2020 Fall

Introduction to Materials Science and Engineering

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I. Phase diagram_ZrO_2-CaO diagram: Eutectic system

$T \leftrightarrow M$ 커다란 부피변화
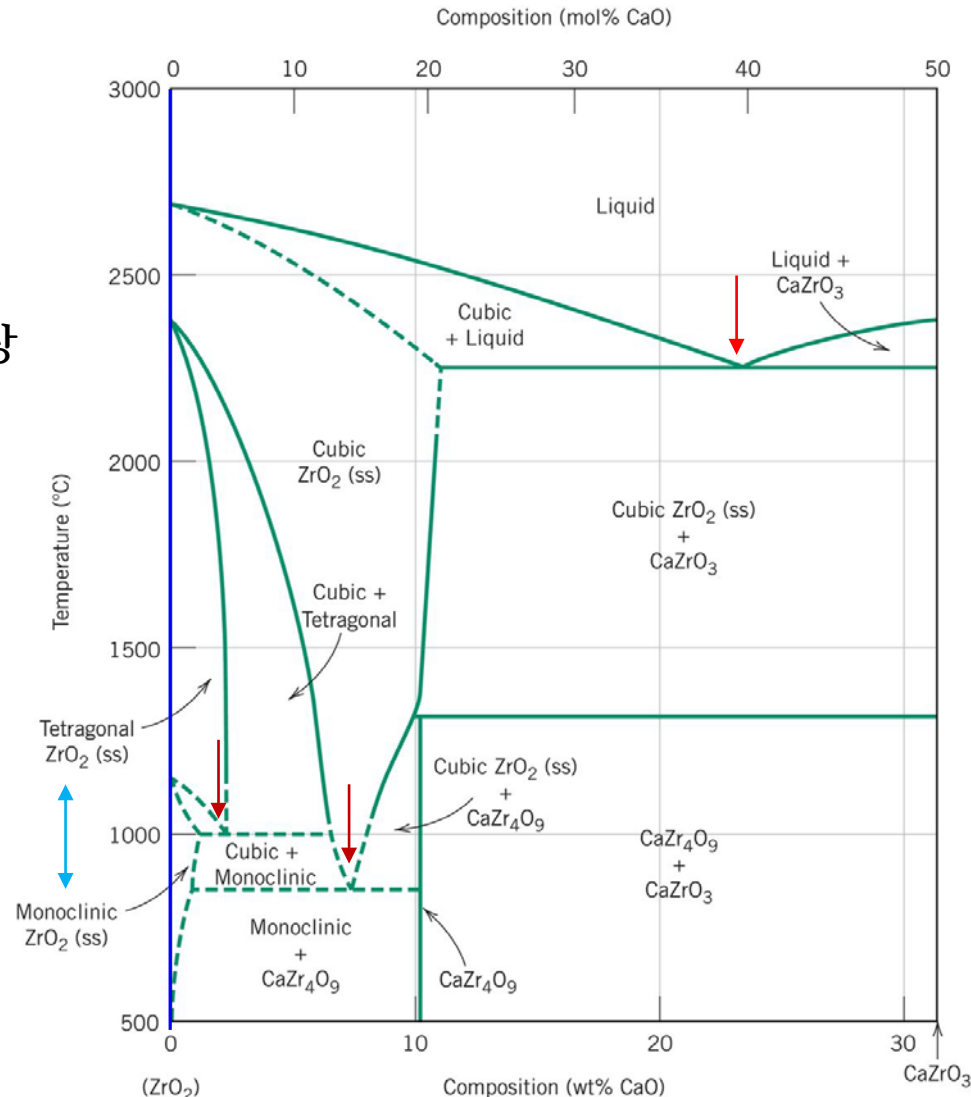: 재료내 균열 야기

→ CaO 첨가

→ Cubic phase 안정화

→ Cubic + Tetragonal 상
  공존 냉각 조건에
  따라 상온에서도
  유지되도록 함

→ 취성이 작은
  안정화 지르코니아
  (Partially stabilized
   Zirconia, PSZ) 형성

→ Y_2O_3, MgO 도
  안정화제

→ 함량 증가시
  Cubic이 상온까지
  안정화

→ 완전 안정화
  지르코니아

Composition (mol% CaO)

Adapted from V. S. Stubican and S. P. Ray, "Phase Equilibria and Ordering in the System ZrO2–CaO," J. Am. Ceram. Soc., 60[11–12] 535 (1977). Reprinted by permission of the American Ceramic Society.

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II. Mechanical Properties

14.6 세라믹의 취성파괴

Ceramic materials are **more brittle** than metals.
: 재료의 파괴시 에너지 흡수가 거의 없이 **취성파괴**를 일으킴

Why is this so?

- Consider **mechanism of deformation**
  - **In crystalline, by dislocation motion**
  - In highly ionic solids, dislocation motion is difficult
    - few slip systems
    - resistance to motion of ions of like charge (e.g., anions) past one another

* 세라믹의 파면

a. 균열의 기원 및 형상

균열이 생성되고 전파하는 동안에 균열 전파가 가속되어 임계 속도 [또는 종착 속도 Terminal speed)]에 도달시 (유리의 경우, 음속의 ½) 균열은 가지를 치게 되는데 (분기, branching) 이 과정이 반복되어 균열 군이 생성됨

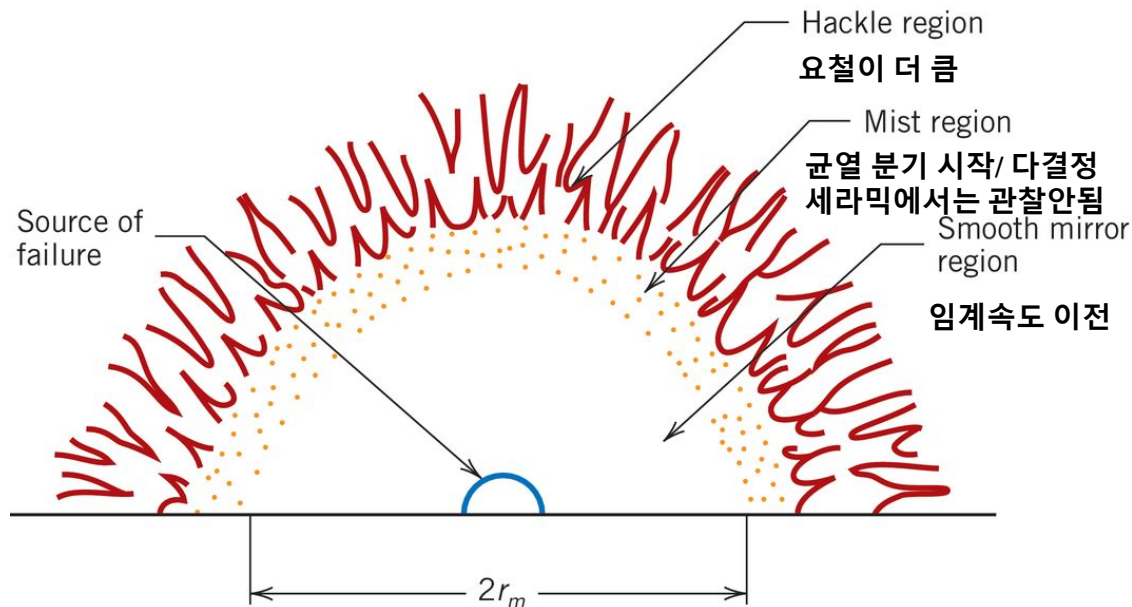균열이 분기되는 정도는 인가된 응력에 따라 증가

b. 파단면 (Fractography)

균열이 전파하는 동안
재료의 미세구조, 응력,
발생된 탄성파 등과
상호작용을 하며
파단면에 특정한 특징을 유발

파괴 응력값 (σ_f)

$$\sigma_f \propto \frac{1}{r_m^{0.5}}$$

응력 증가↑→가속도↑→r_m↓

Figure 14.7 취성 세라믹의 파단면상에서 관찰되는 일반적인 특징 모식도

Hackle region
요철이 더 큼

Mist region
균열 분기 시작/ 다결정 세라믹에서는 관찰안됨

Smooth mirror region
임계속도 이전

Source of failure

$2r_m$

Adapted from J. J. Mecholsky, R. W. Rice, and S. W. Freiman, "Prediction of Fracture Energy and Flaw Size in Glasses from Measurements of Mirror Size," J. Am. Ceram. Soc., 57[10] 440 (1974). Reprinted with permission of The American Ceramic Society, www.ceramics.org. Copyright 1974. All rights reserved.

Flexural Tests – Measurement of **Elastic Modulus** & **Flexural Strength**

- 3-point bend test to measure room-T flexural strength.

cross section

d

R

b

rect.   circ.

F

$L/2$ $L/2$

Adapted from Fig. 14.9, *Callister & Rethwisch 9e.*

δ = midpoint deflection

location of max tension
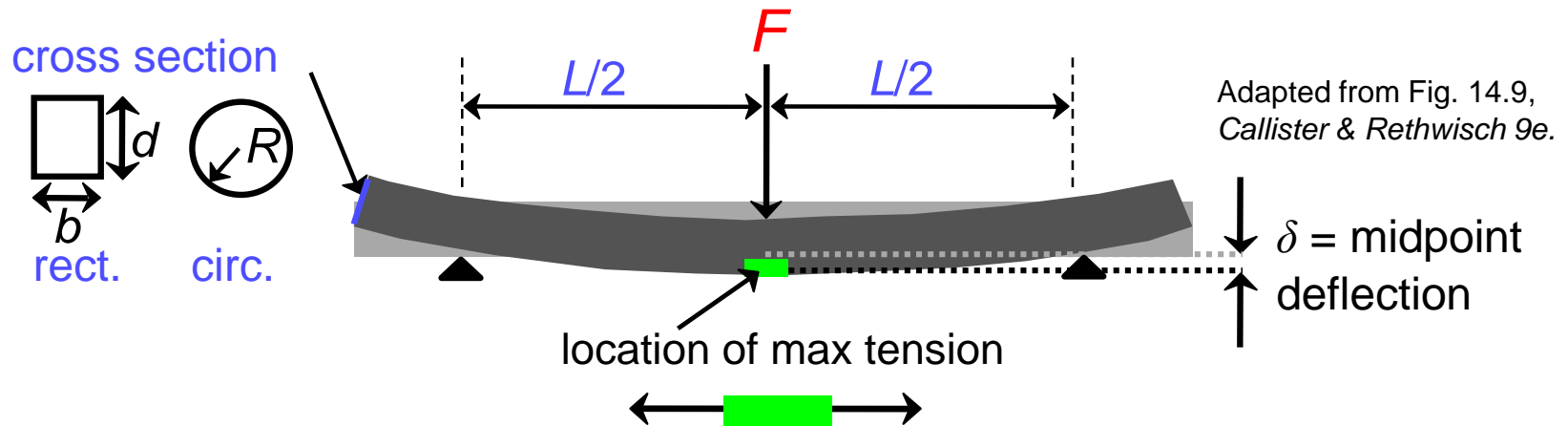
$$E = \frac{F}{\delta}\frac{L^3}{4bd^3}$$ (rect. cross section)

- Flexural strength:

$$\sigma_{fs} = \frac{3F_f L}{2bd^2}$$ (rect. cross section)

- Typical values:

Material	σ_{fs}(MPa)	E(GPa)
Si nitride	250-1000	304
Si carbide	100-820	345
Al oxide	275-700	393
glass (soda-lime)	69	69

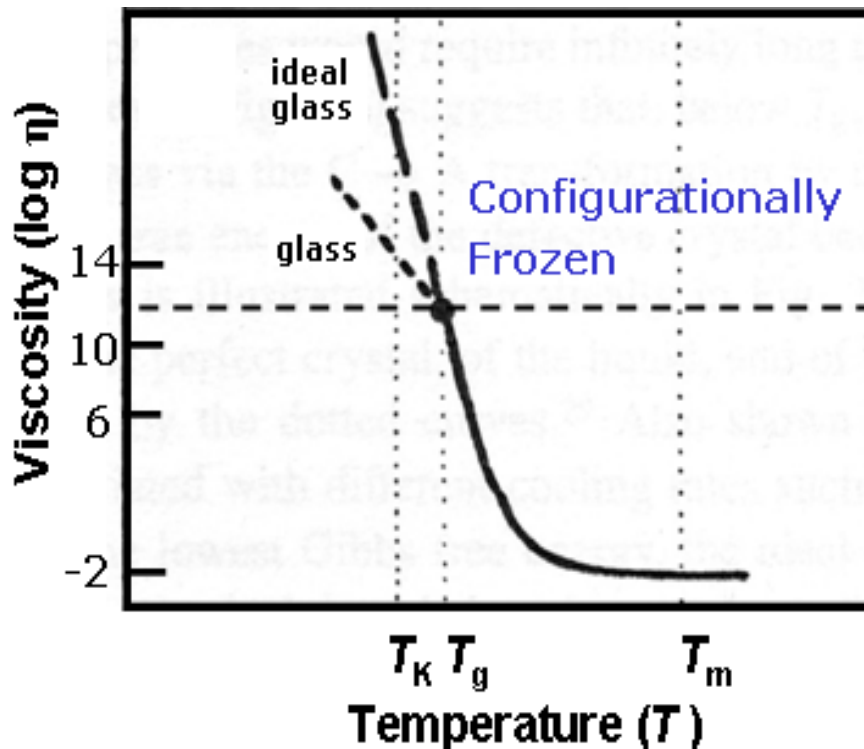Data from Table 14.1, *Callister & Rethwisch 9e.*

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14.8 소성변형기구

Consider mechanism of deformation

In crystalline ceramic, by dislocation motion

In non-crystalline ceramic, by viscous flow

Viscosity (η): 비정질 재료의 변형에 대한 저항

$$\eta = \frac{\tau}{dv/dy} = \frac{F/A}{dv/dy}$$

Solid > 10^{12} Pa s

vs **Liquid ~ $10^{-(2-4)}$ Pa s**

14.9 기타 기계적 고려사항

a. **탄성계수**의 기공도 의존성: $\boxed{E = E_0(1 - 1.9P + 0.9P^2)}$

P (기공의 부피분율)↑ → E ↓

b. 기공 분율이 **굴곡 강도**에 미치는 영향: $\boxed{\sigma_{fs} = \sigma_0\exp(-nP)}$

기공은 (1) 하중이 가해지는 면적을 감소시킴 (2) 응력집중자 역할
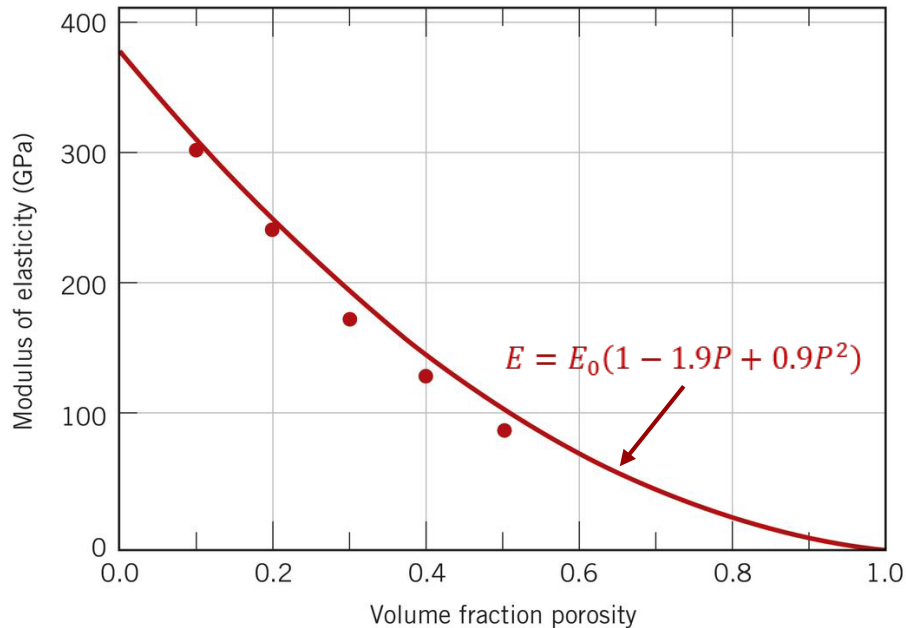
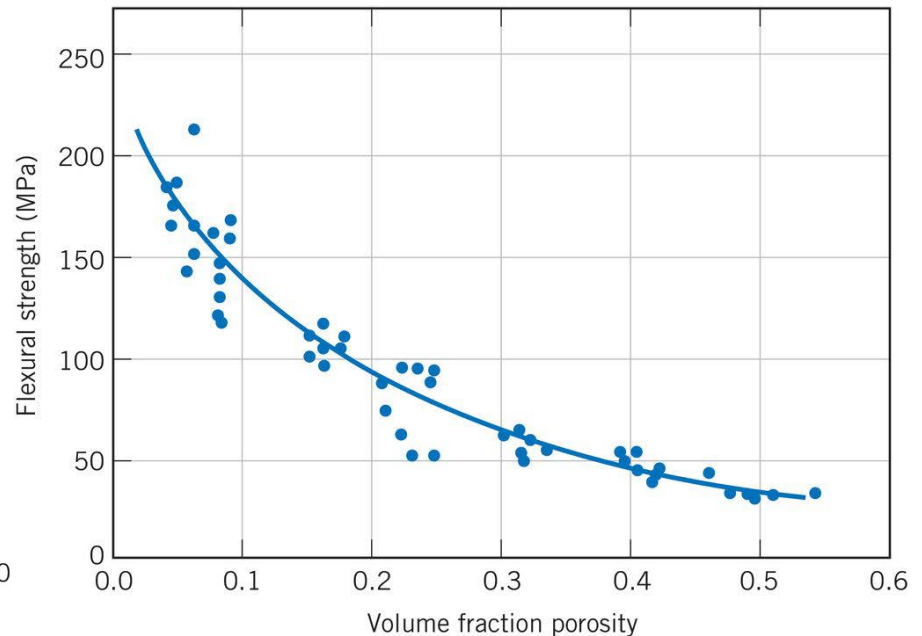P **가 파단 계수를 지수함수적으로 감소시킴 ex) 10% 기공, 강도 50% 이상 감소**

$E = E_0(1 - 1.9P + 0.9P^2)$

Figure 14.12

상온에서 알루미나의 탄성 계수에 미치는 기공의 영향

Figure 14.13

상온에서 알루미나의 굴곡강도에 미치는 기공의 영향 7
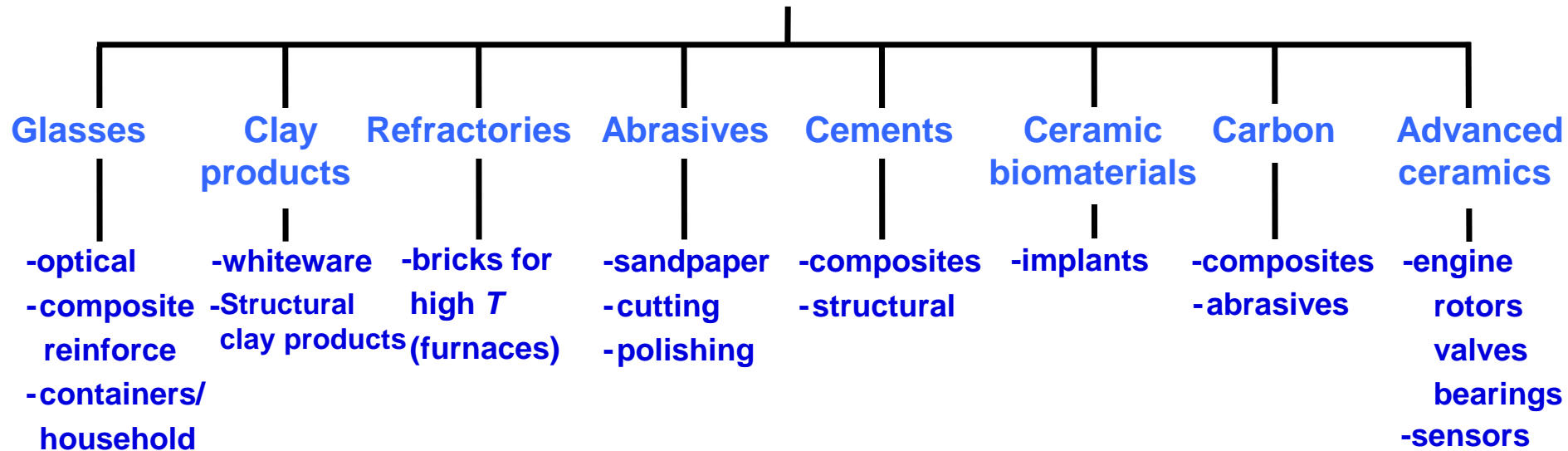
c. 경도 : 경도가 가장 높은 재료들이 세라믹 재료에 속함

- 세라믹 재료는 압입시 쉽게 균열이 발생하여 정확한 경도를 측정하기 어려움
  따라서, 균열을 심하게 유발하는 구형 압입자 [로크웰 Rockwell 경도 시험기와
  브린넬 Brinell 경도시험기]가 사용되지 않고, 피라미드형 압입자인 비커스 Vickers
  와 누프 Knoop 법 (취성이 매우 심한 경우)이 주로 사용됨.

Table 14.2 Vickers (and Knoop) Hardnesses for Eight Ceramic Materials

Material	Vickers Hardness (GPa)	Knoop Hardness (GPa)	Comments
Diamond (carbon)	130	103	Single crystal, (100) face
Boron carbide (B_4C)	44.2	—	Polycrystalline, sintered
Aluminum oxide (Al_2O_3)	26.5	—	Polycrystalline, sintered, 99.7% pure
Silicon carbide (SiC)	25.4	19.8	Polycrystalline, reaction bonded, sintered
Tungsten carbide (WC)	22.1	—	Fused
Silicon nitride (Si_3N_4)	16.0	17.2	Polycrystalline, hot pressed
Zirconia (ZrO_2) (partially stabilized)	11.7	—	Polycrystalline, 9 mol% Y_2O_3
Soda-lime glass	6.1	—	

III. Classification of Ceramics

Ceramic Materials

Glasses	Clay products	Refractories	Abrasives	Cements	Ceramic biomaterials	Carbon	Advanced ceramics
-optical -composite reinforce -containers/ household	-whiteware -Structural clay products	-bricks for high T (furnaces)	-sandpaper -cutting -polishing	-composites -structural	-implants	-composites -abrasives	-engine rotors valves bearings -sensors

Adapted from Fig. 13.1 and discussion in
Sections 13.2-10, *Callister & Rethwisch 10e.*

Figure 13.1 용도에 따라 분류한 세라믹 재료

IV. Fabrication and Processing of Ceramics
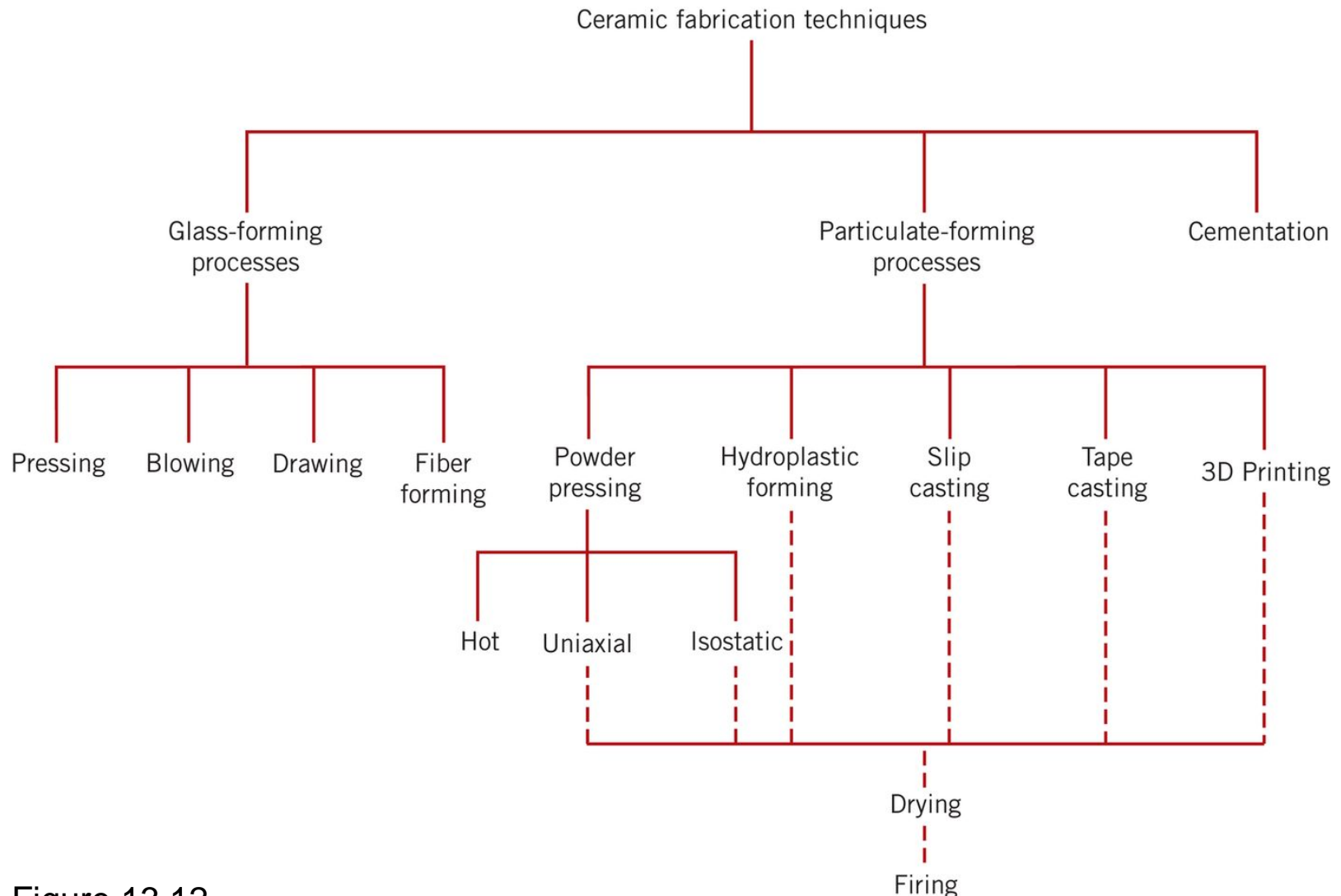
Figure 13.12
A classification scheme for the ceramic-forming techniques discussed in this chapter.

Chapter 14:
Polymer Structures

Lecture note 7 참고

ISSUES TO ADDRESS...

- What are the general structural and chemical characteristics of polymer molecules?

- What are some of the common polymeric materials, and how do they differ chemically?

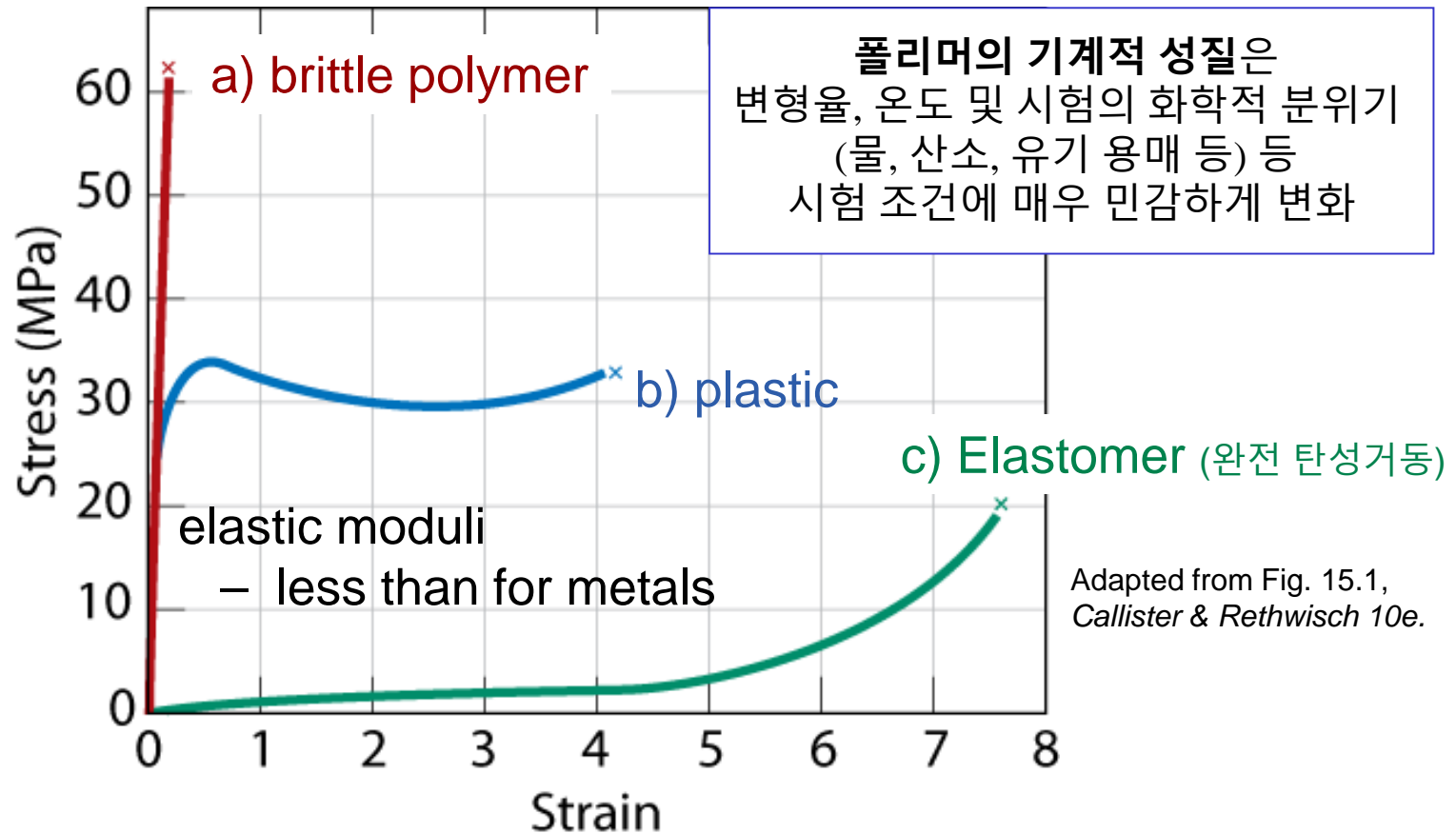- How is the crystalline state in polymers different from that in metals and ceramics ?

Chapter 15:
Characteristics, Applications, and Processing of Polymers

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?

I. Mechanical Properties of Polymers – Stress-Strain Behavior

a) brittle polymer

b) plastic

c) Elastomer (완전 탄성거동)

elastic moduli
– less than for metals

폴리머의 기계적 성질은
변형율, 온도 및 시험의 화학적 분위기
(물, 산소, 유기 용매 등) 등
시험 조건에 매우 민감하게 변화

Adapted from Fig. 15.1,
Callister & Rethwisch 10e.

- Fracture strengths of polymers ~ 10% of those for metals

- Deformation strains for polymers > 1000% (100 times for metals)
  – for most metals, deformation strains < 10%

1) Mechanisms of Deformation—a) Brittle

Crosslinked and Network Polymers
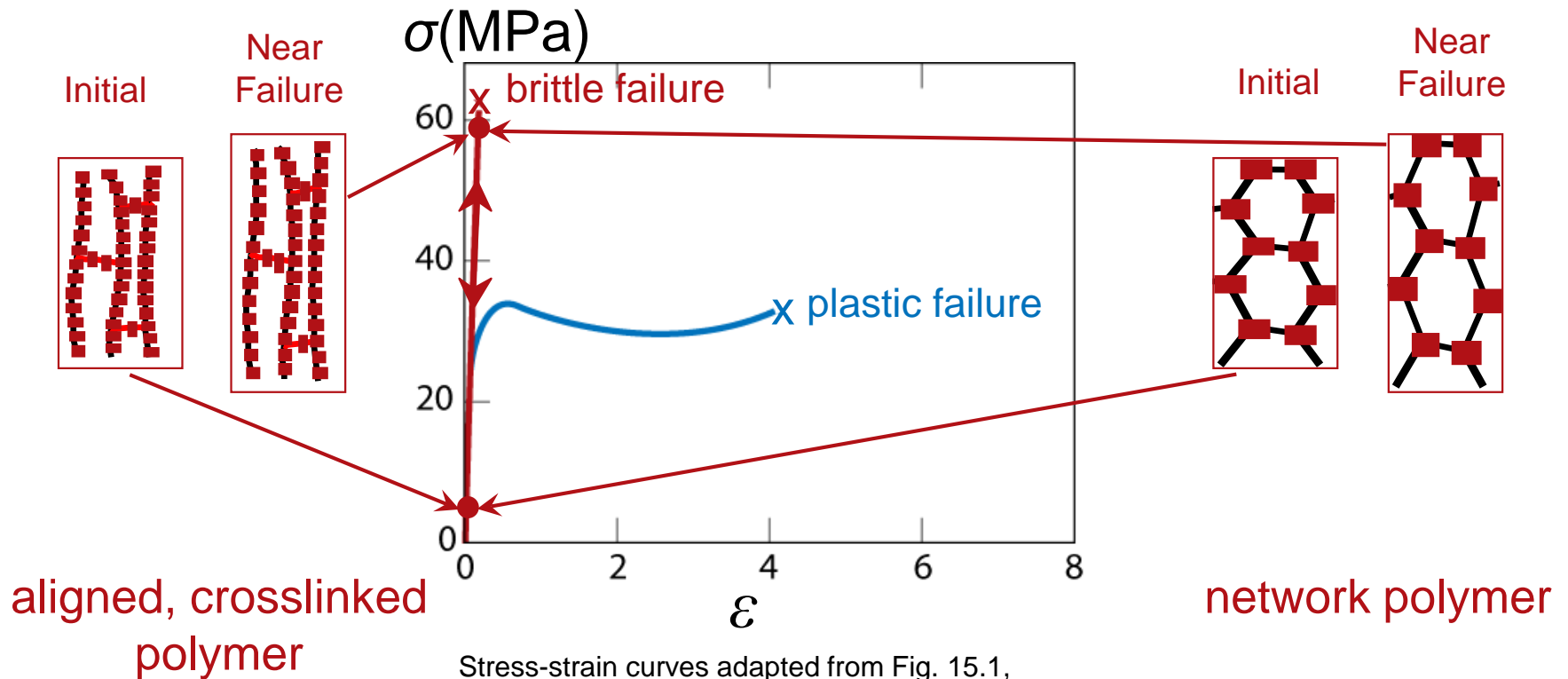
Stress-strain curves adapted from Fig. 15.1, *Callister & Rethwisch 9e.*

Mechanisms of Deformation—b) Plastic
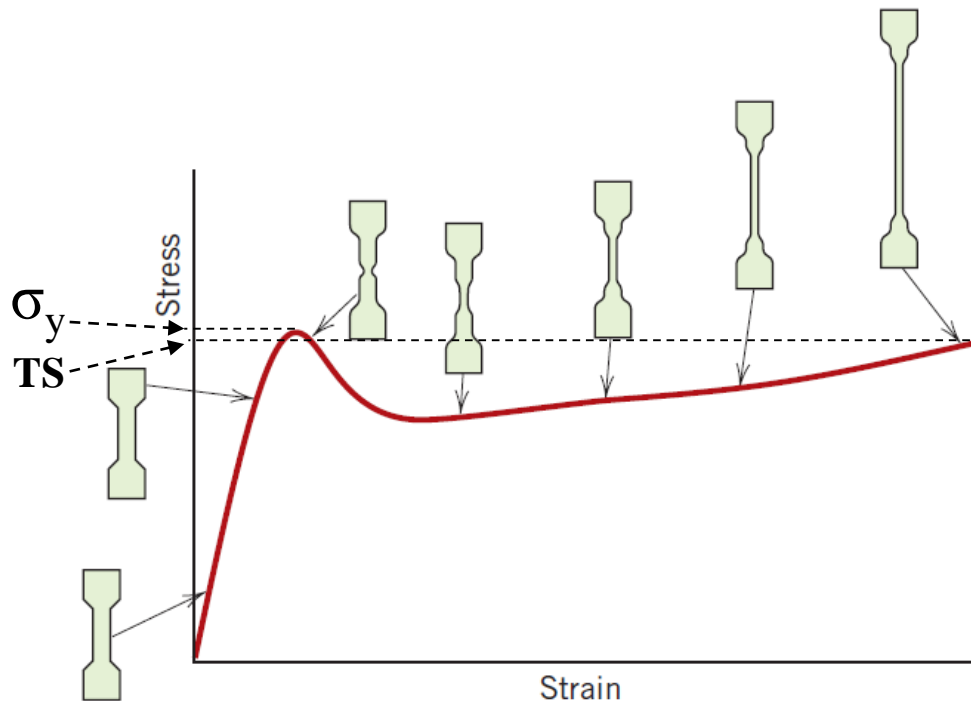
Figure 15.4 Schematic tensile stress–strain curve for a semicrystalline polymer. Specimen contours at several stages of deformation are included. (From Jerold M. Schultz, *Polymer Materials Science,* copyright © 1974, p. 488. Reprinted by permission of Prentice Hall, Inc., Englewood Cliffs, NJ.)

인장강도 (TS) 는 파단이 일어나는 응력, 이 값은 항복 강도 (σ_y)보다 클 수도 작을수도

Mechanisms of Deformation —
Semicrystalline (Plastic) Polymers

Stress-strain curves adapted from Fig. 15.1, *Callister & Rethwisch 9e.* Inset figures along plastic response curve adapted from Figs. 15.12 & 15.13, *Callister & Rethwisch 9e.* (From SCHULTZ, POLYMER MATERIALS SCIENCE, 1st Edition, © 1974. Reprinted by permission of Pearson Education, Inc., Upper Saddle River, NJ.)1974, pp 500-501.)

σ(MPa)

brittle failure

onset of necking

plastic failure

unload/reload

fibrillar structure

near failure

crystalline block segments separate

undeformed structure

amorphous regions elongate

crystalline regions align
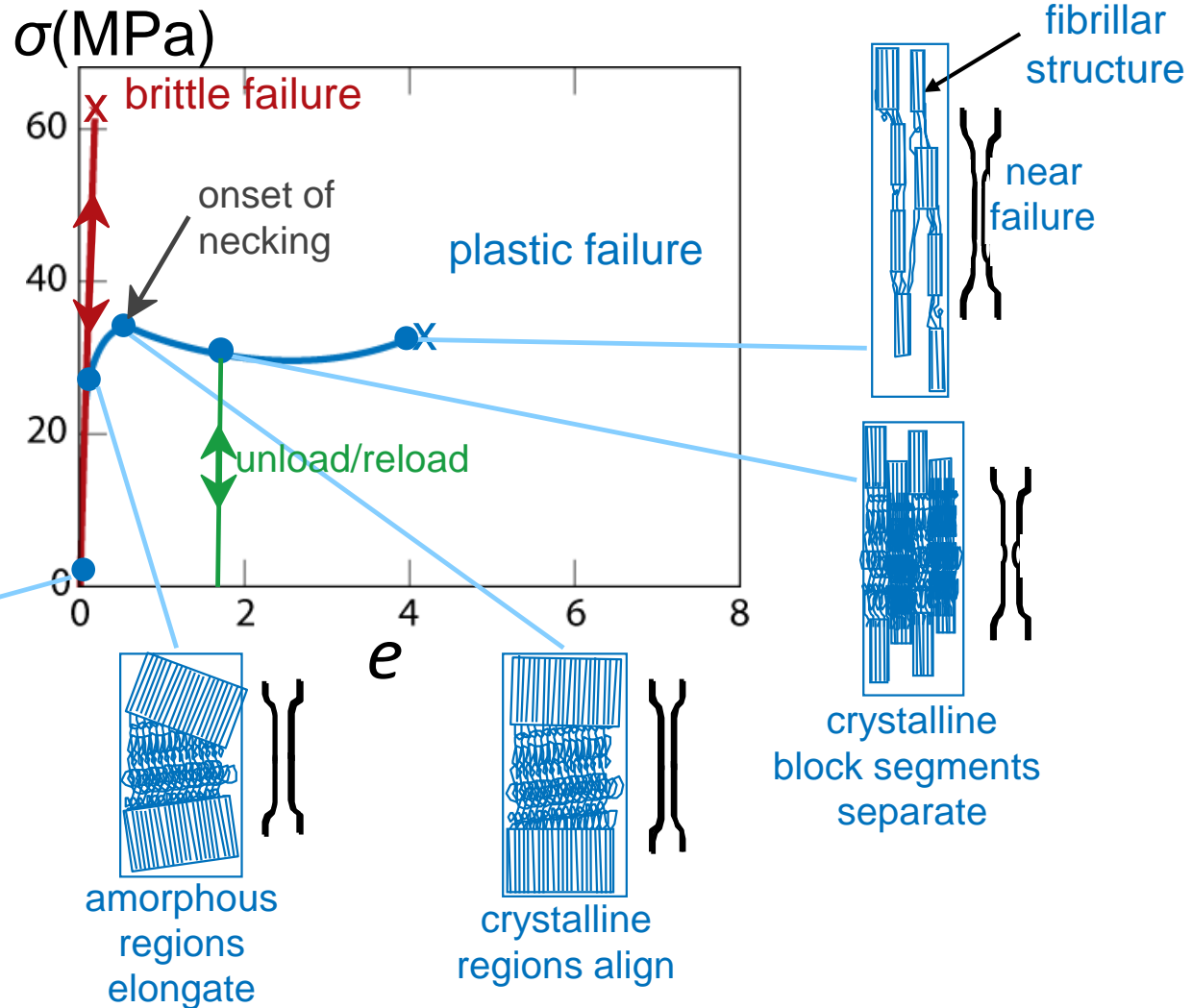
① **Predeformation by Drawing**

- Drawing…(ex: monofilament fishline)
  - -- <u>stretches the polymer prior to use</u>
  - -- aligns chains in the stretching direction
- Results of drawing: (E&TS↑, %EL↓)
  - -- increases the elastic modulus (E) in the stretching direction
  - -- increases the tensile strength (TS) in the stretching direction
  - -- decreases ductility (%EL)

Adapted from Fig. 15.13, *Callister & Rethwisch 10e.*

- Annealing after drawing... (E&TS↓, %EL↑)
  - -- decreases chain alignment
  - -- reverses effects of drawing (reduces E and TS, enhances %EL)

- Contrast to effects of cold working in metals!
  (E&TS↑, %EL↓)
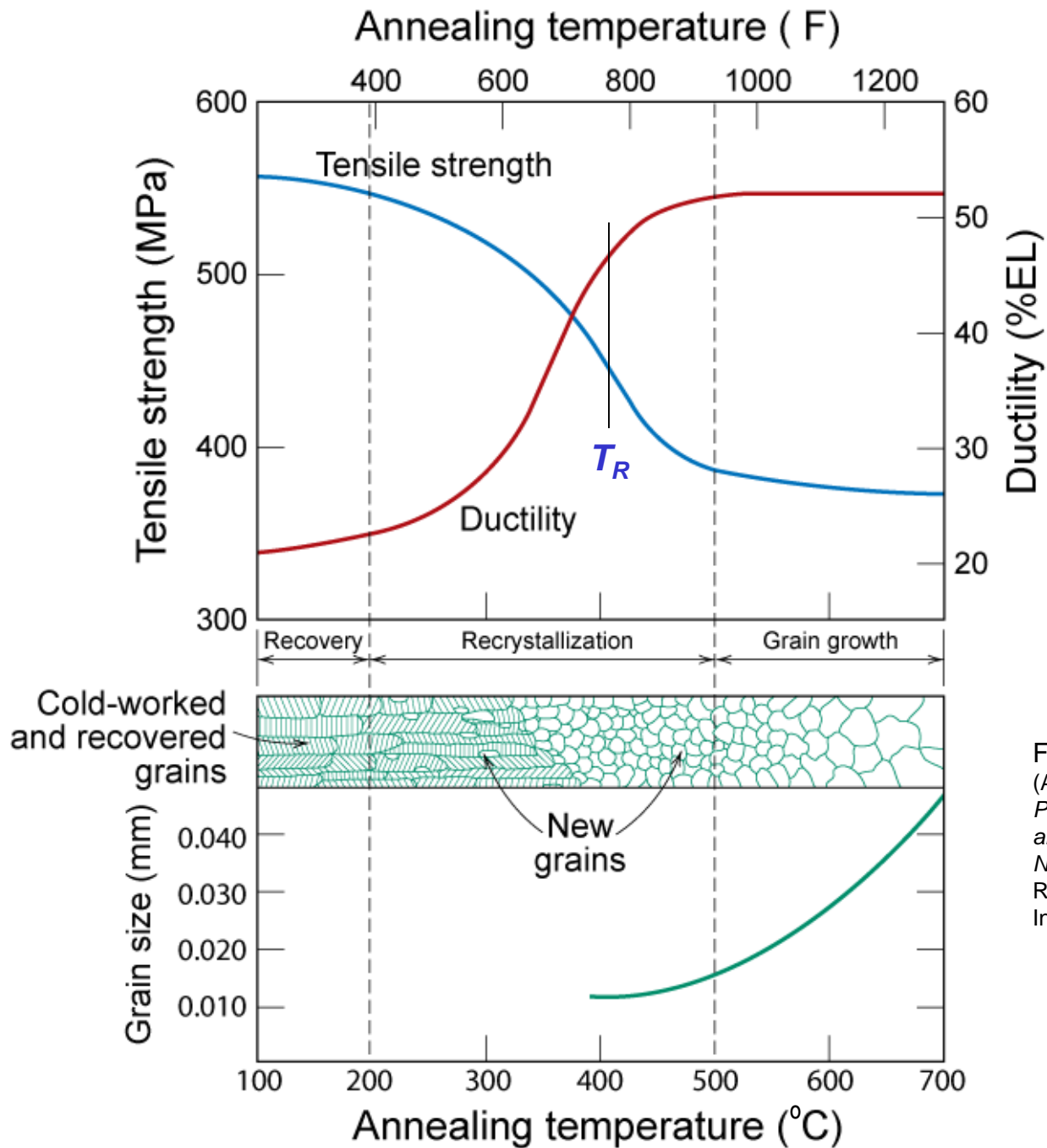
T_R = recrystallization temperature

Fig. 9.22, *Callister & Rethwisch 9e.*
(Adapted from G. Sachs and K. R. Van Horn, *Practical Metallurgy, Applied Metallurgy and the Industrial Processing of Ferrous and Nonferrous Metals and Alloys*, 1940. Reproduced by permission of ASM International, Materials Park, OH.)
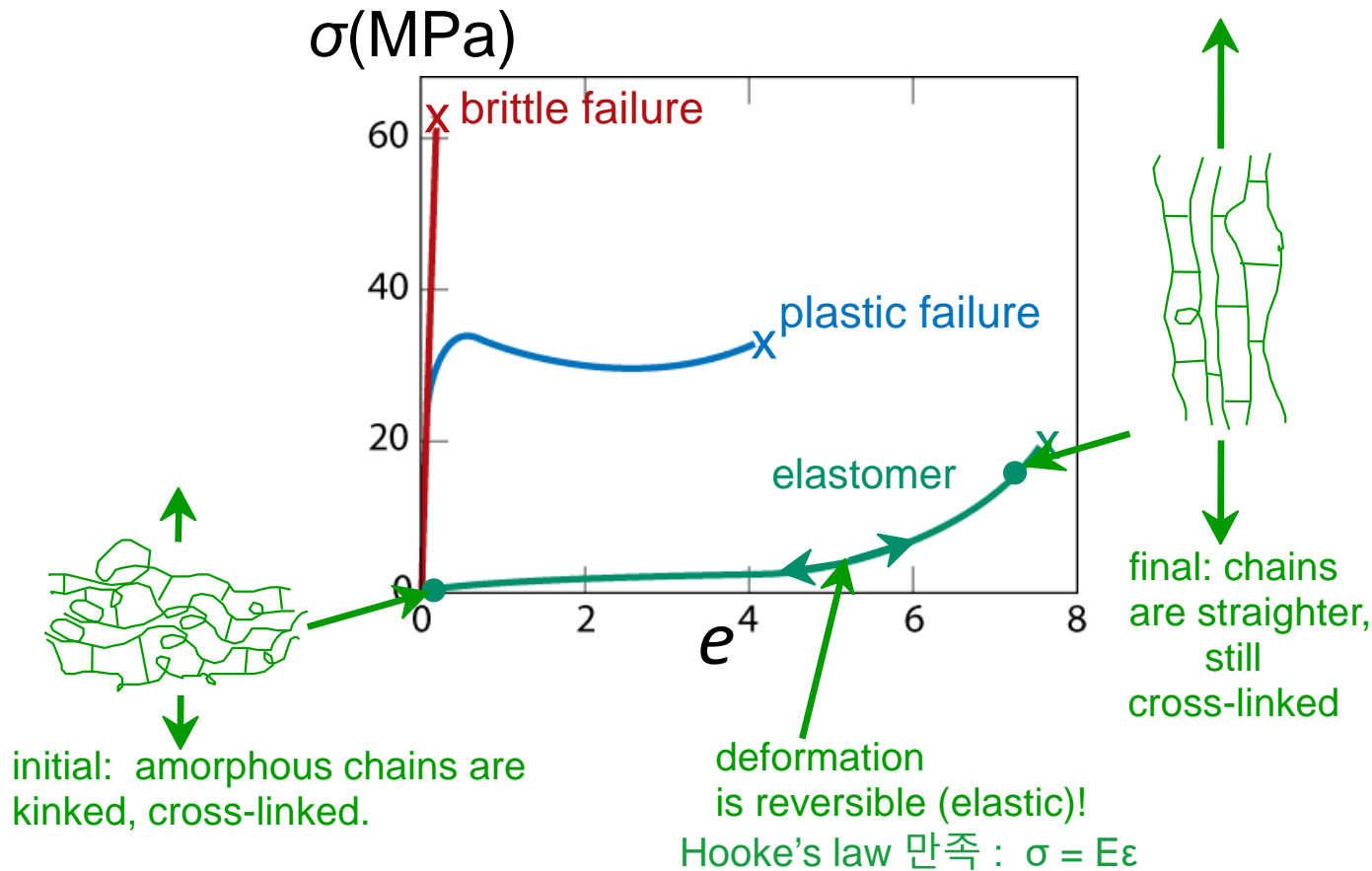
② Influence of *T* and Strain Rate on Thermoplastics

- Decreasing *T*...
  -- increases *E*
  -- increases *TS*
  -- decreases %*EL*
  (E&TS↑, %EL↓)

- Increasing
  strain rate...
  -- same effects
  as decreasing *T*.
  (E&TS↑, %EL↓)
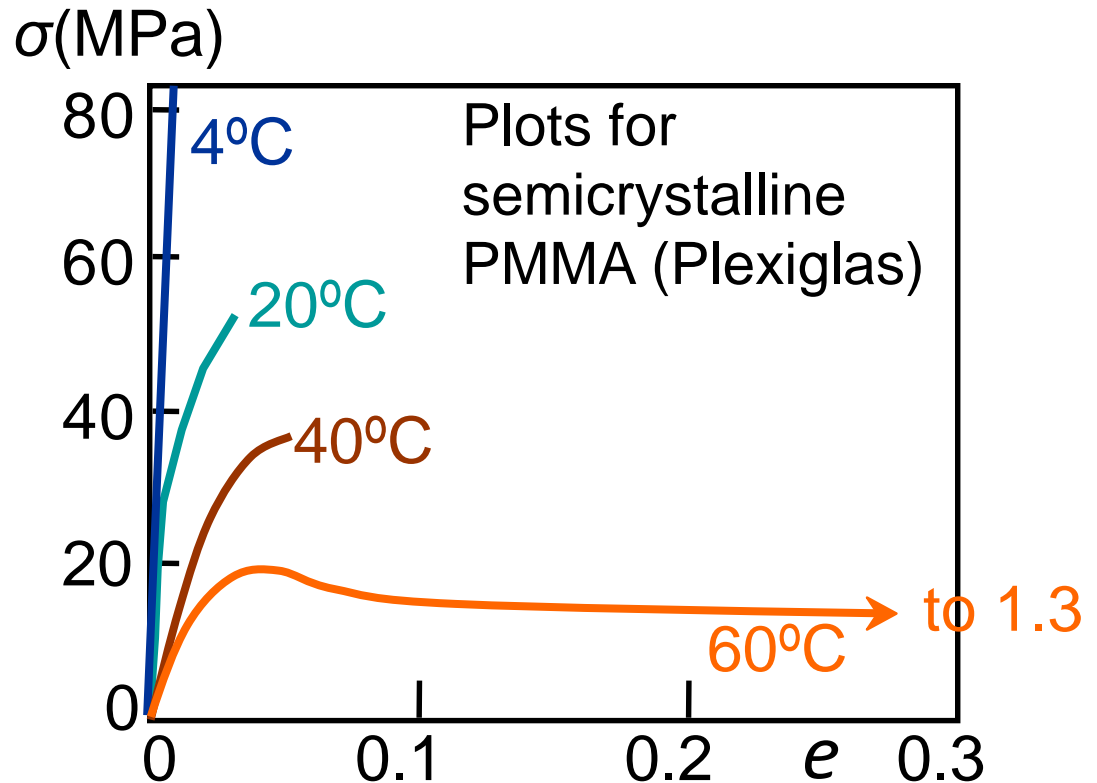
σ(MPa)

80
60
40
20
0

4°C

20°C

40°C

60°C   to 1.3

Plots for semicrystalline PMMA (Plexiglas)

0   0.1   0.2   *e*   0.3

Adapted from Fig. 15.3, *Callister & Rethwisch 10e*. (Reprinted with permission from T. S. Carswell and H. K. Nason, "Effect of Environmental Conditions on the Mechanical Properties of Organic Plastics," in Symposium on Plastics. Copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.)

Mechanisms of Deformation—c) Elastomers

σ(MPa)

x brittle failure

plastic failure

elastomer

e

initial: amorphous chains are kinked, cross-linked.

deformation
is reversible (elastic)!
Hooke's law 만족 : σ = Eε

final: chains
are straighter,
still
cross-linked

Stress-strain curves adapted from Fig. 15.1, *Callister & Rethwisch 10e.* Inset figures along elastomer curve (green) adapted from Fig. 15.15, *Callister & Rethwisch 10e.* (Fig. 15.15 adapted from Z. D. Jastrzebski, The Nature and Properties of Engineering Materials, 3rd edition. Copyright © 1987 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

- 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)

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Elastin is a highly elastic protein in connective tissue and allows many tissues in the body to resume their shape after stretching or contracting. Elastin helps skin to return to its original position when it is poked or pinched.
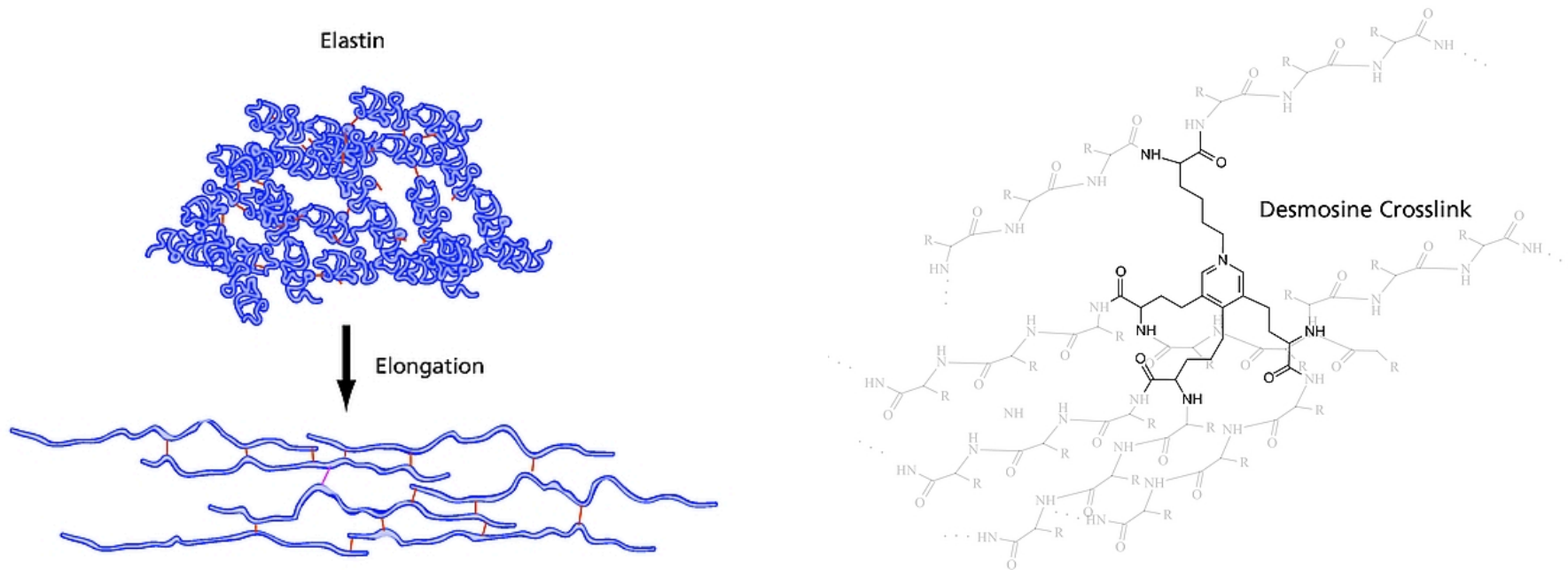
Vulcanization 가황 (탄성체에서의 가교 결합 과정, 비가역적 반응/고온 발생)

The crosslinking process in elastomers is called **vulcanization,** which is achieved by a nonreversible chemical reaction, ordinarily carried out at an elevated temperature. In most vulcanizing reactions, sulfur compounds are added to the heated elastomer; chains of sulfur atoms bond with adjacent polymer backbone chains and crosslink them, which is accomplished according to the following reaction:

$$
\begin{array}{c}
\begin{array}{cccc}
\text{H} & \text{CH}_3 & \text{H} & \text{H} \\
| & | & | & | \\
-\text{C}- & \text{C}= & \text{C}- & \text{C}- \\
| & & & | \\
\text{H} & & & \text{H}
\end{array} \\[1em]
+\,(m + n)\,\text{S} \longrightarrow \\[1em]
\begin{array}{cccc}
\text{H} & & & \text{H} \\
| & & & | \\
-\text{C}- & \text{C}= & \text{C}- & \text{C}- \\
| & | & | & | \\
\text{H} & \text{CH}_3 & \text{H} & \text{H}
\end{array}
\end{array}
\qquad
\begin{array}{c}
\begin{array}{cccc}
\text{H} & \text{CH}_3 & \text{H} & \text{H} \\
| & | & | & | \\
-\text{C}- & \text{C}- & \text{C}- & \text{C}- \\
| & | & | & | \\
\text{H} & & & \text{H}
\end{array} \\[1em]
(\text{S})_m \ (\text{S})_n \\[1em]
\begin{array}{cccc}
\text{H} & & & \text{H} \\
| & | & | & | \\
-\text{C}- & \text{C}- & \text{C}- & \text{C}- \\
| & | & | & | \\
\text{H} & \text{CH}_3 & \text{H} & \text{H}
\end{array}
\end{array}
\qquad (15.4)
$$
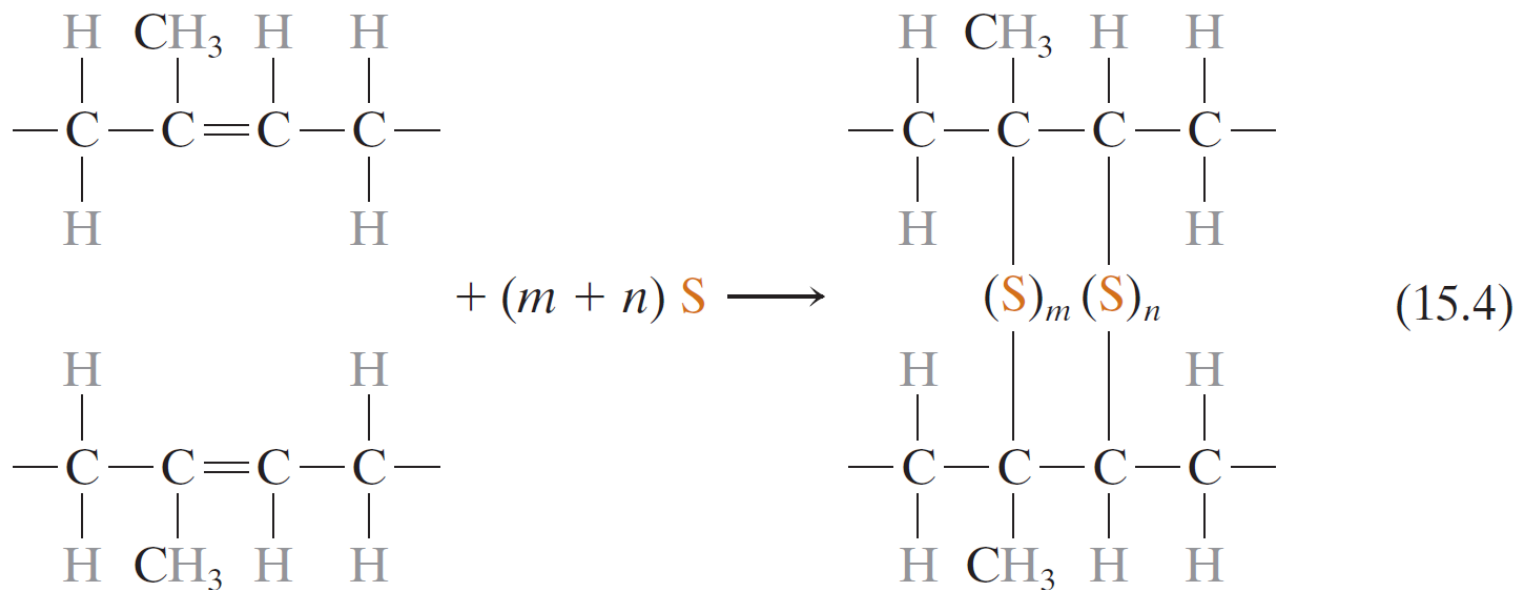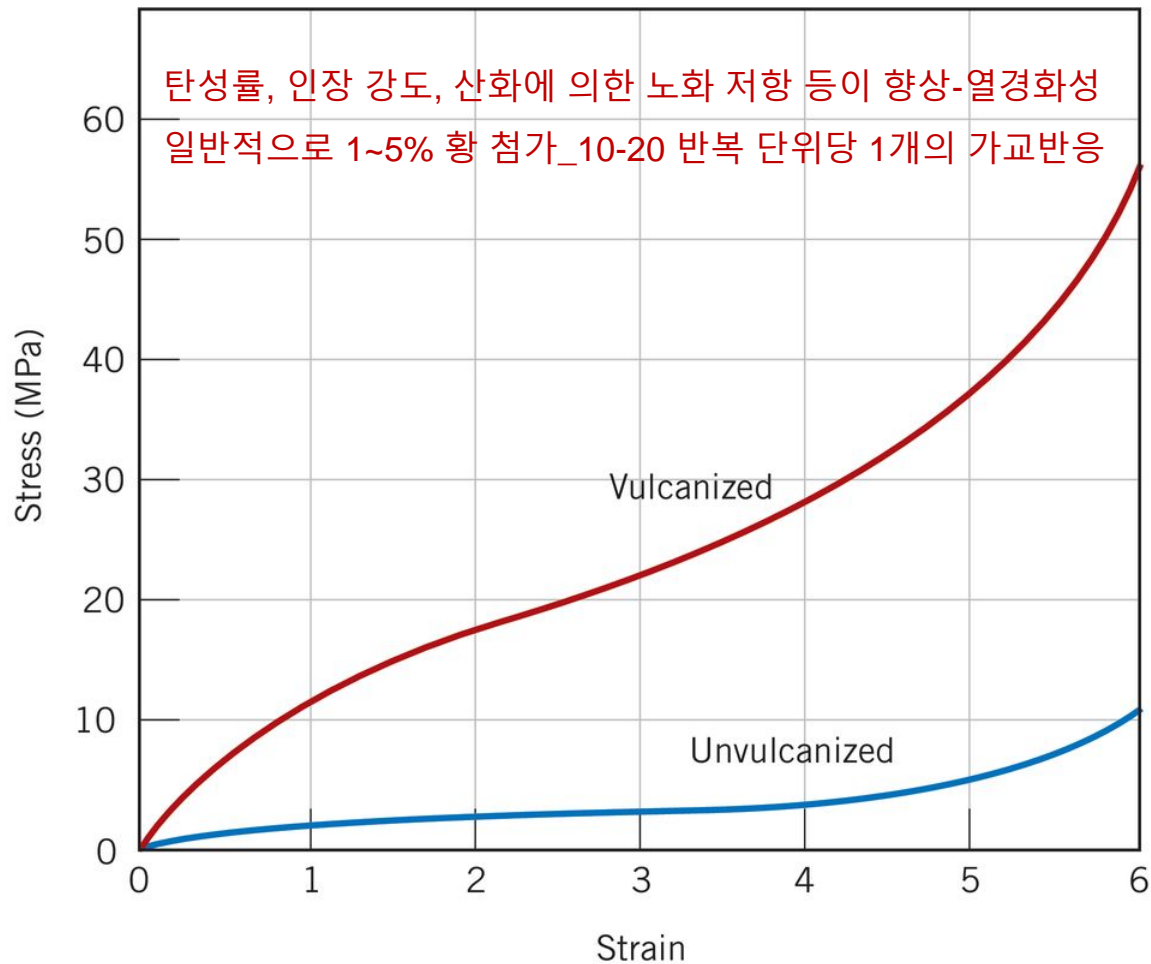
그림 15.16   가황되지 않은 천연 고무와 가황된 천연 고무를
600% 연신시켰을 때 응력-변형률 곡선

2) 폴리머 재료의 <u>점탄성 거동</u>: 시간과 온도에 따라 변화
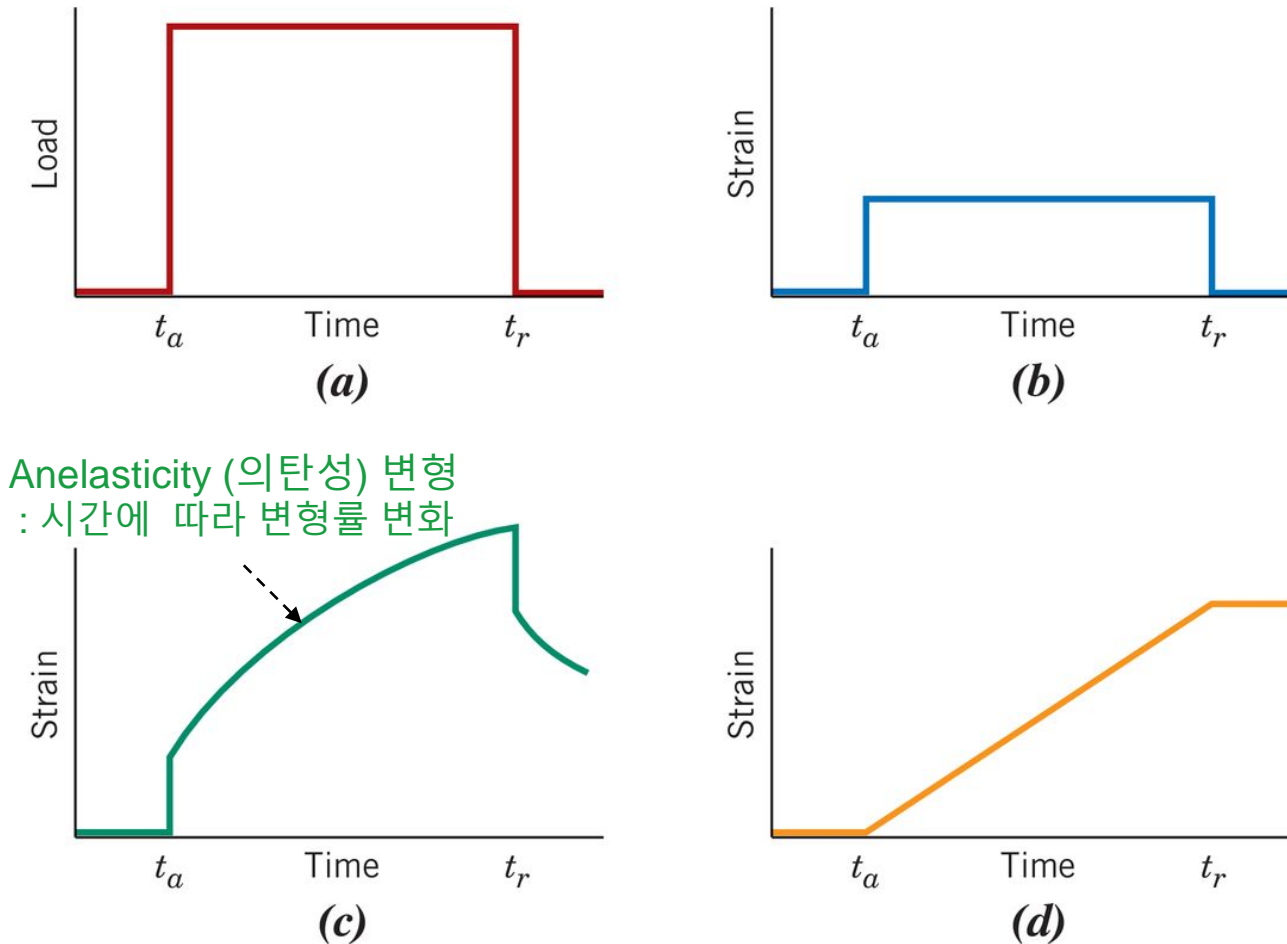
그림 15. 5 (a) 하중-시간 거동. 하중이 t_a에서 순간적으로 가해지고 t_r에서 제거된다. 변형률-시간, (b) 완전탄성체, (c) 점탄성 (e.g. 규소 폴리머), (d) 점성 거동

Time-Dependent Deformation

- Stress relaxation test:

  -- strain in tension to ε_O and hold.

  -- observe decrease in stress with time.

tensile test

ε_O — strain

$\sigma(t)$

time
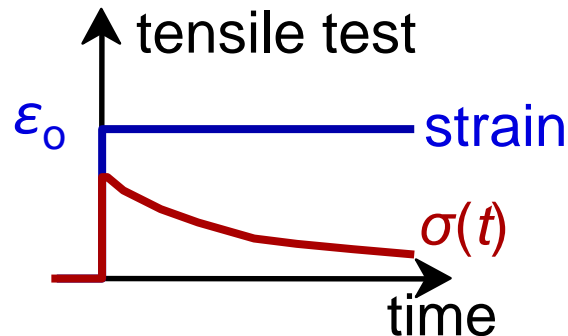
- Relaxation modulus:

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

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

(amorphous polystyrene)

E_r(10 s) in MPa

rigid solid (small relax)

transition region

viscous liquid (large relax)

T_g
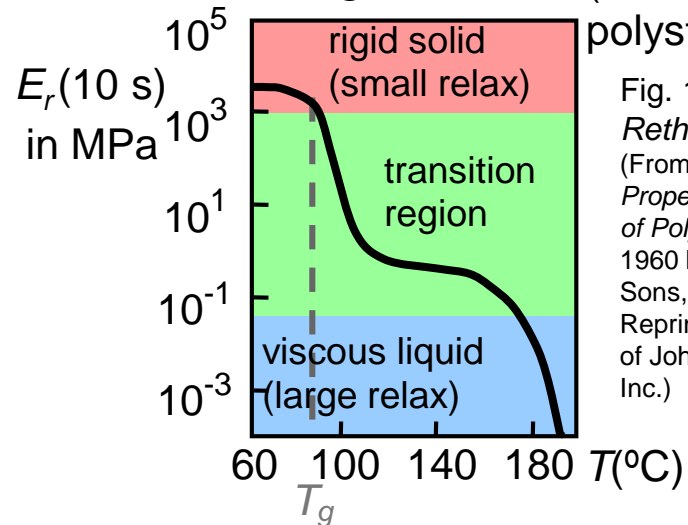
Fig. 15.7, *Callister & Rethwisch 10e.* (From A. V. Tobolsky, *Properties and Structures of Polymers.* Copyright © 1960 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

- Representative T_g values (°C):

PE (low density)   - 110
PE (high density) - 90
PVC   + 87
PS   +100
PC   +150

Selected values from Table 15.2, *Callister & Rethwisch 9e.*
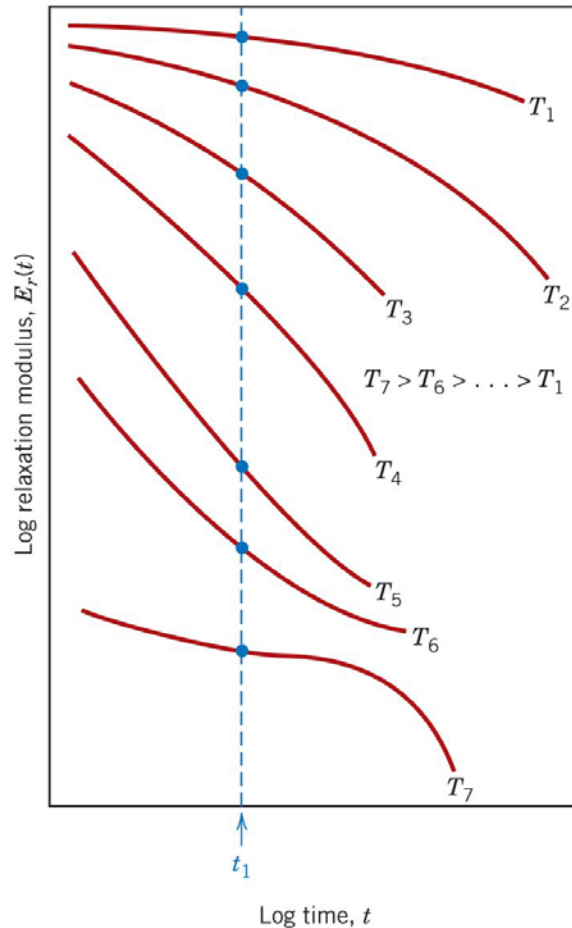
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폴리머 재료의 점탄성 거동: 시간과 온도에 따라 변화

$$E_r(t) = \frac{\sigma(t)}{\epsilon_0}$$

$E_r(t)$ 이완계수 = 시간의존성 탄성계수 ---- t, T 증가시 감소

그림 15.6 탄성 폴리머의 이완계수로 로그값과 시간 로그값의 모식적 관계. 온도를 T_1에서 T_7까지 변화시킴. 이완계수의 온도 의존성은 log $E_r(t_1)$ 온도로 나타냄.

Glassy 강하고 취약, 탄성거동, 온도에 무관

Leathery 유리천이구역, 변형이 온도/시간의존적 외력을 제거하여도 완전회복되지않음 점탄성 거동

탄성 및 점성 성분, E작아 쉽게 변형

Rubbery

Rubbery flow

Viscous flow (liquid)

Viscosity (전단력에 대한 재료의 유동 저항)

t = 10 sec
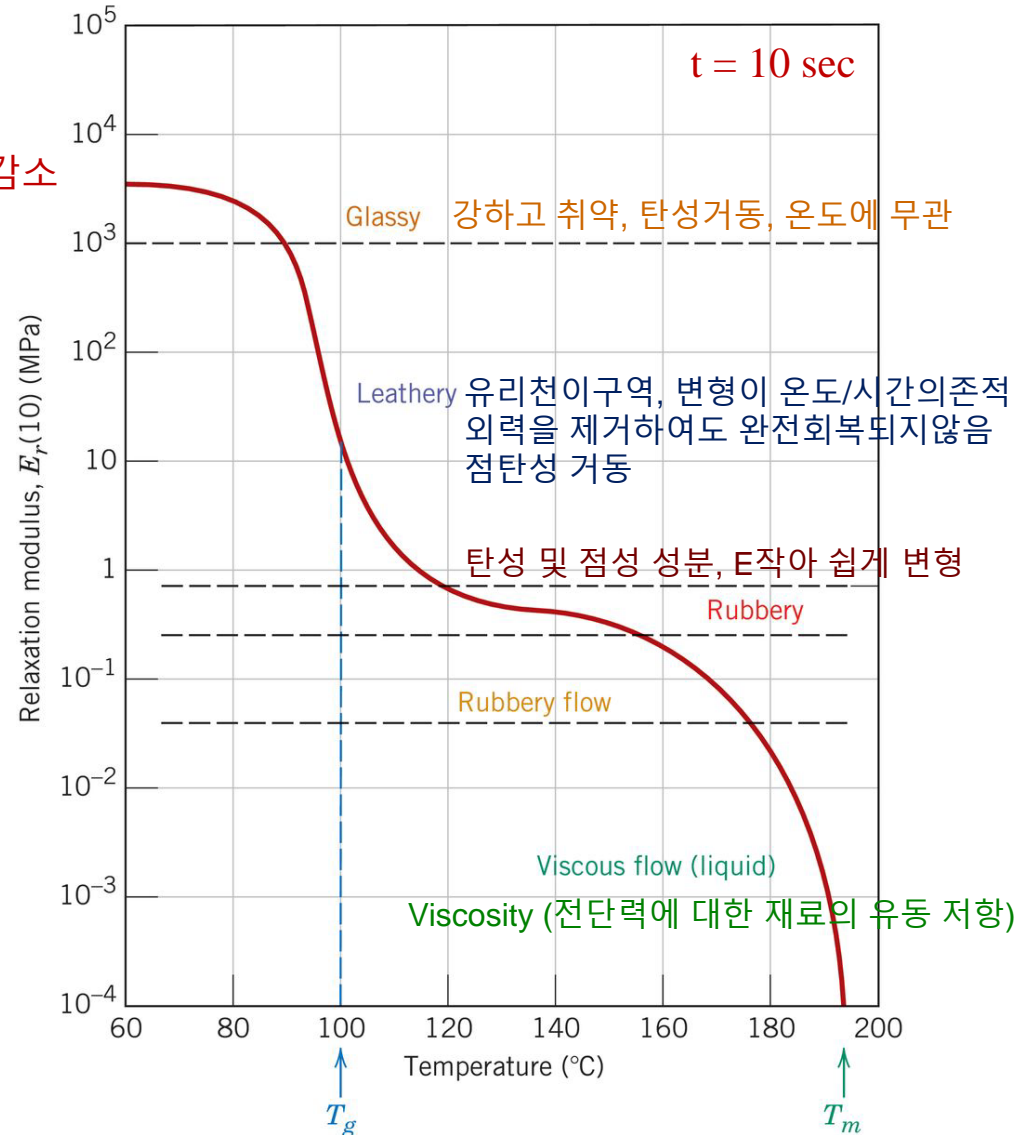
그림 15.6 탄성 폴리머의 이완계수로 로그값과 시간 로그값의 모식적 관계. 온도를 T_1에서 T_7까지 변화시킴. 이완계수의 온도 의존성은 log $E_r(t_1)$ 온도로 나타냄.

폴리머 재료의 점탄성 거동: 시간과 온도에 따라 변화
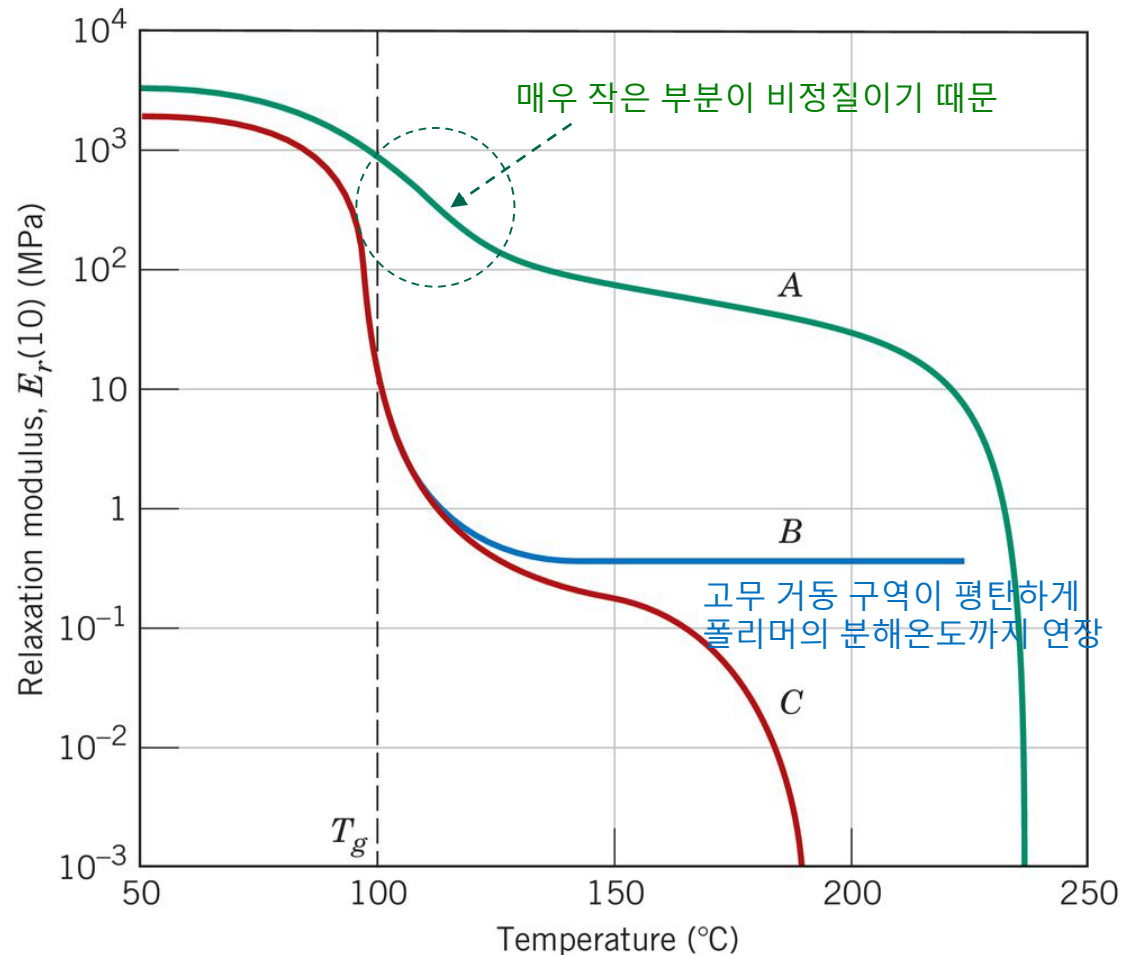
그림 15.8 결정질 이소택틱 (A곡선), 약하게 가교 결합된 어택틱 (B 곡선),
비정질 (C 곡선) 폴리스티렌의 이완 계수 로그값과 온도 관계

3) 점탄성 크리프 (Viscoelastic creep)

Sample deformation at a constant stress (σ) vs. time

$$E_c(t) = \frac{\sigma_0}{\epsilon(t)}$$
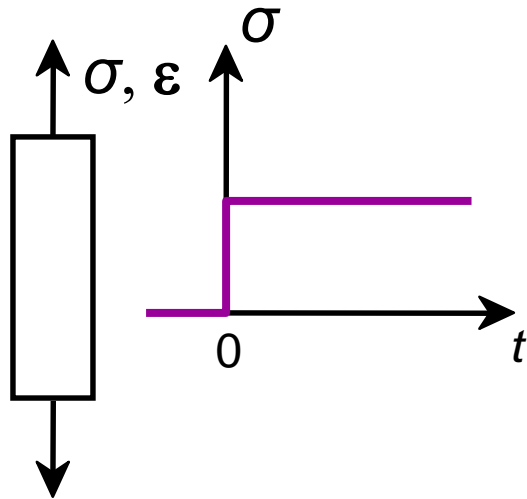
Primary Creep: slope (creep rate) decreases with time.

Secondary Creep: steady-state i.e., constant slope ($\Delta \varepsilon / \Delta t$).

Tertiary Creep: slope (creep rate) increases with time, i.e. acceleration of rate.
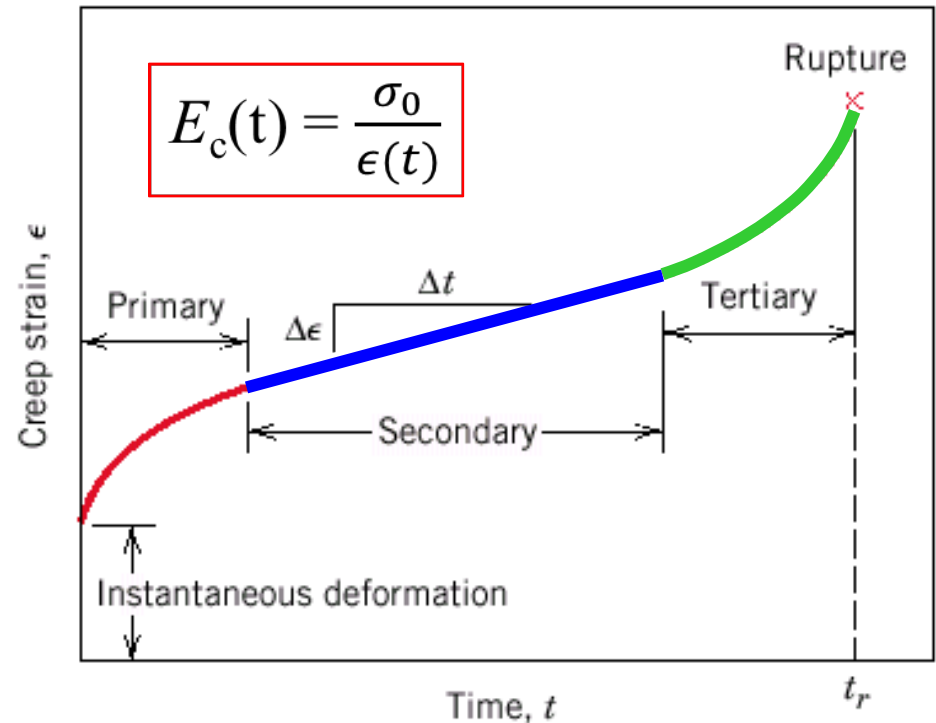
일정 응력하에서 변형률을 시간의 함수로 측정

Adapted from
Fig. 10.29, *Callister & Rethwisch 9e.*

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Creep: Temperature Dependence

- Occurs at elevated temperature, **$T > 0.4\ T_m$** (in K)
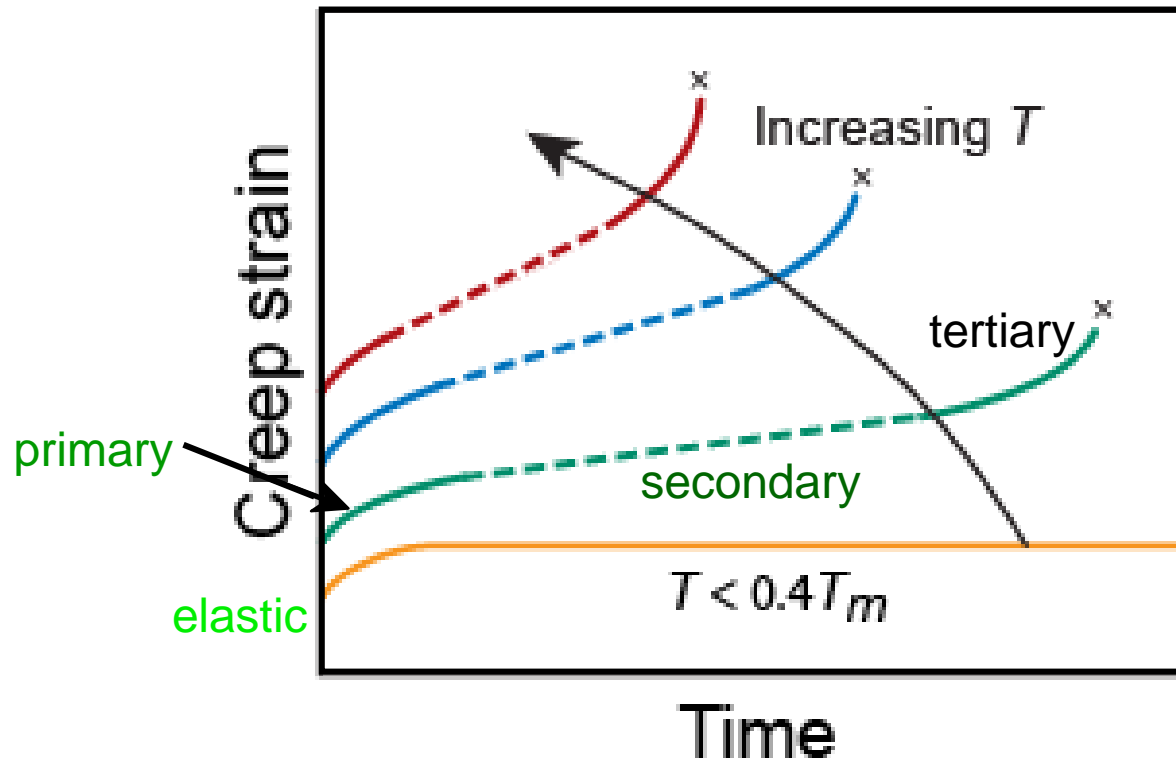
Figs. 10.30, *Callister & Rethwisch 9e.*

4) 폴리머의 파괴

열경화성 폴리머 : 취성파괴

열가소성 폴리머 : 연성 또는 취성 파괴/ 연성-취성 파괴의 전이

              취성파괴 촉진_온도감소, 변형속도 증가, 예리한

              노치의 존재, 시료의 두께 증가, 그리고 유리천이온도를

              증가시키는 폴리머의 구조 변경
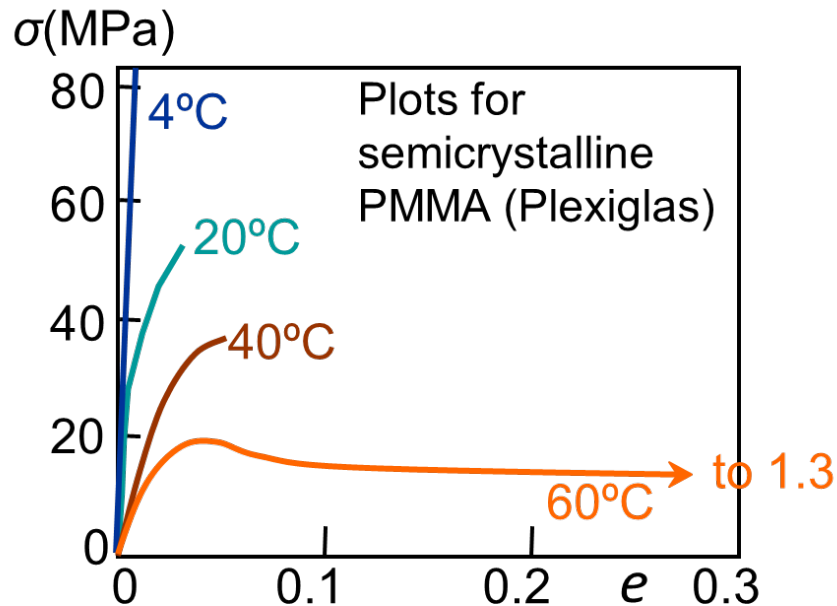
Adapted from Fig. 15.3, *Callister & Rethwisch 9e*. (Reprinted with permission from T. S. Carswell and H. K. Nason, "Effect of Environmental Conditions on the Mechanical Properties of Organic Plastics," in Symposium on Plastics. Copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428.)
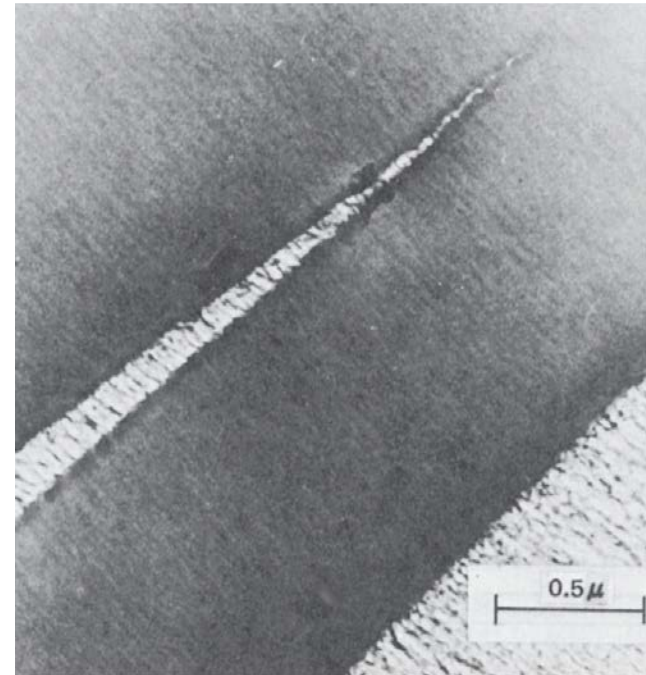
그림 15.10 폴리페닐린 산화물 내의 잔금 사진

Crazing During Fracture of Thermoplastic Polymers

Craze (잔금) formation prior to cracking

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

aligned chains

fibrillar bridges   microvoids   crack
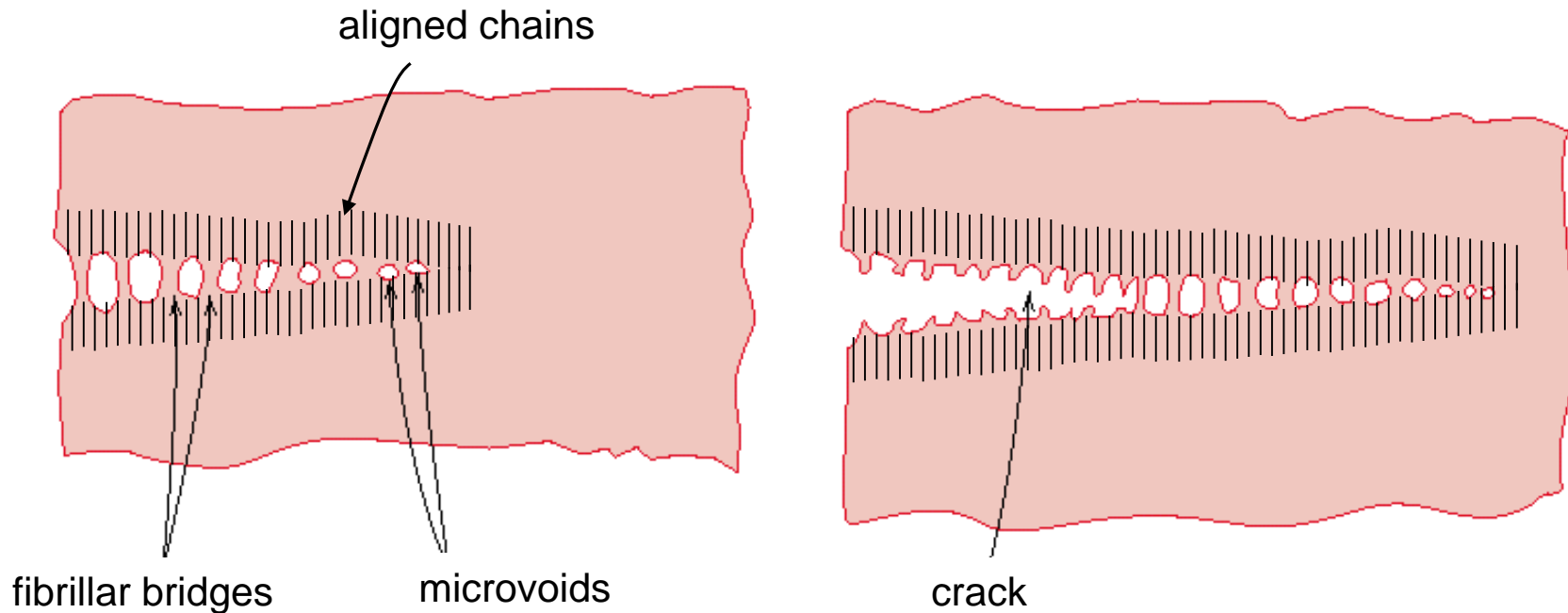
Fig. 15.9, *Callister & Rethwisch 10e.*
(From J. W. S. Hearle, *Polymers and Their Properties*, Vol. 1,
Fundamentals of Structure and Mechanics, Ellis Horwood, Ltd.,
Chichester, West Sussex, England, 1982.)

MATERIALS OF IMPORTANCE

Shrink-Wrap Polymer Films

An interesting application of heat treatment in polymers is the shrink-wrap used in packaging. Shrink-wrap is a polymer film, usually made of poly(vinyl chloride), polyethylene, or polyolefin (a multilayer sheet with alternating layers of polyethylene and polypropylene). It is initially plastically deformed (cold drawn) by about 20–300% to provide a prestretched (aligned) film. The film is wrapped around an object to be packaged and sealed at the edges. When heated to about 100 to 150°C, this prestretched material shrinks to recover 80–90% of its initial deformation, which gives a tightly stretched, wrinkle-free, transparent polymer film. For example, CDs and many other objects that you purchase are packaged in shrink-wrap.
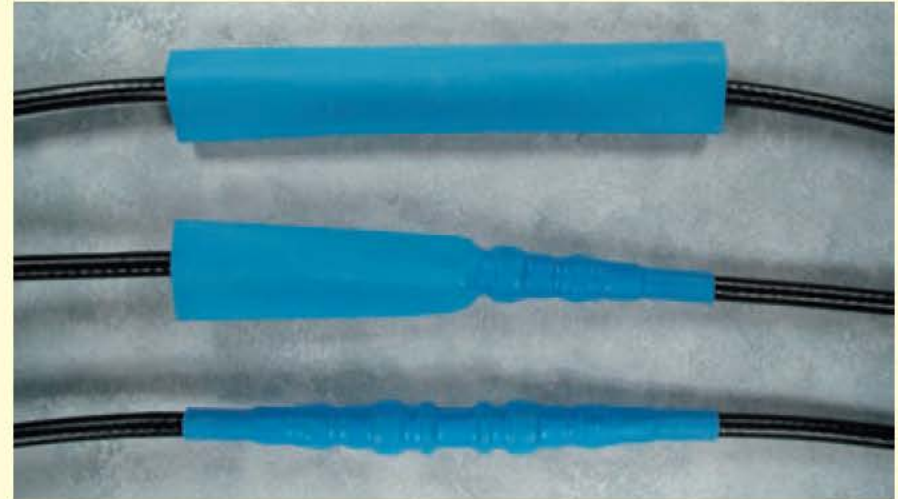
Top: An electrical connection positioned within a section of as-received polymer shrink-tubing.

Center and Bottom: Application of heat to the tubing caused its diameter to shrink. In this constricted form, the polymer tubing stabilizes the connection and provides electrical insulation. (Photograph courtesy of Insulation Products Corporation.)

II. Melting & Glass Transition Temps.

What factors affect T_m and T_g?

- Both T_m and T_g increase with increasing chain stiffness

- Chain stiffness increased by presence of
    1. Bulky side groups
    2. Polar groups or side groups
    3. Chain double bonds and aromatic chain groups

- Regularity of repeat unit arrangements – affects T_m only
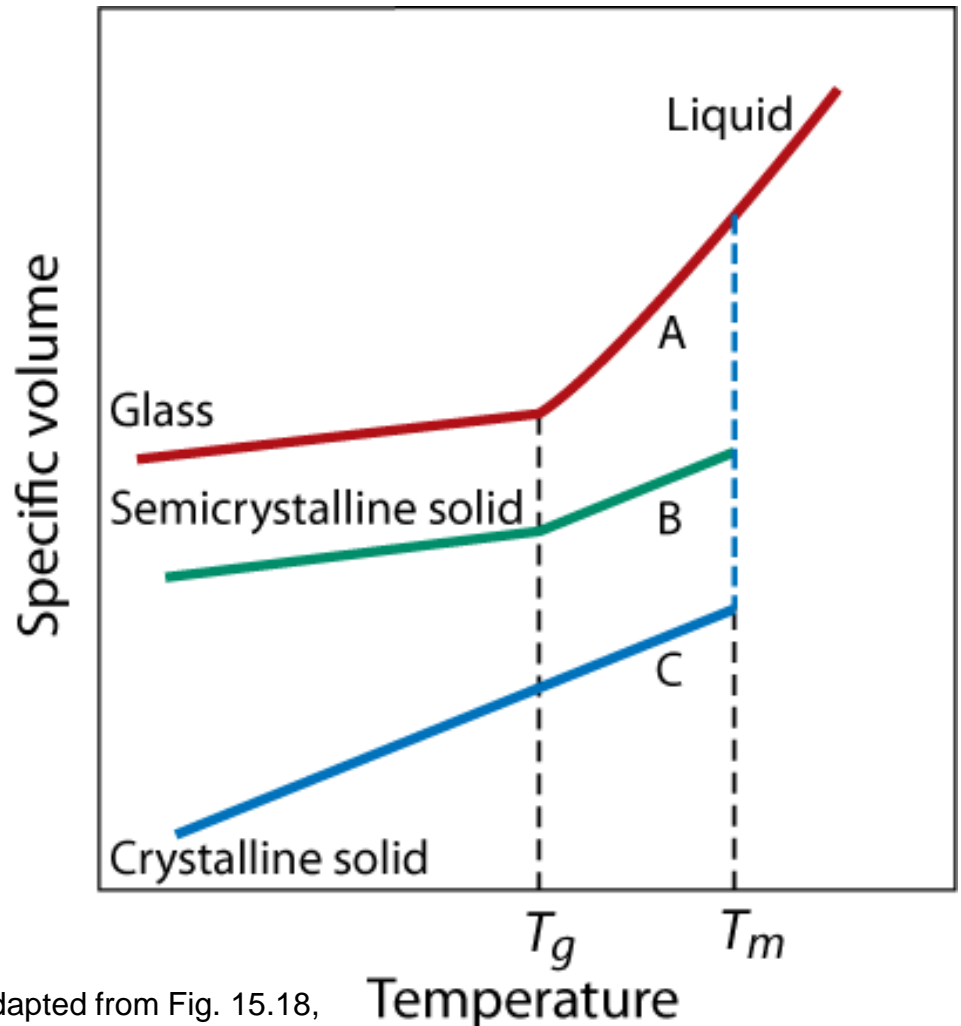
Adapted from Fig. 15.18, *Callister & Rethwisch 10e.*

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)

III. Thermoplastics vs. Thermosets

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

- Thermosets:
  -- significant crosslinking
     (10 to 50% of repeat units)
  -- hard and brittle
  -- do NOT soften w/heating
  -- vulcanized rubber, epoxies,
     polyester resin, phenolic resin

분자량이 폴리머의 용융 온도 및
유리천이온도에 미치는 영향

T

mobile
liquid

viscous
liquid

rubber

T_m

tough
plastic

T_g

crystalline
solid

partially
crystalline
solid

Molecular weight
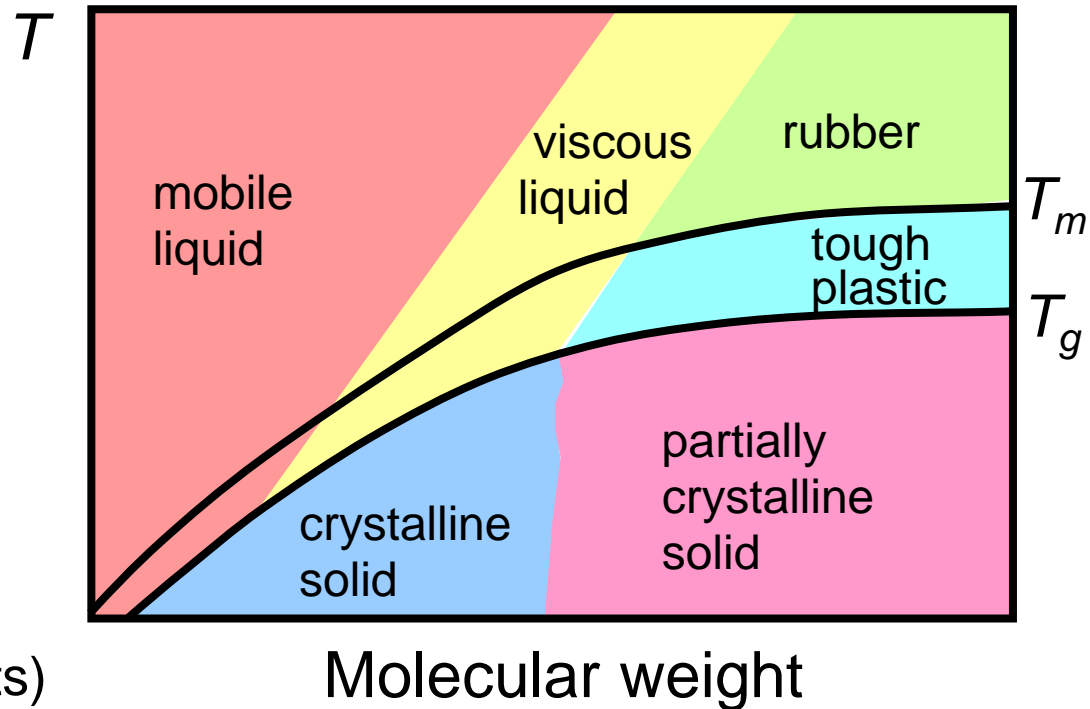
Adapted from Fig. 15.19, *Callister & Rethwisch 10e.*
(From F. W. Billmeyer, Jr., Textbook of Polymer Science, 3rd edition.
Copyright © 1984 by John Wiley & Sons, New York. Reprinted by
permission of John Wiley & Sons, Inc.)

IV. Polymer Types – Fibers

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

Polymer Types – Miscellaneous

- Coatings – thin polymer films applied to surfaces – i.e., paints, varnishes
    - protects from corrosion/degradation
    - 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

V. Polymer Formation

- There are two types of polymerization
  - Addition (or chain) polymerization
  - Condensation (step) polymerization

Addition (Chain) Polymerization

– **Initiation**
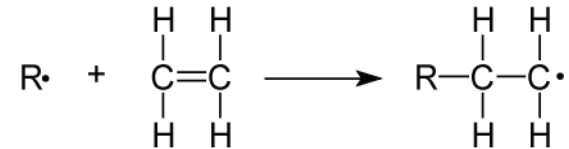
– **Propagation**
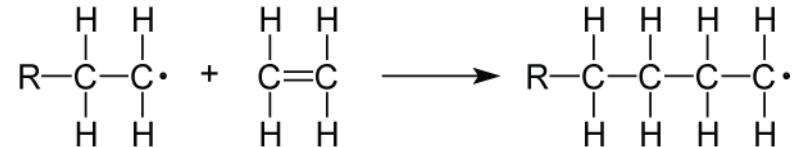
– **Termination**
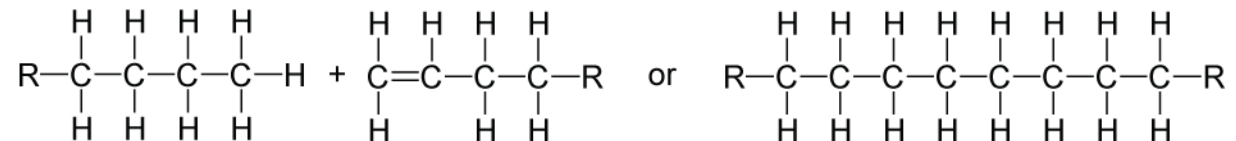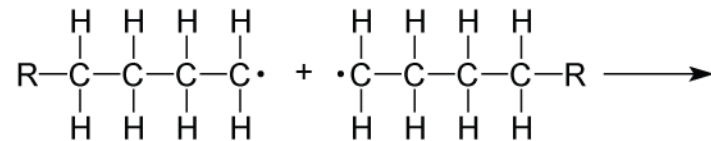
Disproportionation

Combination

Condensation (Step) Polymerization

hexamethylene diamine + adipic acid → nylon-6,6 + H_2O
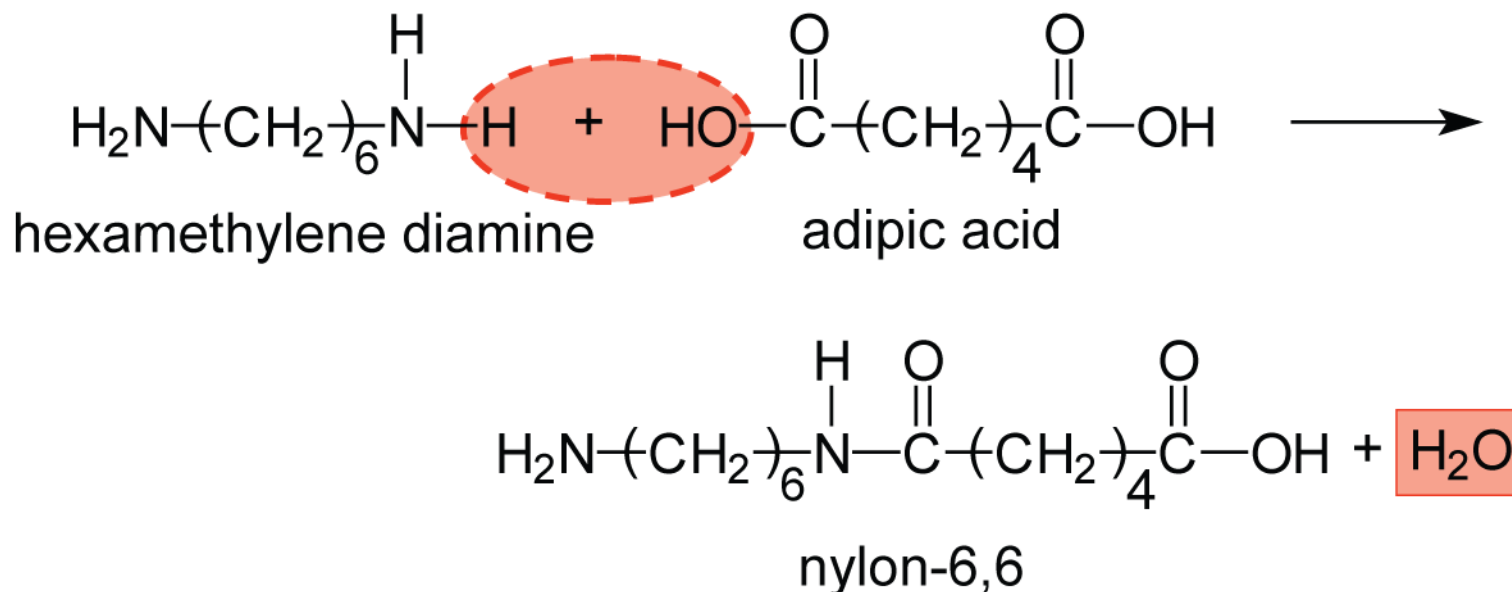
Polymer Additives

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

VI. 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 <u>forms a molecular network</u> (chemical reaction)
  - degrades (doesn't melt) when heated
  - a prepolymer molded into desired shape, then chemical reaction occurs
  - ex: urethane, epoxy

Processing Plastics – I. Forming technique for plastics
a. Compression Molding

Thermoplastics and thermosets
- polymer and additives placed in mold cavity
- mold heated and pressure applied
- fluid polymer assumes shape of mold
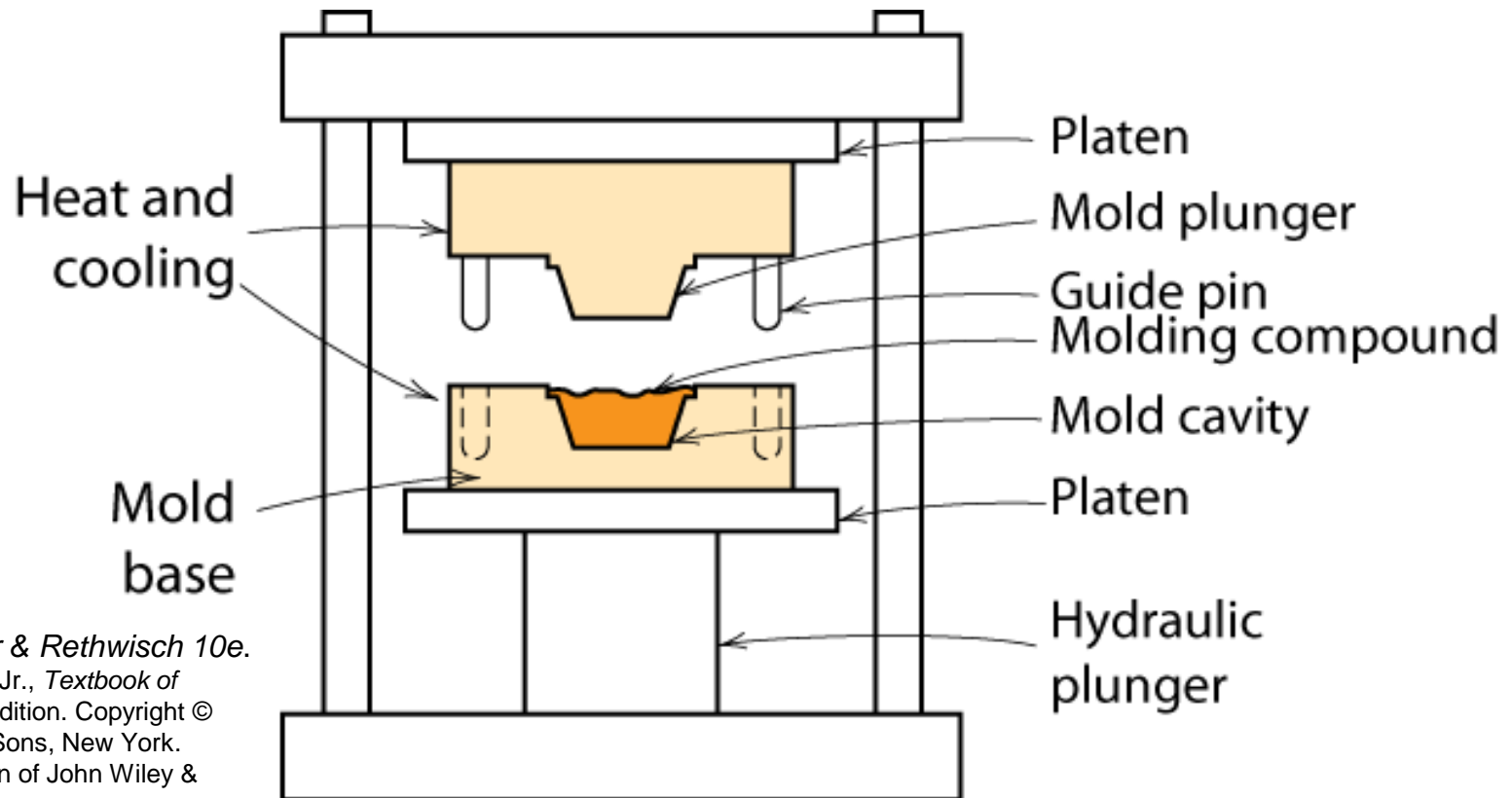
Fig. 15.23, *Callister & Rethwisch 10e*. (From F. W. Billmeyer, Jr., *Textbook of Polymer Science*, 3rd edition. Copyright © 1984 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Processing Plastics – I. Forming technique for plastics
b. Injection Molding

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

Fig. 15.24, *Callister & Rethwisch 10e.* (From F. W. Billmeyer, Jr., *Textbook of Polymer Science,* 3rd edition. Copyright © 1984 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)
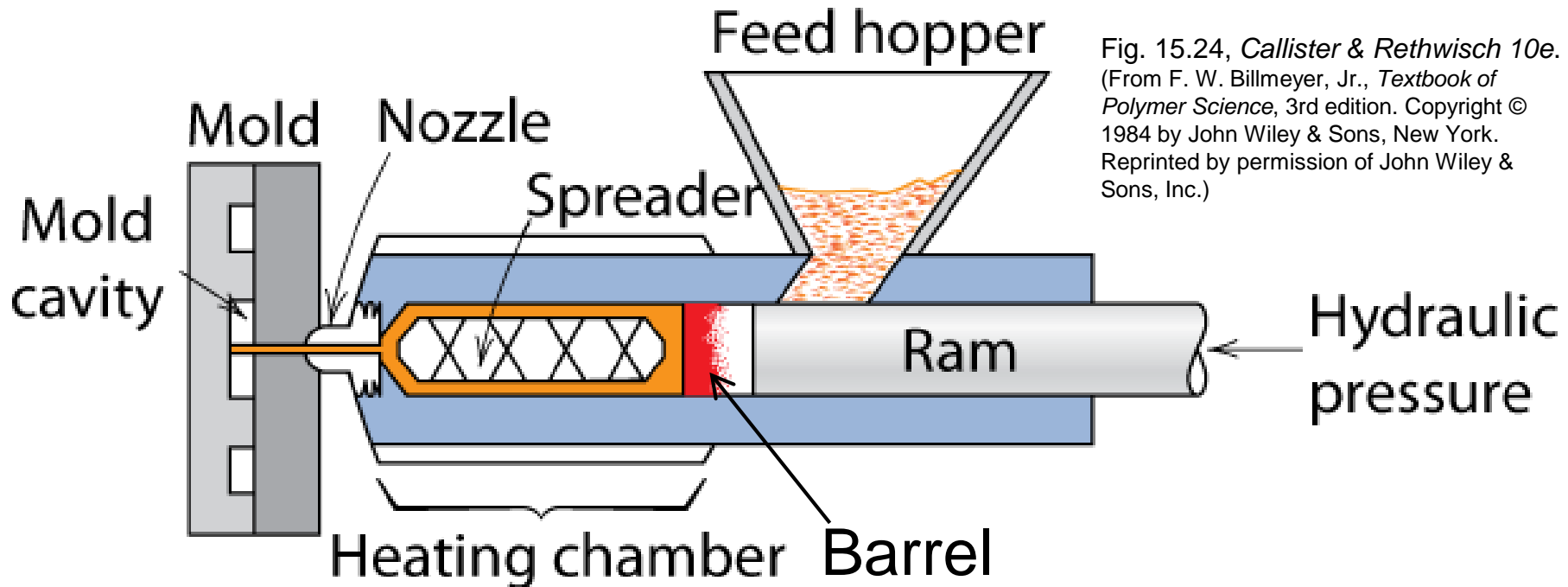
c. Extrusion

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)

Feed hopper
Plastic pellets
Heaters
Shaping die
Tubing and pipes
Turning screw
Barrel
Molten plastic
Extrudate
Sheet and film
Structural parts
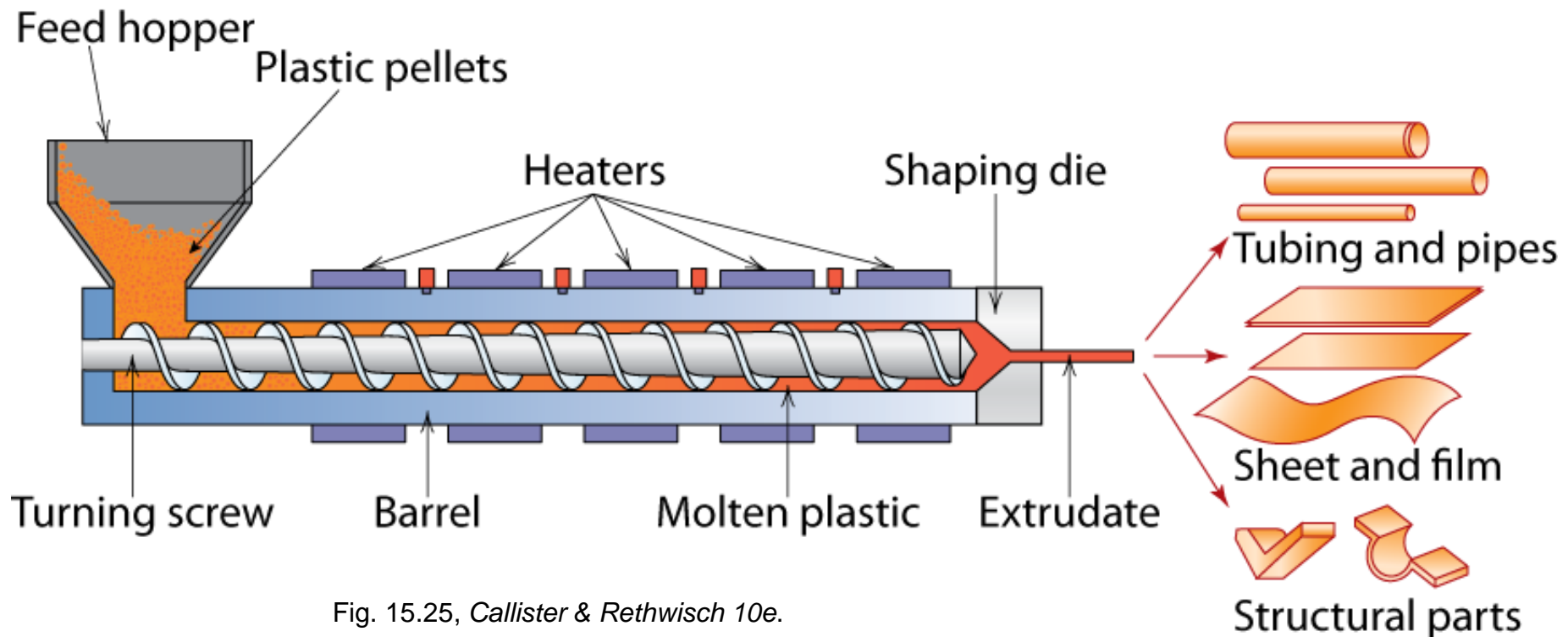
Fig. 15.25, *Callister & Rethwisch 10e.*

d. Blow molding, e. casting…

46

Processing Plastics – II. Fabrication of fibers and films
a. Blown-Film Extrusion
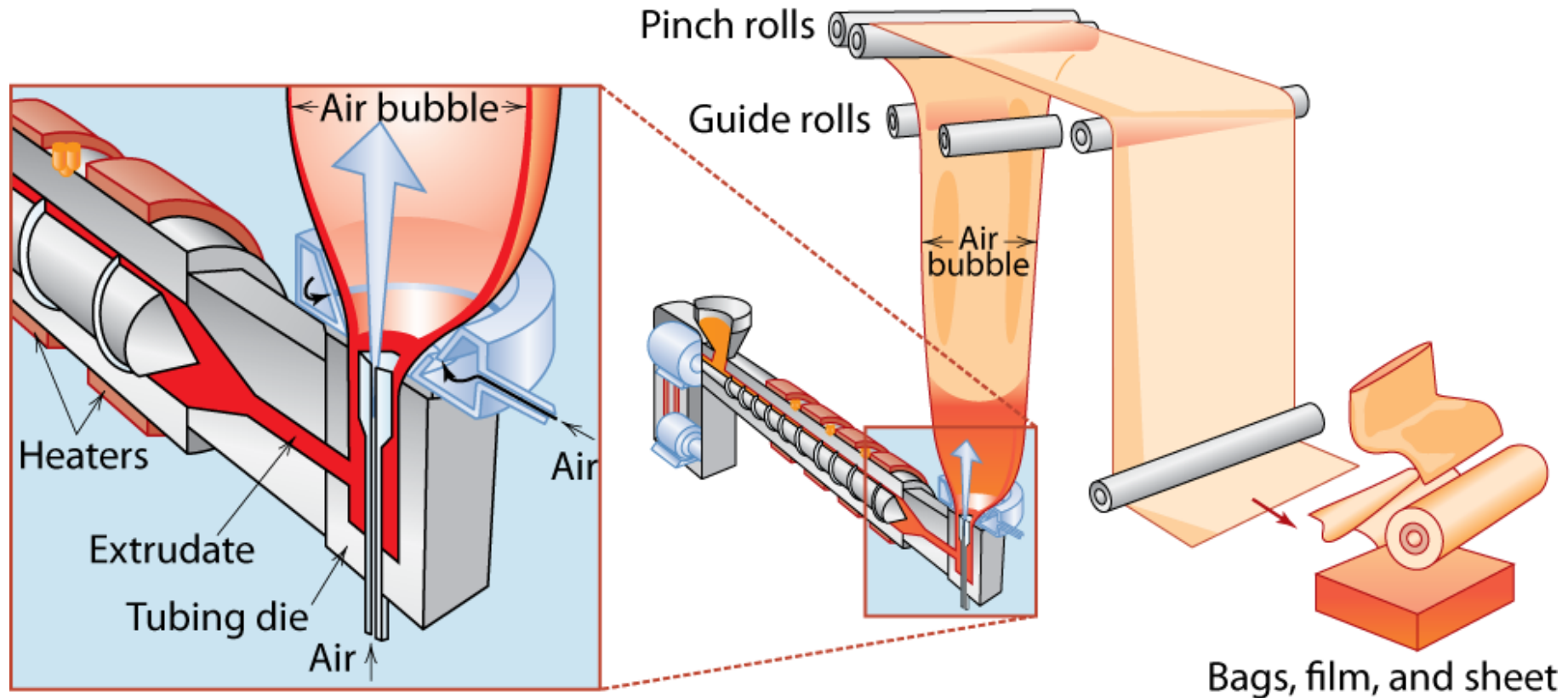
Fig. 17.39, *Callister & Rethwisch 9e*.
(Reprinted with permission from *Encyclopædia Britannica*, © 1997 by Encyclopædia Britannica, Inc.)

Fig. 15.26, *Callister & Rethwisch 10e*.

b. Spinning for fiber…

Processing Plastics – III. 3D printing of polymer

(고체 기반형)
a. Fused Deposition Modeling
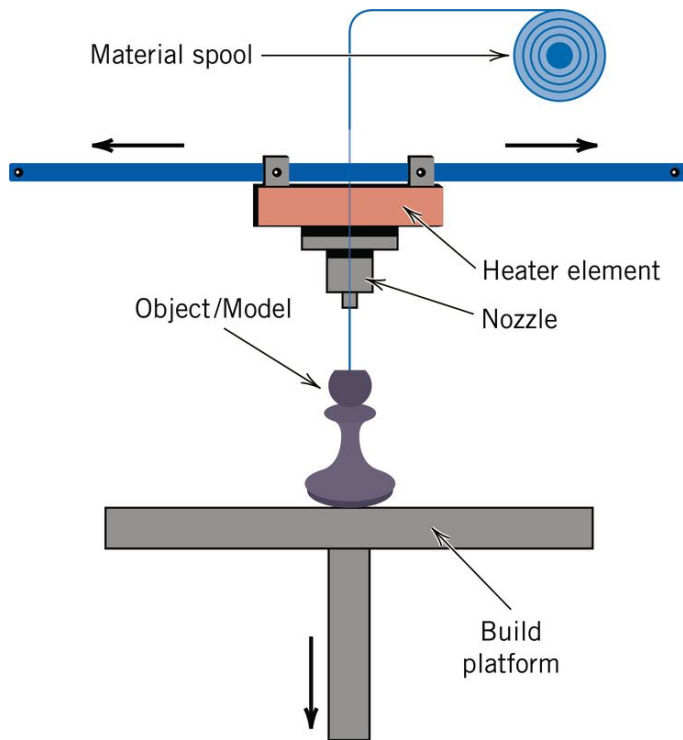
Fig. 15.27 Schematic illustration showing FDM
The generic term is fused filament fabrication (or FFF);
sometimes this technique is also called PJP

⑴ 정의 : 고체 수지재료에 열을 가해 녹인 후 노즐을 통해 사출시키고 적층하여 조형

⑵ 재료 : 와이어 또는 필라멘트형. 열가소성 플라스틱 (thermoplastic), eutetic metal

⑶ 장점 : 제작비용 저렴. 고속. 단순. 가장 많이 사용

⑷ 단점 : 전단응력에 약함. 재료 선택에 제한이 있음

Processing Plastics – III. 3D printing of polymer

DED(direct energy deposition)

ELECTRON BEAM DIRECT MANUFACTURING
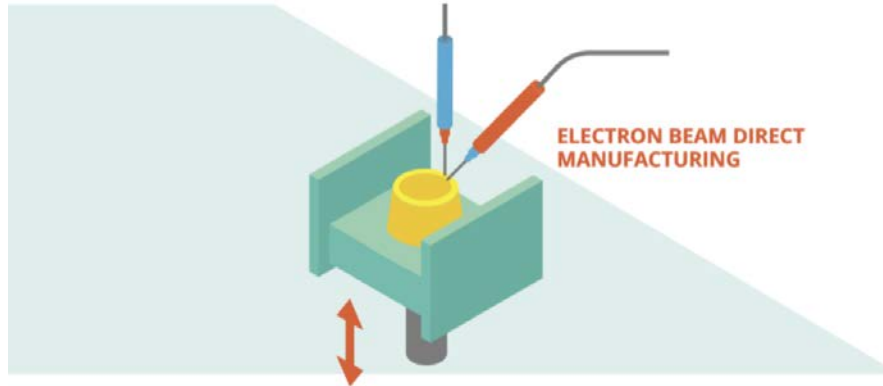
⑴ 정의 : 전자총이 층층의 물체를 만들기 위해 철사를 녹임
⑵ 재료 : 파우더 또는 와이어 형태. 세라믹, 폴리머, 금속
⑶ 장점 : 빠름. 저렴. 기계적 특성 우수
⑷ 단점 : 표면처리가 좋지 않음. 정확도 낮음

LOM (laminated object manufacturing)

SHEET LAMINATION
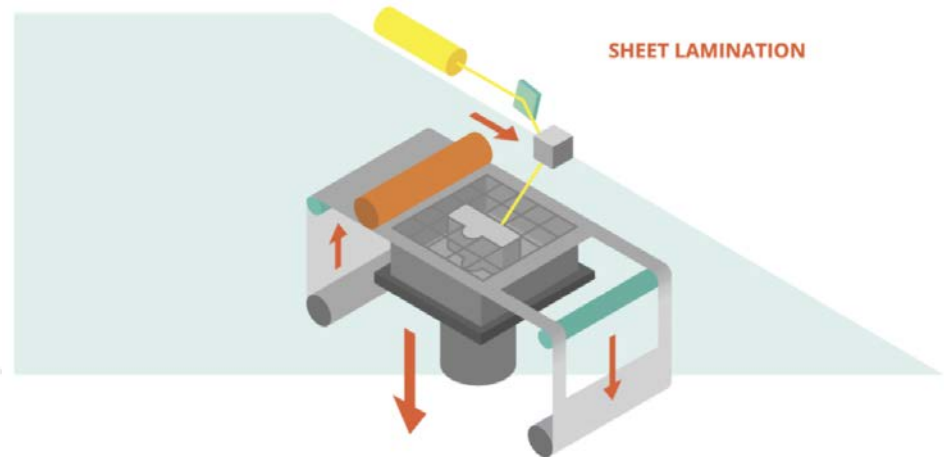
⑴ 정의 : 종이나 플라스틱 시트를 접착하면서 칼을 사용해 절단 후 적층하여 조형
⑵ 재료 : 플라스틱, 세라믹, 금속, 반도체, 종이 등. 시트, 필름, 테이프, 호일 형태
⑶ 장점 : 재료 물질이 가장 저렴. 단순함
⑷ 단점 : 표면처리가 좋지 않음. 복잡한 형상을 만들지 못함

PBF (powder bed fusion)

3D PRINTING

SELECTIVE LASER SINTERING
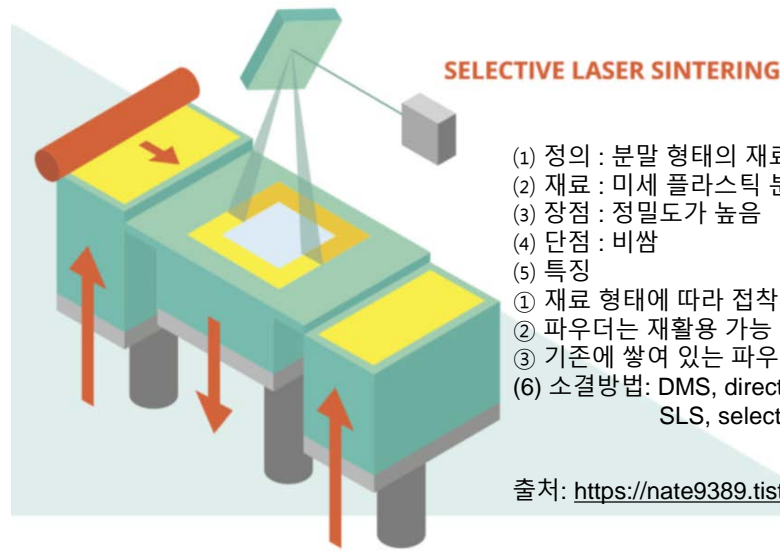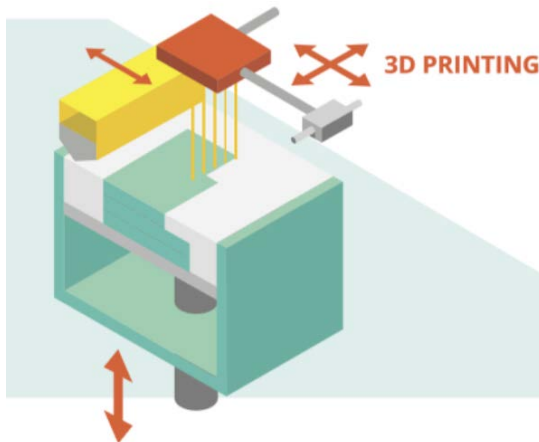
⑴ 정의 : 분말 형태의 재료를 가열해서 결합
⑵ 재료 : 미세 플라스틱 분말, 모래, 금속 성분의 가루 등
⑶ 장점 : 정밀도가 높음
⑷ 단점 : 비쌈
⑸ 특징
① 재료 형태에 따라 접착제를 사용하거나 레이저를 사용하는 프린터가 있음
② 파우더는 재활용 가능
③ 기존에 쌓여 있는 파우더 자체가 서포트(support) 역할을 함
(6) 소결방법: DMS, direct metal laser sintering ; EBM, electron beam melting
 SLS, selective laser sintering …

출처: https://nate9389.tistory.com/65 [정빈이의 공부방]

(액체 기반형)

b. Stereolithography (SLA) and Digital Light Processing (DLP)

DLP

(Continuous Liquid Interface Production)

SLA
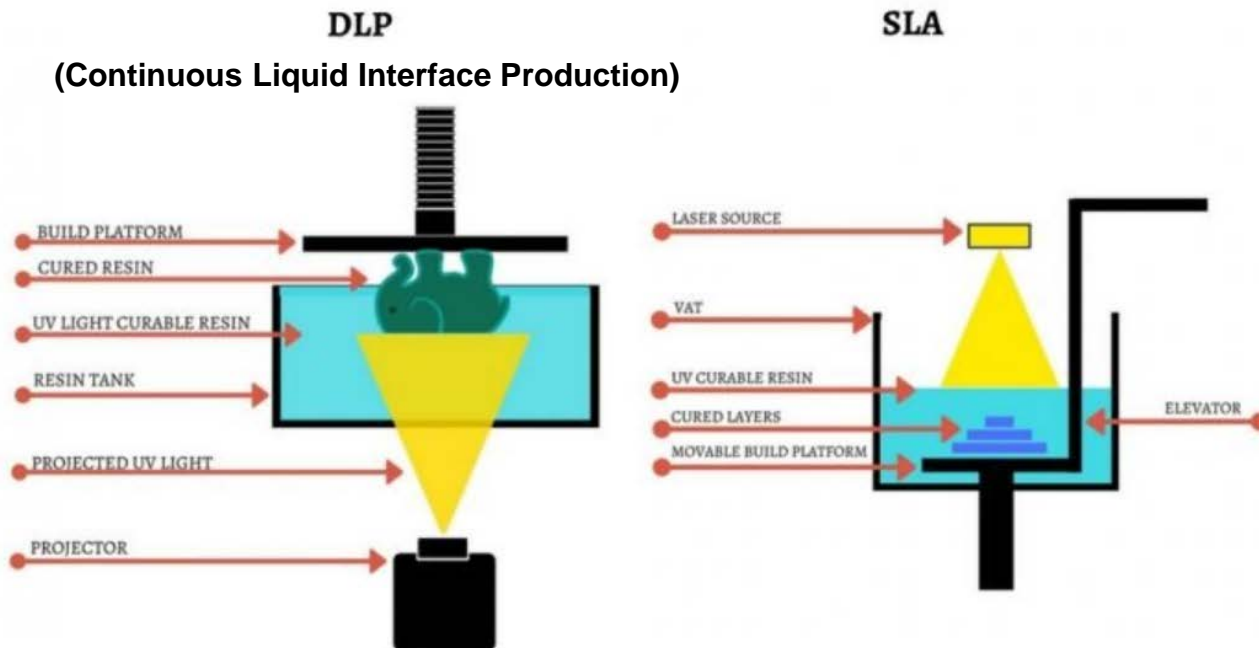
The DLP and SLA printing processes. [Image credit: *Manufactur3D*]**: 광경화 수지 조형**

⑴ 정의 : 레이저나 강한 자외선을 이용하여 재료를 순간적으로 경화시켜 형상 제작
⑵ 재료 : 액체 상태의 photopolymer
⑶ 장점 : 얇고 미세한 형상 제작. 고해상도. 투명한 물체 제작 가능
⑷ 단점 : 물질 제한이 매우 큼. 느림. 비쌈

DLP 3D printers work in almost an identical way to SLA systems. However, the key difference is that DLP uses a digital light projector screen to flash an image of each layer at once. Since an entire layer of resin material is exposed to the light source at once, DLP is typically a faster process than SLA.

Processing Plastics – III. 3D printing of polymer

(융합형)

## c. Polyjet Printing (PJP) (photopolymer jetting or inkjet printing)

SLA와 융합하여
UV에 의해
점성 액체가
경화되는 과정

POLYJET PROCESS
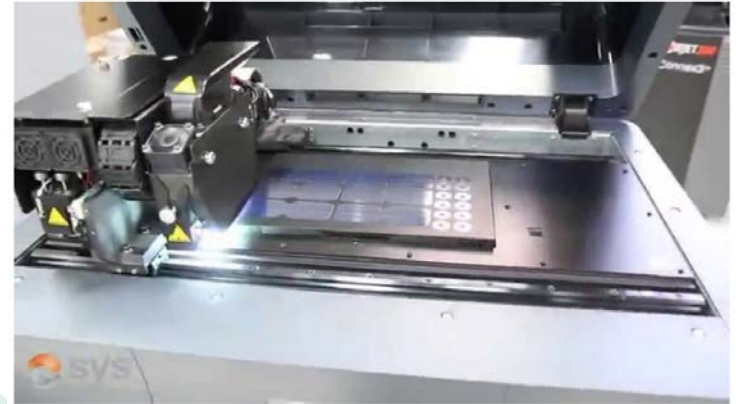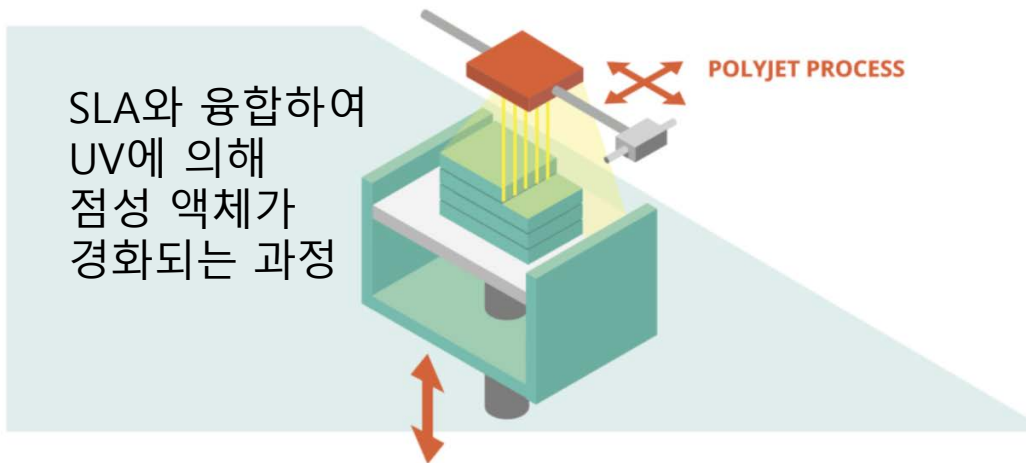
⑴ 정의 : 재료를 헤드에서 녹여 노즐을 통해 분사

⑵ 재료 : 왁스 성질을 가진 펠릿형 (액체에서 고농도로 분산된 분말)

⑶ 장점 : 빠름. 거대한 구조물을 프린트할 수 있음

⑷ 단점 : 해상도 낮음. 층 간의 결합이 잘 안 됨

VII. Advanced Polymers

a. Ultrahigh Molecular Weight Polyethylene (UHMWPE)

- Molecular weight ca. 4×10^6 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)

UHMWPE
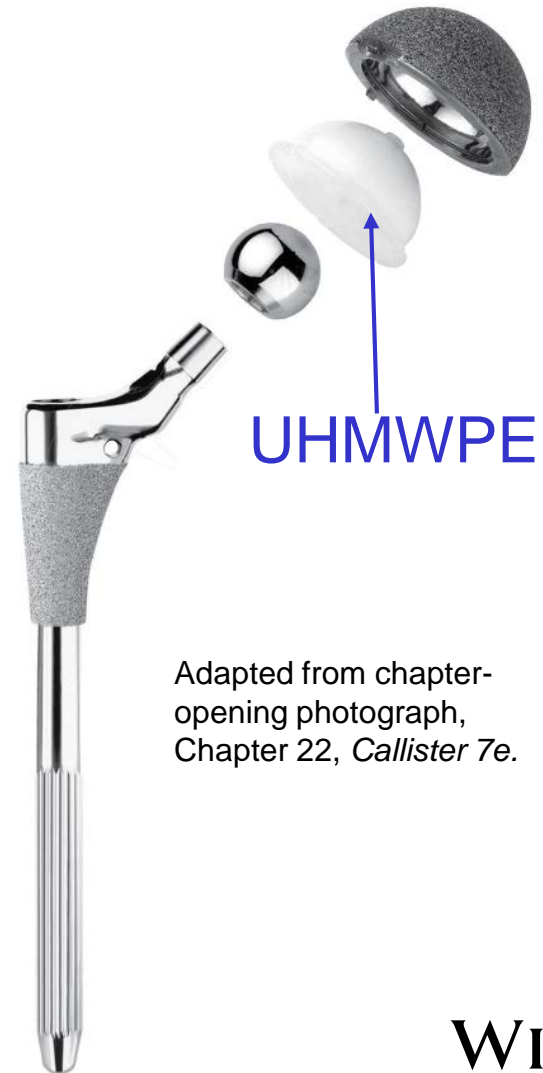
Adapted from chapter-opening photograph, Chapter 22, *Callister 7e.*

WILEY

VII. Advanced Polymers

b. Thermoplastic Elastomers (열가소성 탄성체)

Styrene-butadiene block copolymer

styrene

butadiene

hard component domain

soft component domain
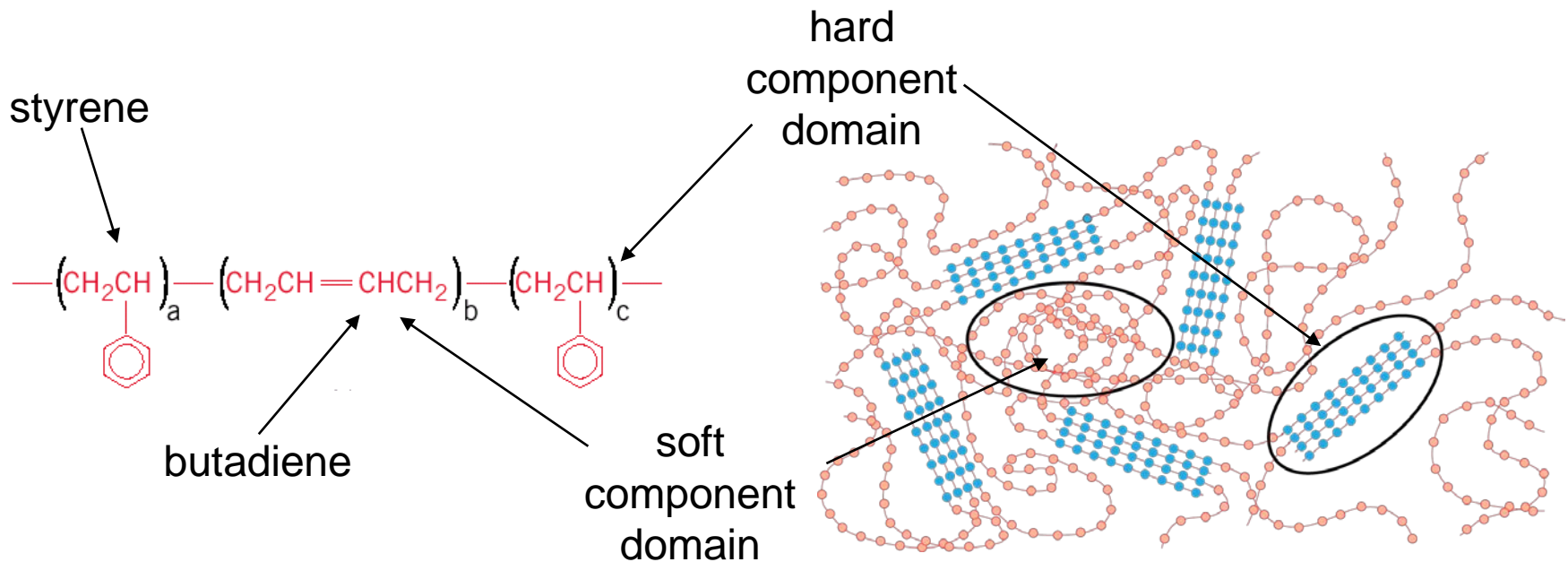
Fig. 15.21(a), *Callister & Rethwisch 10e.*

Fig. 15.22, *Callister & Rethwisch 10e.*

합성고무, 단단하고, 신발, 타이어, 견고성이 중요한 곳에 많이 사용
대부분의 고무 유형은 서로 연결되어 가공이 어렵지만,
열가소성 탄성체는 실온에서는 탄성고무처럼 작용하지만
가열되면 플라스틱처럼 처리 및 성형 될 수 있는 물질

Summary I

- Limitations of polymers:
  -- E, σ_y, K_c, $T_{application}$ are generally small.
  -- Deformation is often time and temperature dependent.

- Thermoplastics (PE, PS, PP, PC):
  -- Smaller E, σ_y, $T_{application}$
  -- Larger K_c
  -- Easier to form and recycle

- Elastomers (rubber):
  -- Large reversible strains!

- Thermosets (epoxies, polyesters):
  -- Larger E, σ_y, $T_{application}$
  -- Smaller K_c

Table 15.3 *Callister & Rethwisch 9e*:

Good overview
of applications
and trade names
of polymers.

Summary II

- Polymer melting and glass transition temperatures

- Polymer Processing
  - -- compression and injection molding, extrusion,
    blow molding, casting
  - -- spinning, blown film extrusion
  - -- 3D printing

- Polymer applications
  - -- elastomers   -- fibers
  - -- coatings   -- adhesives
  - -- films   -- foams
  - -- advanced polymeric materials

2020 Fall

Introduction to Materials Science and Engineering

11. 26. 2020

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Chapter 15:
Characteristics, Applications, and Processing of Polymers

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?

Summary

- Limitations of polymers:
  -- E, σ_y, K_c, $T_{application}$ are generally small.
  -- Deformation is often time and temperature dependent.

- Thermoplastics (PE, PS, PP, PC):
  -- Smaller E, σ_y, $T_{application}$
  -- Larger K_c
  -- Easier to form and recycle

  Table 15.3 *Callister & Rethwisch 9e*:

  Good overview
  of applications
  and trade names
  of polymers.

- Elastomers (rubber):
  -- Large reversible strains!

- Thermosets (epoxies, polyesters):
  -- Larger E, σ_y, $T_{application}$
  -- Smaller K_c

- Polymer Processing
  -- compression and injection molding, extrusion, blow molding, casting
  -- spinning, blown film extrusion   -- 3D printing

- Polymer melting and glass transition temperatures

Adapted from Fig. 15.1, *Callister & Rethwisch 9e.*

- Fracture strengths of polymers ~ 10% of those for metals
- Deformation strains for polymers > 1000% (100 times for metals)
  - for most metals, deformation strains < 10%

4

폴리머 재료의 점탄성 거동: 시간과 온도에 따라 변화

$$E_r(t) = \frac{\sigma(t)}{\epsilon_0}$$

$E_r(t)$ 이완계수 = 시간의존성 탄성계수 ---- t, T 증가시 감소

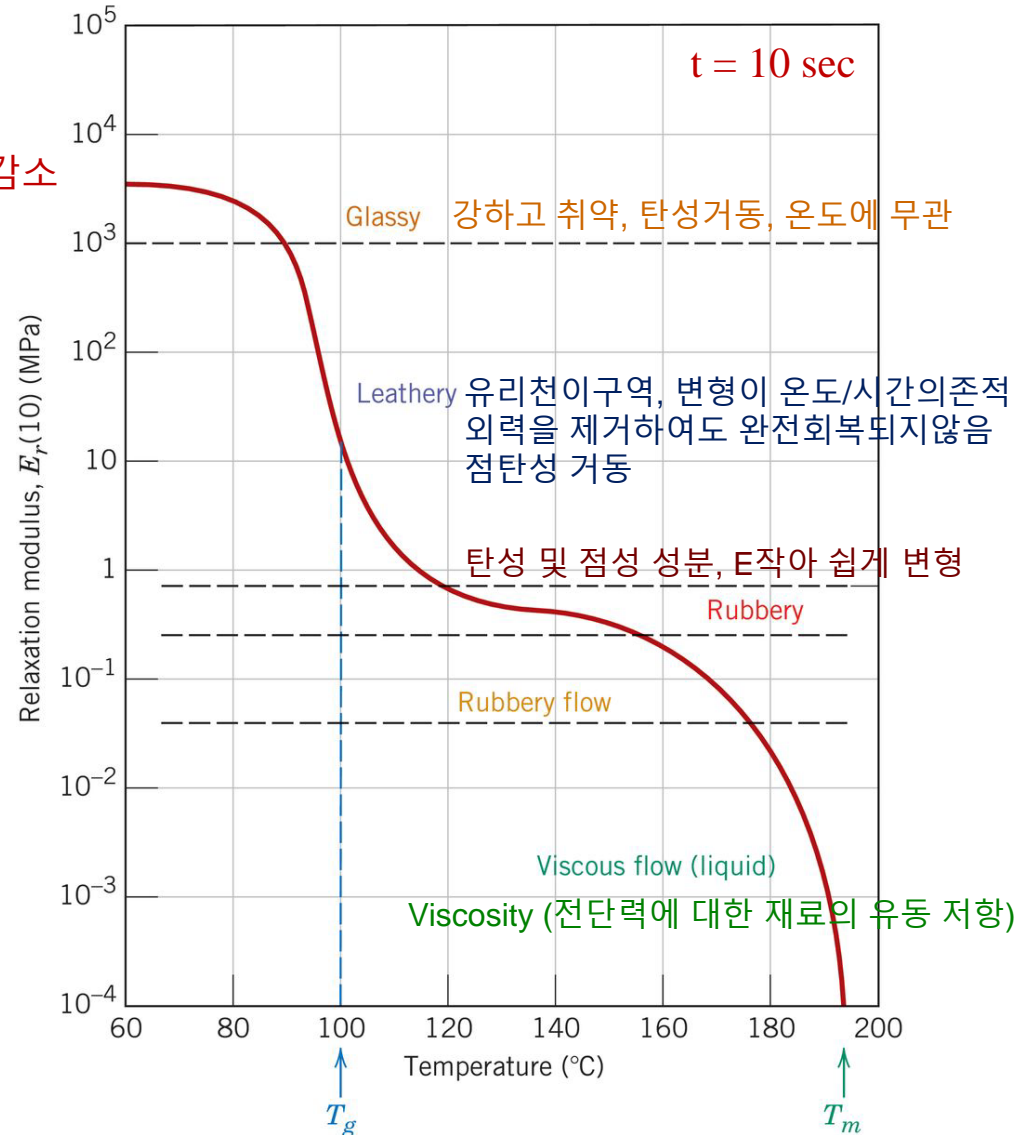그림 15.6 탄성 폴리머의 이완계수로 로그값과 시간 로그값의 모식적 관계. 온도를 T_1에서 T_7까지 변화시킴. 이완계수의 온도 의존성은 log $E_r(t_1)$ 온도로 나타냄.

t = 10 sec

Glassy 강하고 취약, 탄성거동, 온도에 무관

Leathery 유리천이구역, 변형이 온도/시간의존적 외력을 제거하여도 완전회복되지않음 점탄성 거동

탄성 및 점성 성분, E 작아 쉽게 변형
Rubbery

Rubbery flow

Viscous flow (liquid)

Viscosity (전단력에 대한 재료의 유동 저항)
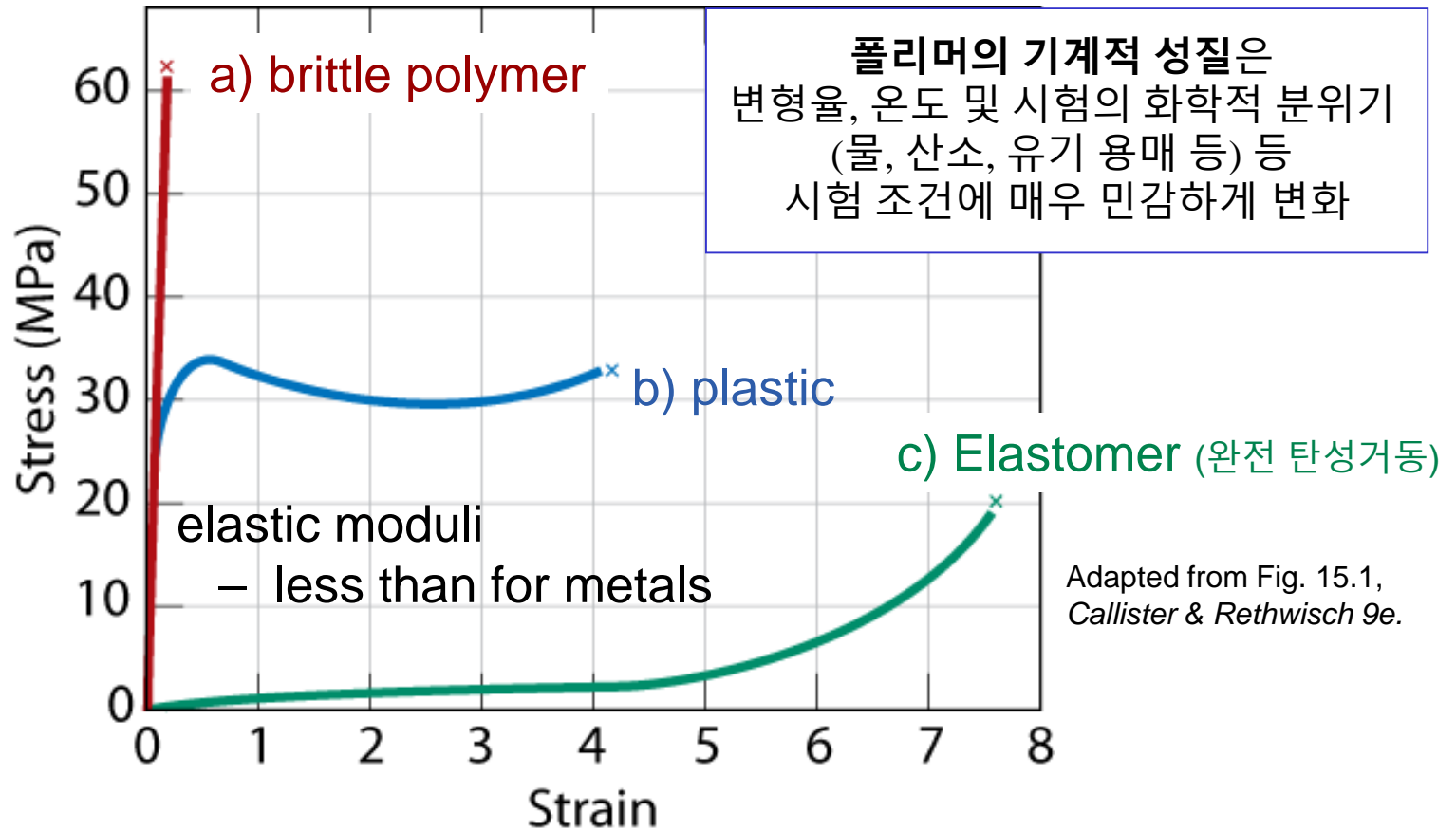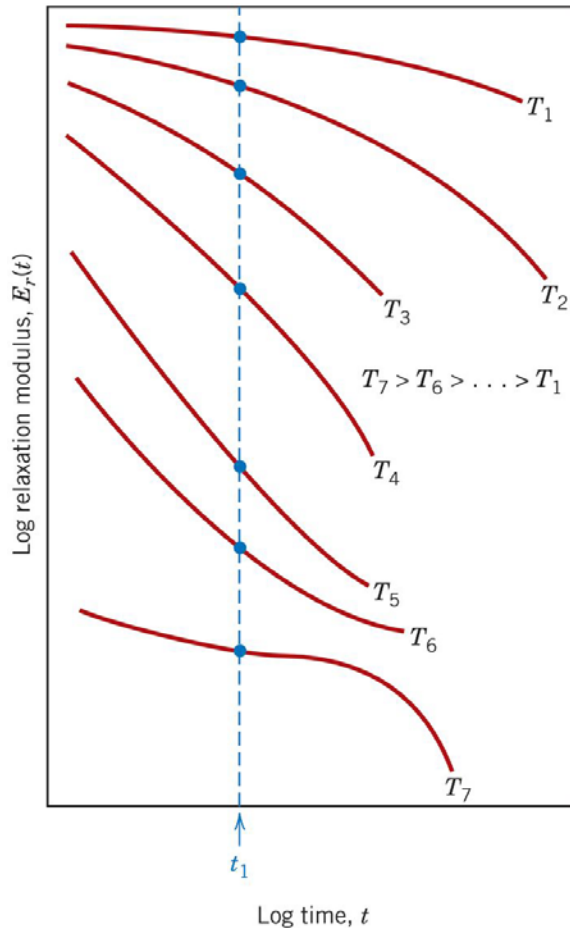
그림 15.7 탄성 폴리머의 이완계수로 로그값과 시간 로그값의 모식적 관계. 온도를 T_1에서 T_7까지 변화시킴. 이완계수의 온도 의존성은 log $E_r(t_1)$ 온도로 나타냄.

Chapter 16: Composites

ISSUES TO ADDRESS...

- What are the classes and types of composites?

- What are the advantages of using composite materials?

- How do we predict the stiffness and strength of the various types of composites?

Composite

Blending very different materials

M. F. Ashby et al. Acta Mater. (2003)
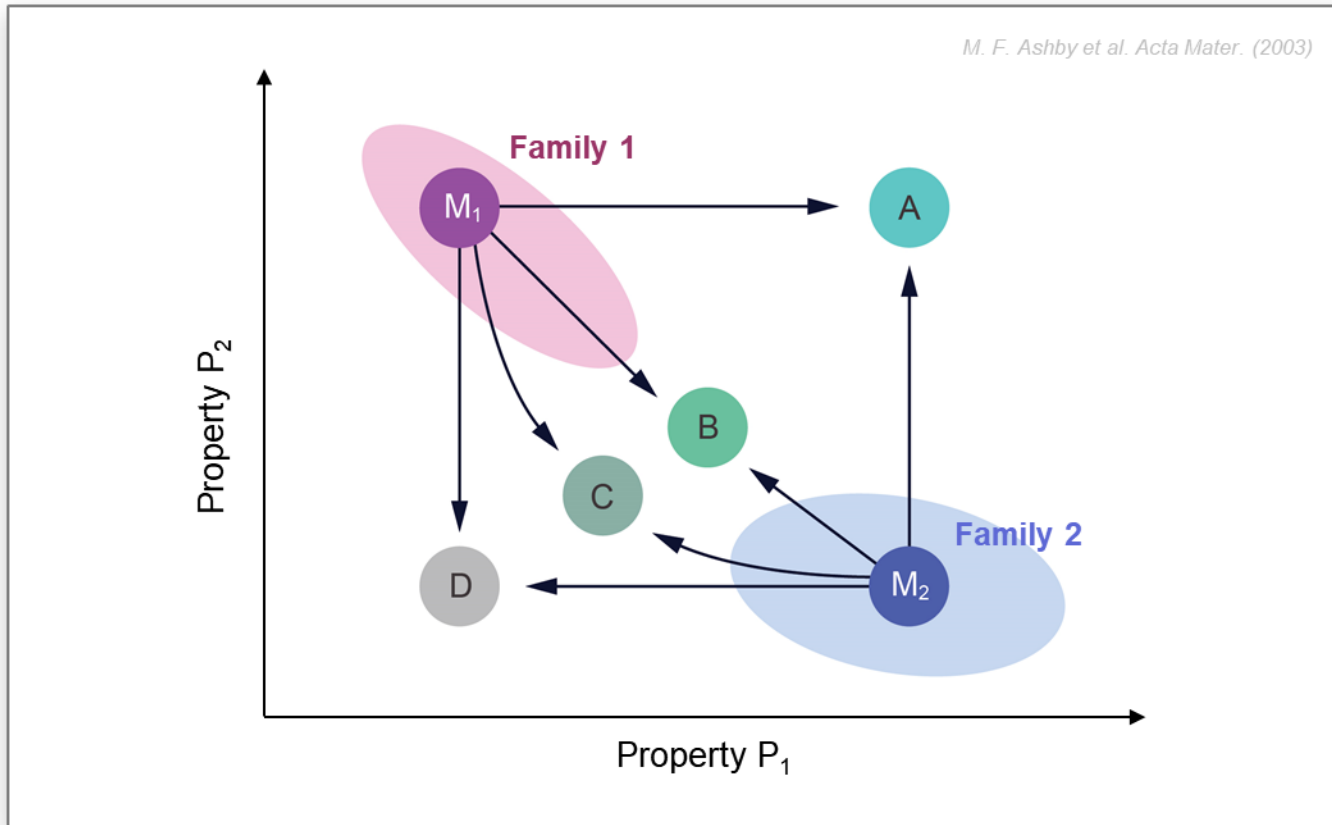
- Combination of two or more individual materials
- Design goal: obtain a more desirable combination of properties (principle of combined action)
  - e.g., low density and high strength

Terminology/Classification

- Composite:

  -- Multiphase material that is artificially made.

- Phase types:

  -- Matrix - is continuous

  -- Dispersed - is discontinuous and
      surrounded by matrix
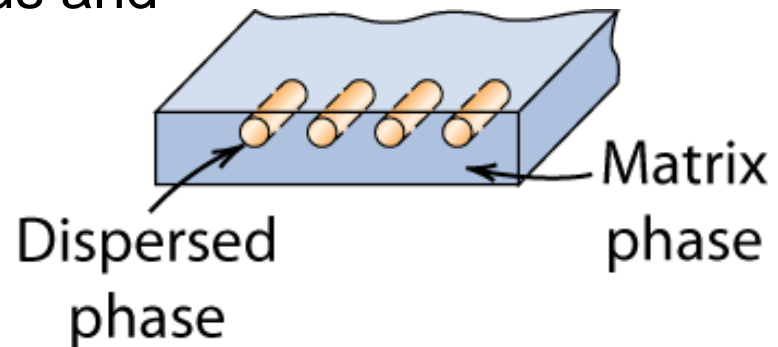
Adapted from Fig. 16.1(a),
Callister & Rethwisch 9e.

Terminology/Classification
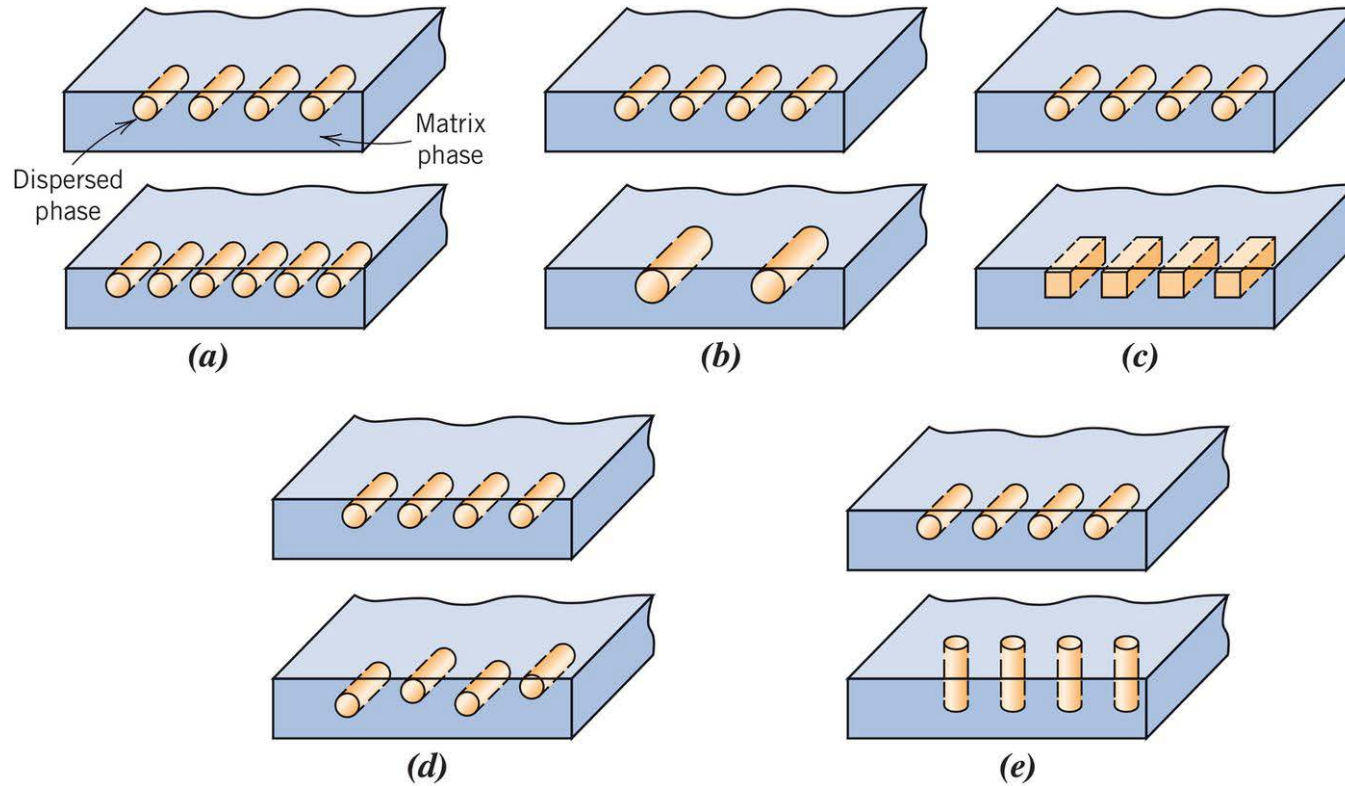
그림 16.1 복합재료 특성에 영향을 미치는 분산상 입자의 기하학적·공간적 특성에 대한 모식적 표현

(a) 농 도, (b) 크 기, (c) 형 상, (d) 분 포, (e) 배 향

Terminology/Classification

- Matrix phase:
  - -- Purposes are to:
    - - transfer stress to dispersed phase
    - - protect dispersed phase from environment
  - -- Types: MMC, CMC, PMC

    metal   ceramic   polymer

- Dispersed phase:
  - -- Purpose:

    MMC: increase σ_y, TS, creep resist.

    CMC: increase K_{Ic}

    PMC: increase E, σ_y, TS, creep resist.

  - -- Types: particle, fiber, structural

woven fibers

0.5mm

cross section view

0.5mm
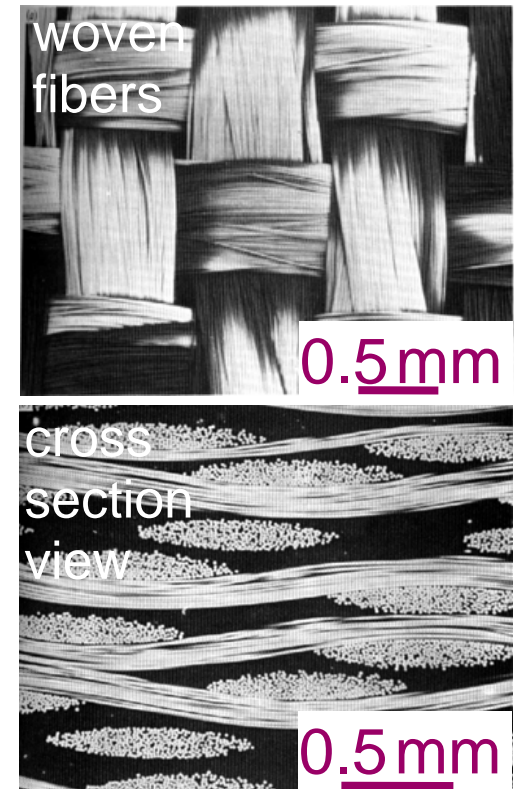
Reprinted with permission from D. Hull and T.W. Clyne, *An Introduction to Composite Materials*, 2nd ed., Cambridge University Press, New York, 1996, Fig. 3.6, p. 47.

Classification of Composites
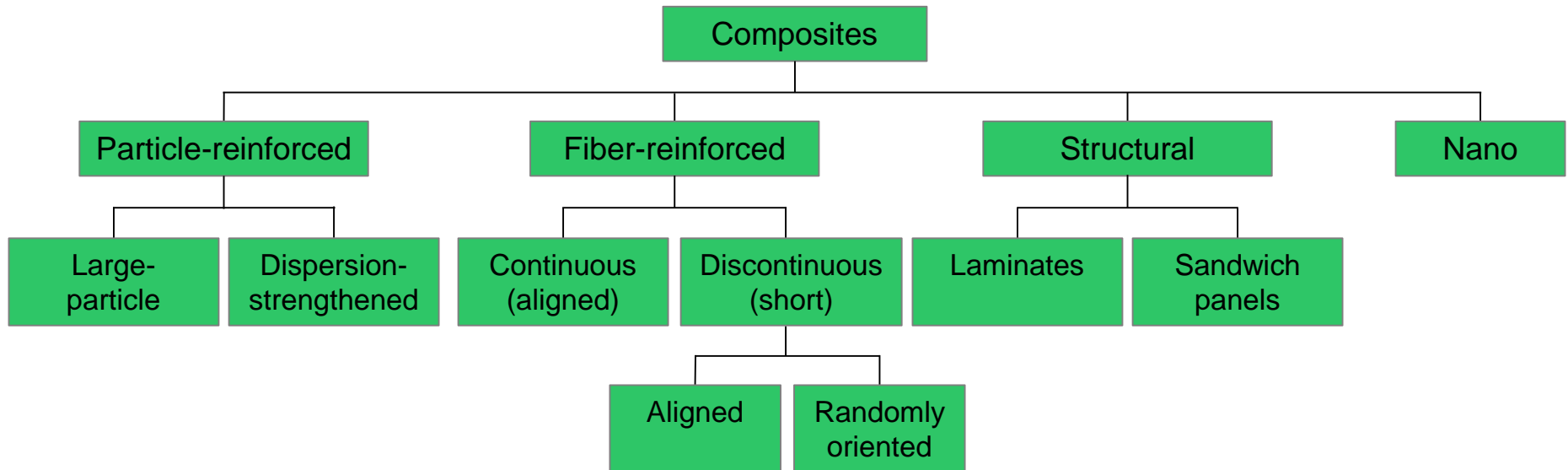
Adapted from Fig. 16.2,
Callister & Rethwisch 10e.

Classification: Particle-Reinforced (i)

Particle-reinforced   Fiber-reinforced   Structural

- Examples:
  - Spheroidite steel

    matrix: ferrite (α) (ductile)
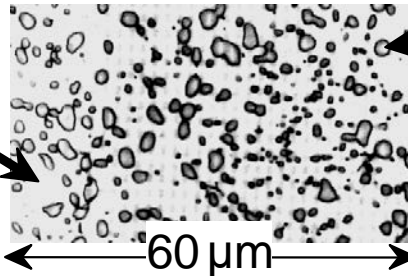
    particles: cementite (Fe_3C) (brittle)

    Fig. 10.19, *Callister & Rethwisch 10e*. (Copyright 1971 by United States Steel Corporation.)
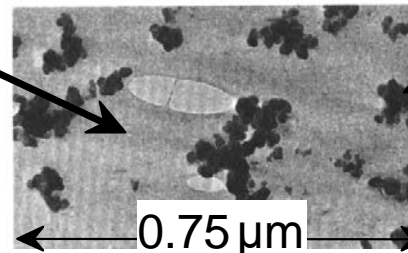
    60 μm

  - WC/Co cemented carbide

    matrix: cobalt (ductile, tough)
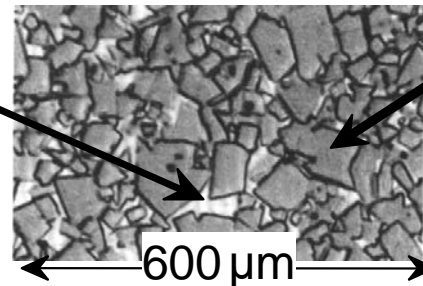
    particles: WC (brittle, hard)

    Fig. 16.4, *Callister & Rethwisch 10e*. (Courtesy of Carboloy Systems Department, General Electric Company.)

    600 μm

  - Automobile tire rubber

    matrix: rubber (compliant)

    particles: carbon black (stiff)

    Fig. 16.5, *Callister & Rethwisch 10e*. (Courtesy of Goodyear Tire and Rubber Company.)

    0.75 μm

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Classification: Particle-Reinforced (ii)

Particle-reinforced — Fiber-reinforced — Structural

Concrete – gravel + sand + cement + water
- Why sand *and* gravel?   Sand fills voids between gravel particles

Reinforced concrete – Reinforce with steel rebar or remesh
- increases strength - even if cement matrix is cracked

Prestressed concrete
- Rebar/remesh placed under tension during setting of concrete
- Release of tension after setting places concrete in a state of compression
- To fracture concrete, applied tensile stress must exceed this
   compressive stress

Post-tensioning – tighten nuts to place concrete under compression

threaded rod

nut
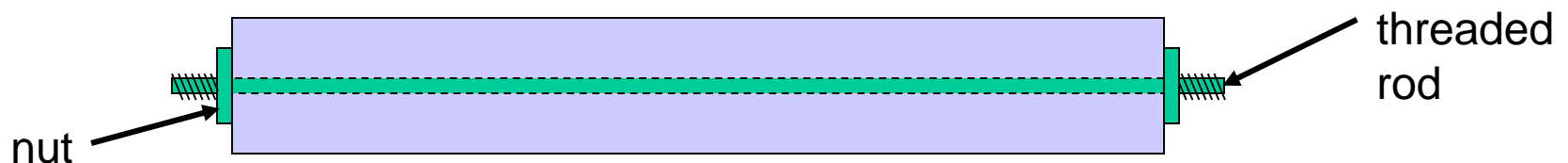
Classification: Particle-Reinforced (iii)

Particle-reinforced   Fiber-reinforced   Structural

- Elastic modulus, E_c, of composites:
  -- two "rule of mixture" extremes:

upper limit: $E_c = V_m E_m + V_p E_p$

Data:
Cu matrix
w/tungsten
particles

E(GPa)

lower limit:

$$\frac{1}{E_c} = \frac{V_m}{E_m} + \frac{V_p}{E_p}$$
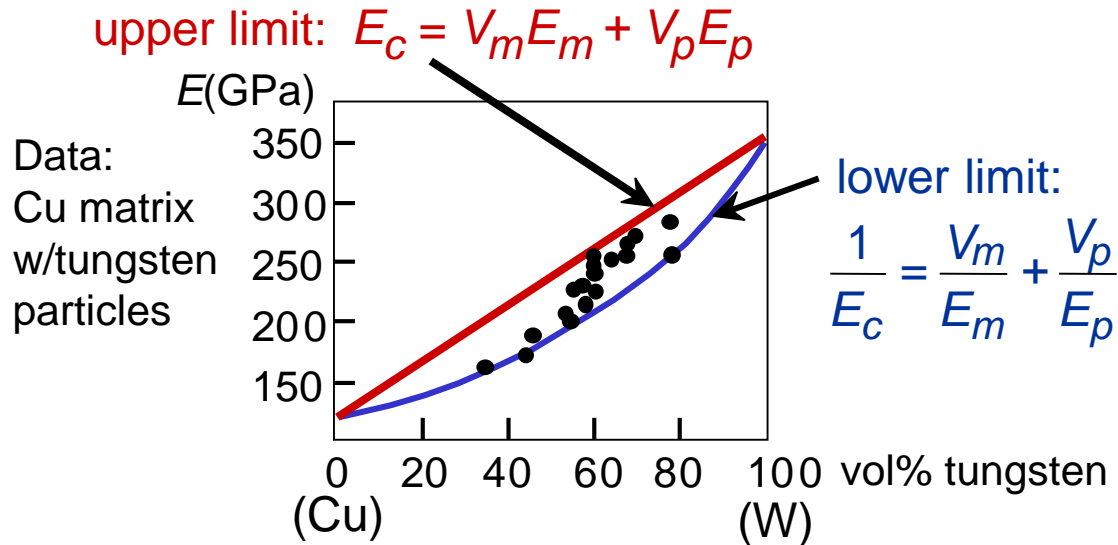
Fig. 16.3, *Callister & Rethwisch 9e*. (Reprinted with permission from R. H. Krock, *ASTM Proceedings*, Vol. 63, 1963. Copyright ASTM International, 100 Barr Harbor Drive, West Conschohocken, PA 19428.)

- Application to other properties:

  -- Electrical conductivity, σ_e: Replace E's in equations with σ_e's.

  -- Thermal conductivity, k: Replace E's in equations with k's.

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Classification: Fiber-Reinforced (i)

Particle-reinforced   **Fiber-reinforced**   Structural
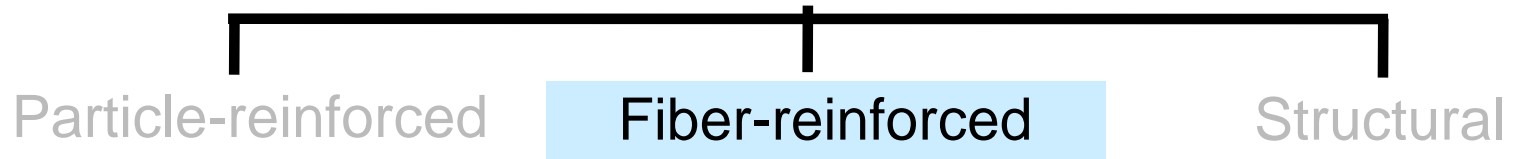
- Fibers very strong in tension

  – Provide significant strength improvement to the composite

  – Ex: fiber-glass - continuous glass filaments in a polymer matrix

    - Glass fibers
      – strength and stiffness
    - Polymer matrix
      – holds fibers in place
      – protects fiber surfaces
      – transfers load to fibers

Classification: Fiber-Reinforced (ii)

Particle-reinforced | Fiber-reinforced | Structural
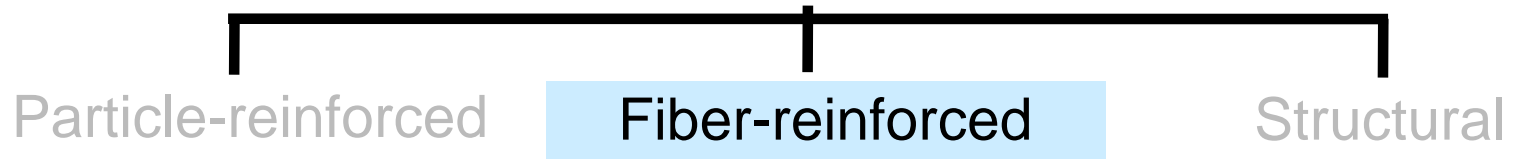
- **Fiber Types**
– **Whiskers** - thin single crystals - large length to diameter ratios
- graphite, silicon nitride, silicon carbide
- high crystal perfection – extremely strong, strongest known
- very expensive and difficult to disperse

– **Fibers**
- polycrystalline or amorphous
- generally polymers or ceramics
- Ex: alumina, aramid, E-glass, boron, UHMWPE

– **Wires**
- metals – steel, molybdenum, tungsten

Fiber Alignment

Longitudinal direction

Transverse direction

aligned
continuous

aligned
discontinuous

random

Classification: Fiber-Reinforced (iii)

- **Aligned Continuous** fibers
- Examples:

-- Metal: γ'(Ni$_3$Al)-α(Mo)
by eutectic solidification.
matrix: α(Mo) (ductile)

2 µm
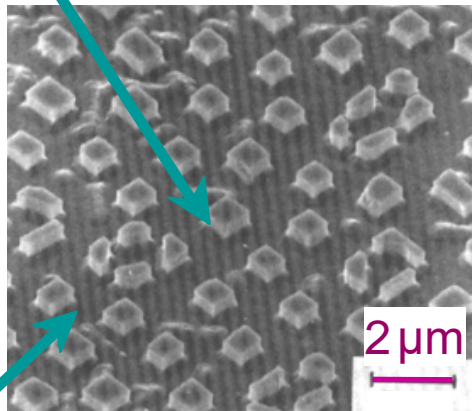
fibers: γ' (Ni$_3$Al) (brittle)

From W. Funk and E. Blank, "Creep deformation of Ni$_3$Al-Mo in-situ composites", *Metall. Trans. A* Vol. 19(4), pp. 987-998, 1988. Used with permission.

-- Ceramic: Glass w/SiC fibers
formed by glass slurry
E_{glass} = 76 GPa; E_{SiC} = 400 GPa.
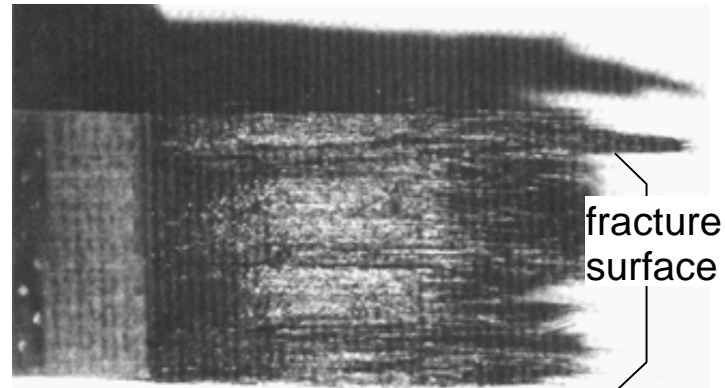
fracture surface

From F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. Used with permission of CRC Press, Boca Raton, FL.

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Classification: Fiber-Reinforced (iv)

Particle-reinforced | **Fiber-reinforced** | Structural

- Discontinuous fibers, random in 2 dimensions

- Example: Carbon-Carbon
  -- fabrication process:
  - carbon fibers embedded in polymer resin matrix,
  - polymer resin pyrolyzed at up to 2500° C.
  -- uses: disk brakes, gas turbine exhaust flaps, missile nose cones.
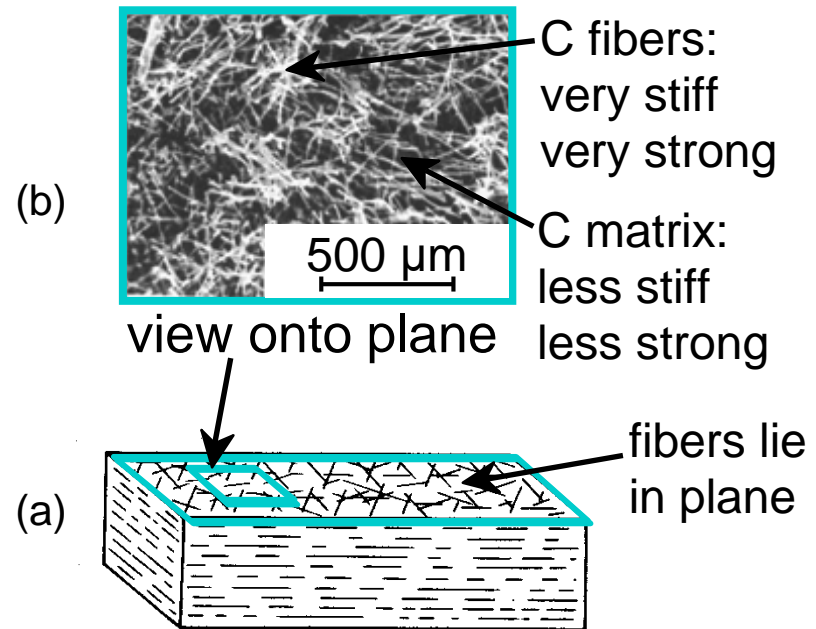
- Other possibilities:
  -- Discontinuous, random 3D
  -- Discontinuous, aligned

(b)

500 µm

view onto plane

(a)

C fibers: very stiff very strong

C matrix: less stiff less strong

fibers lie in plane

Adapted from F.L. Matthews and R.L. Rawlings, *Composite Materials; Engineering and Science*, Reprint ed., CRC Press, Boca Raton, FL, 2000. (a) Fig. 4.24(a), p. 151; (b) Fig. 4.24(b) p. 151. (Courtesy I.J. Davies) Reproduced with permission of CRC Press, Boca Raton, FL.

Classification: Fiber-Reinforced (v)

Particle-reinforced | **Fiber-reinforced** | Structural

- Critical fiber length for effective stiffening & strengthening:

fiber ultimate tensile strength →   ← fiber diameter
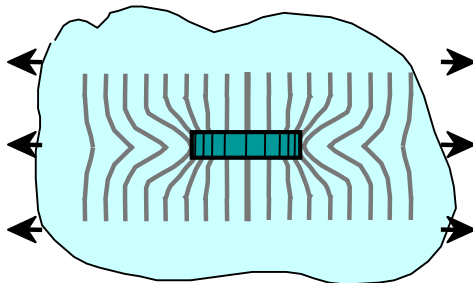
$$\text{fiber length} > \frac{\sigma_f d}{2\tau_c}$$

← shear strength of fiber-matrix interface

- Ex: For fiberglass, common fiber length > 15 mm needed
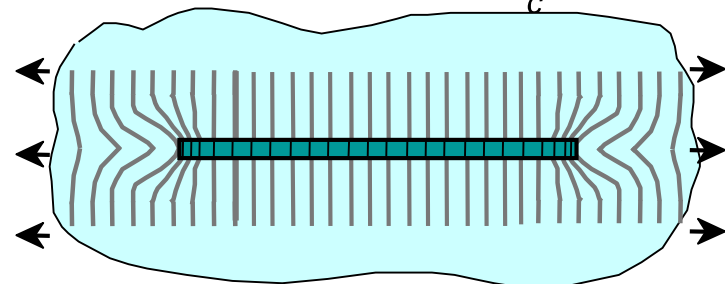- For longer fibers, stress transference from matrix is more efficient

Short, thick fibers:
$$\text{fiber length} < \frac{\sigma_f d}{2\tau_c}$$

Long, thin fibers:
$$\text{fiber length} > \frac{\sigma_f d}{2\tau_c}$$

Low fiber efficiency

High fiber efficiency
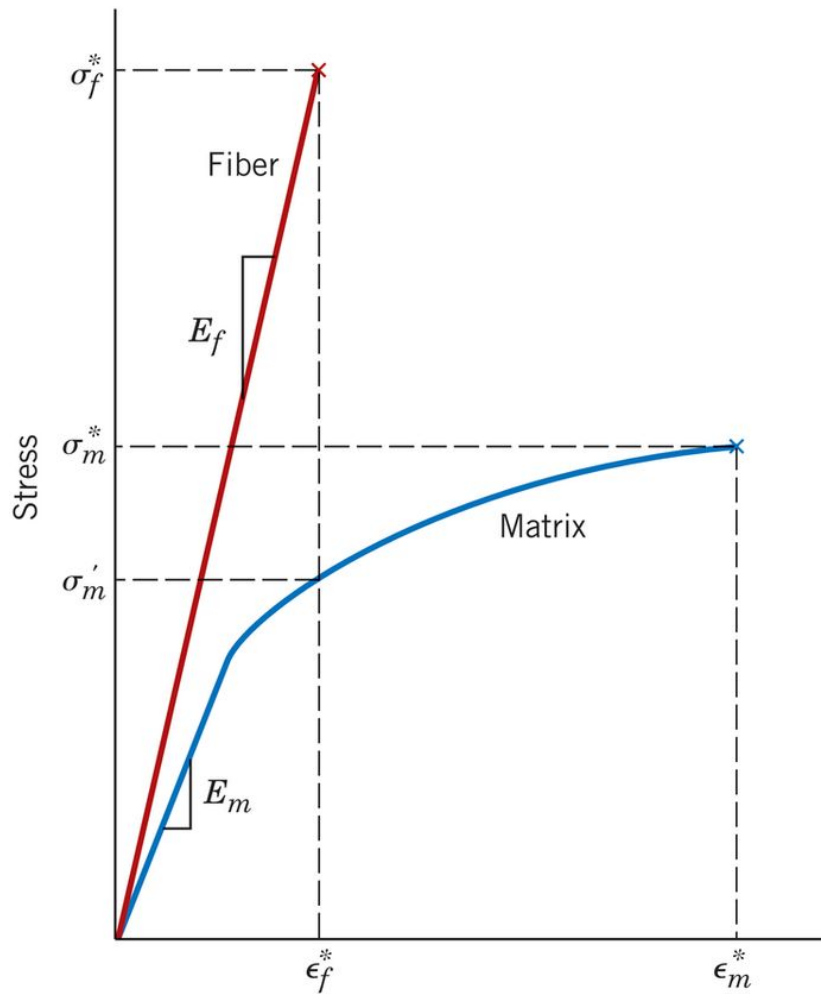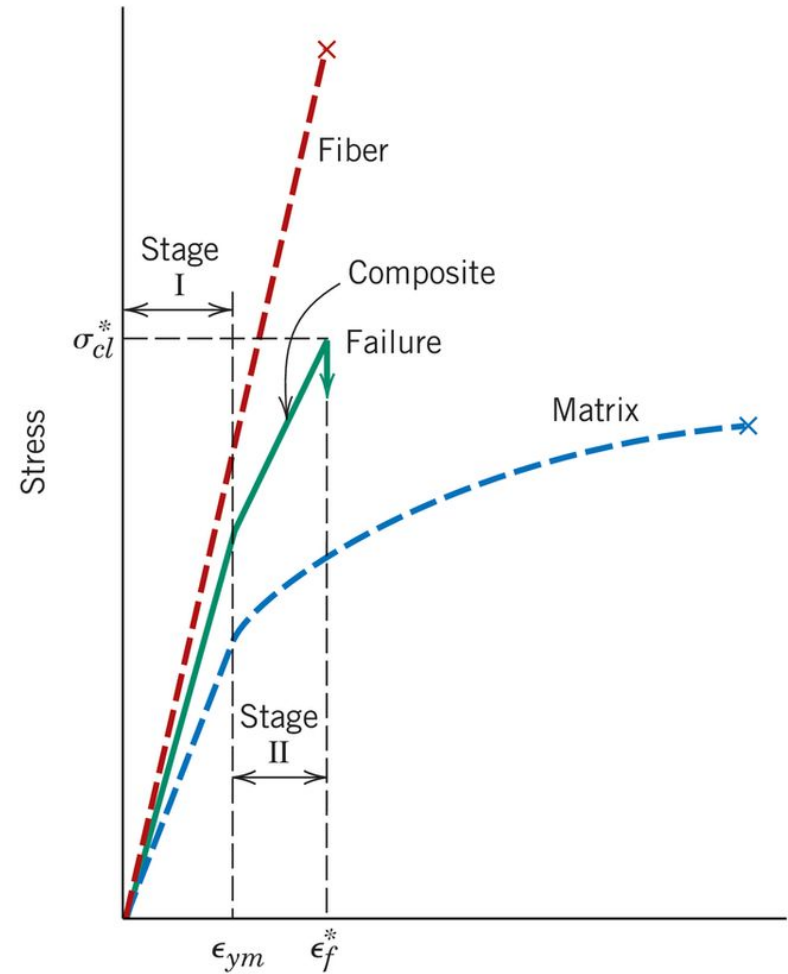
그림 16.9 (a) 취성의 섬유와 연성의 기지 재료의 응력-연신율 커브의 모식도. 이들 재료의 파단 응력과 연신율이 나타나 있다. (b) 섬유의 정렬 방향으로 일축응력이 가해진 조건에서 **정렬된 섬유강화 복합재료**의 응력-변형률 모식도. (a)에 나타낸 섬유와 기지 재료의 커브를 중첩하여 나타냈다.

Composite Stiffness: Longitudinal Loading

Continuous fibers - Estimate fiber-reinforced composite modulus of elasticity for continuous fibers

- Longitudinal deformation

$$\sigma_c = \sigma_m V_m + \sigma_f V_f \qquad \text{and} \qquad \varepsilon_c = \varepsilon_m = \varepsilon_f$$

volume fraction   isostrain

$$\therefore \quad \boxed{E_{cl} = E_m V_m + E_f V_f} \qquad E_{cl} = \text{longitudinal modulus}$$

$c = composite$
$f = $ fiber
$m = $ matrix

Composite Stiffness: Transverse Loading

- In transverse loading the fibers carry less of the load

$$\varepsilon_c = \varepsilon_m V_m + \varepsilon_f V_f \qquad \text{and} \qquad \sigma_c = \sigma_m = \sigma_f = \sigma$$

isostress

$$\therefore \quad \frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f}$$

E_{ct} = transverse modulus

$$E_{ct} = \frac{E_m E_f}{V_m E_f + V_f E_m}$$

$c = composite$
$f = $ fiber
$m = $ matrix

Composite Stiffness

Particle-reinforced   Fiber-reinforced   Structural

- Estimate of E_{cd} for discontinuous fibers:

  -- valid when fiber length $< 15 \dfrac{\sigma_f d}{\tau_c}$

  -- Elastic modulus in fiber direction:

  $$E_{cd} = E_m V_m + K E_f V_f$$

  efficiency factor:
  -- aligned: $K = 1$ (aligned parallel)
  -- aligned: $K = 0$ (aligned perpendicular)
  -- random 2D: $K = 3/8$ (2D isotropy)
  -- random 3D: $K = 1/5$ (3D isotropy)

  Table 16.3, *Callister & Rethwisch 9e*.
  (Source is H. Krenchel, *Fibre Reinforcement*, Copenhagen: Akademisk Forlag, 1964.)

Composite Strength

Particle-reinforced   Fiber-reinforced   Structural

- Estimate of σ_{cd}^* for discontinuous fibers:

1. When $l > l_c$

$$\sigma_{cd'}^* = \sigma_f^* V_f \left(1 - \frac{l_c}{2l} \right) + \sigma_m' (1 - V_f)$$

2. When $l < l_c$

$$\sigma_{cd'}^* = \frac{l\tau_c}{d} V_f + \sigma_m' (1 - V_f)$$

Processing of fiber-reinforced composites (i)

Pultrusion (인발 압출법)

- Continuous fibers pulled through resin tank to impregnate fibers with thermosetting resin
- Impregnated fibers pass through steel die that preforms to the desired shape
- Preformed stock passes through a curing die that is
  - precision machined to impart final shape
  - heated to initiate curing of the resin matrix
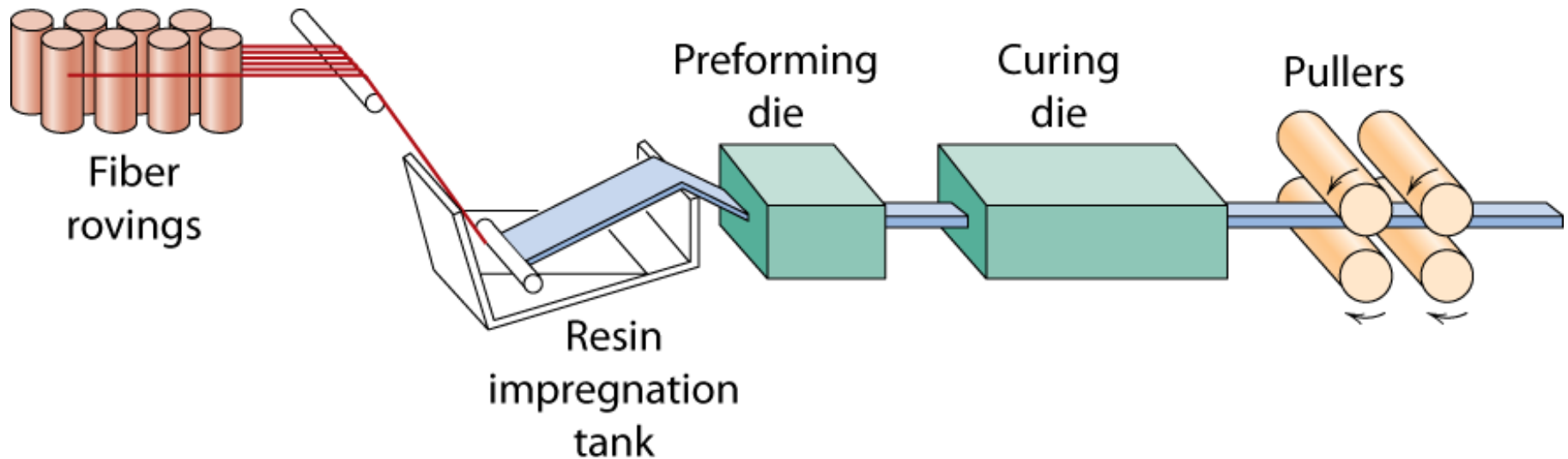
Fig. 16.13, *Callister & Rethwisch 9e*.

Processing of fiber-reinforced composites (ii)

Prepreg (예비 함침 제조 공정)
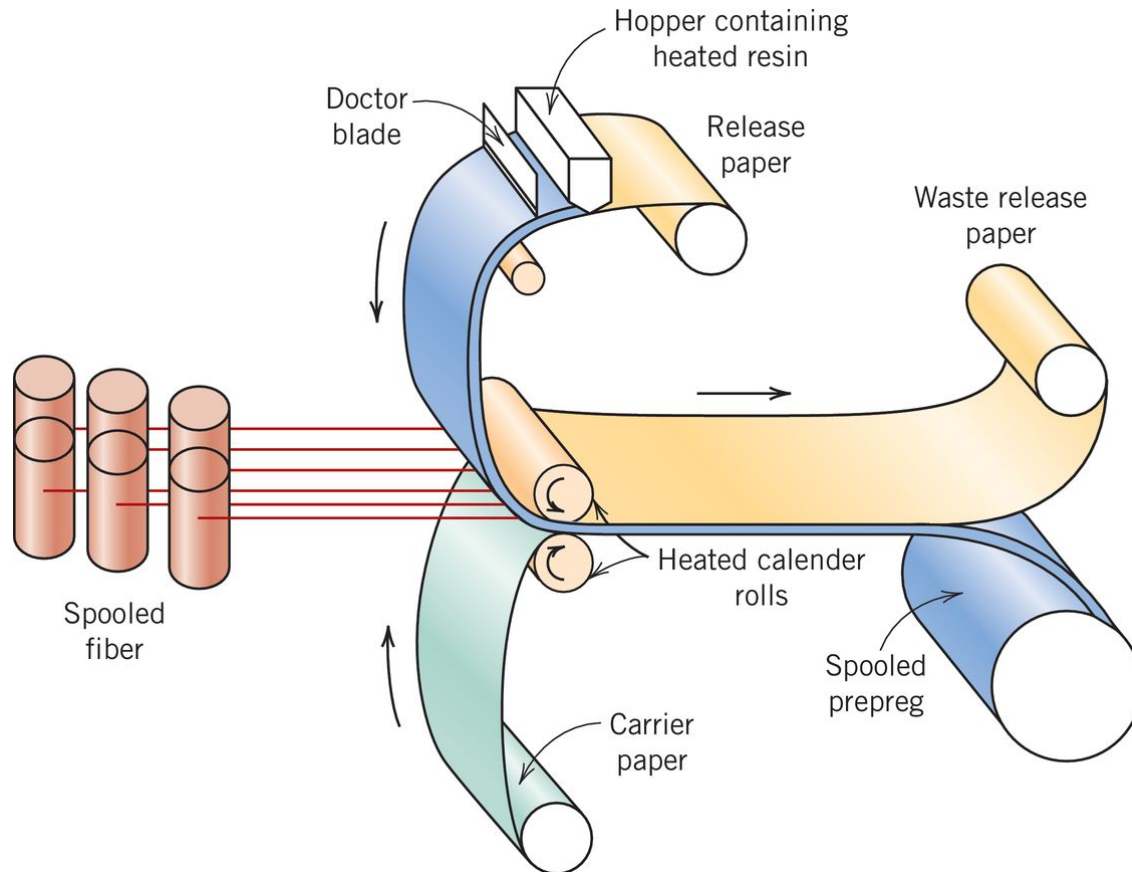
Processing of fiber-reinforced composites (iii)

- Filament Winding (필라멘트 감기)
  - Continuous reinforcing fibers are accurately positioned in a predetermined pattern to form a hollow (usually cylindrical) shape
  - Fibers are fed through a resin bath to impregnate with thermosetting resin
  - Impregnated fibers are continuously wound (typically automatically) onto a mandrel
  - After appropriate number of layers added, curing is carried out either in an oven or at room temperature
  - The mandrel is removed to give the final product

Helical winding

Circumferential winding

Polar winding
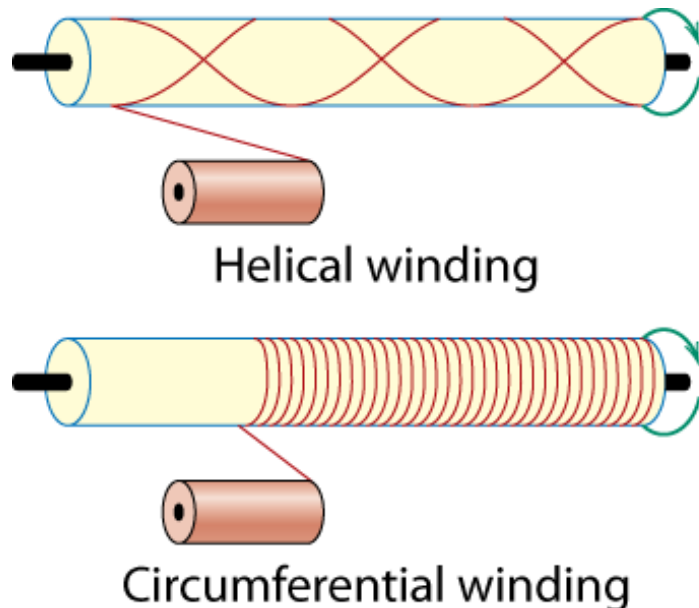
Fig. 16.15, *Callister & Rethwisch 10e*.
[From N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials*, The Macmillan Company, New York, 1981.]
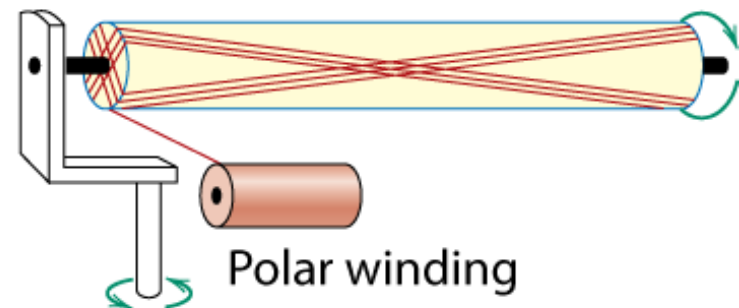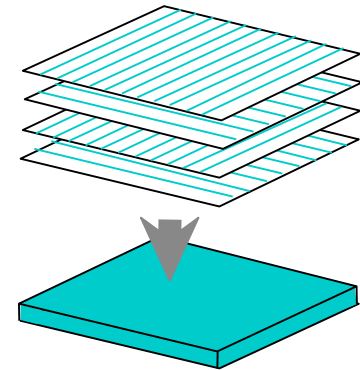
Classification: Structural

Particle-reinforced   Fiber-reinforced   Structural

- ## Laminates -

  -- stacked and bonded fiber-reinforced sheets
  - stacking sequence: e.g., 0⁰/90⁰
  - benefit: balanced in-plane stiffness

Adapted from Fig. 16.16, *Callister & Rethwisch 8e*.

- ## Sandwich panels

  -- honeycomb core between two facing sheets
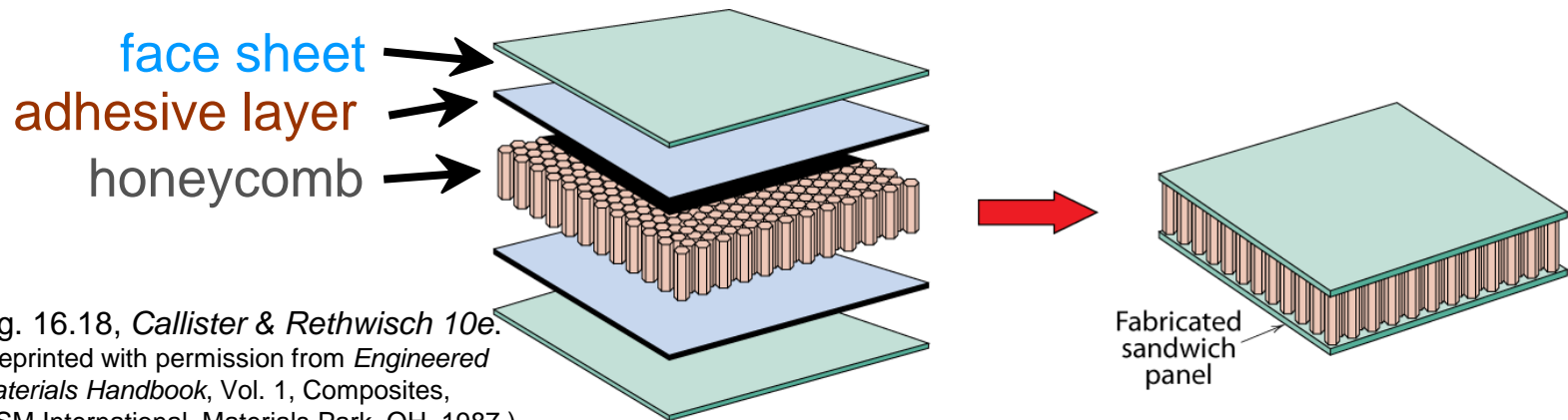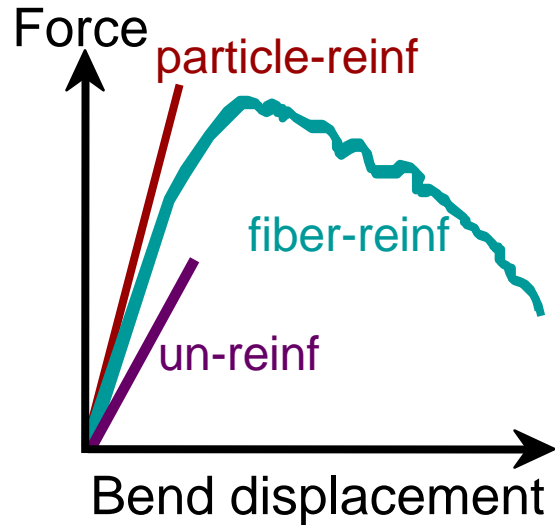 - benefits: low density, large bending stiffness

face sheet →
adhesive layer →
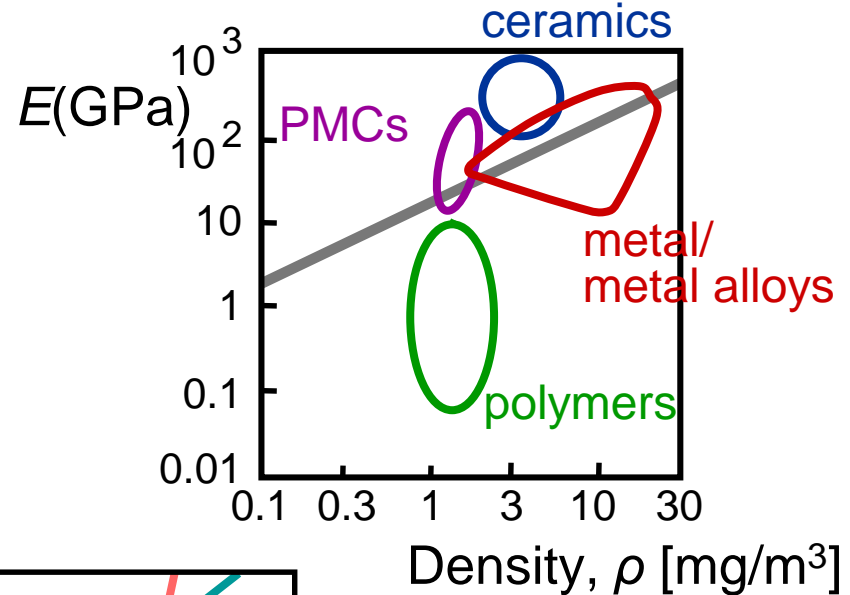honeycomb →

Fabricated sandwich panel

Fig. 16.18, *Callister & Rethwisch 10e*.
(Reprinted with permission from *Engineered Materials Handbook*, Vol. 1, Composites, ASM International, Materials Park, OH, 1987.)
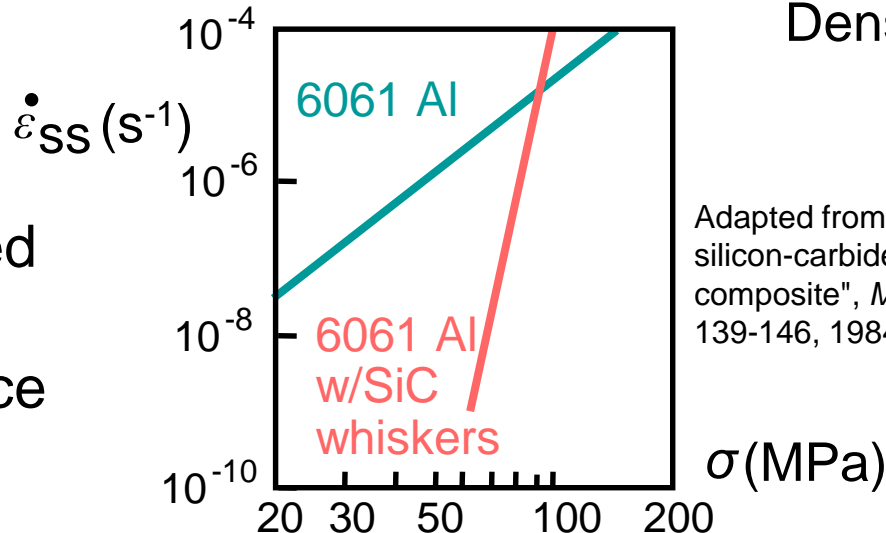
# Composite Benefits

- CMCs: Increased toughness

Force

particle-reinf

fiber-reinf

un-reinf

Bend displacement

- PMCs: Increased E/ρ

ceramics

E(GPa)

PMCs

metal/
metal alloys

polymers

10^3
10^2
10
1
0.1
0.01

0.1 0.3 1 3 10 30

Density, ρ [mg/m^3]

- MMCs: Increased creep resistance

$\dot{\varepsilon}_{ss}$ (s^{-1})

10^{-4}

6061 Al

10^{-6}

10^{-8}

6061 Al w/SiC whiskers

10^{-10}

20 30 50 100 200

σ(MPa)

Adapted from T.G. Nieh, "Creep rupture of a silicon-carbide reinforced aluminum composite", *Metall. Trans. A* Vol. 15(1), pp. 139-146, 1984. Used with permission.
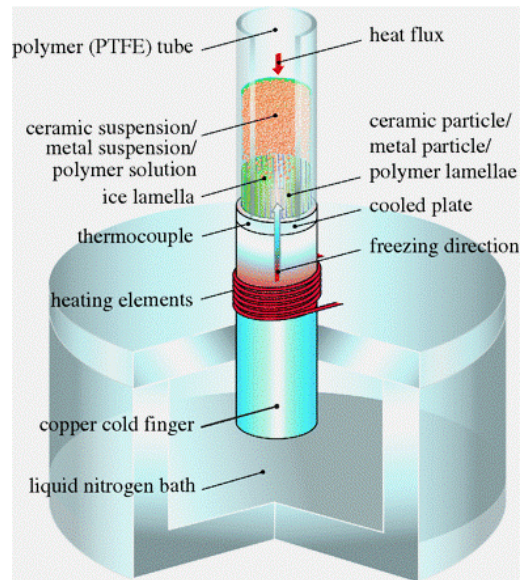
30
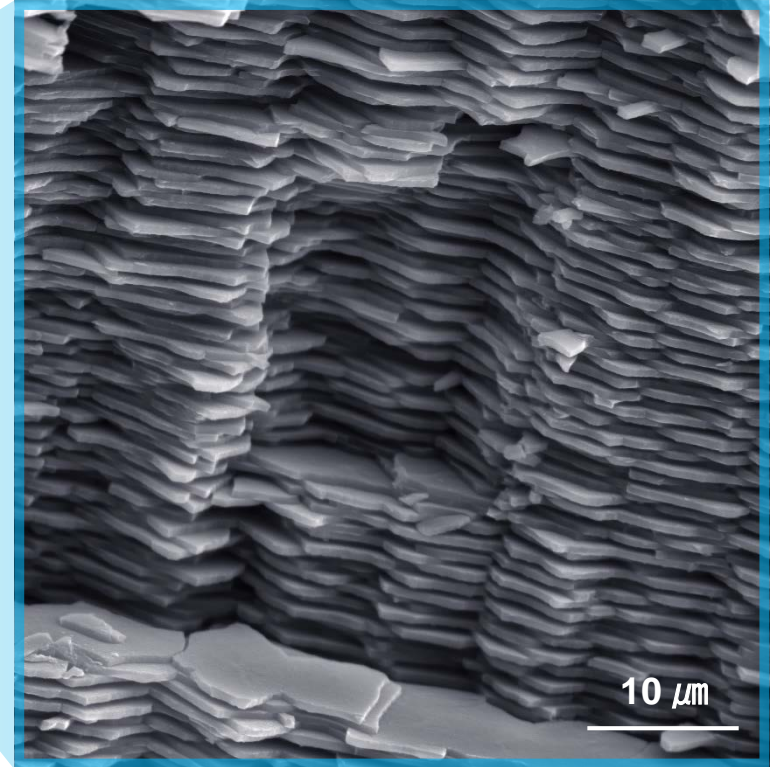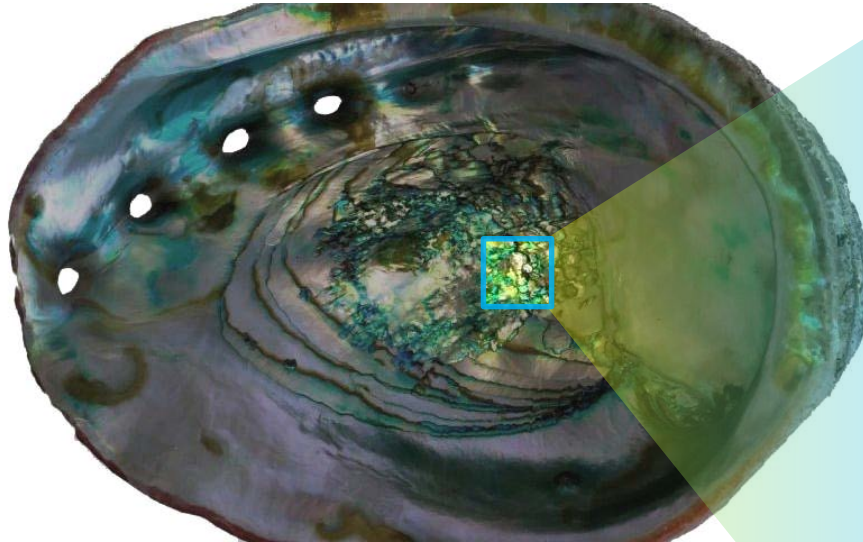
Microstructure of nacre

$V_{f.CaCo3}$ ~ 95 vol.%
$CaCo_3$: 5 – 10 μm (width)
$CaCo_3$: ~ 250 nm / protein: ~ 10 nm (thickness)
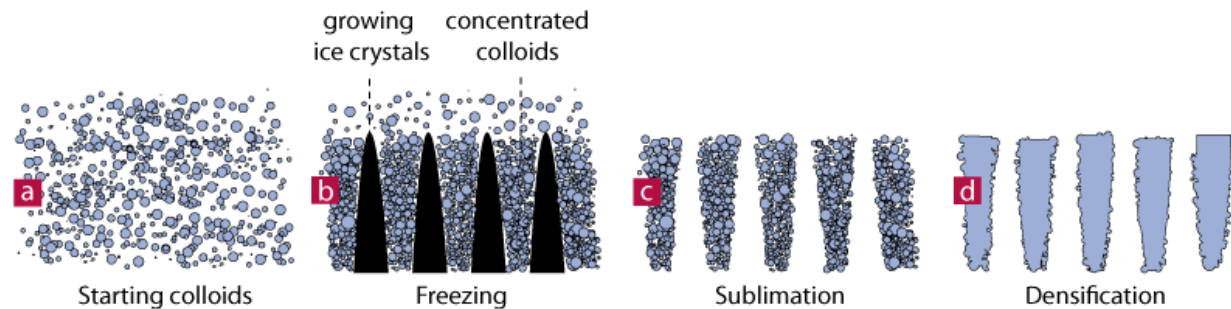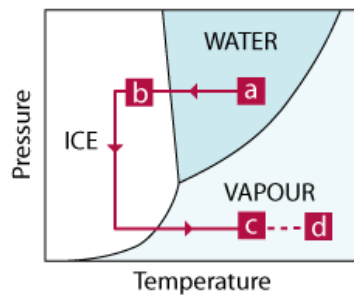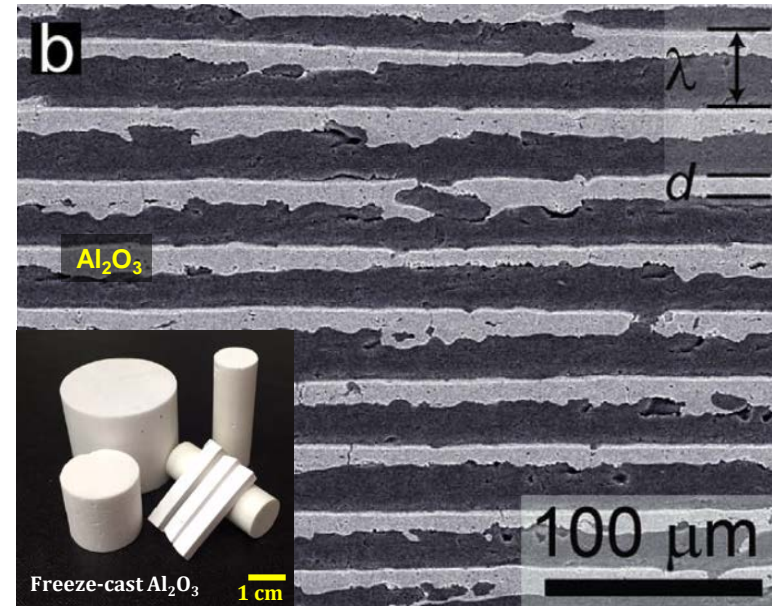
10 μm

Brick-and-mortar structure

$CaCO_3$

~ 0.25 MPam$^{1/2}$

Nacre

~10 MPam$^{1/2}$ (Fracture toughness)

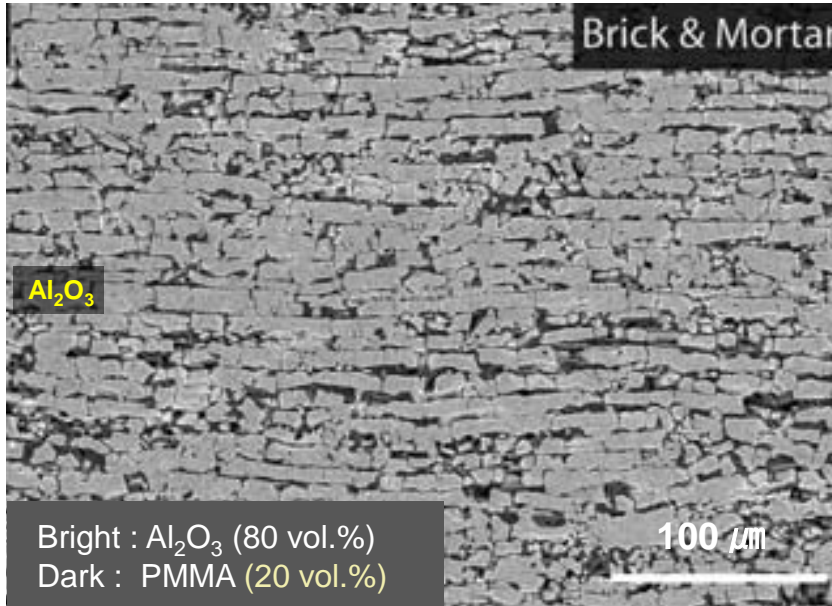Freeze-casting technique

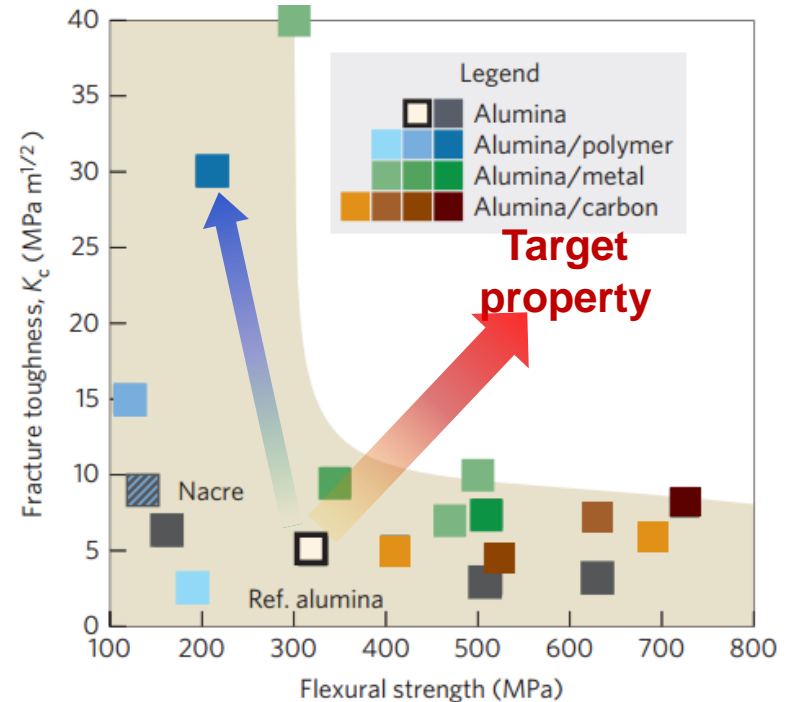*U.G.K Wegst et al. (2010)*

S. Deville et al. Adv. Eng. Mater. (2008)

Bio-inspired design of hybrid materials

E. Munch et al. Science (2008)

F. Bouville et al. Nat. Mater. (2014)

Brick & Mortar

Al_2O_3

Bright : Al_2O_3 (80 vol.%)
Dark : PMMA (20 vol.%)

100 μm

Legend
- Alumina
- Alumina/polymer
- Alumina/metal
- Alumina/carbon

Target property

Nacre

Ref. alumina

Fracture toughness, K_c (MPa m$^{1/2}$)

Flexural strength (MPa)

Natural materials

Bio-inspired materials

Organic protein / CaCo$_3$ → **PMMA / Al$_2$O$_3$** → **BMG / Al$_2$O$_3$**

Polymeric mortar

Metallic mortar

100 µm

The first nacre-like metal-ceramic composites synthesized by melt infiltration process

A.Wat, J.I. Lee* et al. Nat. Commun. (2019) / KR No. 10-1806309 (2017)*

ARTICLE

OPEN

Bioinspired nacre-like alumina with a bulk-metallic glass-forming alloy as a compliant phase

Amy Wat[1,2], Je In Lee[3,4], Chae Woo Ryu[3], Bernd Gludovatz[5], Jinyeon Kim[3,6], Antoni P. Tomsia[2], Takehiko Ishikawa[7], Julianna Schmitz[8], Andreas Meyer[8], Markus Alfreider[9], Daniel Kiener [9], Eun Soo Park [3] & Robert O. Ritchie [1,2]

Bioinspired ceramics with micron-scale ceramic "bricks" bonded by a metallic "mortar" are projected to result in higher strength and toughness ceramics, but their processing is challenging as metals do not typically wet ceramics. To resolve this issue, we made alumina structures using rapid pressureless infiltration of a zirconium-based bulk-metallic glass mortar that reactively wets the surface of freeze-cast alumina preforms. The mechanical properties of the resulting Al_2O_3 with a glass-forming compliant-phase change with infiltration temperature and ceramic content, leading to a trade-off between flexural strength (varying from 89 to 800 MPa) and fracture toughness (varying from 4 to more than 9 MPa·m$^{1/2}$). The high toughness levels are attributed to brick pull-out and crack deflection along the ceramic/metal interfaces. Since these mechanisms are enabled by interfacial failure rather than failure within the metallic mortar, the potential for optimizing these bioinspired materials for damage tolerance has still not been fully realized.

Summary

- Composites types are designated by:
  -- the matrix material (CMC, MMC, PMC)
  -- the reinforcement (particles, fibers, structural)

- Composite property benefits:
  -- MMC: enhanced E, σ^*, creep performance
  -- CMC: enhanced K_{lc}
  -- PMC: enhanced E/ρ, σ_y, TS/ρ

- Particulate-reinforced:
  -- Types: large-particle and dispersion-strengthened
  -- Properties are isotropic

- Fiber-reinforced:
  -- Types: continuous (aligned)
                  discontinuous (aligned or random)
  -- Properties can be isotropic or anisotropic

- Structural:
  -- Laminates and sandwich panels

Materials Science and Engineering

Paradigm of Materials Science and Engineering (Materials Paradigm_a model or set of idea)

Processing
- Sintering
- Heat treatment
- Thin Film
- Melt process
- Mechanical

Structure
- Atomic
- Crystal
- Microstructure
- Macrostructure

Phase transformation
- Thermodynamic
- Kinetic (diffusion)
- Interface

Properties & Applications
- Mechanical
- Electrical
- Magnetic
- Thermal
- Optical

Performance

Reuse/recyclability

38
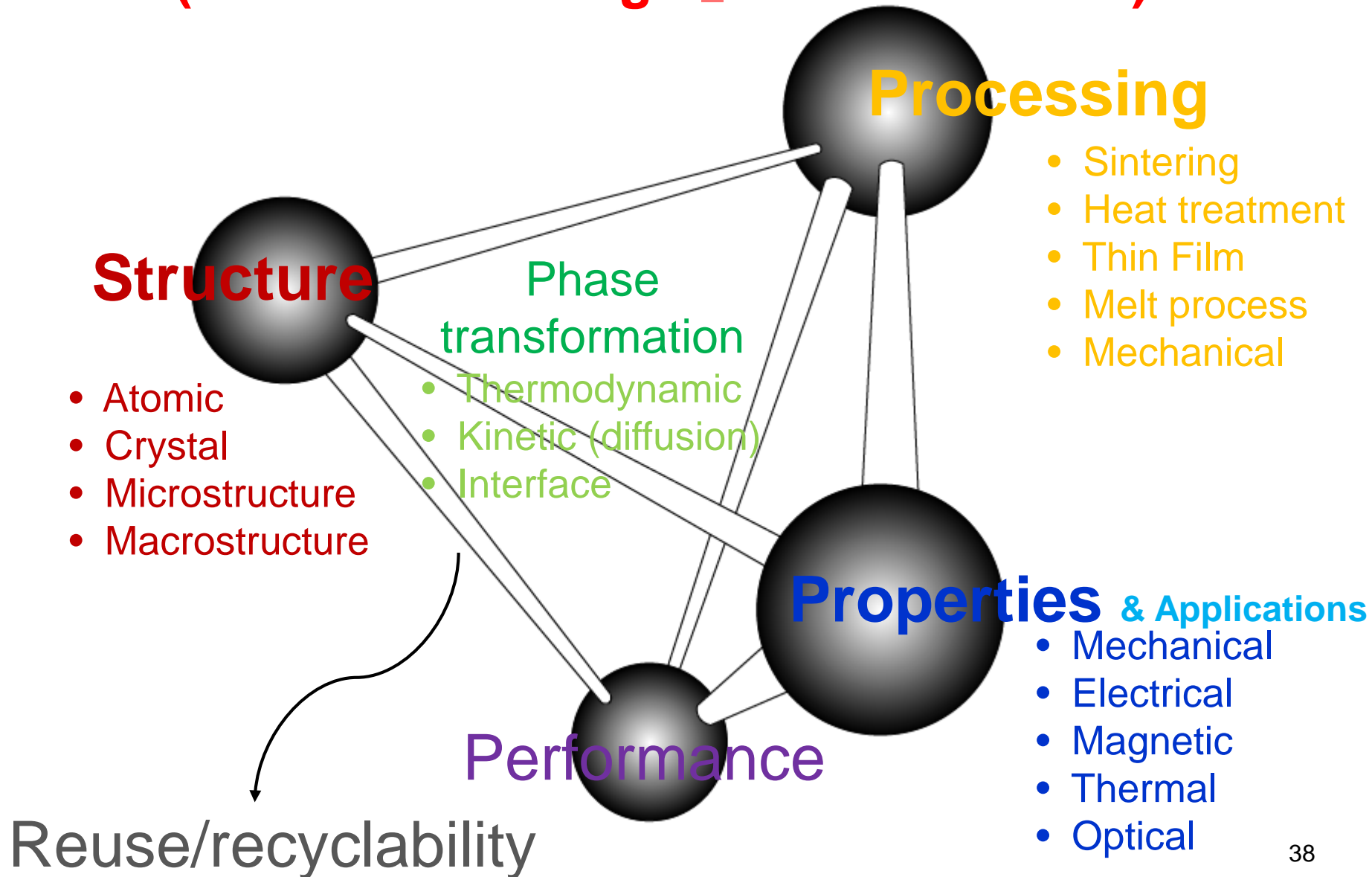
기말고사 : 12월 11일 오후 6시-9시

시험범위: Text, Lecture note, Homework

- **Chapter 9 장 – Chapter 16 장 (10 판 기준)**

 (Ceramic 구조/ Polymer 구조 포함)

- **주교재 – 영문기준 271-644 page까지 (10판 기준)**

- **Lecture notes 15~24 &**

- **Lecture note 6의 41-71 pages, Lecture note 7**
 * 계산기 지참 요망

장   소 : **33동 327,328,330,331 호로 총 4 개 강의실**

Office hours: 재공원 중간고사 검토 및 상담 + 질의응답

12월 3일 12시-3시 사이

12월 8일 12시-3시 사이

1인당 최대 30 분 이내로 Zoom 미팅
(꼭 원하는 경우 대면 미팅)

이메일로 개별 신청 후 일정 확인
더 많은 학생이 원하면 시간을 늘리도록 하겠습니다.

한학기 동안 Zoom 강의를 통해 여러분을 만나서 행복했습니다!

다른 수업에서는 대면으로 만날 수 있기를 기약하며…