melting, and Glass-Transition Phenomena in Polymers
- Polymer Types
- Polymer Synthesis and Processing

Mechanical Behavior of Polymers

- Stress-Strain Behavior
- Macroscopic Deformation
- Viscoelastic Deformation
- Fracture of Polymers
- Miscellaneous Mechanical Characteristics

15.2 Stress-Strain Behavior

- Mechanical properties are classified similar to metals:
  - Modulus of elasticity
  - Yield
  - Tensile strength
- Stress-strain test is useful
- Polymer properties are highly sensitive to:
  - Rate of deformation
  - Temperature
  - Environment (surrounding atmosphere)



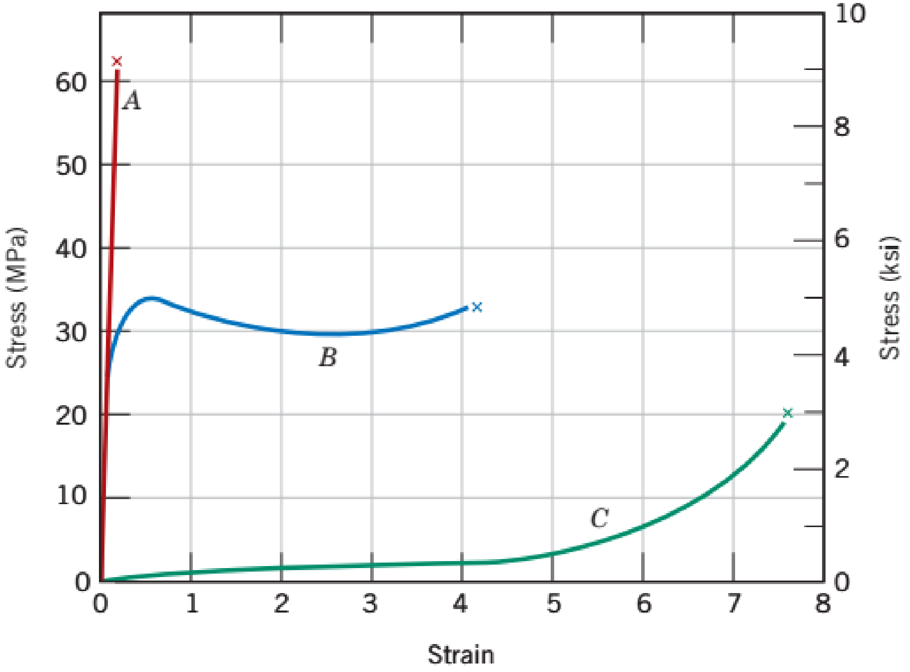


Figure 15.1 The stress–strain behavior for brittle (curve *A*), plastic (curve *B*), and highly elastic (elastomeric) (curve *C*) polymers.

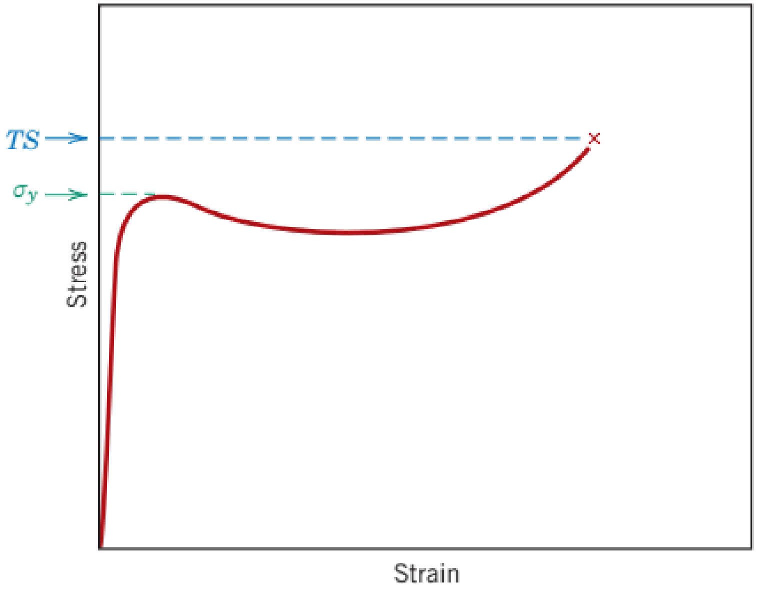


Figure 15.2 Schematic stress–strain curve for a plastic polymer showing how yield and tensile strengths are determined.

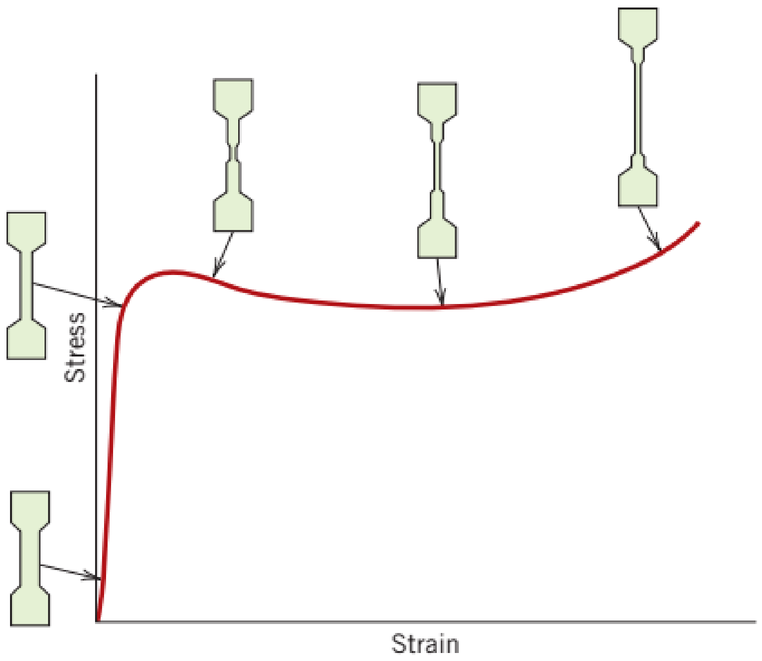


Figure 15.4 Schematic tensile stress–strain curve for a semicrystalline polymer. Specimen contours at several stages of deformation are included.

15.2 Stress-Strain Behavior

- Similar to metals:
  - Modulus of elasticity (a.k.a. tensile modulus, or modulus)
  - Ductility
  - σ_y – maximum yield strength
  - *TS* – Tensile strength
    - *TS* may be > or < σ_y

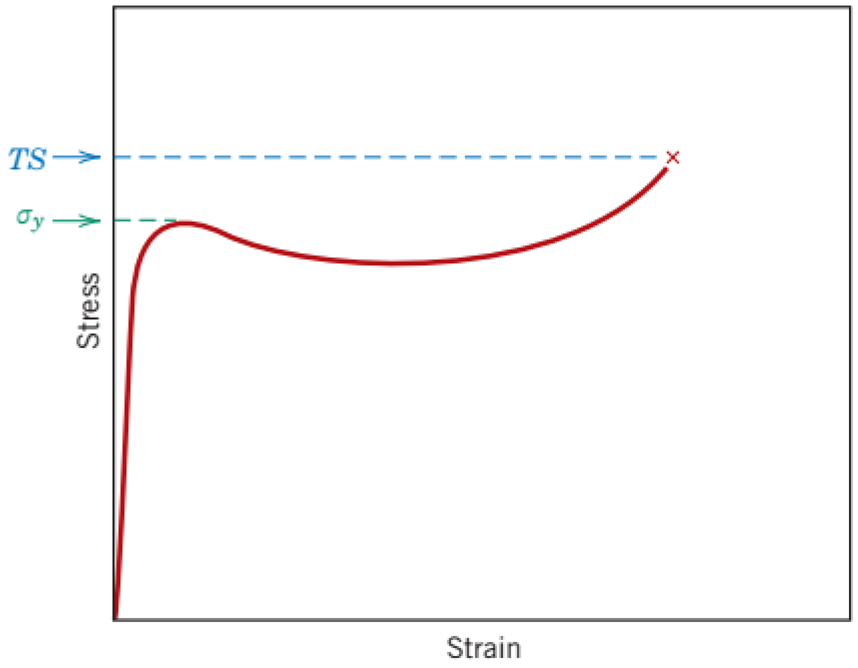


Table 15.1 Room-Temperature Mechanical Characteristics of Some of the More Common Polymers

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: Based on *Modern Plastics Encyclopedia '96*. Copyright 1995, The McGraw-Hill Companies.

15.2 Stress-Strain Behavior

- Different from metals
  - Modulus is much lower than metals
    - 7MPa to 4GPa – polymers
    - 48 to 410 GPa - metals
  - *TS* – much lower as well
    - 100 MPa – polymers
    - 4100 MPa – metals
  - Polymers are more elastic
    - Metals rarely elongate plastically more than 100%
    - Highly elastic polymers elongate greater than 1000%
- Polymers are sensitive to temperature (close to 25°C)
  - Plexiglass has a significant change in elasticity between 4 – 60 °C, from brittle to ductile.
  - Strain rate (SR) has the same effect as temperature. Lower SR behaves like high temperature.

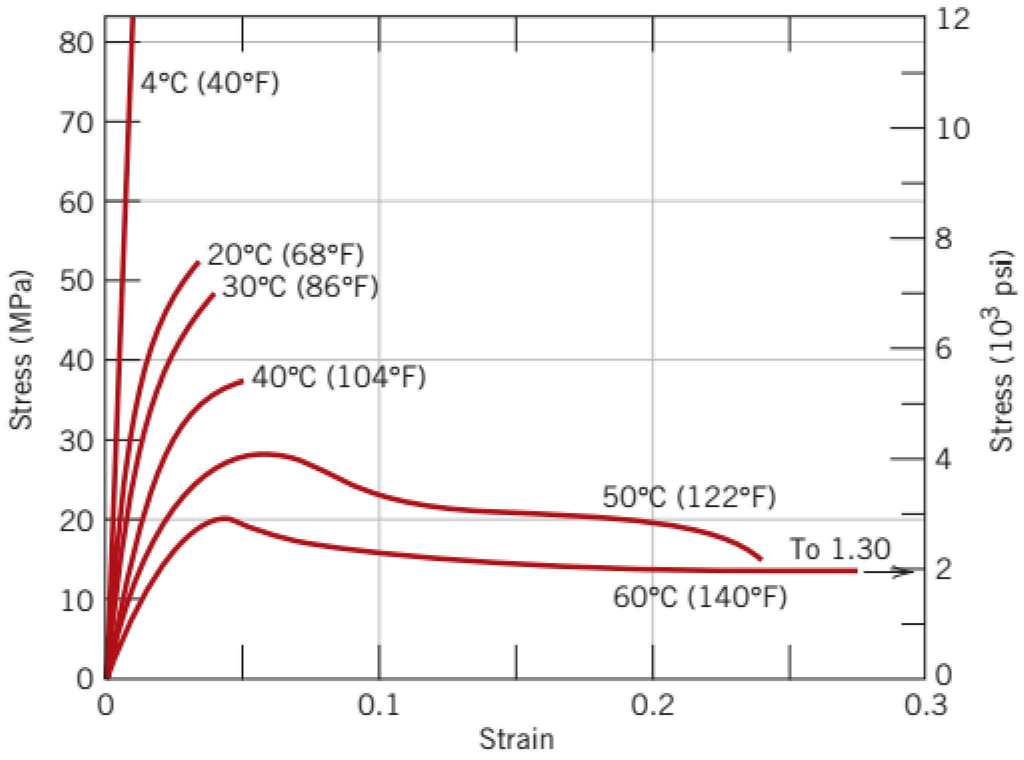
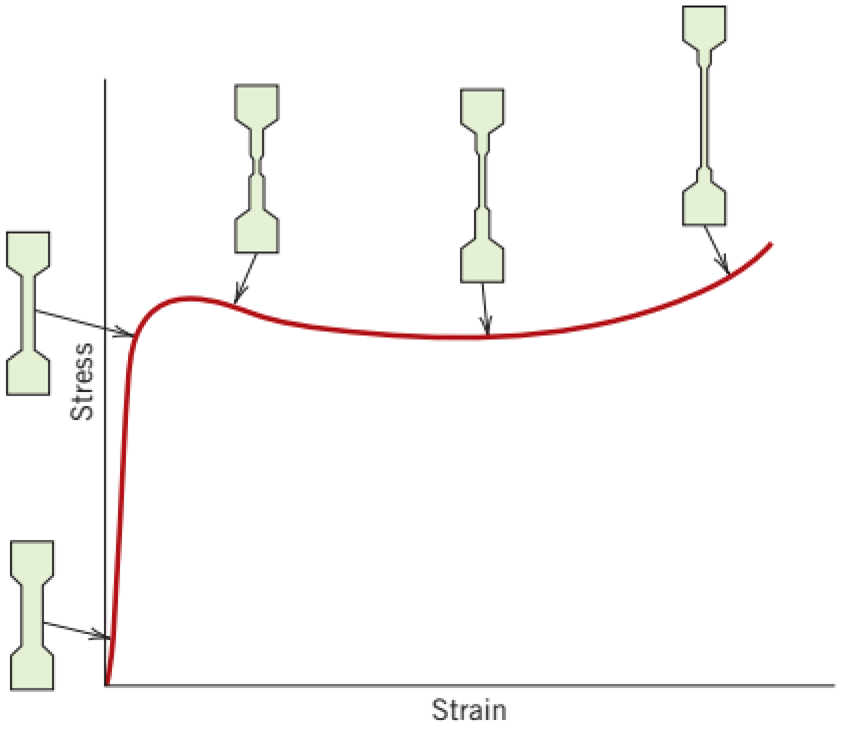


Figure 15.3 The influence of temperature on the stress–strain characteristics of poly(methyl methacrylate).

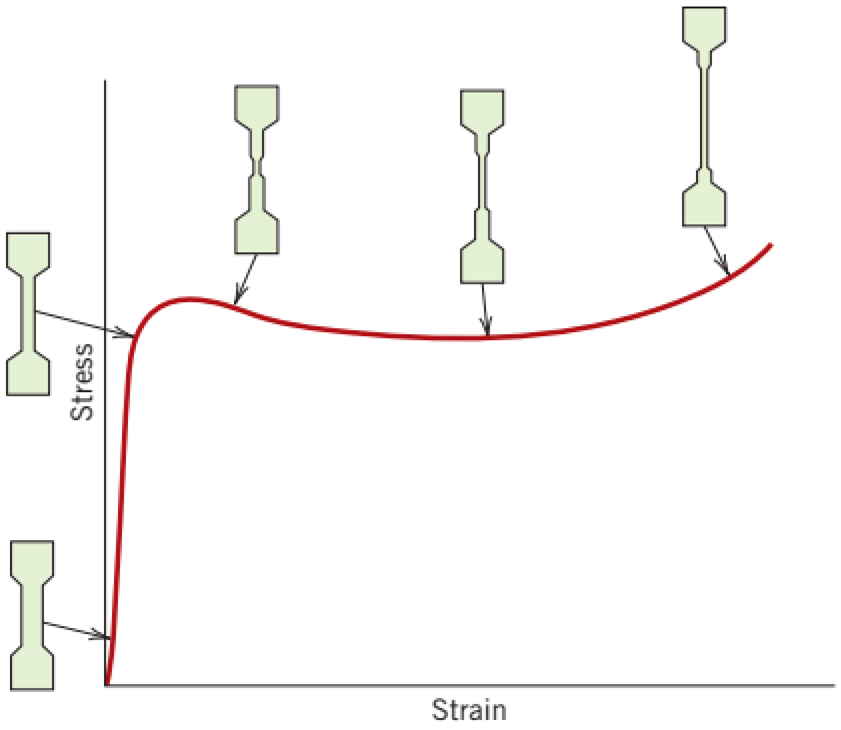
Concept Check!!!

- What is the difference between Stress and Strain?
- Explain on this curve where each of the following items is:
  - Modulus of elasticity
  - Yield strength
  - Tensile strength
  - Maximum yield strength



15.3 Macroscopic Deformation

- Upper yield strength
  - Necking Starts
- Lower yield strength
  - Necking continues in the rest of the gauge length



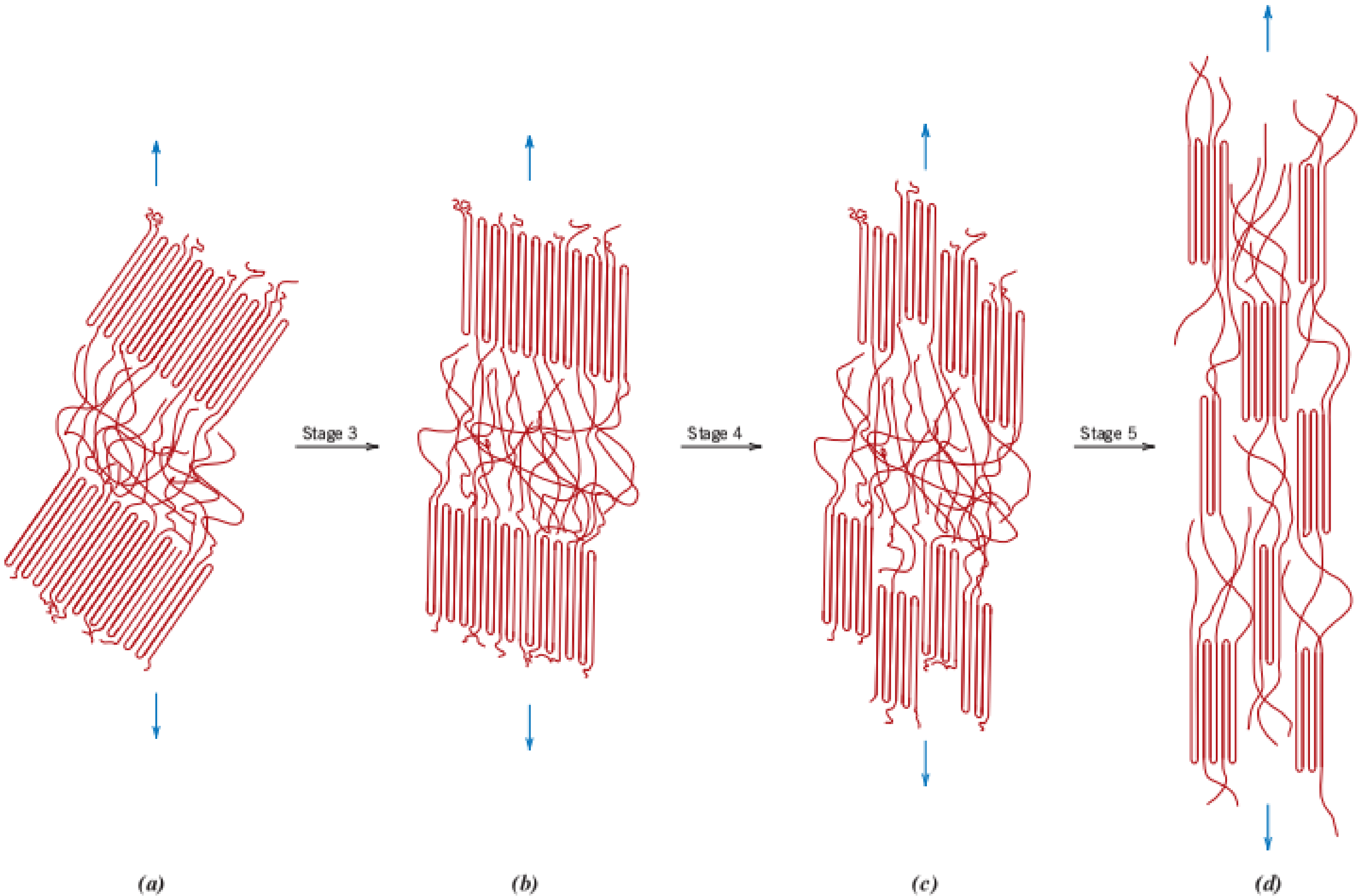


Figure 15.13 Stages in the plastic deformation of a semicrystalline polymer. (*a*) Two adjacent chain-folded lamellae and interlamellar amorphous material after elastic deformation (also shown as Figure 15.12*c*). (*b*) Tilting of lamellar chain folds. (*c*) Separation of crystalline block segments. (*d*) Orientation of block segments and tie chains with the tensile axis in the final plastic deformation stage.

Concept Check!!!

- What is ductility? How is it defined numerically?

Memory Device

Stress is the force, applied with might,
Over an area, it's force per unit's right.

Strain measures deformation's claim,
Change in size or shape, in materials' game.

Modulus of Elasticity, Young's name we hear,
Stiffness it tells, without giving in to fear.

Yield Strength marks plastic's start,
Where change is lasting, and we must be smart.

Tensile Strength, the ultimate test,
Breaking point, under tension's quest.

15.4 Viscoelastic Deformation

- Amorphous polymer
  - Solid below glass transition
  - Viscous liquid at high temperatures past glass transition
  - Viscoelastic material at temperatures above the glass transition
- Think Silly Putty!
- Relaxation Modulus

$$E_r(t) = \frac{\sigma(t)}{\varepsilon_0}$$

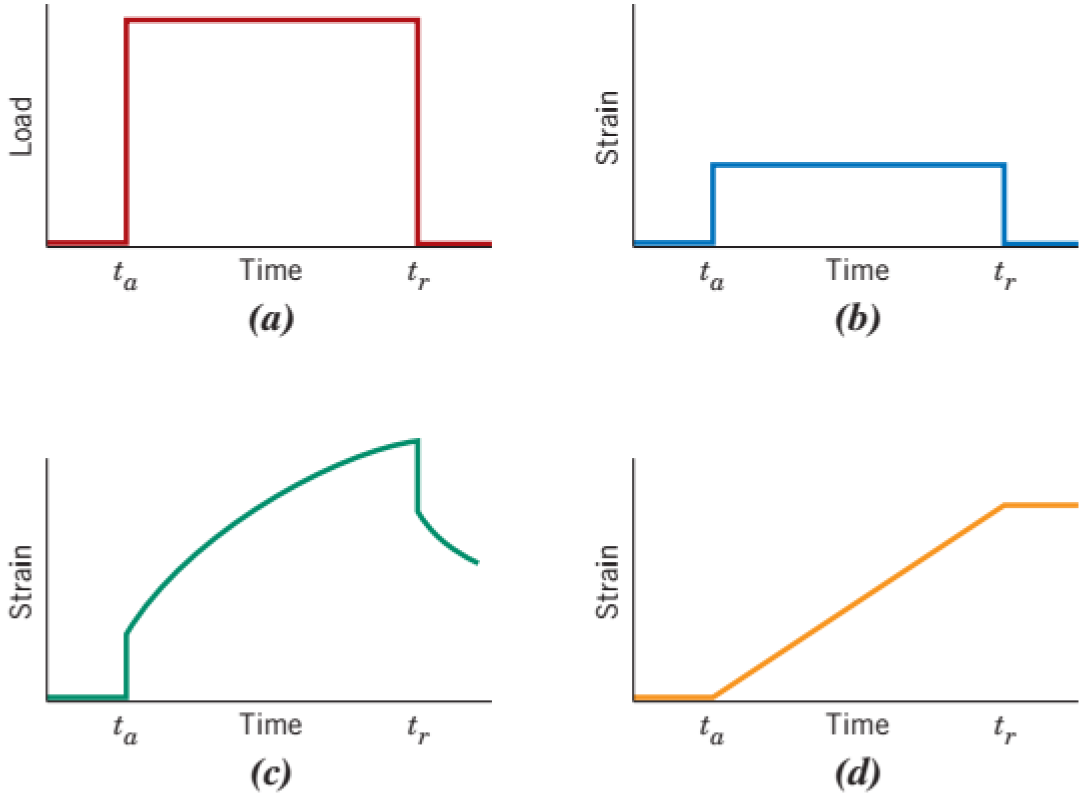
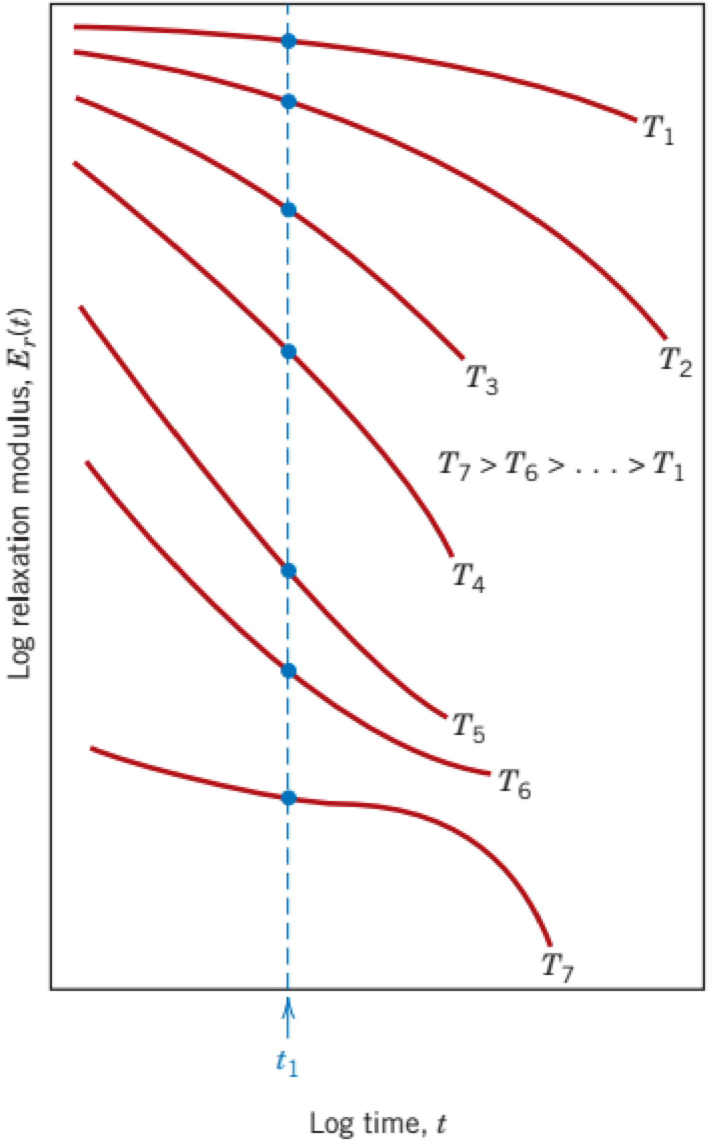


Figure 15.5 (*a*) Load versus time, where load is applied instantaneously at time t_a and released at t_r. For the load–time cycle in (*a*), the strain-versus-time responses are for totally elastic (*b*), viscoelastic (*c*), and viscous (*d*) behaviors.

Figure 15.6 Schematic plot of logarithm of relaxation modulus versus logarithm of time for a viscoelastic polymer; isothermal curves are generated at temperatures T_1 through T_7. The temperature dependence of the relaxation modulus is represented as $\log E_r(t_1)$ versus temperature.

$$E_r(t) = \frac{\sigma(t)}{\varepsilon_0}$$



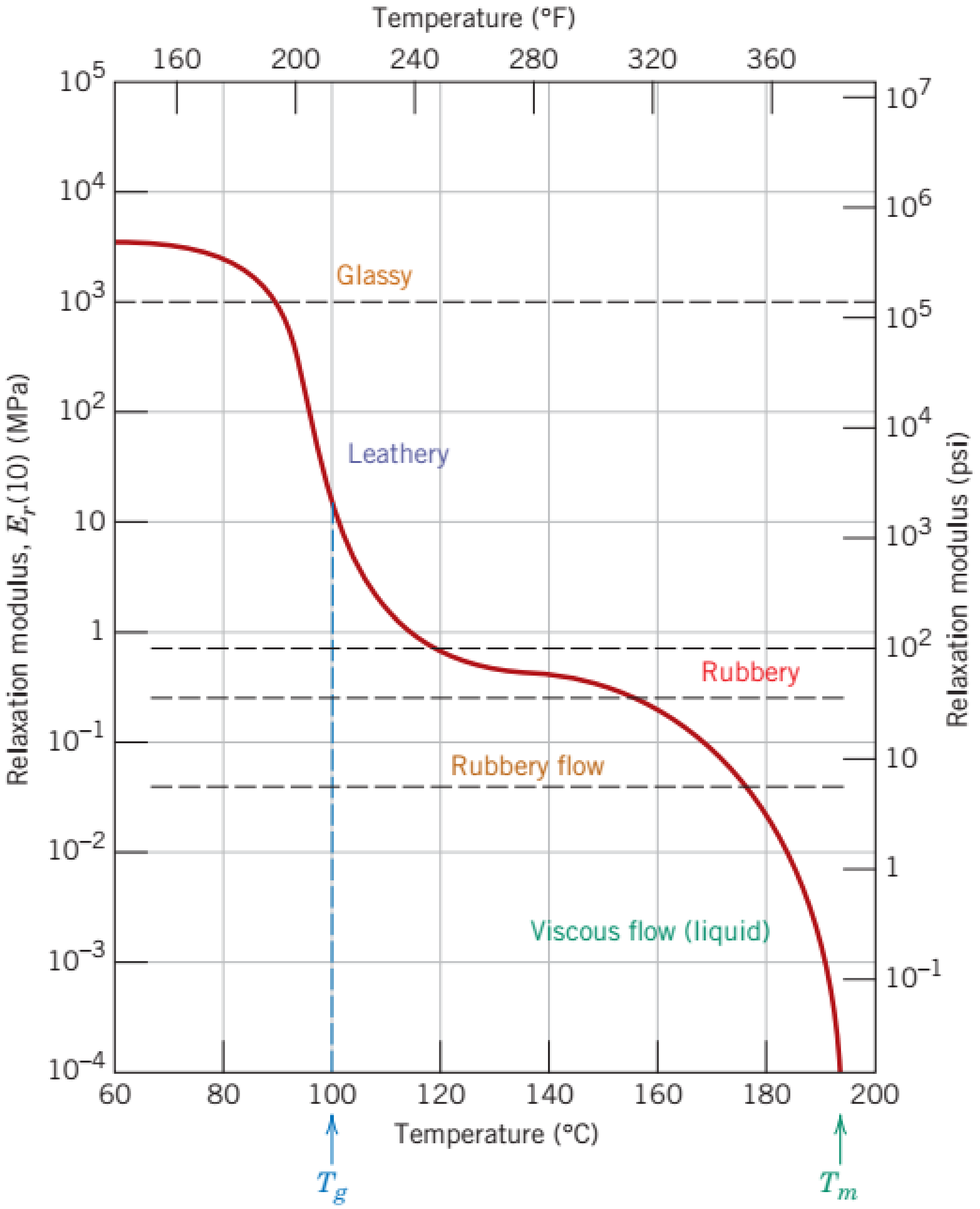


Figure 15.7 Logarithm of the relaxation modulus versus temperature for amorphous polystyrene, showing the five different regions of viscoelastic behavior.

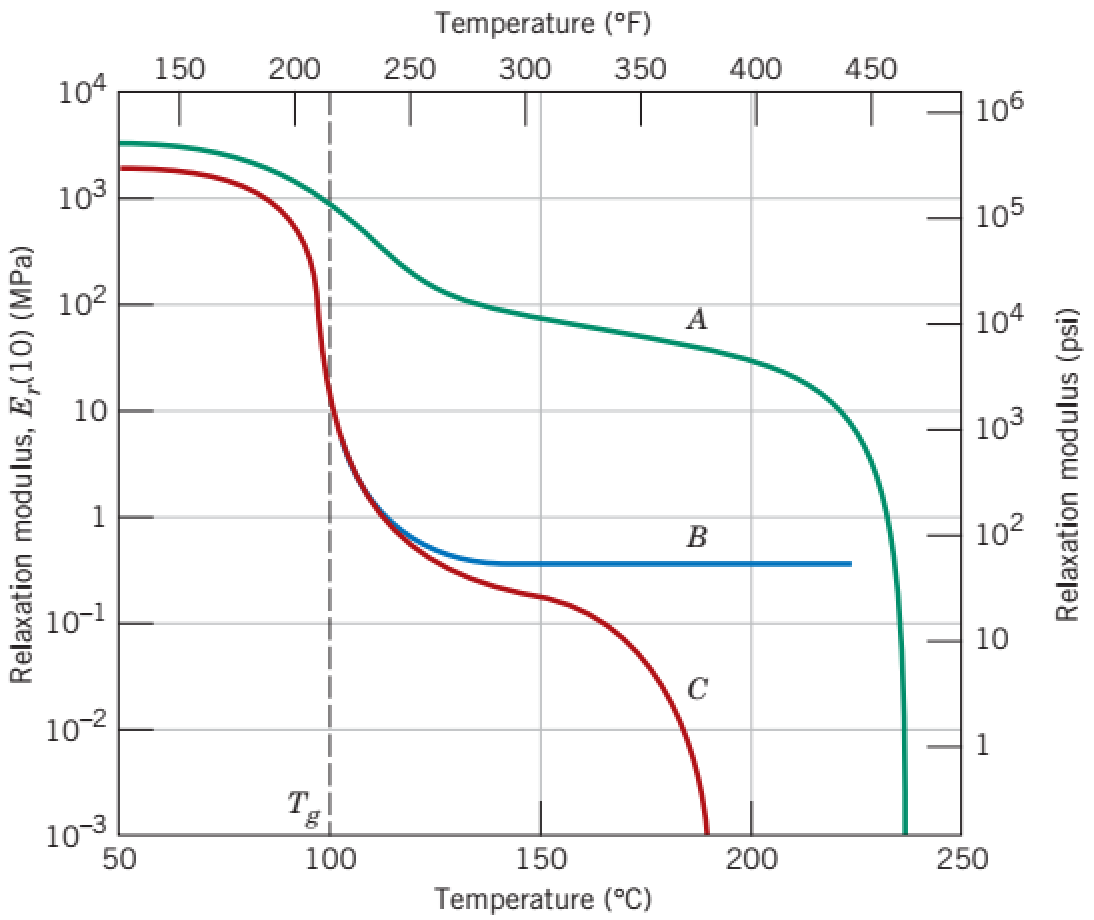


Figure 15.8 Logarithm of the relaxation modulus versus temperature for crystalline isotactic (curve *A*), lightly crosslinked atactic (curve *B*), and amorphous (curve *C*) polystyrene. (From A. V. Tobolsky, *Properties and Structures of Polymers.* Copyright © 1960 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

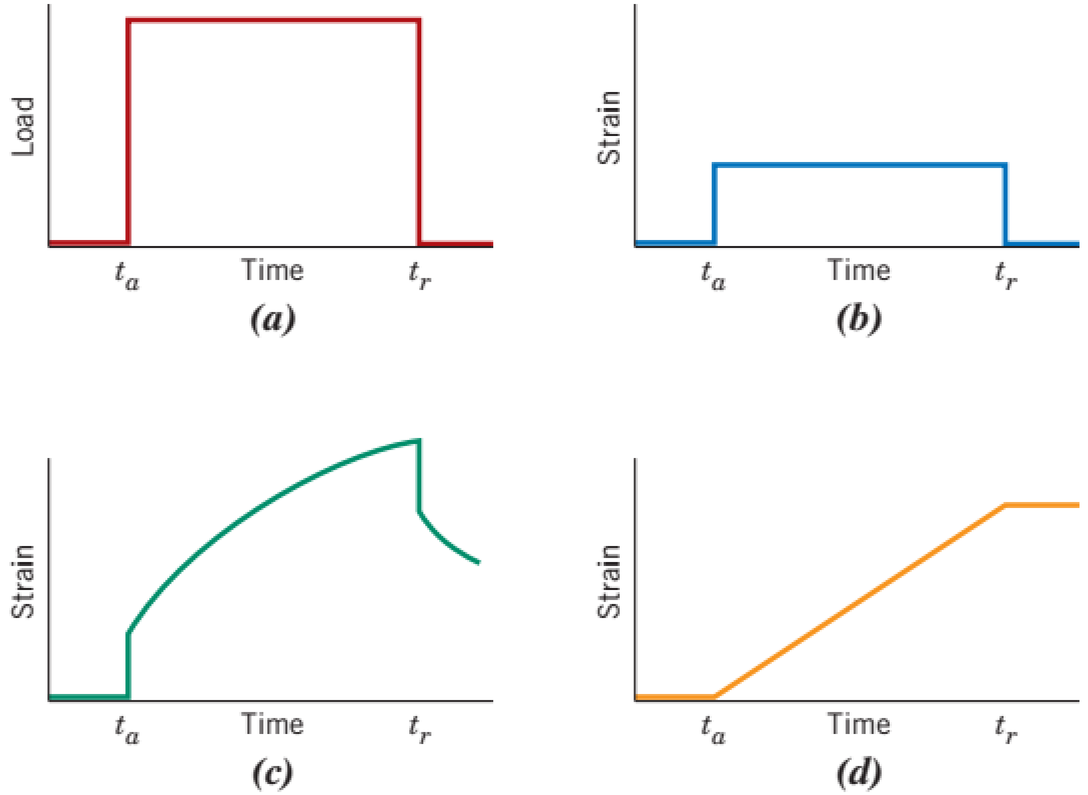
15.4 Viscoelastic Deformation

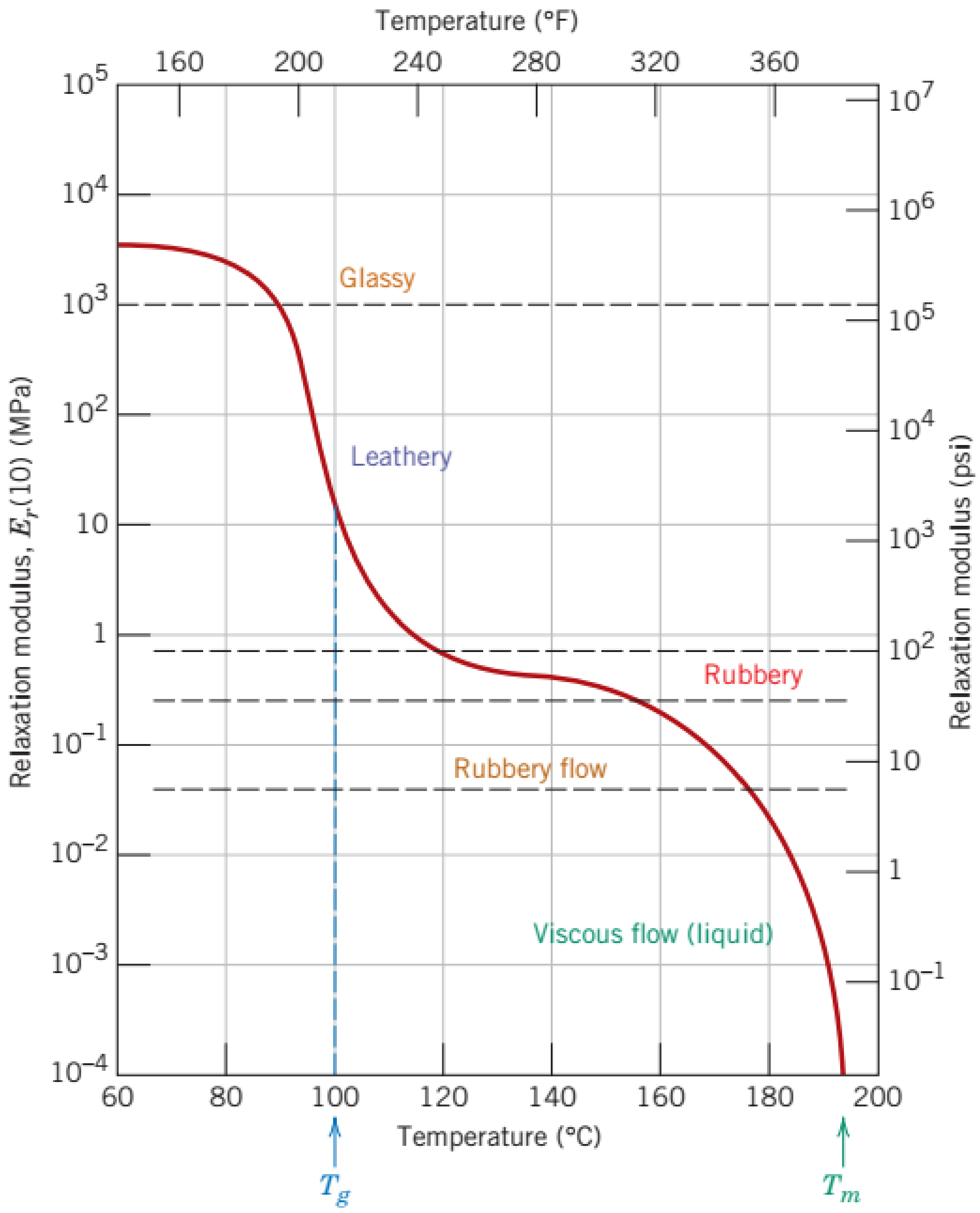
- Viscoelastic Creep
  - The material strains under constant stress over time
  - This can happen even at low temperatures and at stress less than yield strength.
    - Tiers can develop flat spots if parked for a long period!

$$E_c(t) = \frac{\sigma_0}{\varepsilon(t)}$$

Concept Check!!!

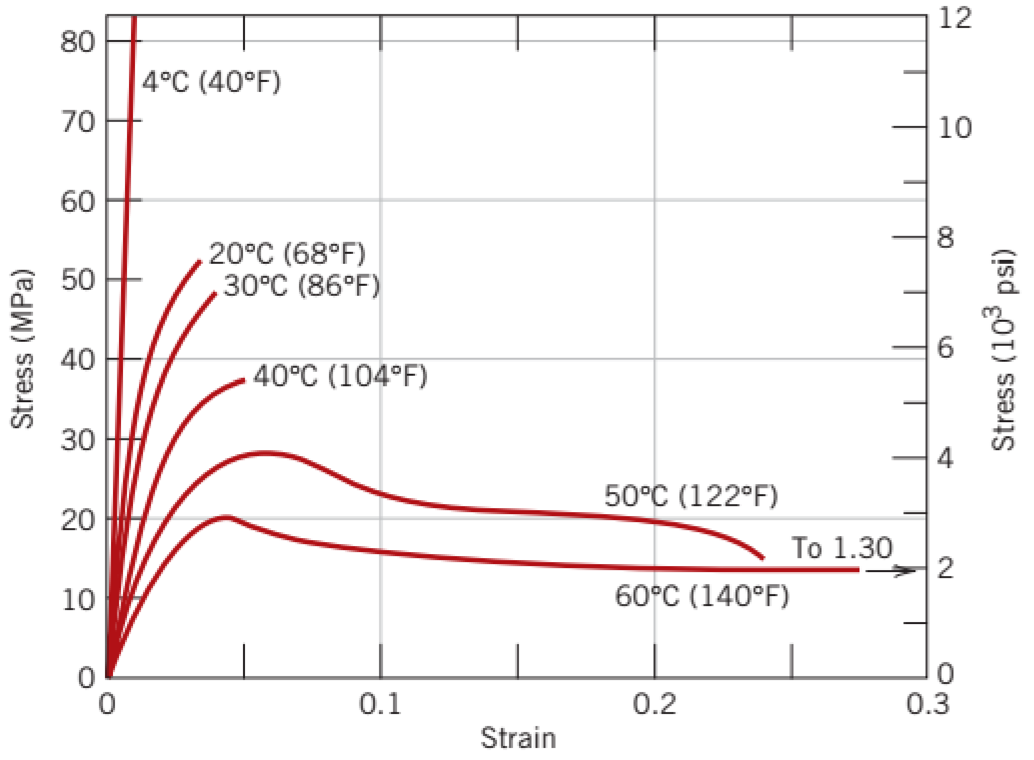
- An amorphous polystyrene that is deformed at 120°C will exhibit which of the behaviors shown in the figure? (b, c, or d)





15.5 Fracture of Polymers

- Thermosetting polymers
  - Brittle Fracture, occurs at structural flaws
- Thermoplastic polymers
  - Both ductile and brittle
  - Brittle fracture more likely when:
    - Low temperature
    - Increased strain rate
    - Presence of sharp notch
    - Increased specimen thickness
    - Any molecular structure that raises T_g



15.5 Fracture of Polymers

- Thermoplastic polymers
  - Crazing
    - Fibrillar bridge
    - Micro-void
    - Crack
    - Crazing is not cracking because it can still support a load across the face.
    - Makes polymers more resistant to fracture failure

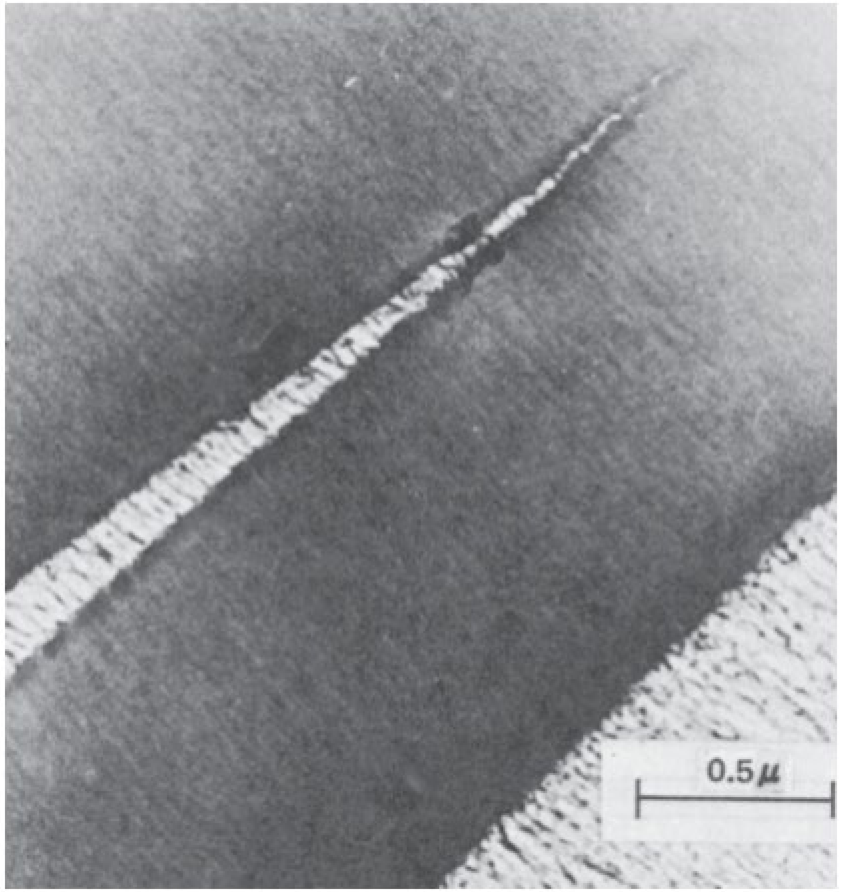


Figure 15.10 Photomicrograph of a craze in poly(phenylene oxide).

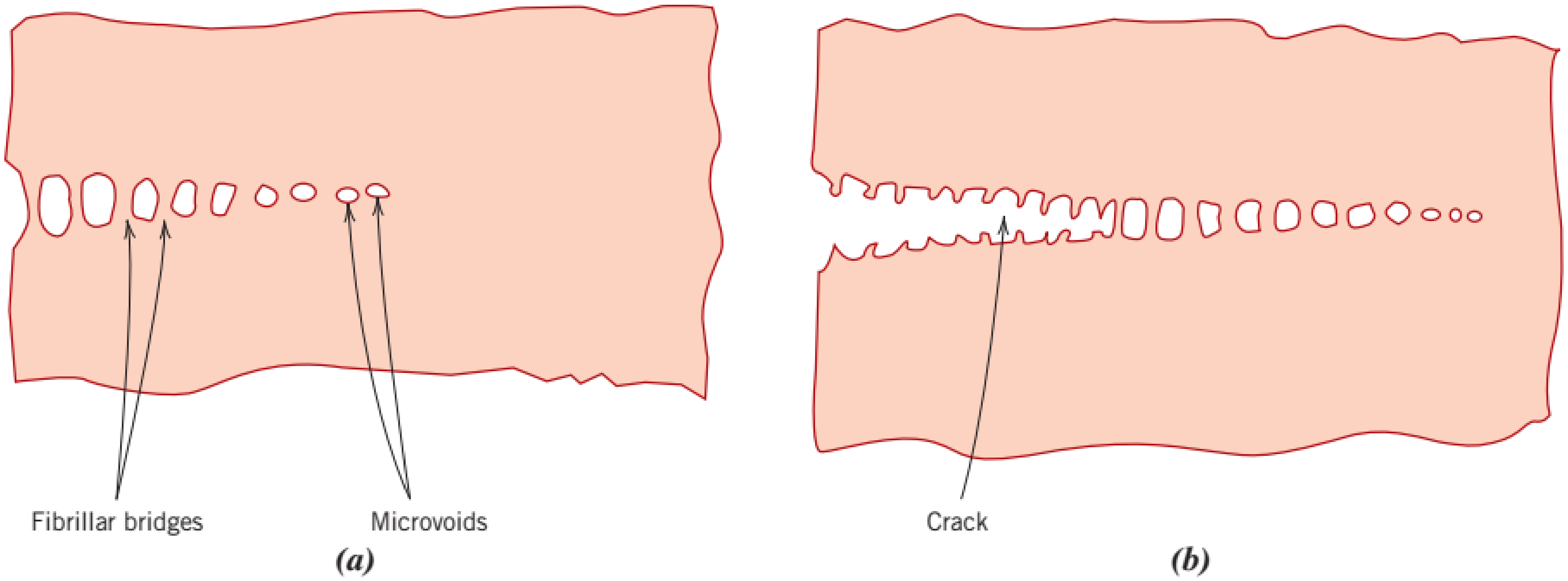


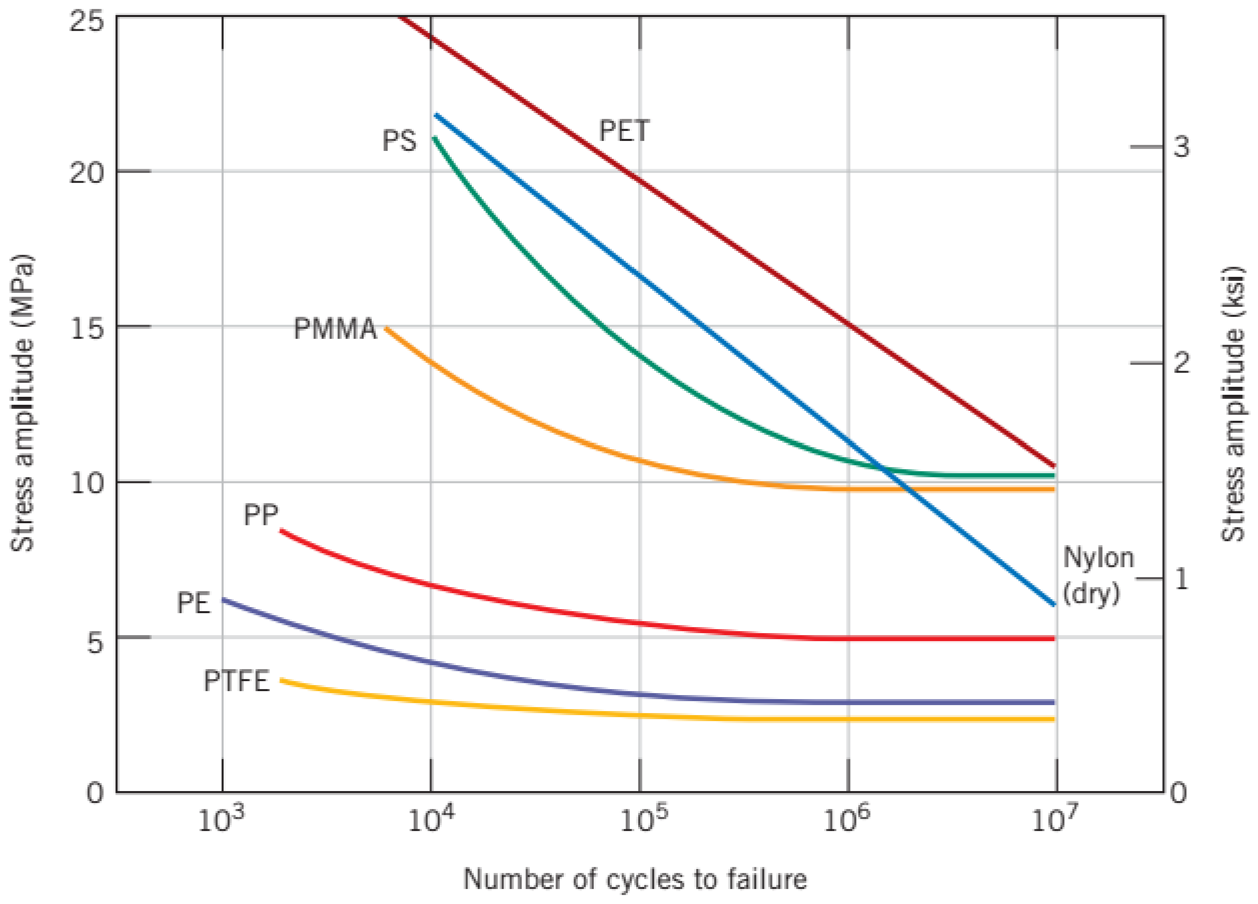
Figure 15.9 Schematic drawings of (*a*) a craze showing microvoids and fibrillar bridges and (*b*) a craze followed by a crack.

Concept Check!!!

- What types of polymers form crazes? Why?

15.6 Miscellaneous Mechanical Characteristics

- Impact Strength
  - Izod or Charpy Tests used.
  - Low temperatures = brittle
  - Semicrystalline and amorphous polymers have low impact strength
- Fatigue
  - These tests are done the same on polymers as with metals.
  - Fatigue limits
- Tear Resistance
  - Same as metals, but weaker
  - Rockwell, Durometer, Barcol



Fatigue Curves