2019 Fall

Introduction to Materials Science and Engineering

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Chapter 14: Properties and Applications of Ceramics

I. Phase diagram_ZrO_2-CaO diagram: Eutectic system

T ↔ M 커다란 부피변화
: 재료내 균열 야기

→ CaO 첨가

→ Cubic phase 안정화

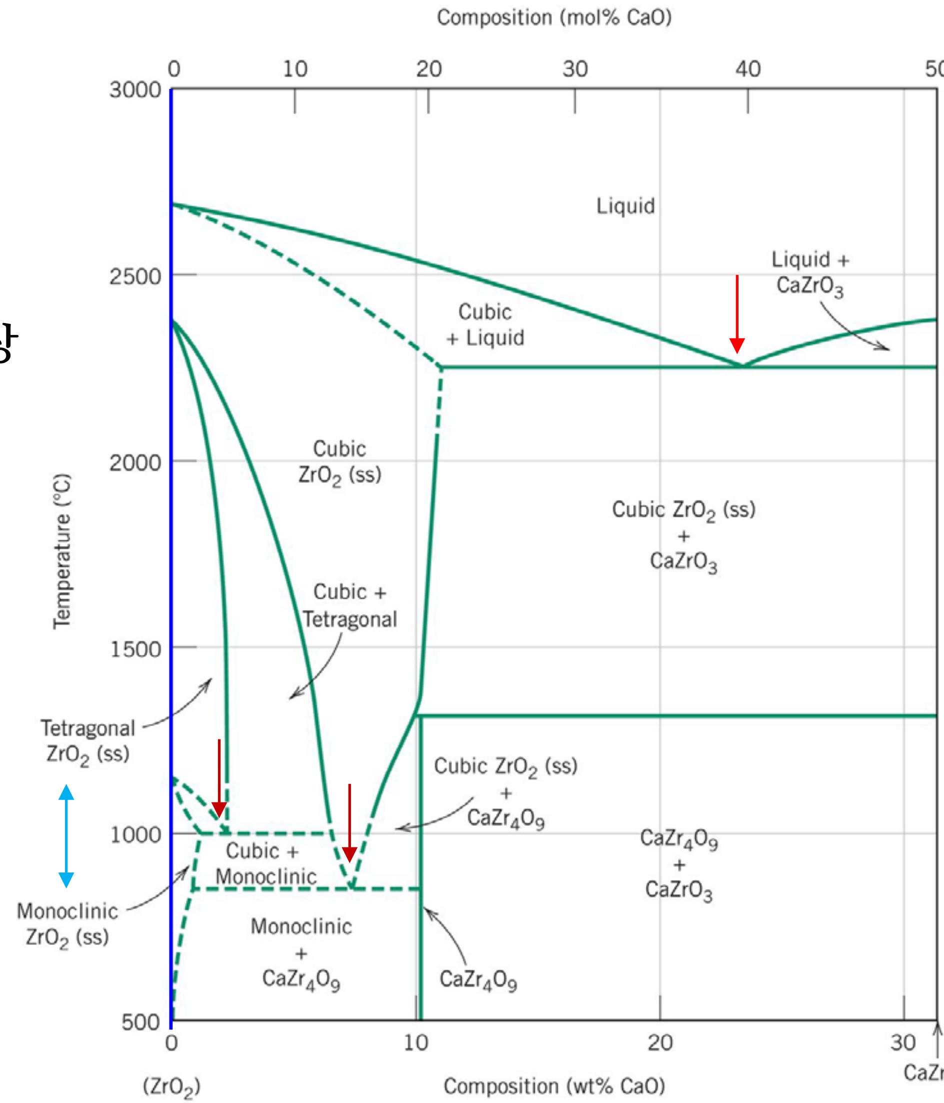
→ Cubic + Tetragonal 상 공존 냉각 조건에 따라 상온에서도 유지되도록 함

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

→ Y_2O_3, MgO 도 안정화제

→ 함량 증가시 Cubic이 상온까지 안정화

→ 완전 안정화 지르코니아



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.

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)

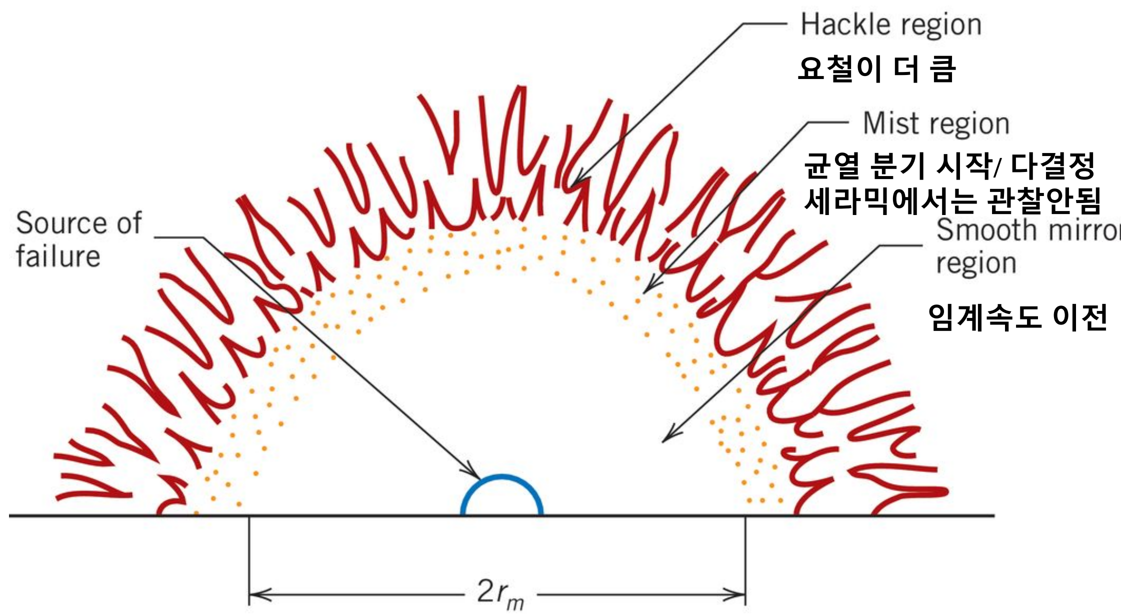
균열이 전파하는 동안
재료의 미세구조, 응력,
발생된 탄성파 등과
상호작용을 하며
파단면에 특정한 특징을 유발

파괴 응력값 (σ_f)

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

응력 증가↑→가속도↑→r_m↓

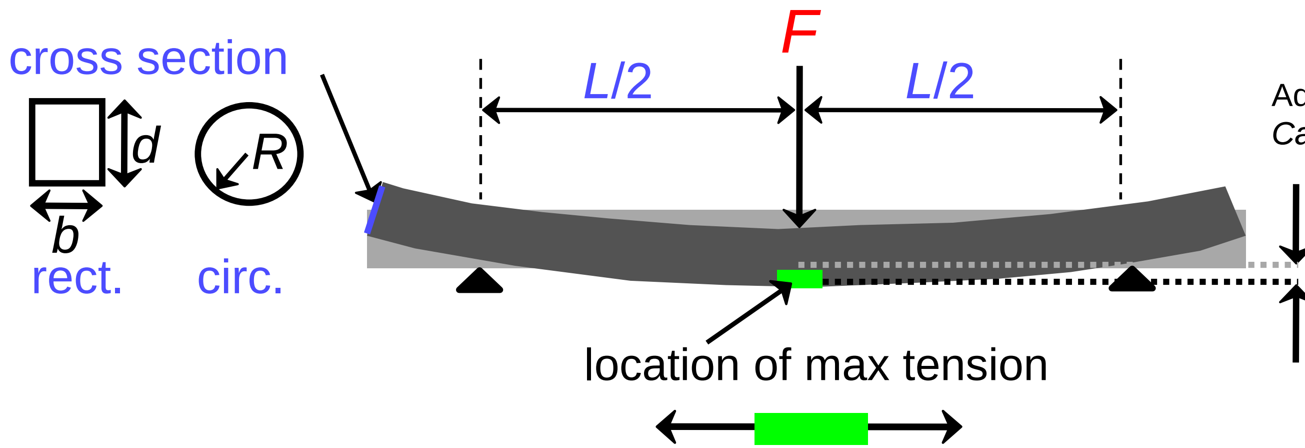
Figure 14.7 취성 세라믹의 파단면상에서 관찰되는 일반적인 특징 모식도



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.



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

$$E = \frac{F}{\delta}\frac{L^3}{4bd^3}$$ (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.*

14.8 소성변형기구

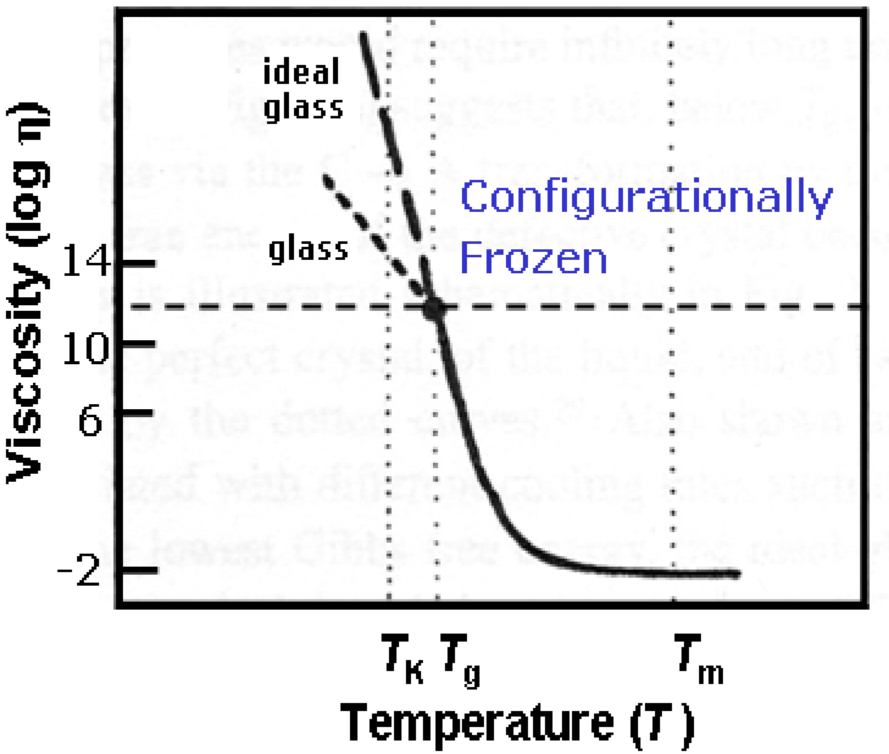
Consider mechanism of deformation

In crystalline ceramic, by dislocation motion

In non-crystalline ceramic, by viscous flow

Viscosity (η): 비정질 재료의 변형에 대한 저항

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



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)$\uparrow \rightarrow E \downarrow$

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

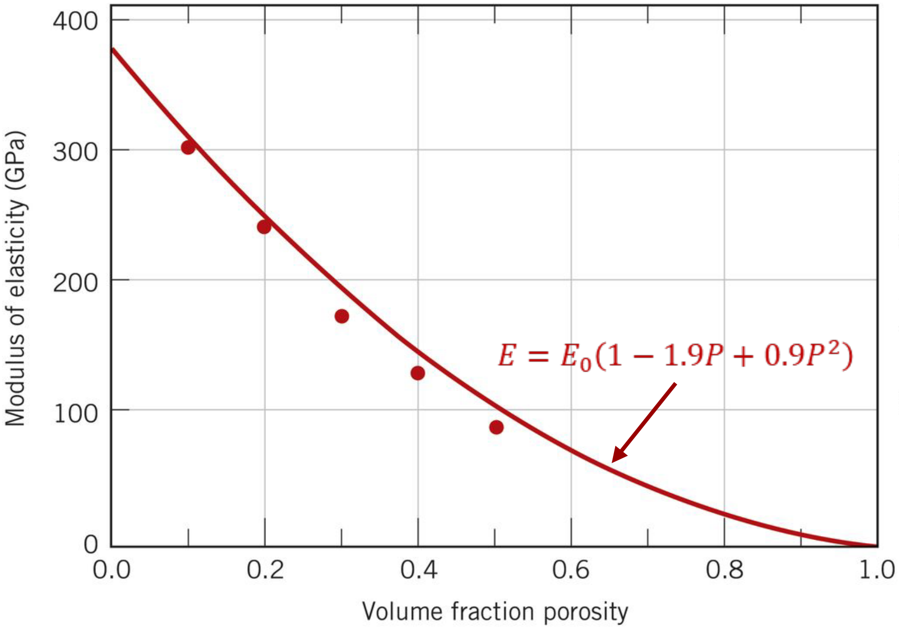


Figure 14.12

상온에서 알루미나의 탄성 계수에 미치는 기공의 영향

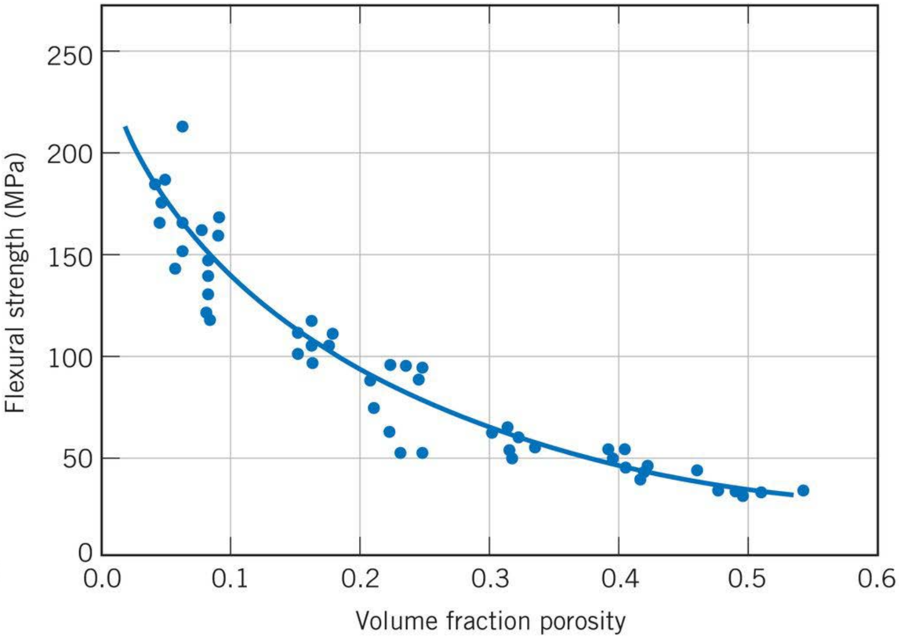


Figure 14.13

상온에서 알루미나의 굴곡강도에 미치는 기공의 영향

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**
  - -optical
  - -composite reinforce
  - -containers/ household
- **Clay products**
  - -whiteware
  - -Structural (벽돌, 타일 등)
- **Refractories**
  - -bricks for high *T* (furnaces)
- **Abrasives**
  - -sandpaper
  - -cutting
  - -polishing
- **Cements**
  - -composites
  - -structural
- **Carbon**
  - - diamond
  - - graphite
  - - carbon fiber
- **Advanced ceramics**
  - -engine rotors valves bearings
  - -sensors

Adapted from Fig. 14.14 and discussion in Section 14.10-16, *Callister & Rethwisch 9e.*

Figure 14.14 용도에 따라 분류한 세라믹 재료

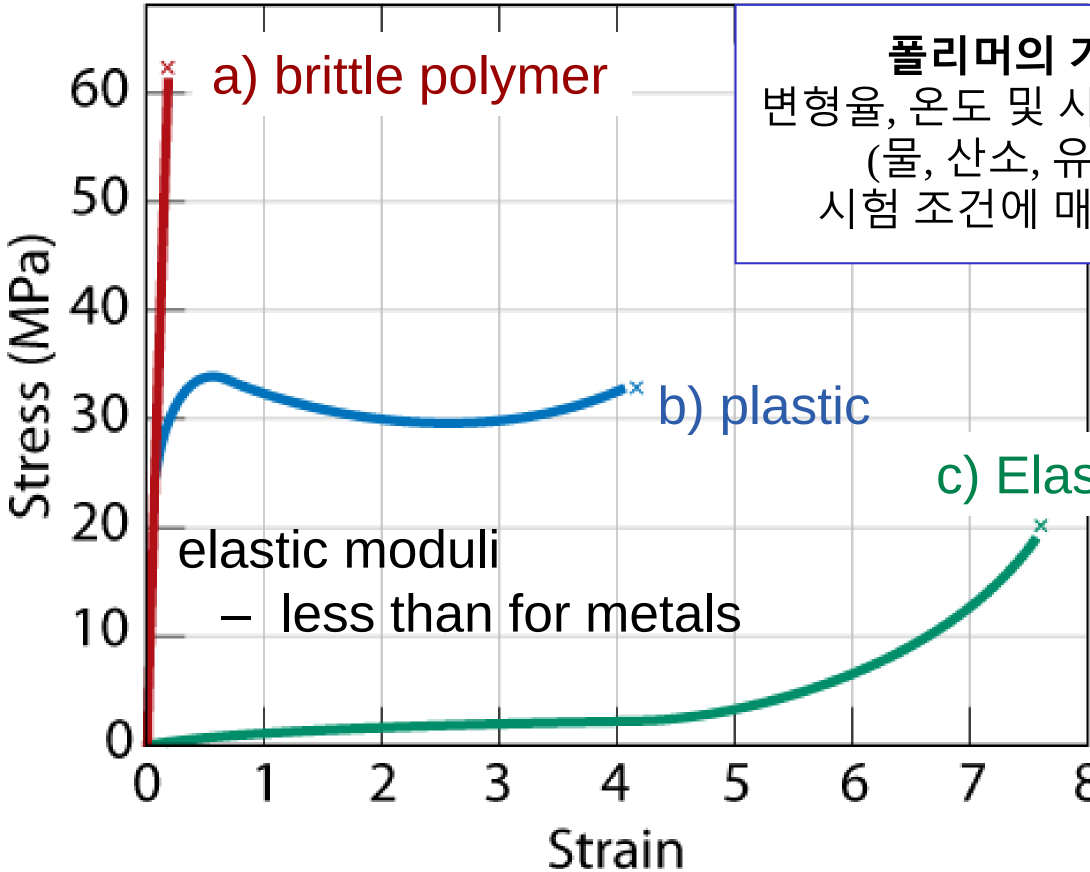
Chapter 15:
Characteristics & Applications of Polymers

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?

1) Mechanical Properties of Polymers – Stress-Strain Behavior

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

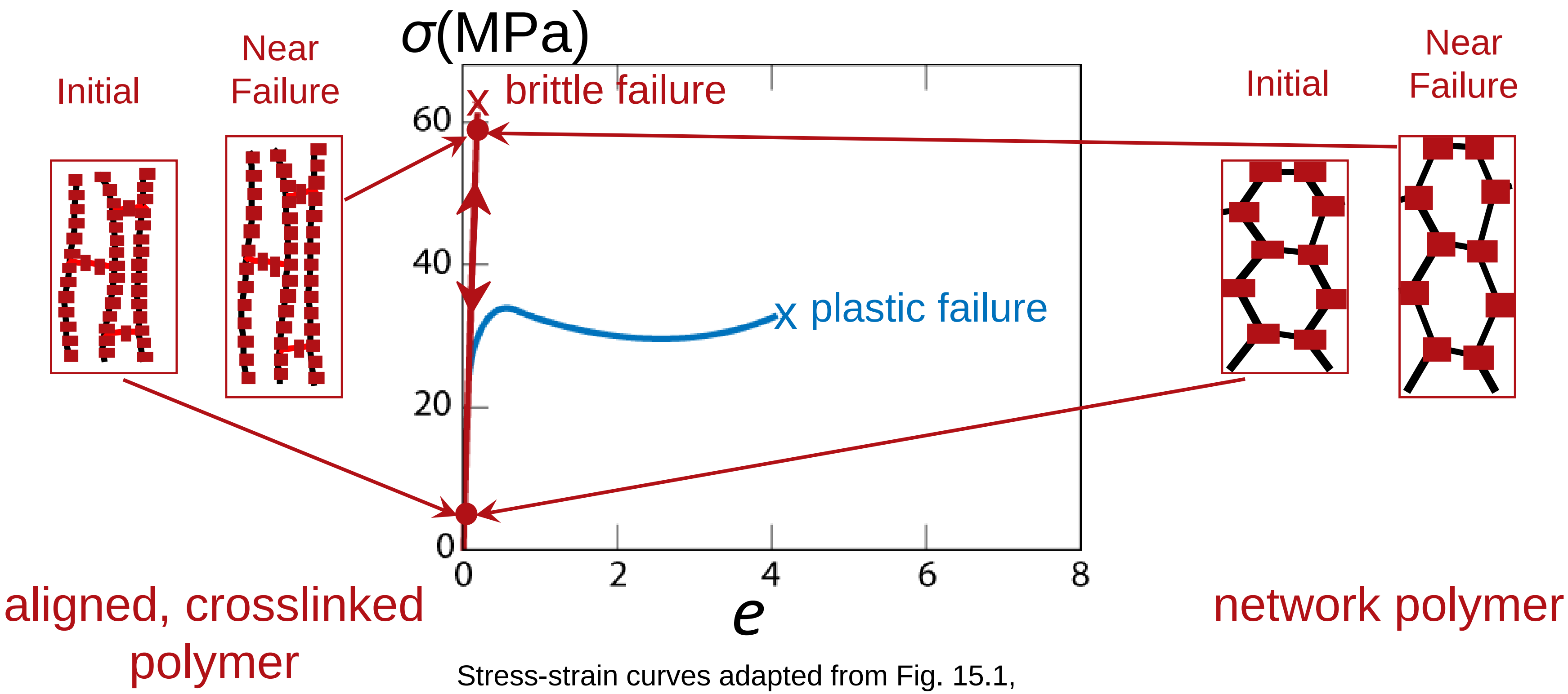


Adapted from Fig. 15.1, *Callister & Rethwisch 9e.*

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

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

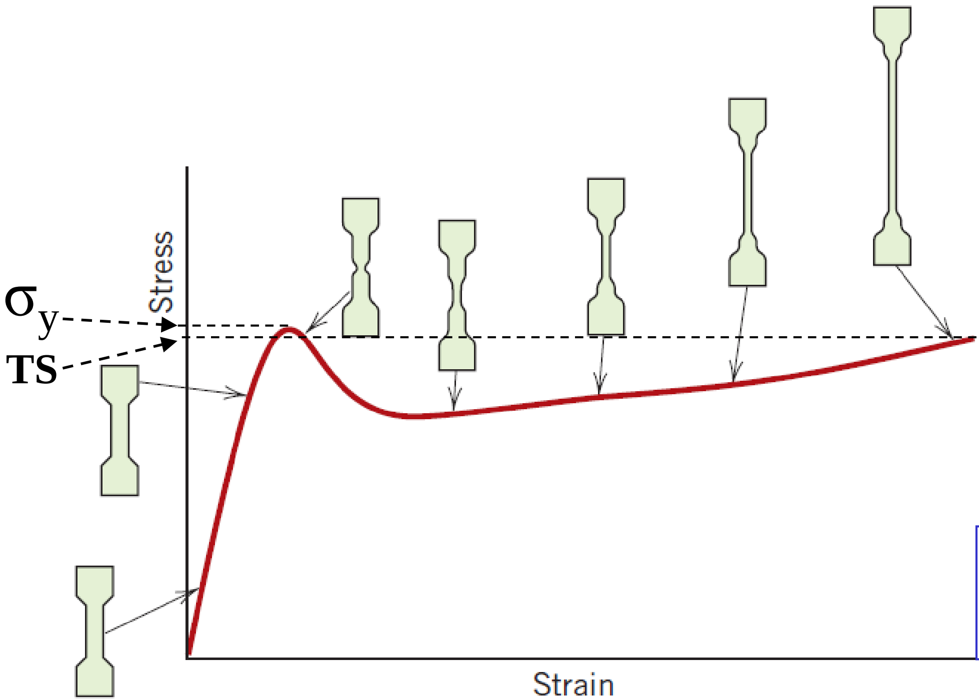
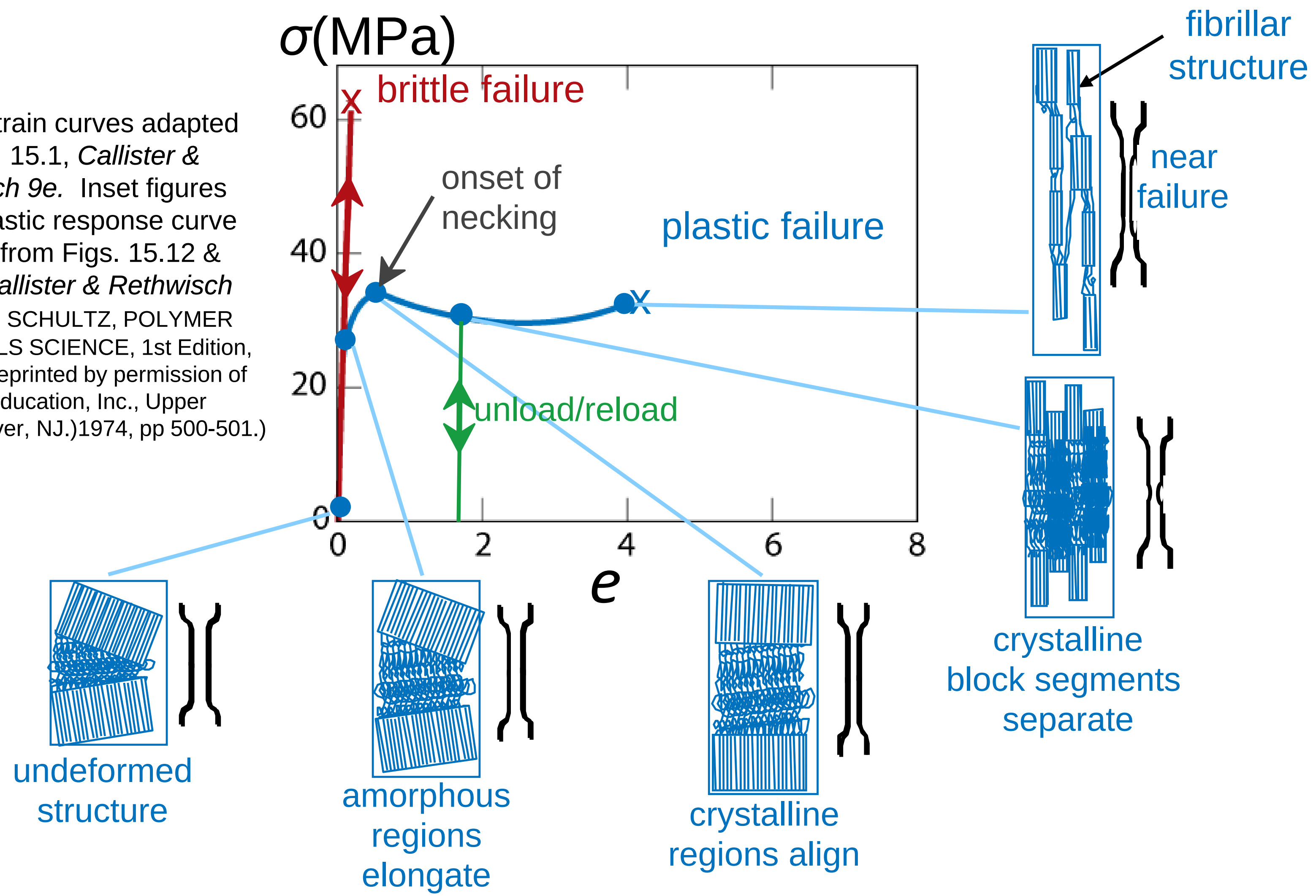


Figure 15.4 Schematic tensile stress–strain curve for a semicrystalline polymer. Specimen contours at several stages of deformation are included. (From Jerold M. Schultz, *Polymer Materials Science*, copyright © 1974, p. 488. Reprinted by permission of Prentice Hall, Inc., Englewood Cliffs, NJ.)

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

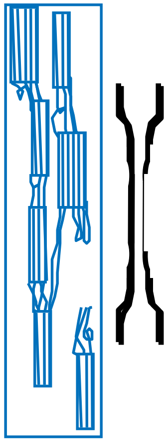
Mechanisms of Deformation —
Semicrystalline (Plastic) Polymers

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.)



Predeformation by Drawing

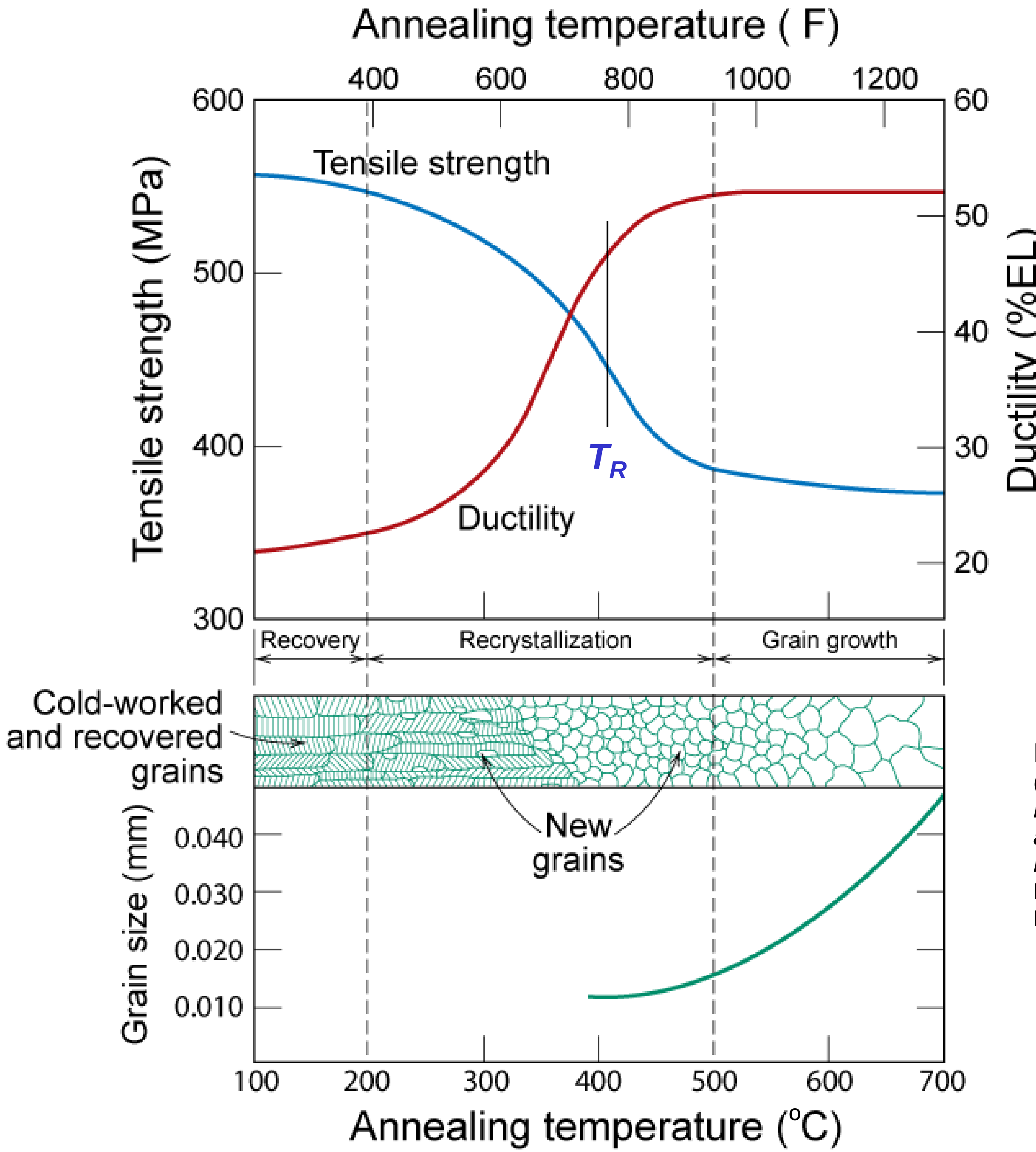
- Drawing…(ex: monofilament fishline)
  -- stretches the polymer prior to use
  -- aligns chains in the stretching direction
- Results of drawing: (E&TS↑, %EL↓)
  -- increases the elastic modulus (*E*) in the stretching direction
  -- increases the tensile strength (*TS*) in the stretching direction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



Adapted from Fig. 15.13, *Callister & Rethwisch 9e*.
(From Schultz, *Polymer Materials Science*, 1st Edition, © 1974. Reprinted by permission of Pearson Education, Inc., Upper Saddle River, NJ.)1974, pp 500-501.)

- 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 + Annealing 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.)

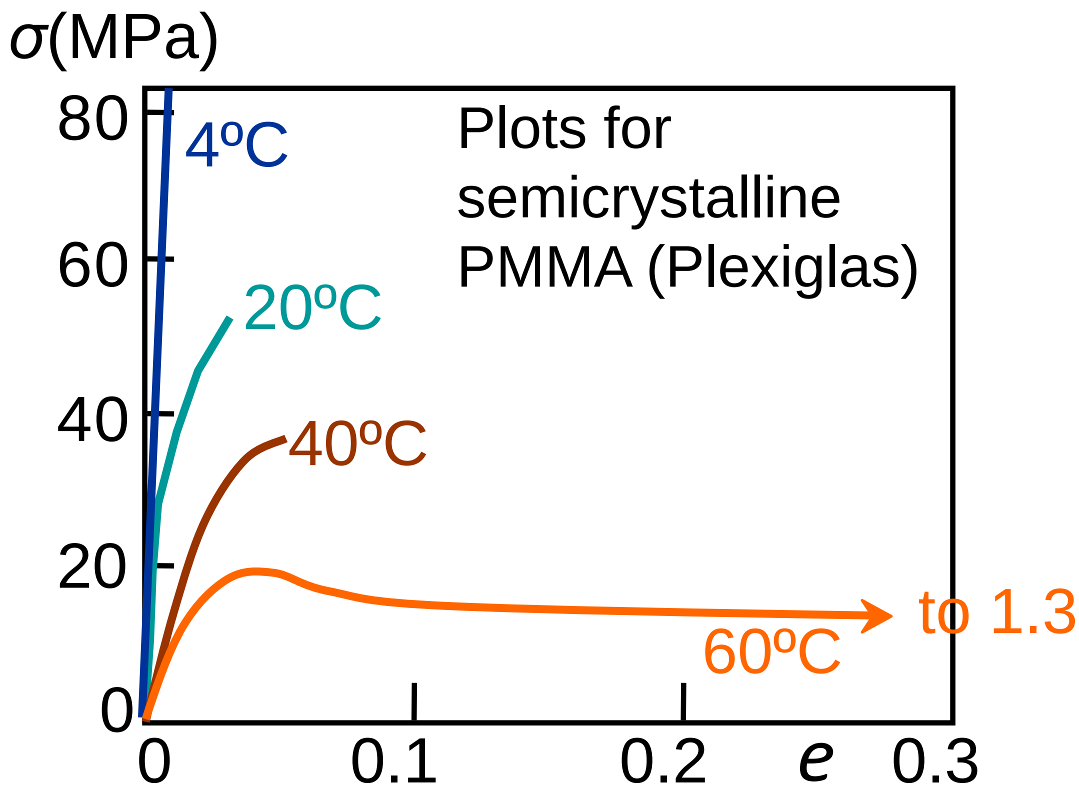
Influence of *T* and Strain Rate on Thermoplastics

- Decreasing *T*...
  - -- increases *E*
  - -- increases *TS*
  - -- decreases %*EL*

  (E&TS↑, %EL↓)

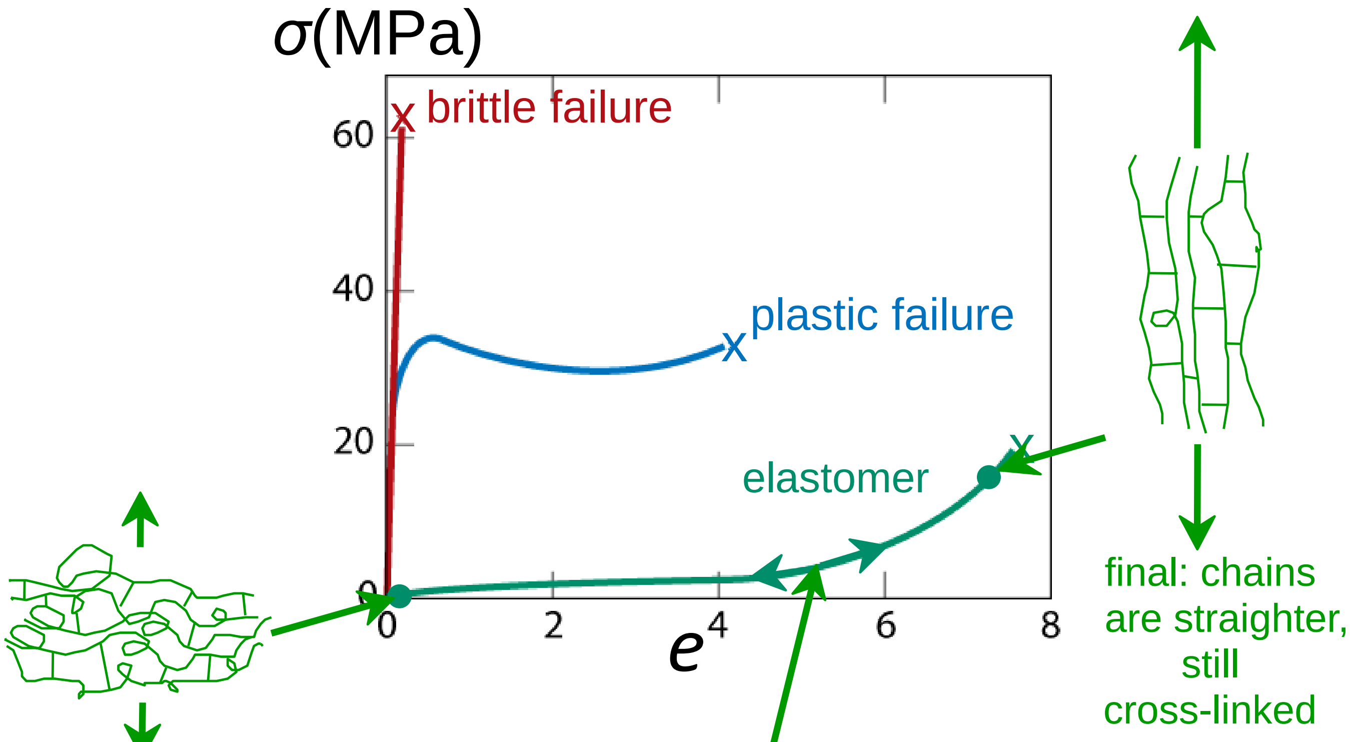
- Increasing strain rate...
  - -- same effects as decreasing *T*.

  (E&TS↑, %EL↓)



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.)

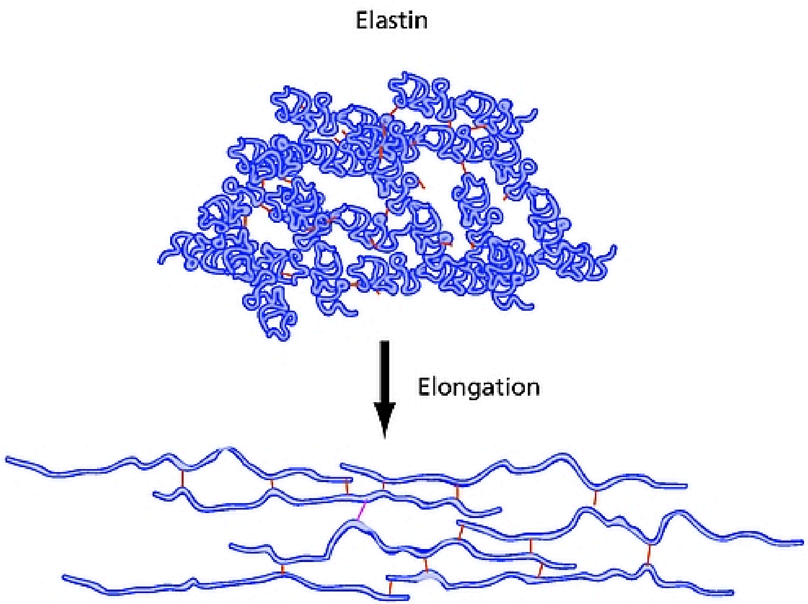
Mechanisms of Deformation—c) Elastomers

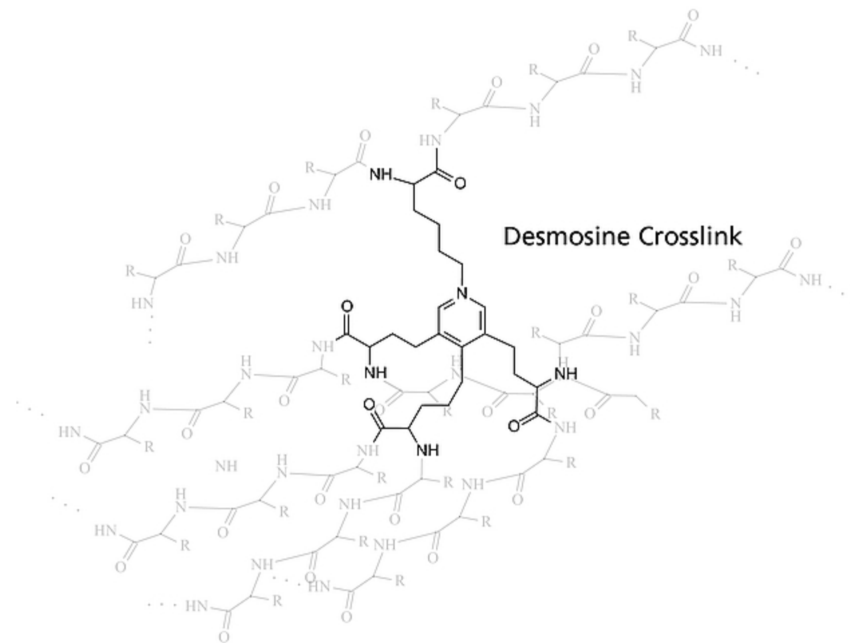


Stress-strain curves adapted from Fig. 15.1, *Callister & Rethwisch 9e.* Inset figures along elastomer curve (green) adapted from Fig. 15.15, *Callister & Rethwisch 9e*. (Fig. 15.15 adapted from Z. D. Jastrzebski, The Nature and Properties of Engineering Materials, 3rd edition. Copyright © 1987 by John 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)

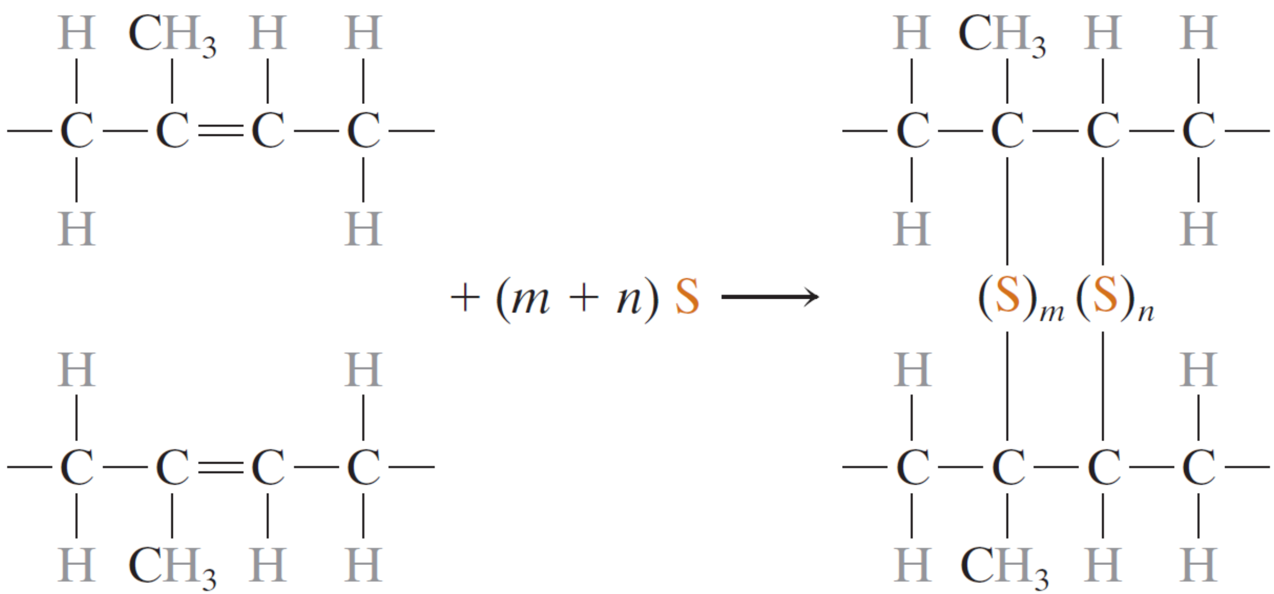
Elastin is a highly elastic protein in connective tissue and allows many tissues in the body to resume their shape after stretching or contracting. Elastin helps skin to return to its original position when it is poked or pinched.





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:



(15.4)

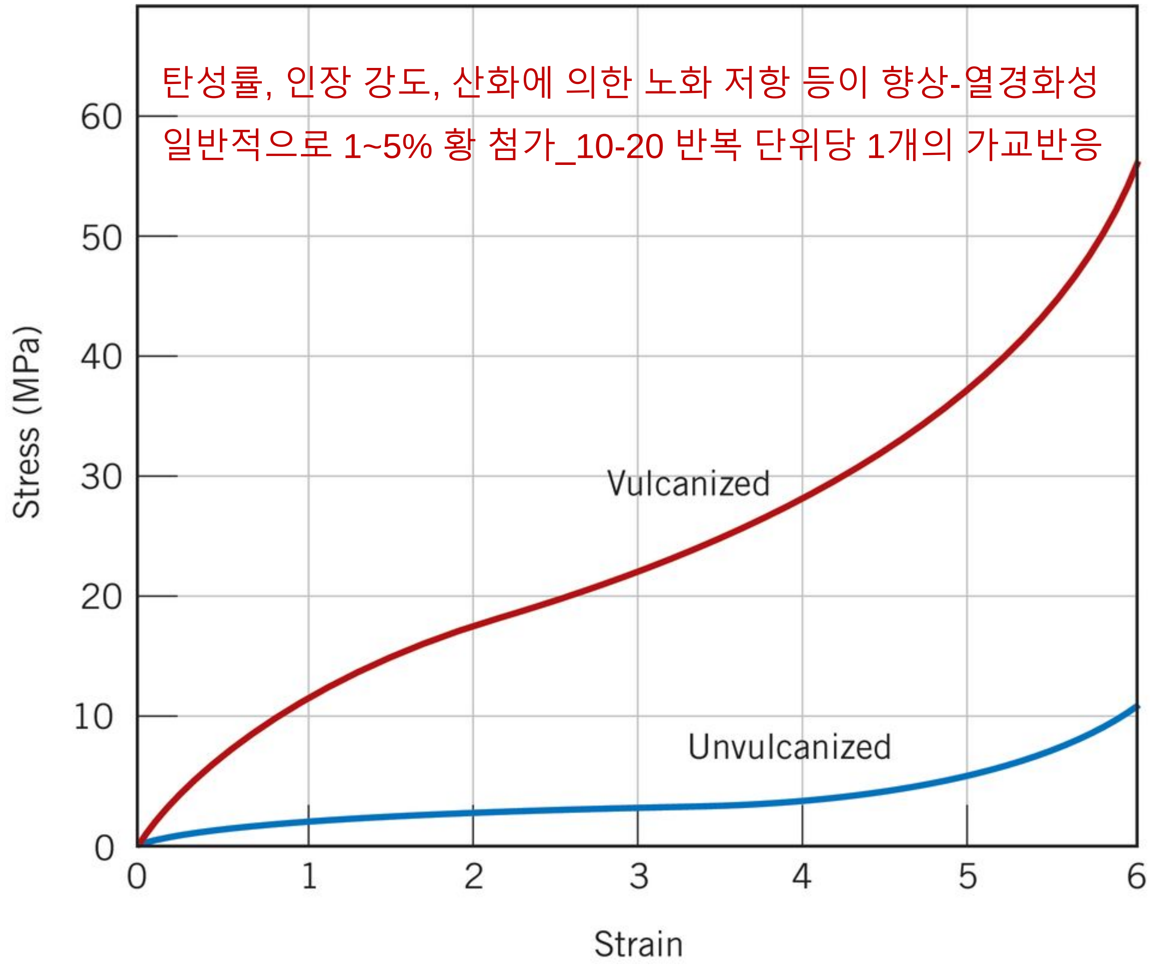


그림 15.16 가황되지 않은 천연 고무와 가황된 천연 고무를 600% 연신시켰을 때 응력-변형률 곡선

폴리머 재료의 점탄성 거동: 시간과 온도에 따라 변화

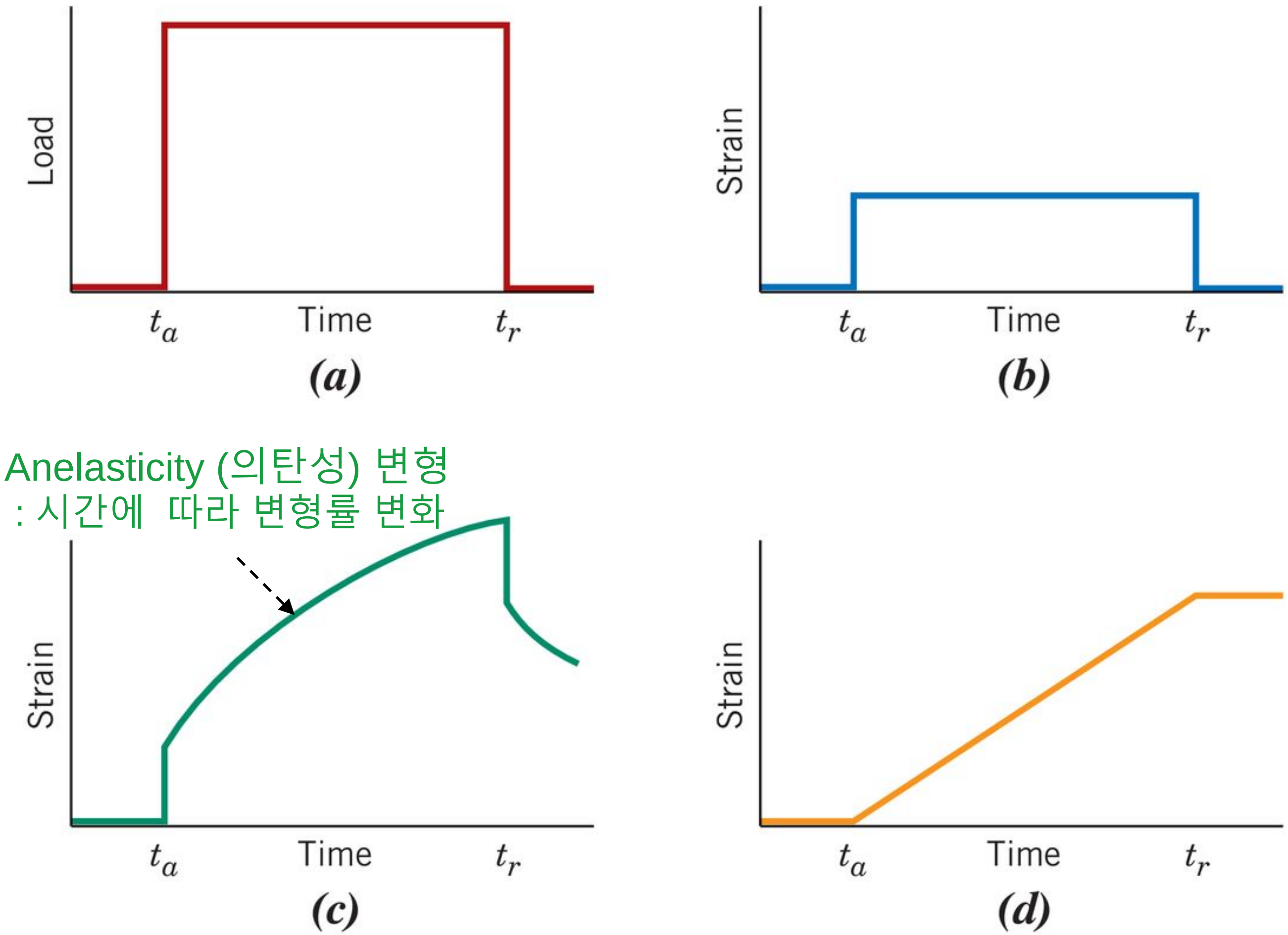


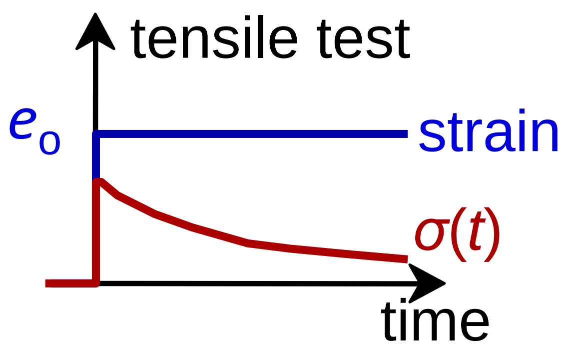
그림 15. 5 (a) 하중-시간 거동. 하중이 t_a에서 순간적으로 가해지고 t_r에서 제거된다. 변형률-시간, (b) 완전탄성체, (c) 점탄성 (e.g. 규소 폴리머), (d) 점성 거동

Time-Dependent Deformation

- Stress relaxation test:

  -- strain in tension to e_o and hold.

  -- observe decrease in stress with time.



- Relaxation modulus:

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

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

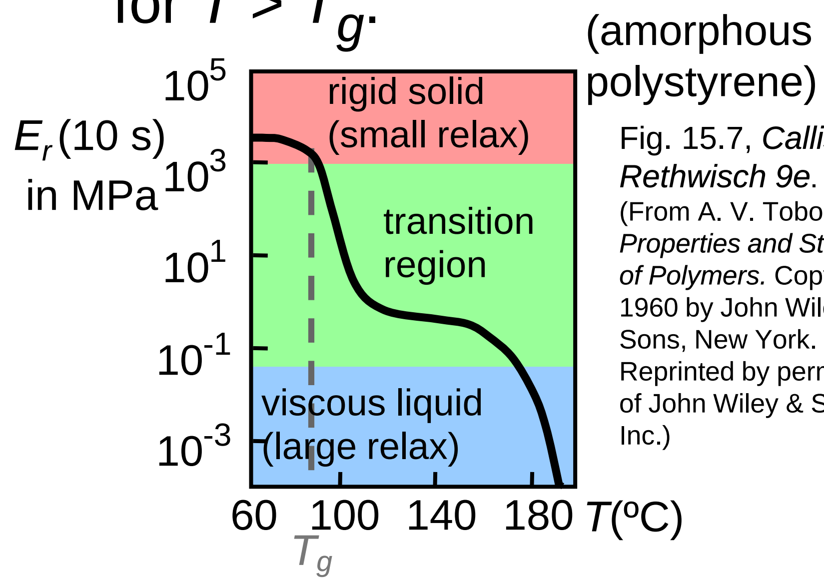


Fig. 15.7, *Callister & Rethwisch 9e*. (From A. V. Tobolsky, *Properties and Structures of Polymers*. Copyright © 1960 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

- Representative T_g values (°C):

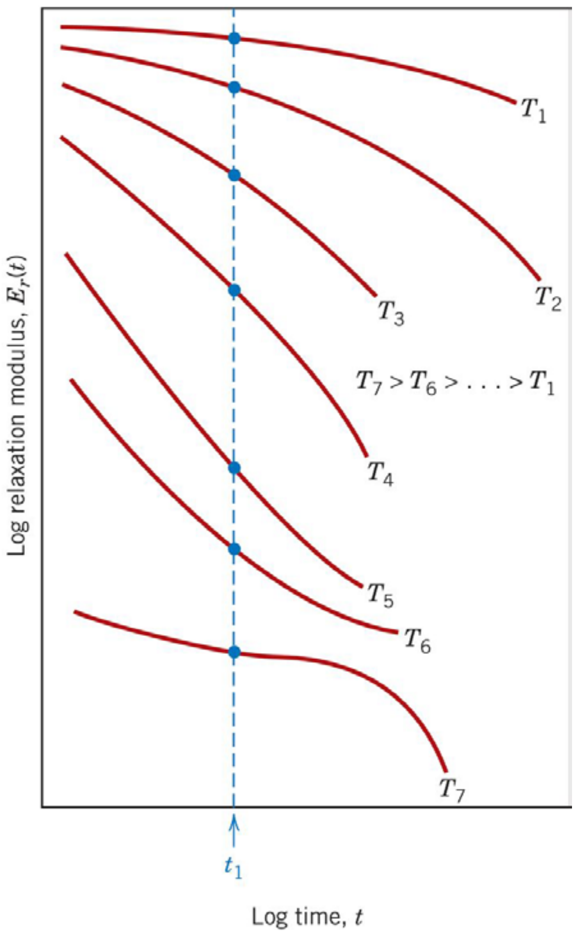
PE (low density)	- 110
PE (high density)	- 90
PVC	+ 87
PS	+100
PC	+150

Selected values from Table 15.2, *Callister & Rethwisch 9e*.

폴리머 재료의 점탄성 거동: 시간과 온도에 따라 변화

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

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



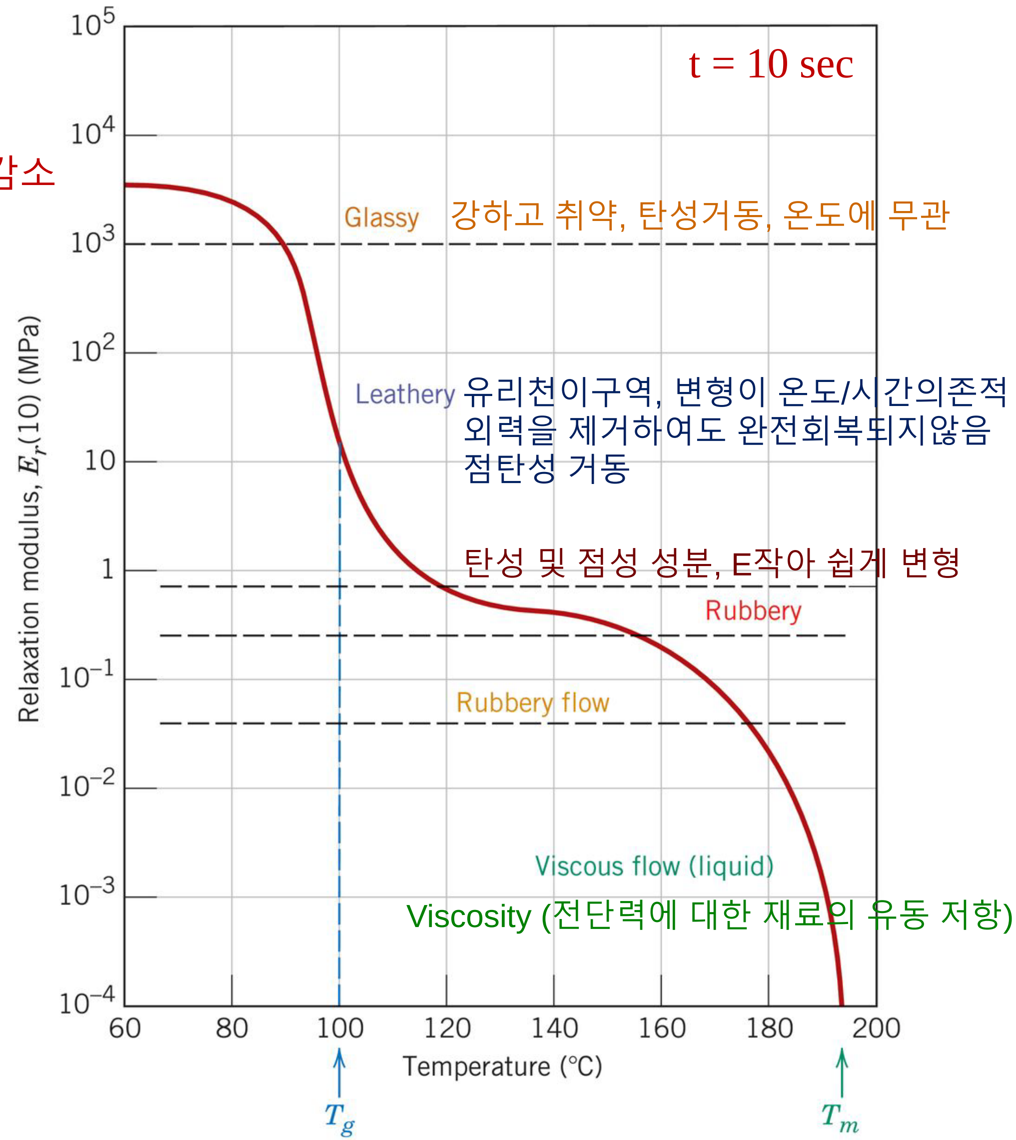


그림 15.6 탄성 폴리머의 이완계수로 로그값과 시간 로그값의 모식적 관계. 온도를 T_1에서 T_7까지 변화시킴. 이완계수의 온도 의존성은 log $E_r(t_1)$ 온도로 나타냄.

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

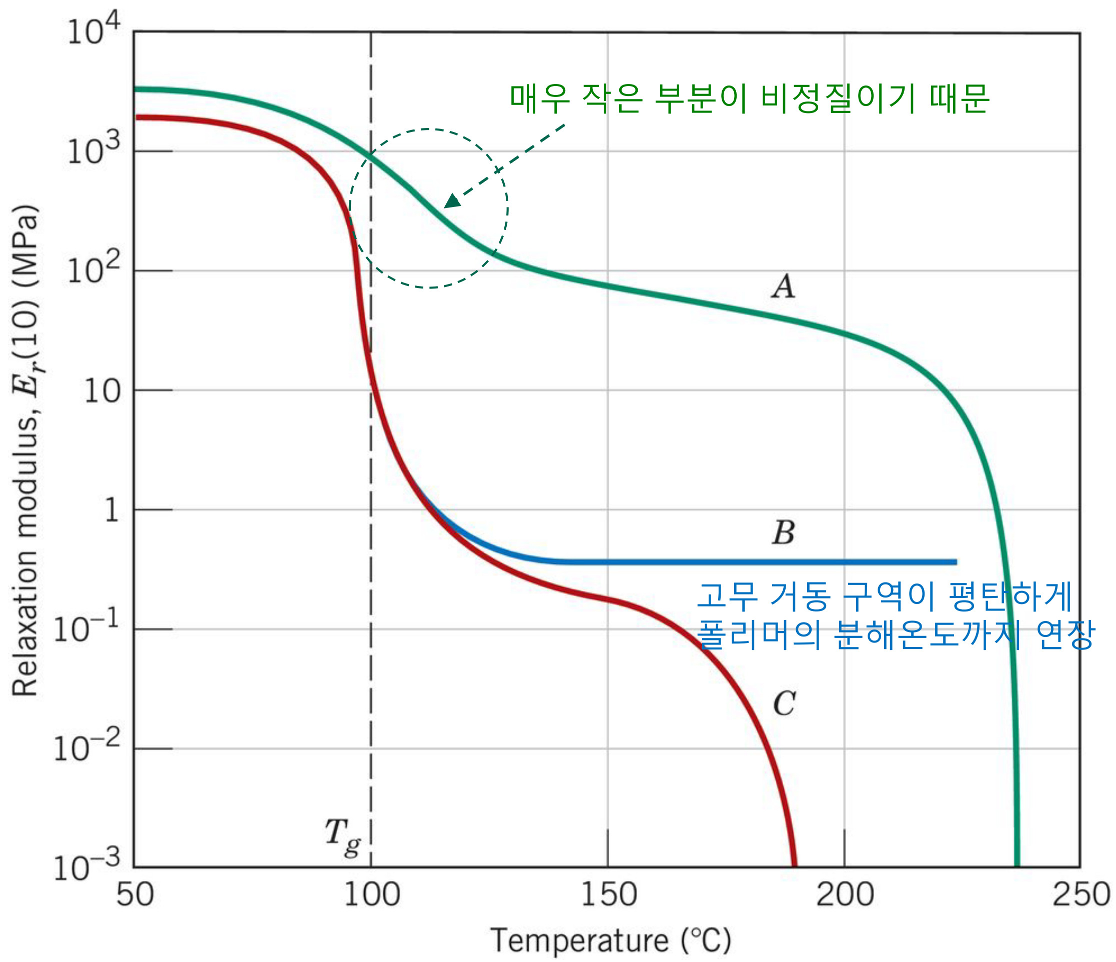
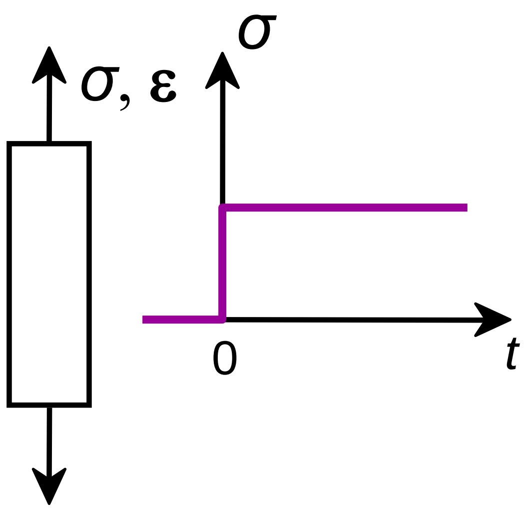


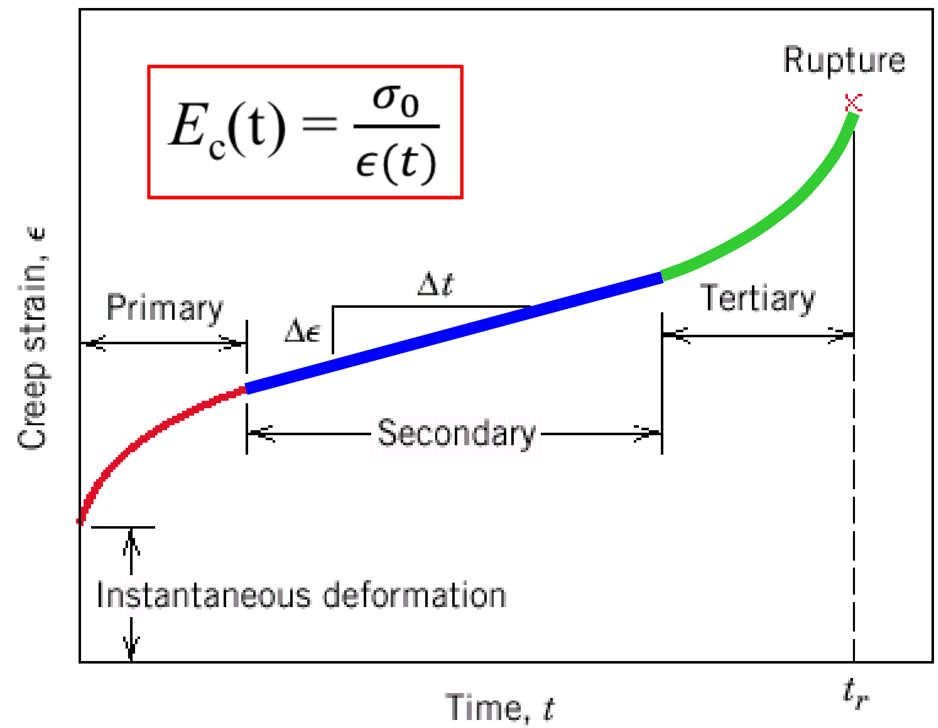
그림 15.8 결정질 이소택틱 (A곡선), 약하게 가교 결합된 어택틱 (B 곡선),

비정질 (C 곡선) 폴리스티렌의 이완 계수 로그값과 온도 관계

점탄성 크리프 (Viscoelastic creep)

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





일정 응력하에서 변형률을 시간의 함수로 측정

Primary Creep: slope (creep rate) decreases with time.

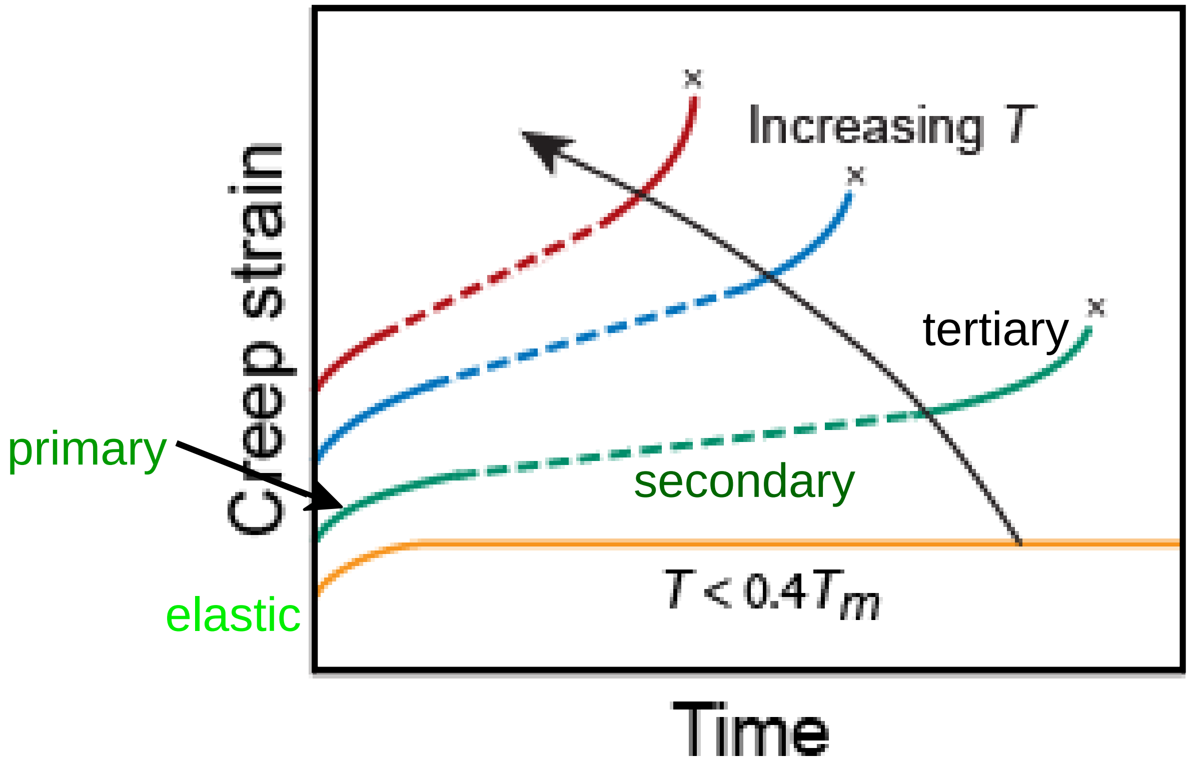
Secondary Creep: steady-state i.e., constant slope ($\Delta\,\varepsilon\,/\Delta t$).

Tertiary Creep: slope (creep rate) increases with time, i.e. acceleration of rate.

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

Creep: Temperature Dependence

- Occurs at elevated temperature, $T > 0.4\ T_m$ (in K)



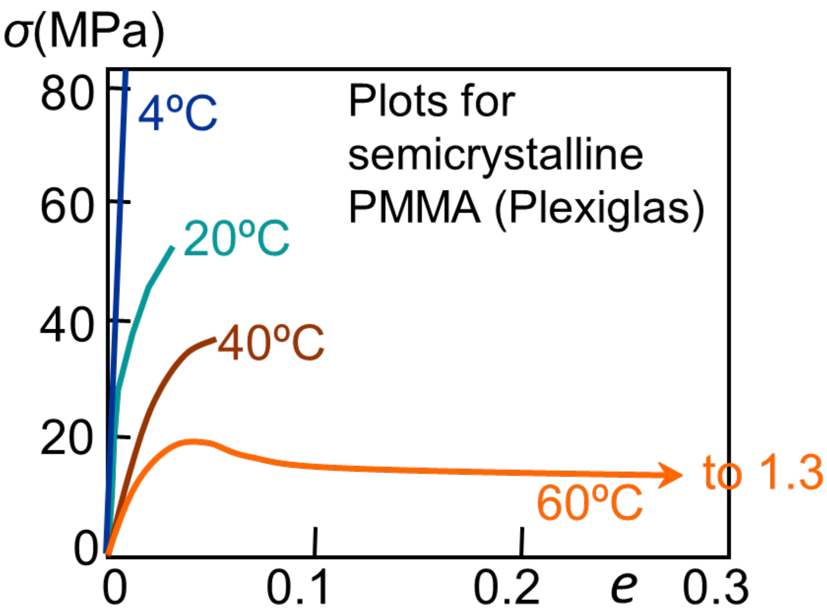
Figs. 10.30, *Callister & Rethwisch 9e.*

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.)

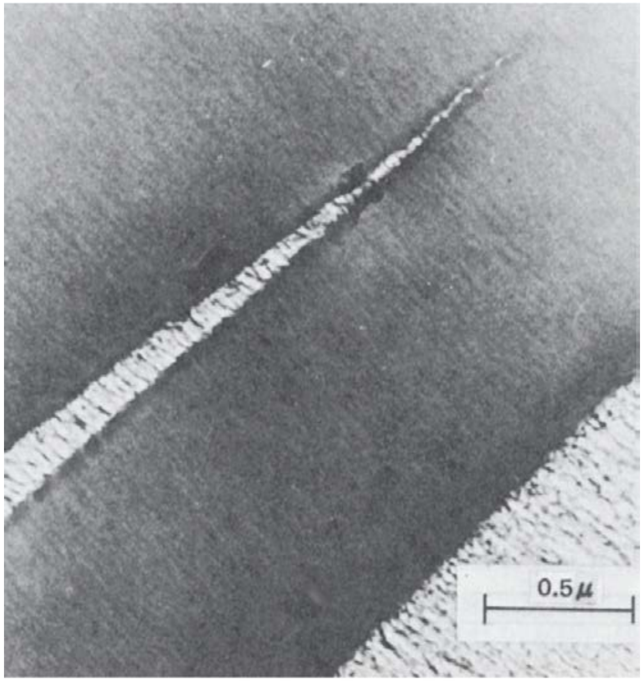


그림 15.10 폴리페닐린 산화물 내의 잔금 사진

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

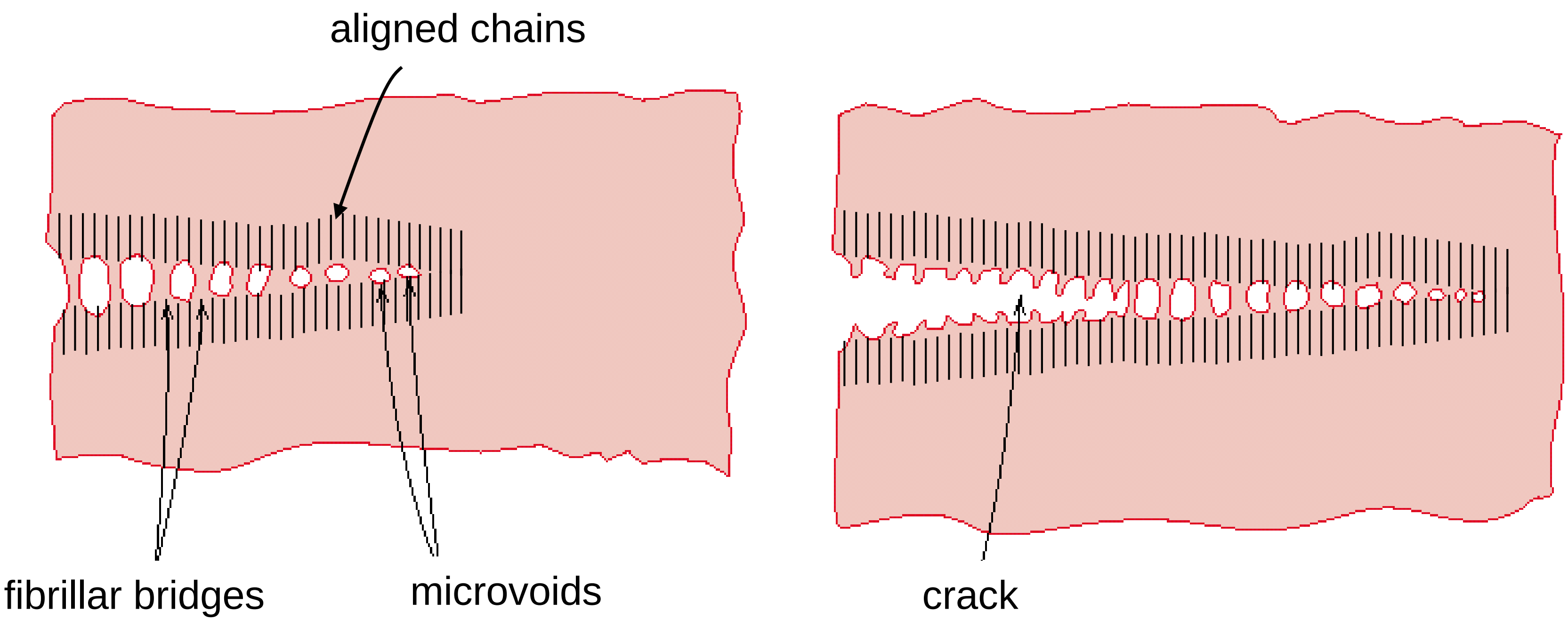
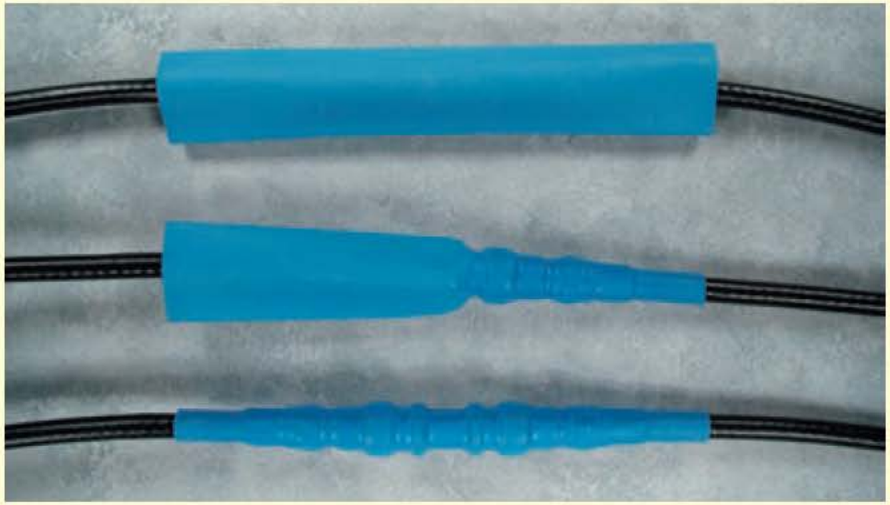


Fig. 15.9, *Callister & Rethwisch 9e.*
(From J. W. S. Hearle, *Polymers and Their Properties*, Vol. 1, *Fundamentals of Structure and Mechanics*, Ellis Horwood, Ltd., Chichester, West Sussex, England, 1982.)

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 150ºC, 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.)

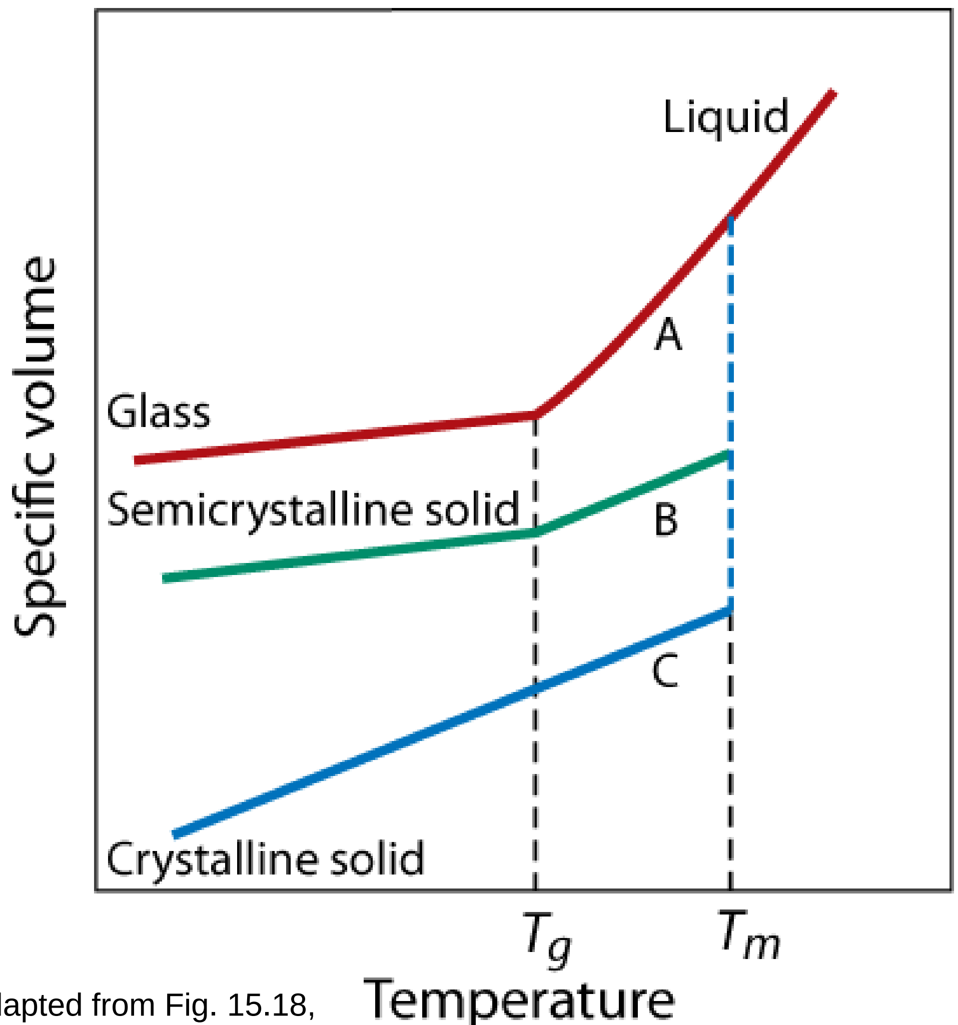
Melting & Glass Transition Temps.

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 9e.*

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

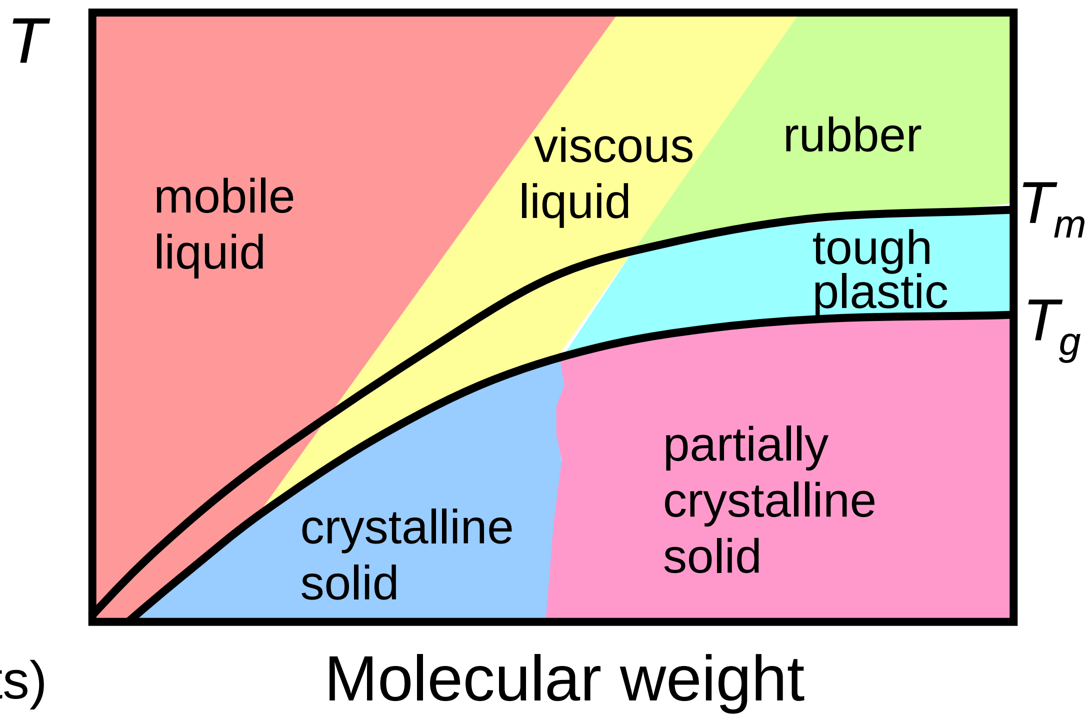
Material	*Glass Transition Temperature [°C (°F)]*	*Melting Temperature [°C (°F)]*
Polyethylene (low density)	−110 (−165)	115 (240)
Polytetrafluoroethylene	−97 (−140)	327 (620)
Polyethylene (high density)	−90 (−130)	137 (279)
Polypropylene	−18 (0)	175 (347)
Nylon 6,6	57 (135)	265 (510)
Poly(ethylene terephthalate)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

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



Adapted from Fig. 15.19, *Callister & Rethwisch 9e.*
(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.)

Summary I

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

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

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

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

Table 15.3 *Callister & Rethwisch 9e*:

Good overview of applications and trade names of polymers.

Chapter 16: Composite Materials

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

- 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

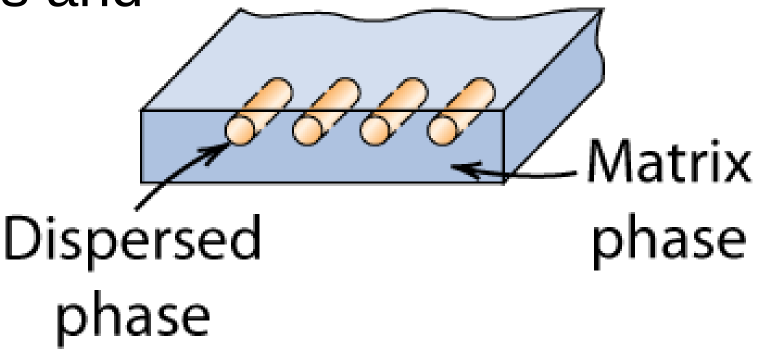
- Composite:

  -- 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

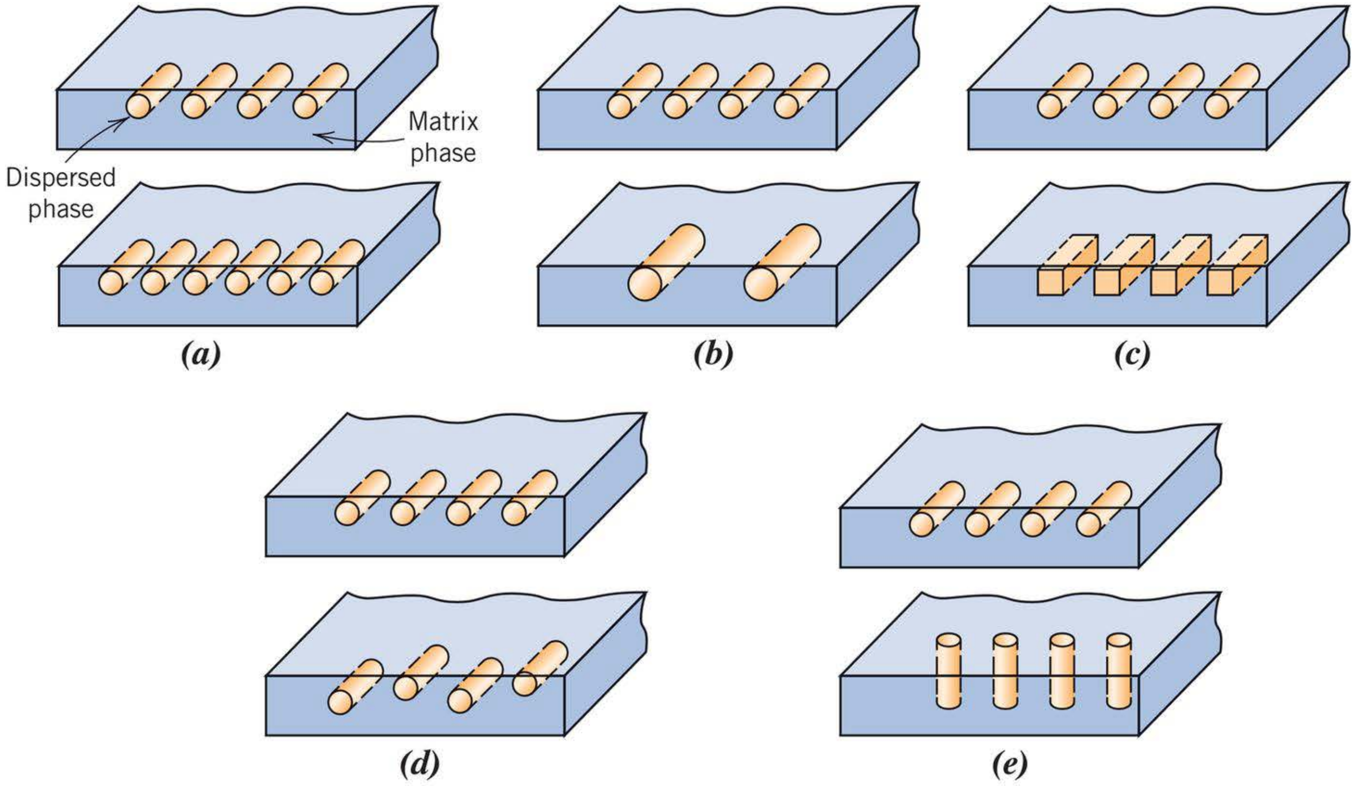


그림 16.1 복합재료 특성에 영향을 미치는 분산상 입자의 기하학적·공간적 특성에 대한 모식적 표현

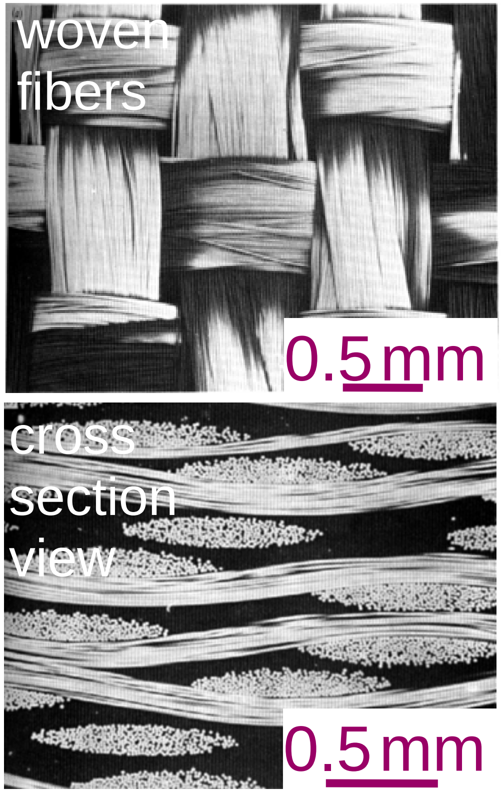
(a) 농 도, (b) 크 기, (c) 형 상, (d) 분 포, (e) 배 향

Terminology/Classification

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

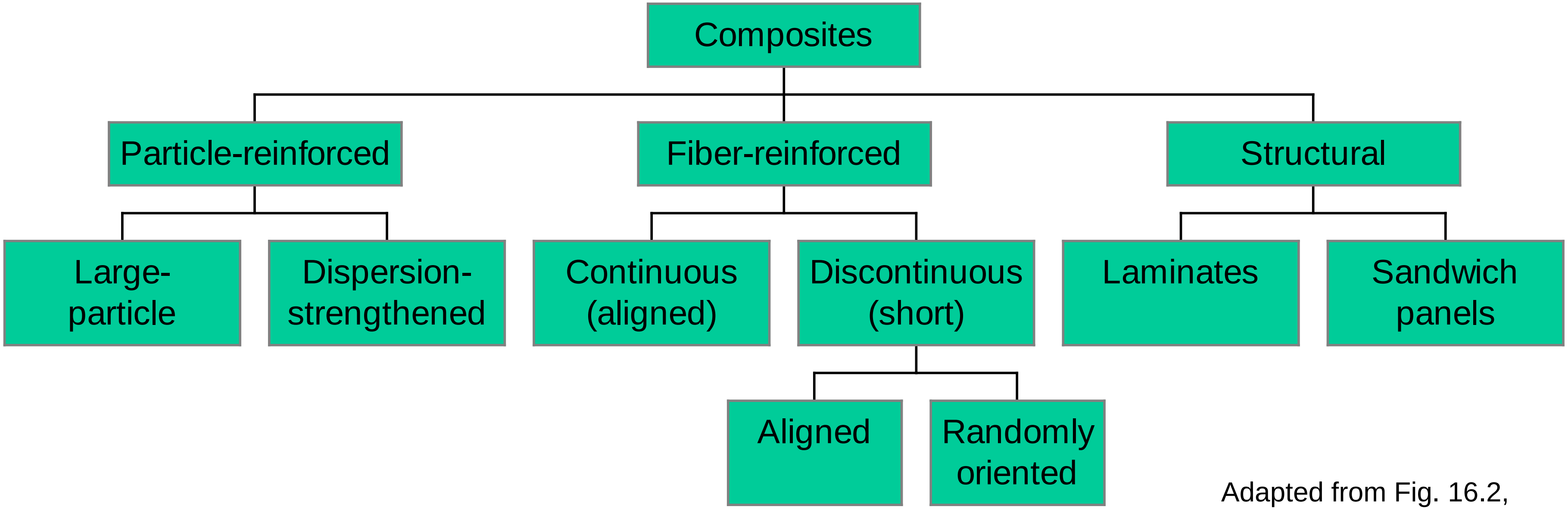
    metal ceramic polymer

- 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



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 9e*.

Classification: Particle-Reinforced (i)

Particle-reinforced | Fiber-reinforced | Structural

- Examples:
  - Spheroidite steel
    - matrix: ferrite (α) (ductile)
    - particles: cementite (Fe_3C) (brittle)

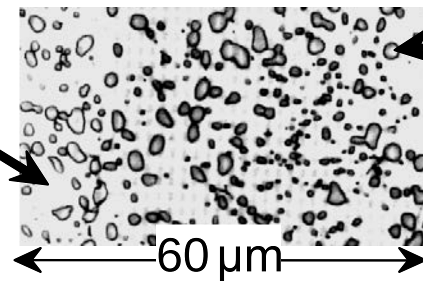


Fig. 17.12, *Callister & Rethwisch 9e*. (Copyright 1971 by United States Steel Corporation.)

  - WC/Co cemented carbide
    - matrix: cobalt (ductile, tough)
    - particles: WC (brittle, hard)

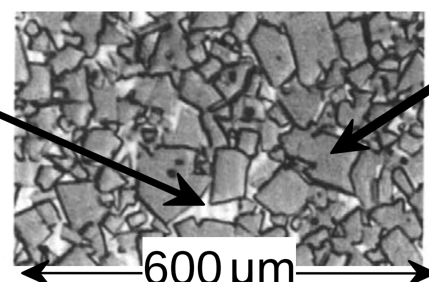


Fig. 16.4, *Callister & Rethwisch 9e*. (Courtesy of Carboloy Systems Department, General Electric Company.)

  - Automobile tire rubber
    - matrix: rubber (compliant)
    - particles: carbon black (stiff)

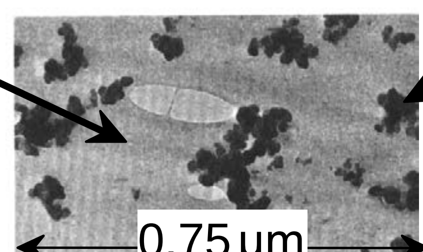


Fig. 16.5, *Callister & Rethwisch 9e*. (Courtesy of Goodyear Tire and Rubber Company.)

Classification: Particle-Reinforced (ii)

Particle-reinforced | Fiber-reinforced | Structural

Concrete – gravel + sand + cement + water

- Why sand *and* gravel? Sand fills voids between gravel particles

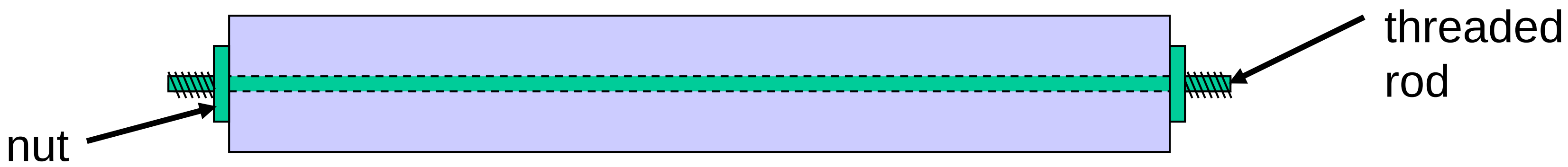
Reinforced concrete – Reinforce with steel rebar or remesh

- 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



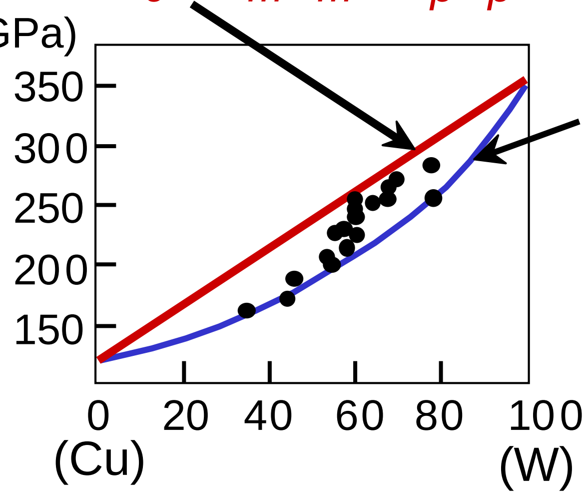
Classification: Particle-Reinforced (iii)

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



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.

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

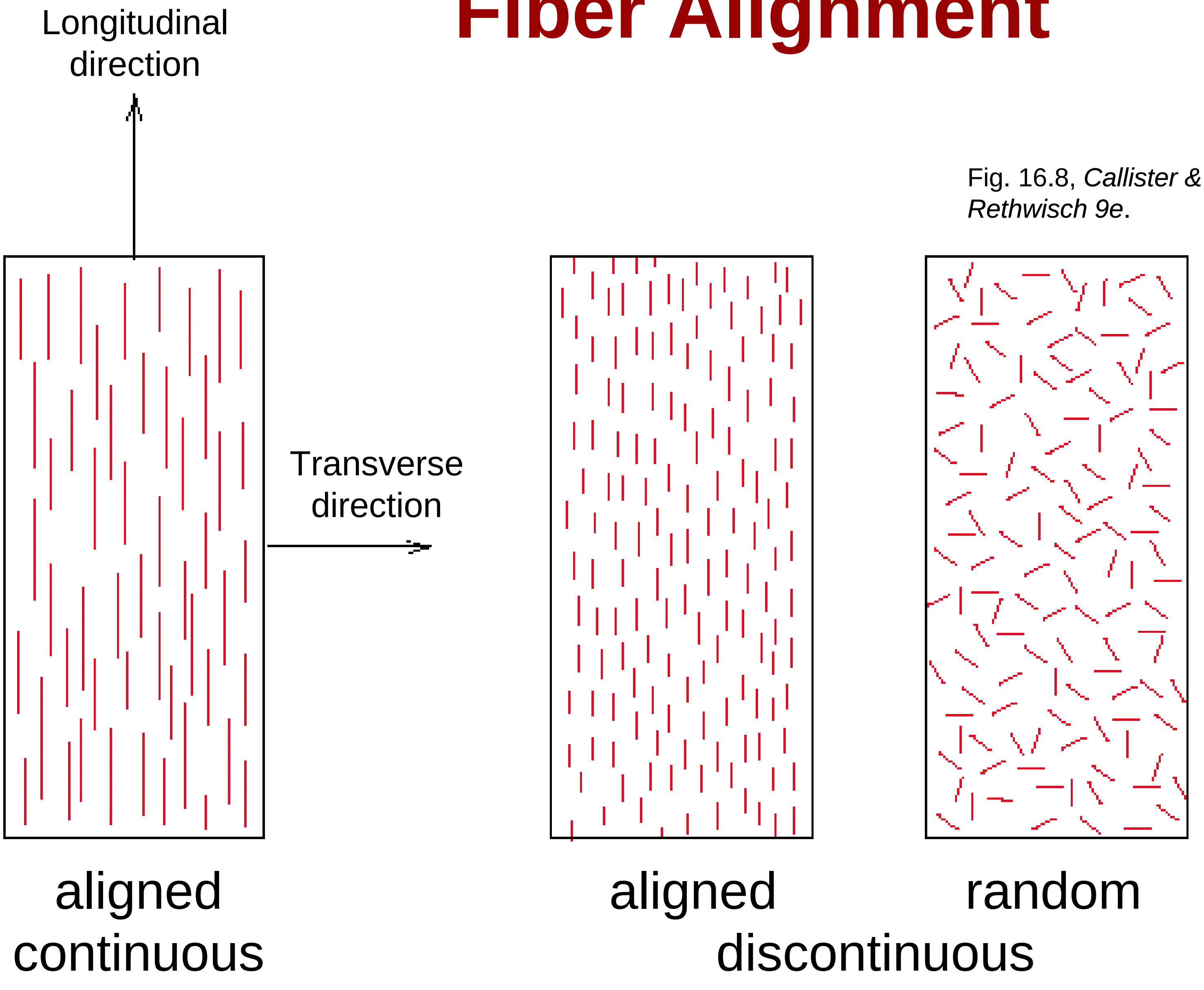


Fig. 16.8, *Callister & Rethwisch 9e*.

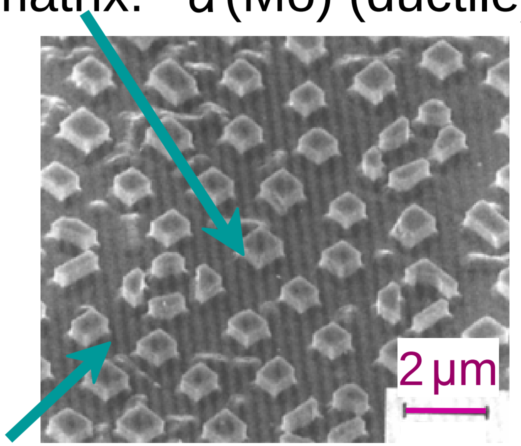
Classification: Fiber-Reinforced (iii)

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

- Aligned Continuous fibers
- Examples:

-- Metal: γ'(Ni_3Al)-α(Mo) by eutectic solidification.

matrix: α(Mo) (ductile)

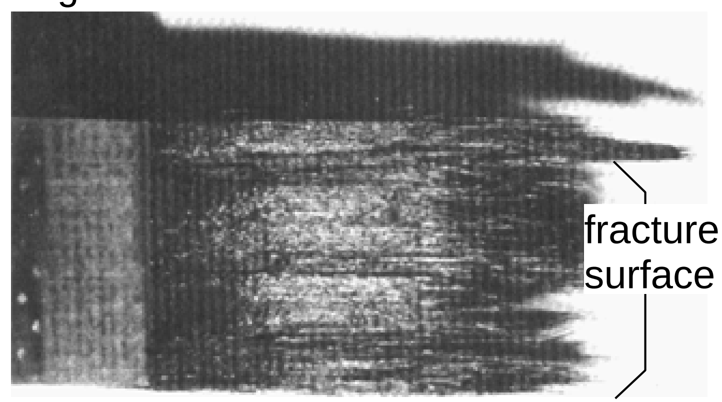


fibers: γ' (Ni_3Al) (brittle)

From W. Funk and E. Blank, "Creep deformation of Ni_3Al-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.



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.

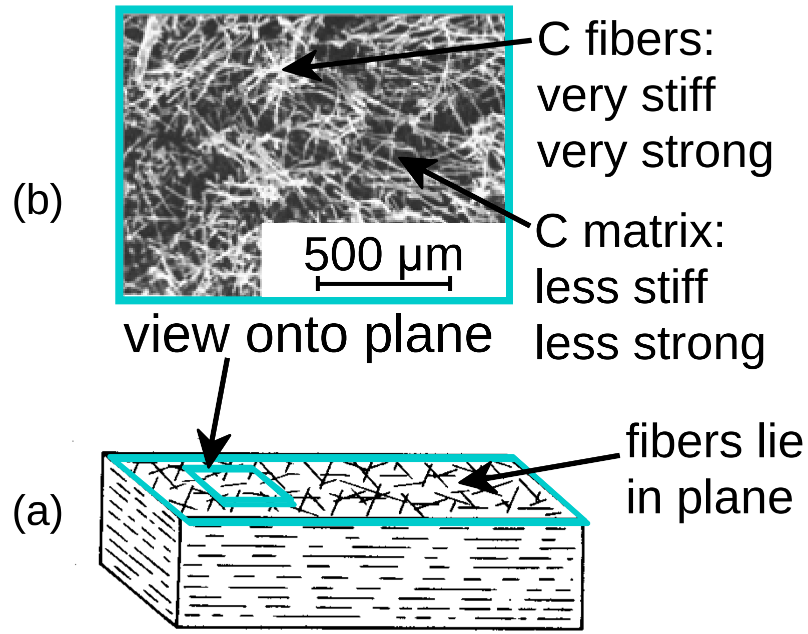
Classification: Fiber-Reinforced (iv)

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.



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.

- Other possibilities:
  -- Discontinuous, random 3D
  -- Discontinuous, aligned

Classification: Fiber-Reinforced (v)

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

- Critical fiber length for effective stiffening & strengthening:

fiber ultimate tensile strength

fiber diameter

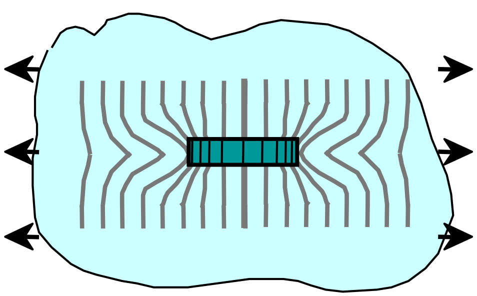
$$\text{fiber length} > \frac{\sigma_f d}{2\tau_c}$$

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:

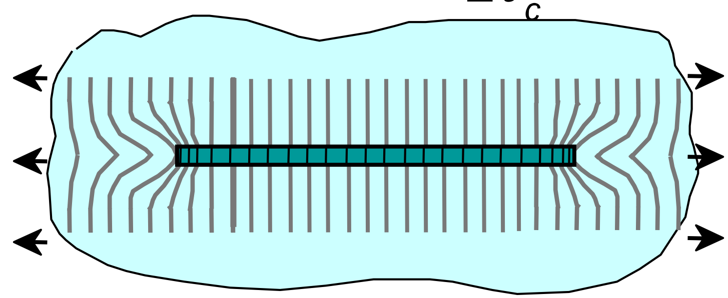
$$\text{fiber length} < \frac{\sigma_f d}{2\tau_c}$$



Low fiber efficiency

Long, thin fibers:

$$\text{fiber length} > \frac{\sigma_f d}{2\tau_c}$$



High fiber efficiency

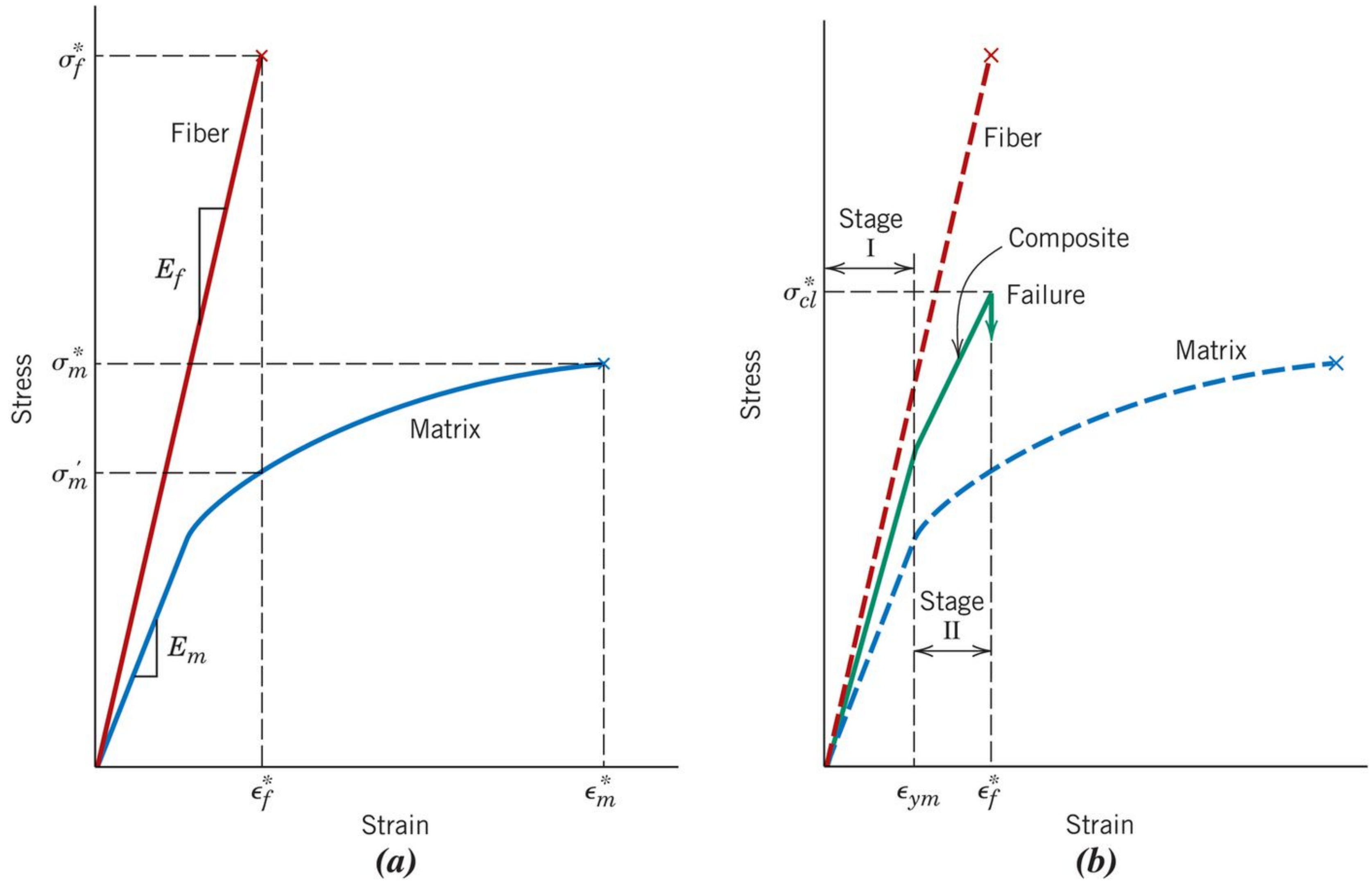


그림 16.9 (a) 취성의 섬유와 연성의 기지 재료의 응력-연신율 커브의 모식도. 이들 재료의 파단 응력과 연신율이 나타나 있다. (b) 섬유의 정렬 방향으로 일축응력이 가해진 조건에서 정렬된 섬유강화 복합재료의 응력-변형률 모식도. (a)에 나타낸 섬유와 기지 재료의 커브를 중첩하여 나타냈다.

Composite Stiffness: Longitudinal Loading

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

- Longitudinal deformation

$$\sigma_c = \sigma_m V_m + \sigma_f V_f \quad \text{and} \quad e_c = e_m = e_f$$

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

$e_c = e_m V_m + e_f V_f$ and $\sigma_c = \sigma_m = \sigma_f = \sigma$

isostress

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

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

E_{ct} = transverse modulus

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 $\sigma^*_{cd'}$ 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 $l < l_c$

$$\sigma^*_{cd'} = \frac{l \tau_c}{d} V_f + \sigma'_m (1 - V_f)$$

Composite Production Methods (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

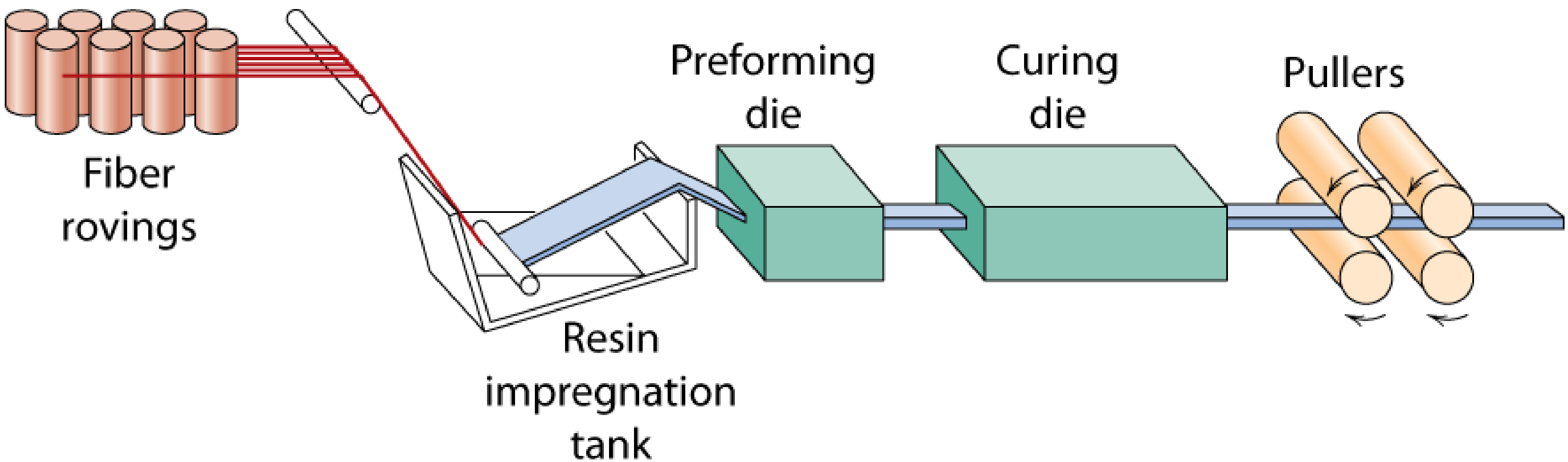
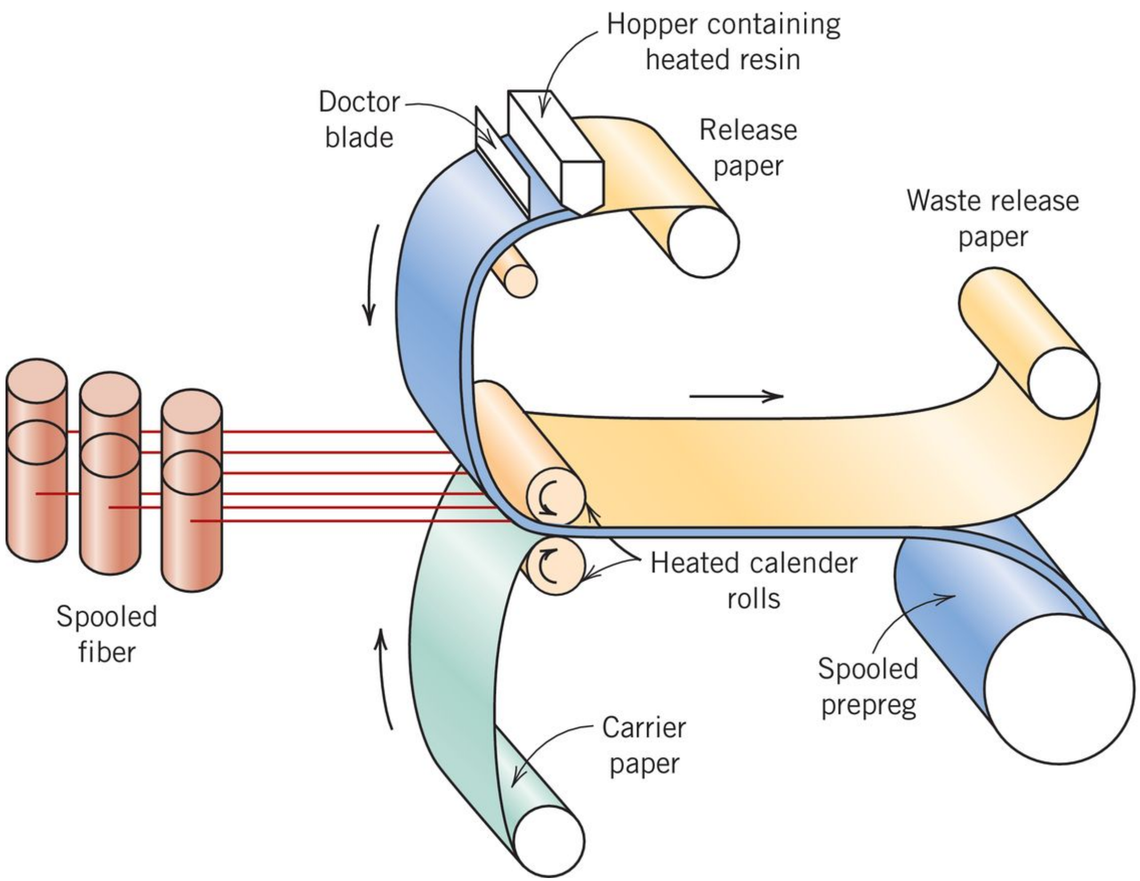


Fig. 16.13, *Callister & Rethwisch 9e*.

Fiber-reinforced

Composite Production Methods (ii)

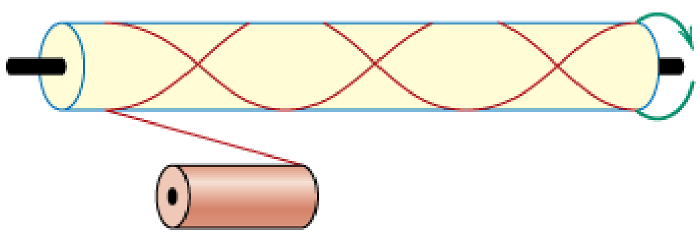
Prepreg (예비 함침 제조 공정)

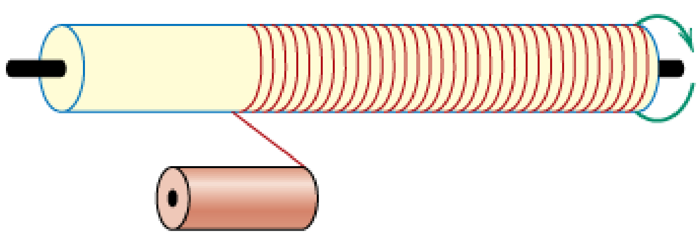


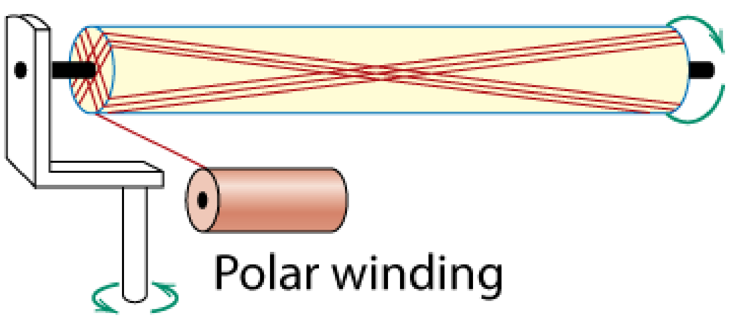
Composite Production Methods (iii)

- 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

Fig. 16.15, *Callister & Rethwisch 9e*.
[From N. L. Hancox, (Editor), *Fibre Composite Hybrid Materials*, The Macmillan Company, New York, 1981.]


Helical winding


Circumferential winding


Polar winding

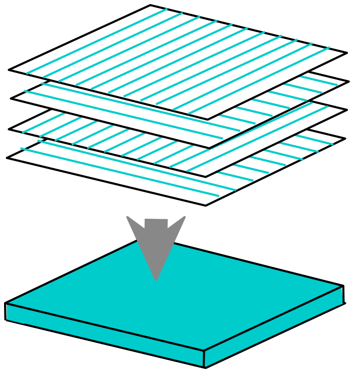
Classification: Structural

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

- Laminates -

  -- stacked and bonded fiber-reinforced sheets

  - stacking sequence: e.g., 0º/90º
  - 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

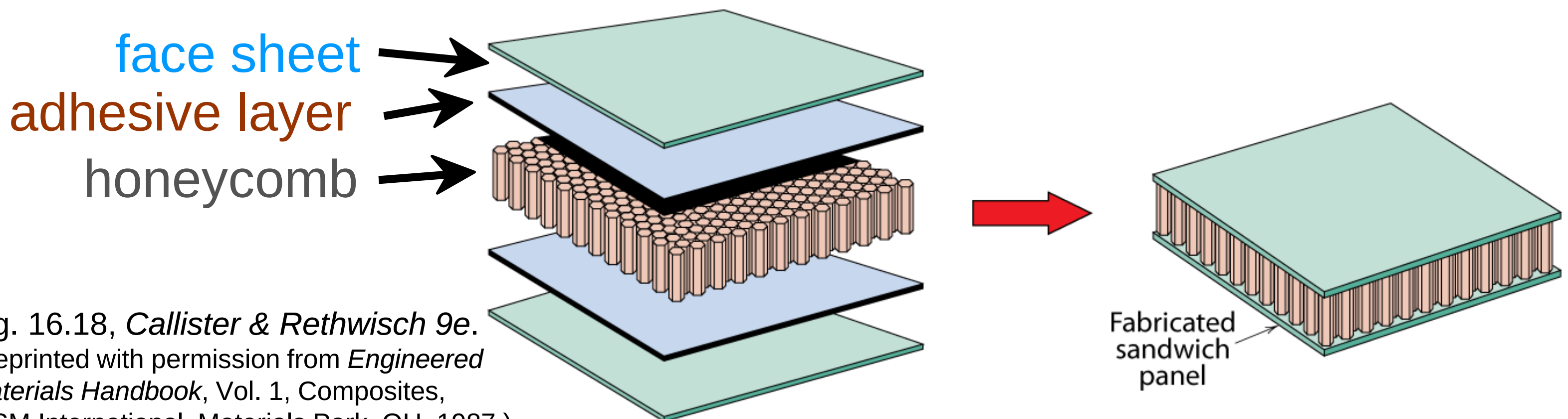
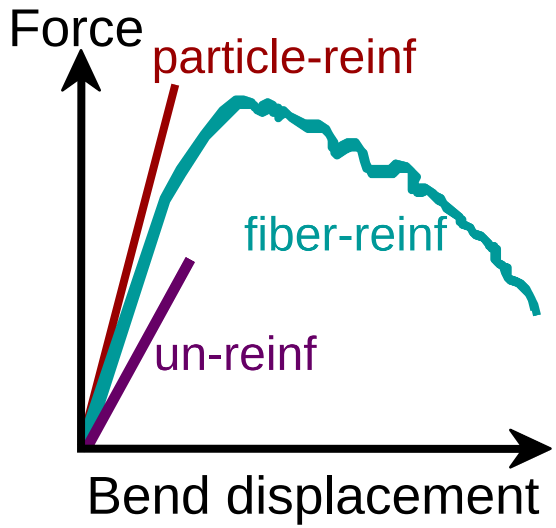


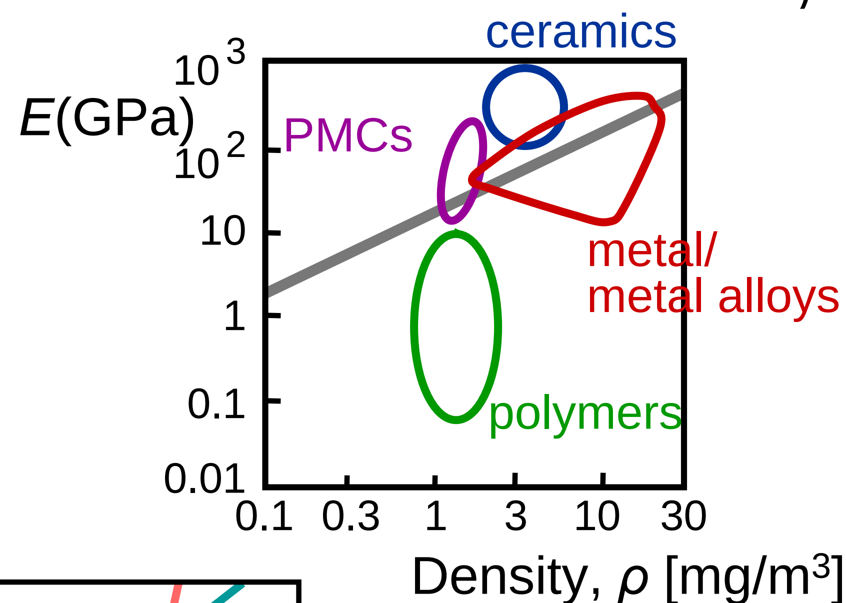
Fig. 16.18, *Callister & Rethwisch 9e*.
(Reprinted with permission from *Engineered Materials Handbook*, Vol. 1, Composites, ASM International, Materials Park, OH, 1987.)

Composite Benefits

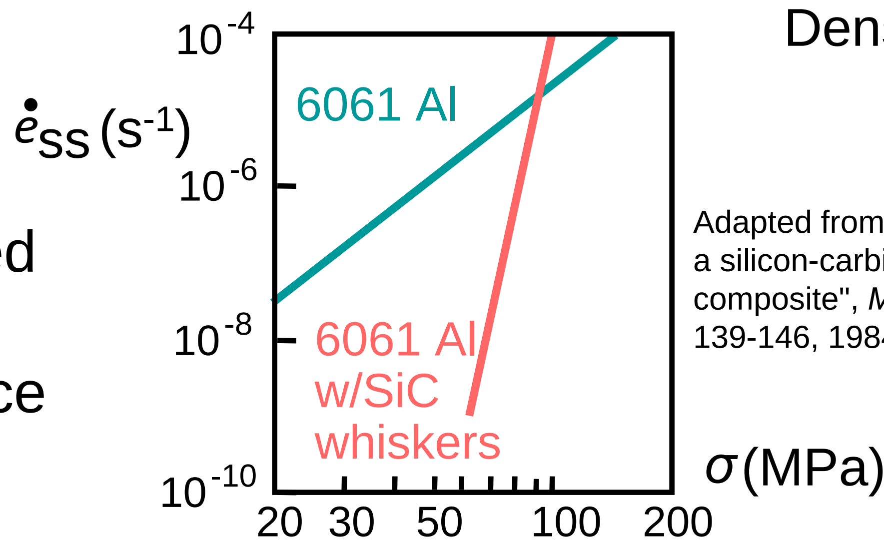
- CMCs: Increased toughness



- PMCs: Increased E/ρ

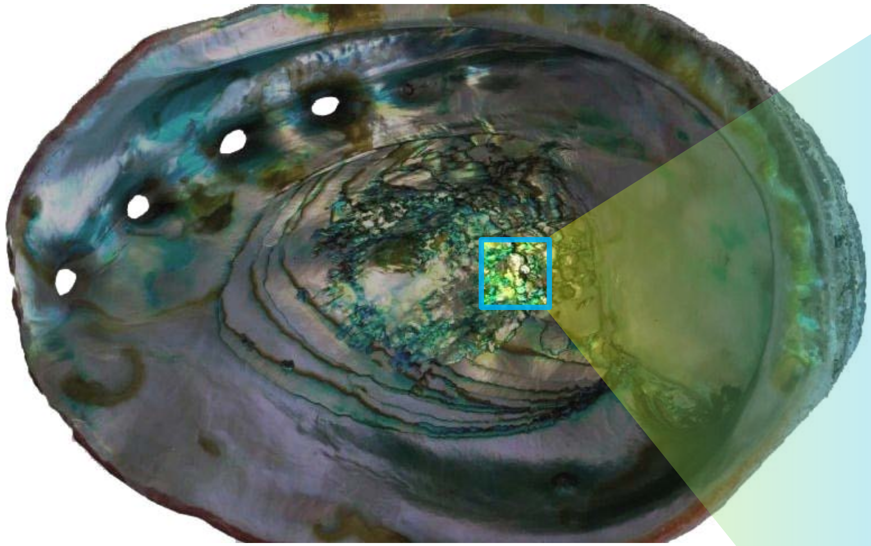


- MMCs:
  Increased
  creep
  resistance



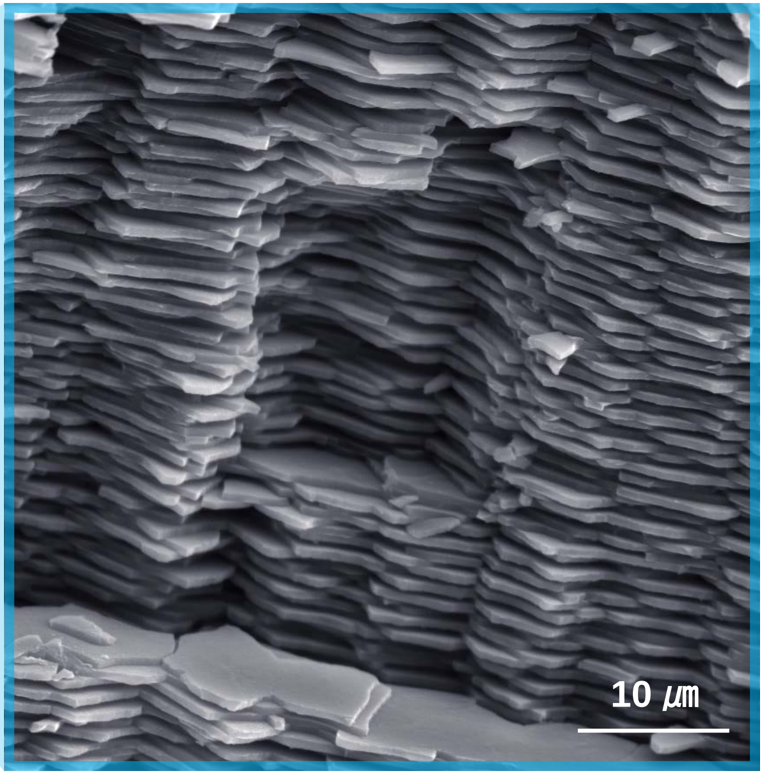
Adapted from T.G. Nieh, "Creep rupture of a silicon-carbide reinforced aluminum composite", *Metall. Trans. A* Vol. 15(1), pp. 139-146, 1984. Used with permission.

Natural structural materials - Nacre



Microstructure of nacre

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



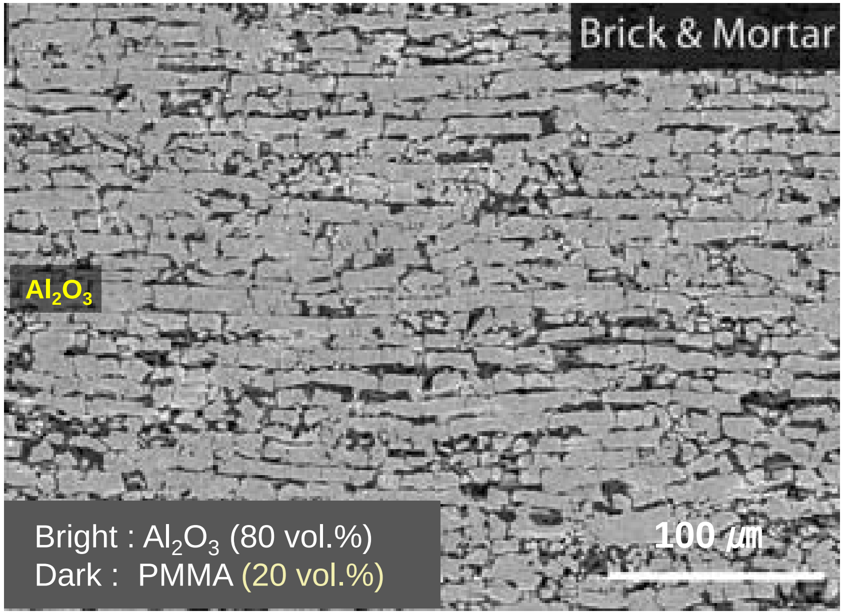
Brick-and-mortar structure

$CaCO_3$
~ 0.25 MPam$^{1/2}$

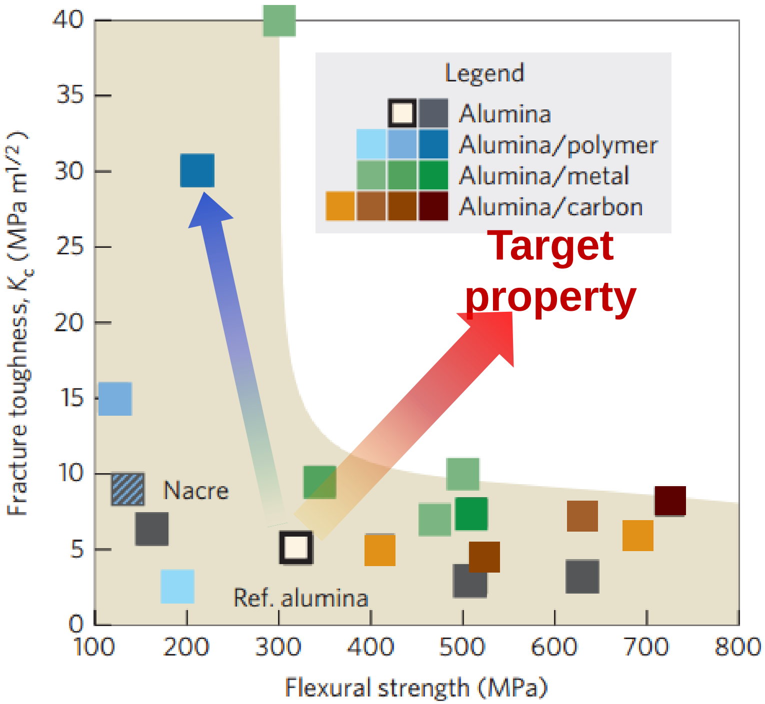
Nacre
~10 MPam$^{1/2}$ (Fracture toughness)

Bio-inspired design of hybrid materials

E. Munch et al. Science (2008)



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



Natural materials

Organic protein / $CaCo_3$

Bio-inspired materials

PMMA / Al_2O_3

Polymeric mortar

BMG / Al_2O_3

Metallic mortar

Bio-inspired nacre-like BMG-Al_2O_3 composites

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)*

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ARTICLE

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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 II

- 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_{Ic}
  -- 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