2019 Fall

Introduction to Materials Science and Engineering

11. 28. 2019

Eun Soo Park

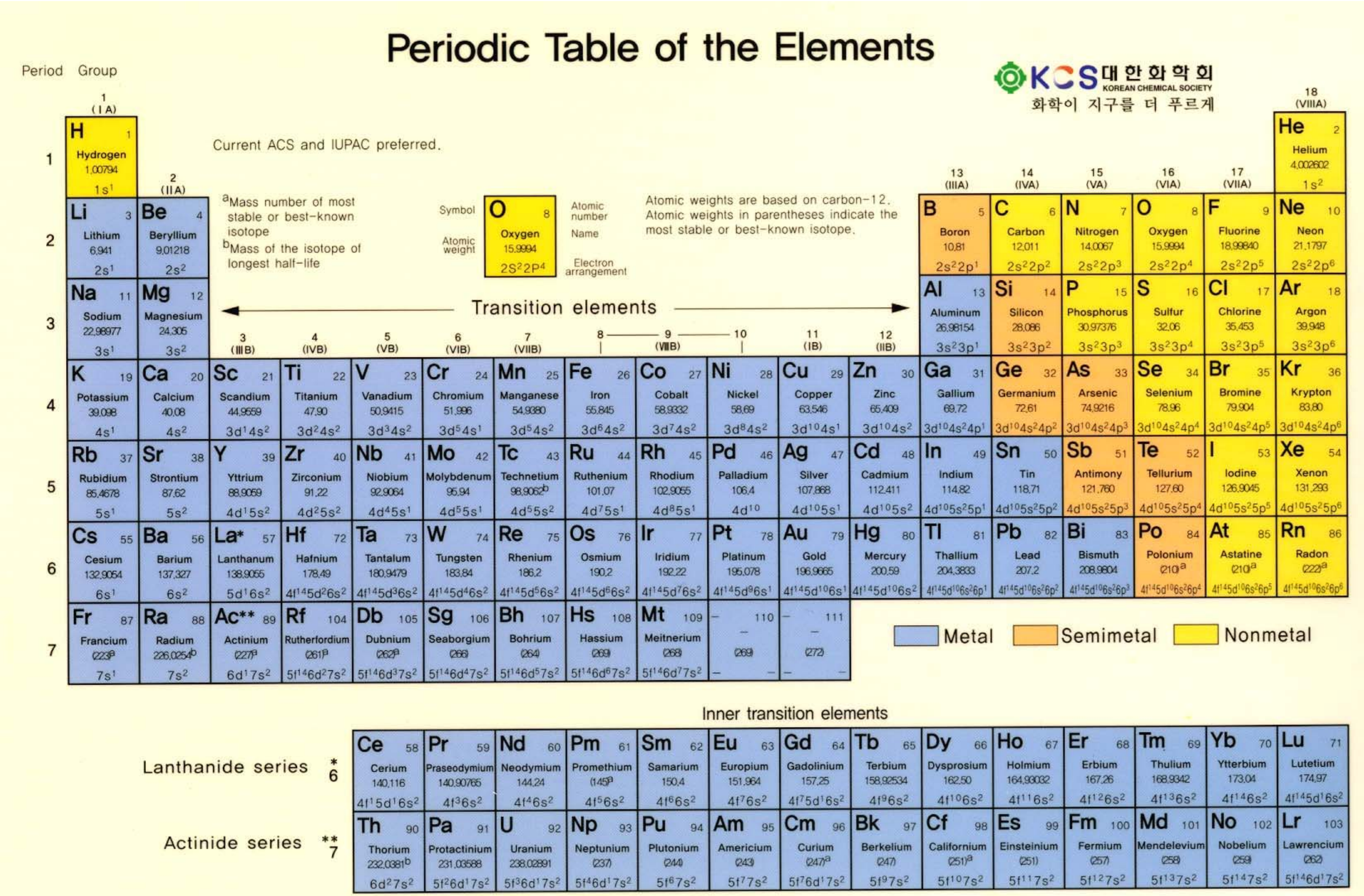
Office: 33-313
Telephone: 880-7221
Email: espark@snu.ac.kr
Office hours: by appointment

Chapter 13:
Properties and Applications of Metals

ISSUES TO ADDRESS...

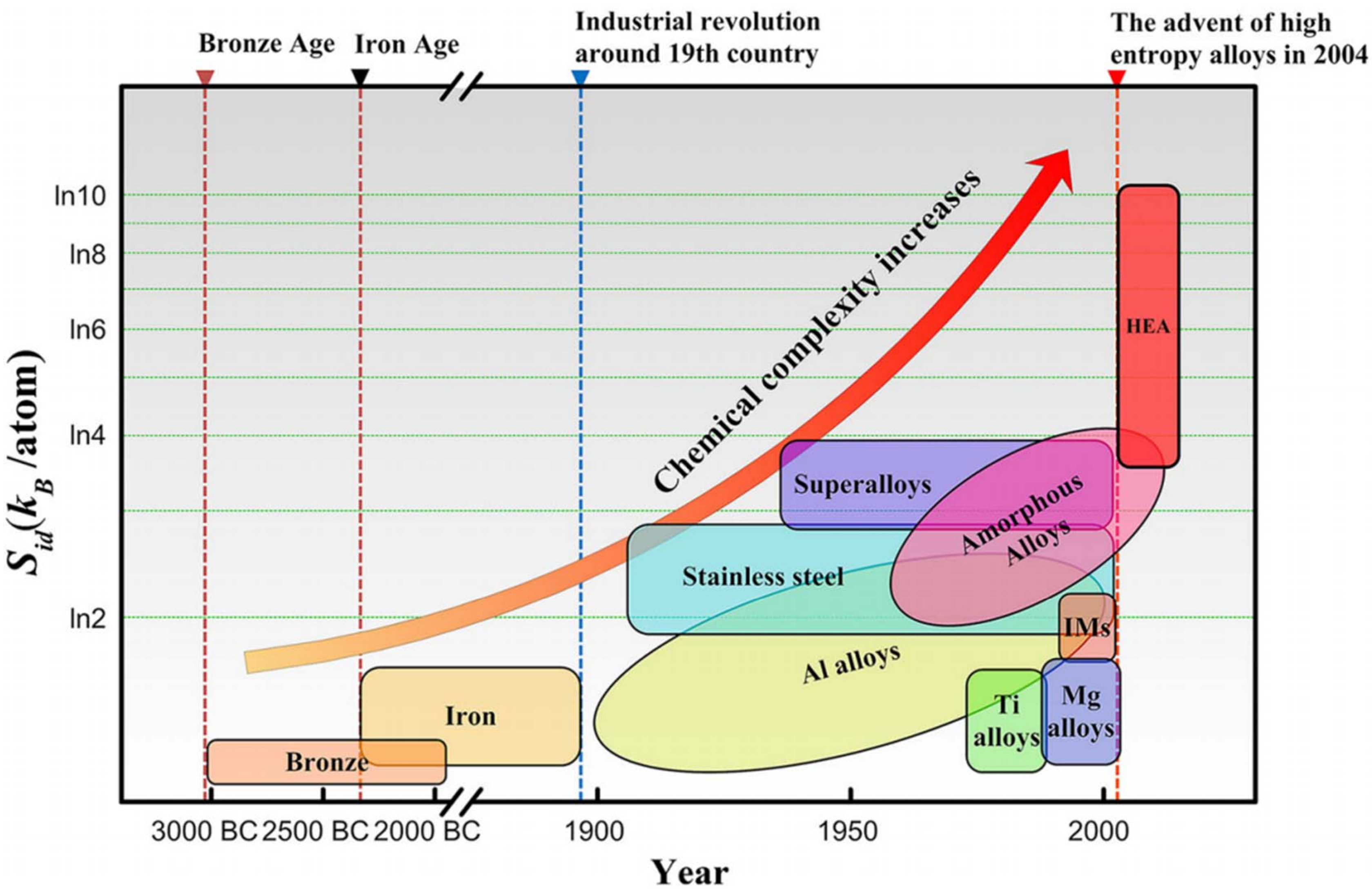
- How are metal alloys classified and what are their common applications?
- What are the microstructure and general characteristics of cast irons?
- What are the distinctive physical and mechanical properties of nonferrous alloys?

Materials Design-for-Properties : “Alloyed Pleasure”



Design-for-properties (since the Bronze Age!)

Materials Design-for-Properties : "Alloyed Pleasure"



Rising trend of alloy chemical complexity versus time. Note that ''IMs'' stands for intermetallics or metallic compounds and ''HEA'' for high-entropy alloy.

Classification of Metal Alloys

Metal Alloys

- **Ferrous**
  - Steels <1.4 wt% C
  - Cast Irons 3-4.5 wt% C
- **Nonferrous**

Adapted from Fig. 13.1, *Callister & Rethwisch 9e.*

microstructure: ferrite, graphite/cementite

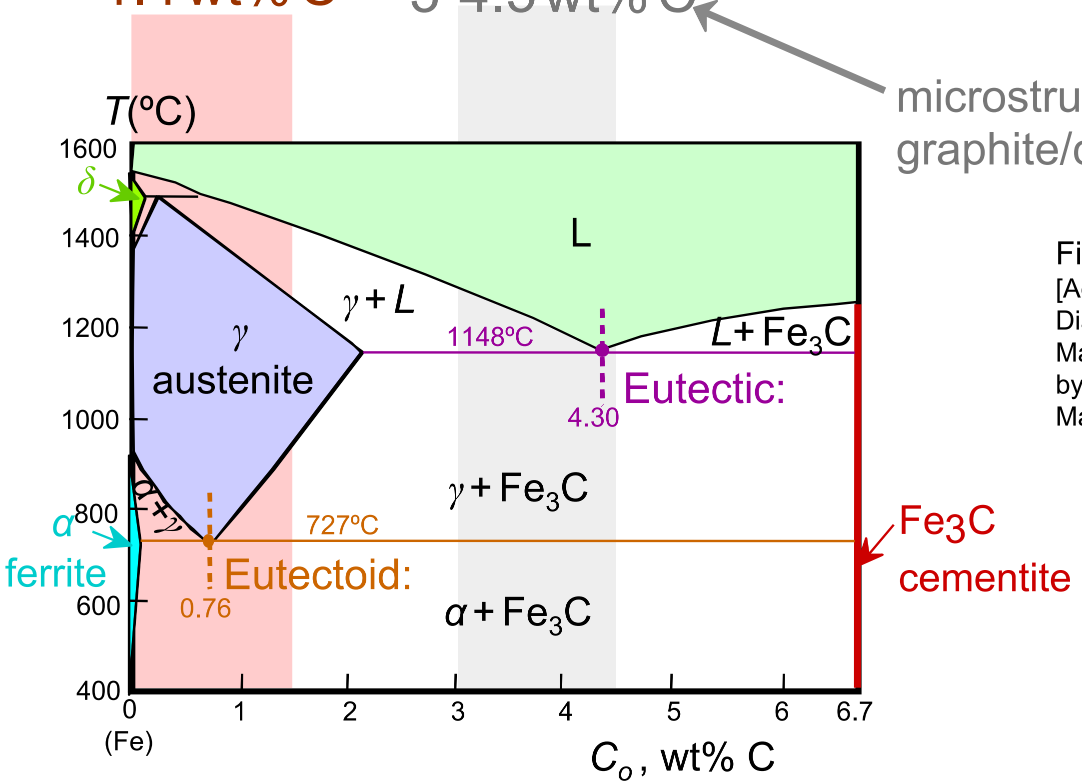
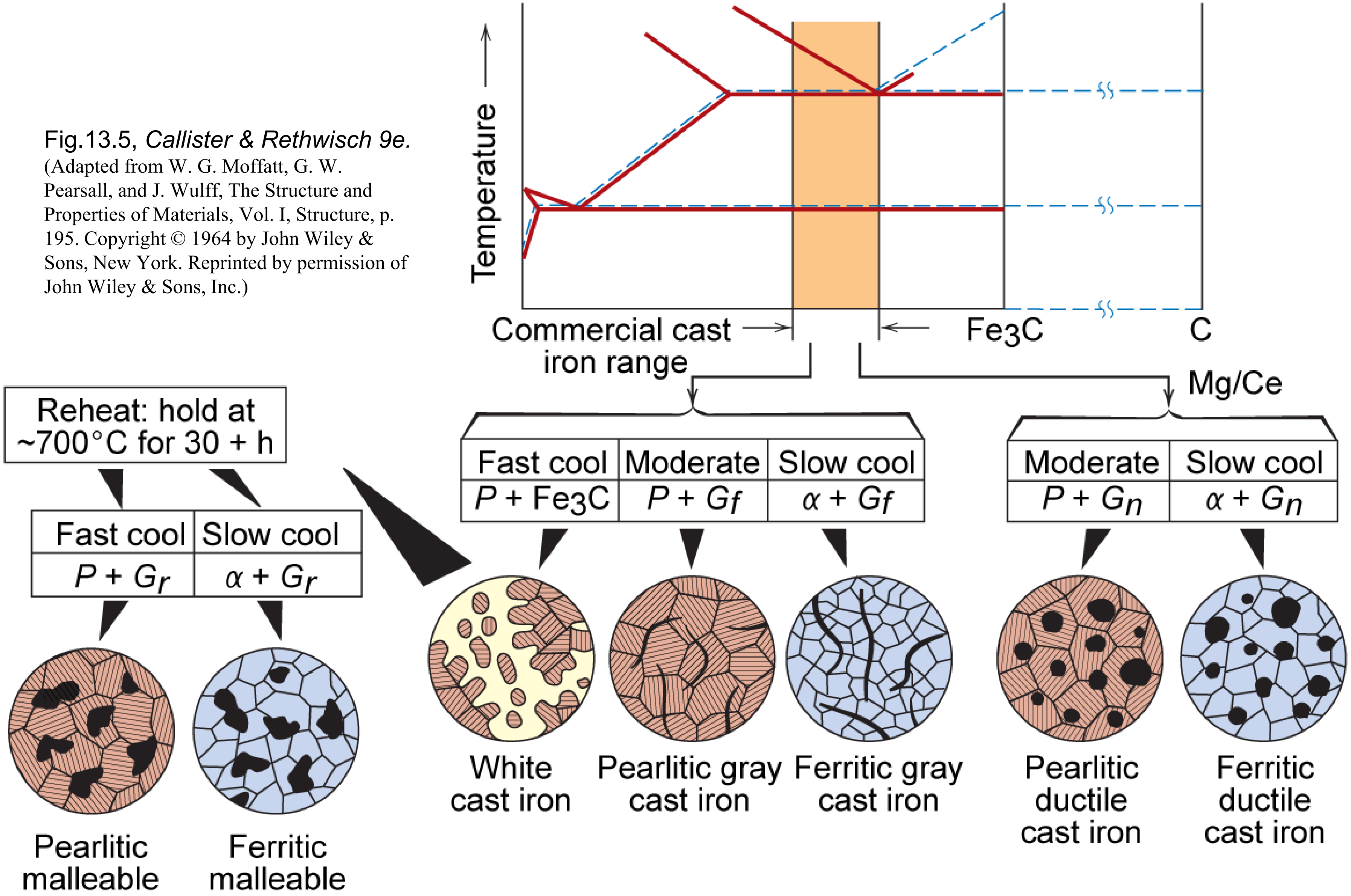


Fig. 11.23, *Callister & Rethwisch 9e*.
[Adapted from Binary Alloy Phase Diagrams, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

Production of Cast Irons

Fig.13.5, *Callister & Rethwisch 9e.*
(Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, The Structure and Properties of Materials, Vol. I, Structure, p. 195. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



Steels

Low Alloy
- low carbon: < 0.25 wt% C
- Med carbon: $0.25-0.6$ wt% C
- high carbon: $0.6-1.4$ wt% C

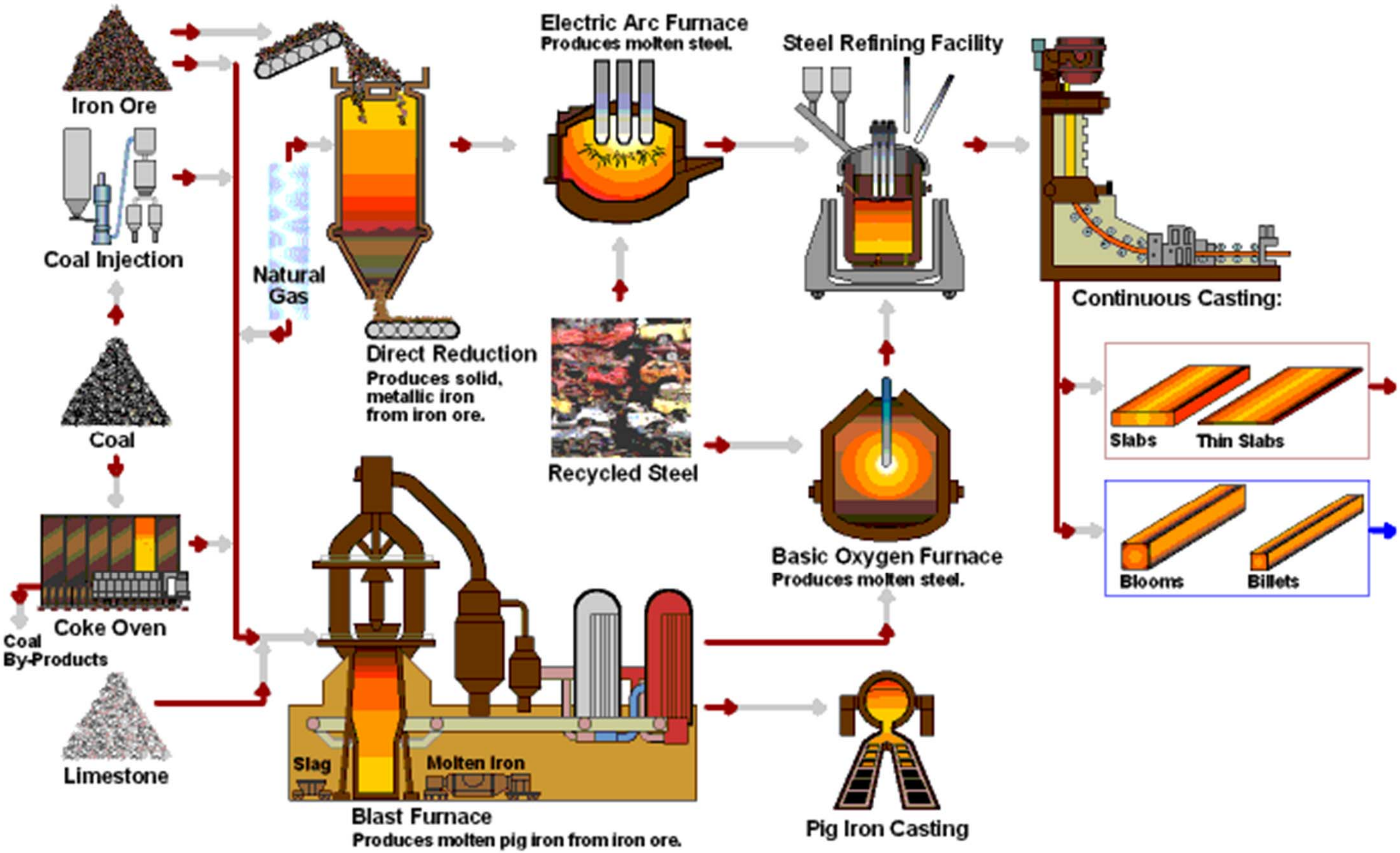
High Alloy

	low carbon		Med carbon		high carbon		High Alloy
Name	plain	HSLA	plain	heat treatable	plain	tool	stainless
Additions	none	Cr,V Ni, Mo	none	Cr, Ni Mo	none	Cr, V, Mo, W	Cr, Ni, Mo
Example	1010	4310	1040	4340	1095	4190	304, 409
Hardenability	0	+	+	++	++	+++	varies
TS	-	0	+	++	+	++	varies
EL	+	+	0	-	-	--	++
Uses	auto struc. sheet	bridges towers press. vessels	crank shafts bolts hammers blades	pistons gears wear applic.	wear applic.	drills saws dies	high T applic. turbines furnaces Very corros. resistant

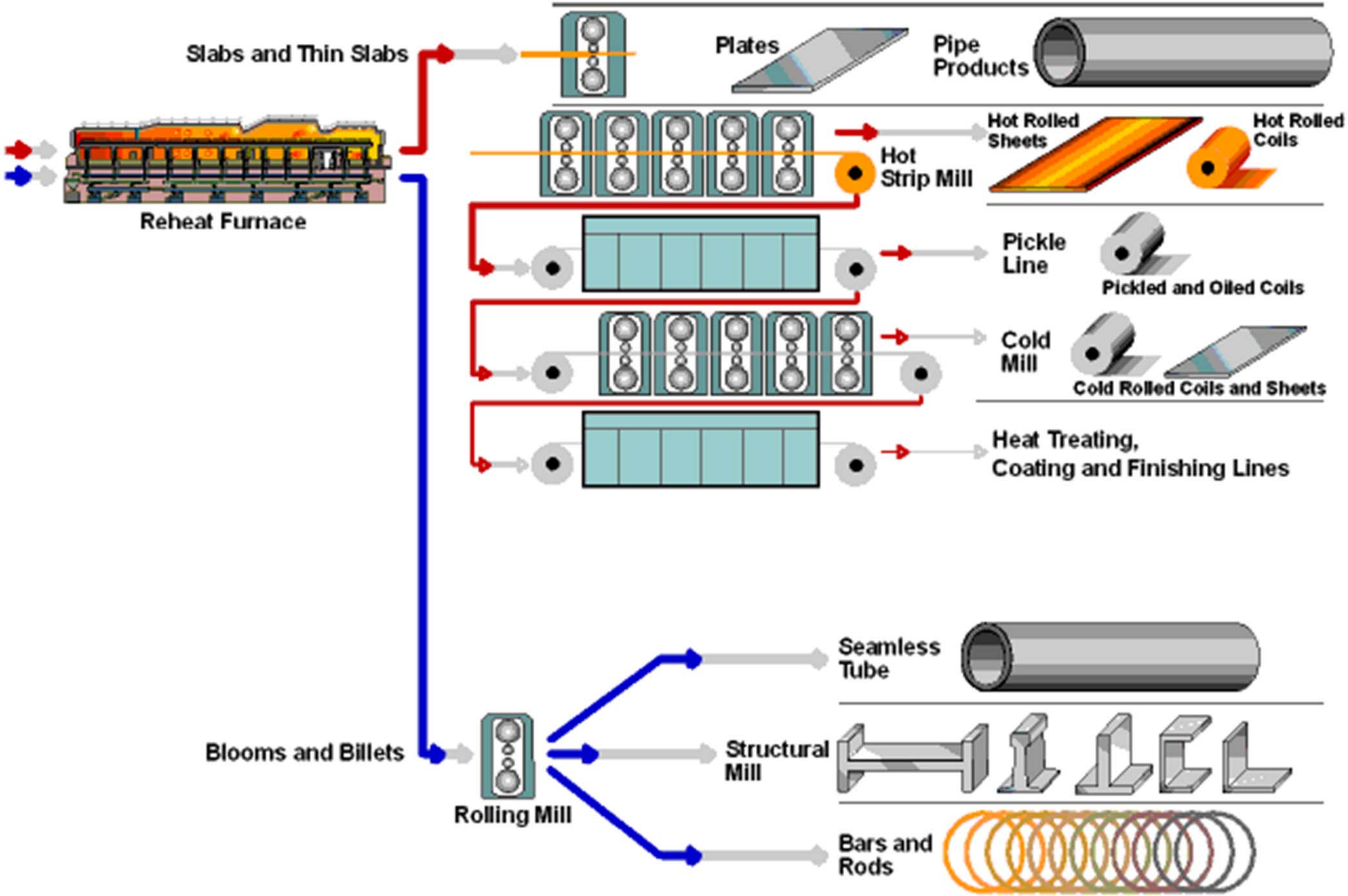
increasing strength, cost, decreasing ductility →

Based on data provided in Tables 13.1(b), 14.4(b), 13.3, and 13.4, *Callister & Rethwisch 9e.*

철강의 생산과정 : Iron making → Steelmaking → Rolling



철강의 생산과정 : Iron making → Steelmaking → Rolling



II. Nonferrous Alloys

NonFerrous Alloys

- **Cu Alloys**

Brass: Zn is subst. impurity (costume jewelry, coins, corrosion resistant)

Bronze : Sn, Al, Si, Ni are subst. impurities (bushings, landing gear)

Cu-Be: precip. hardened for strength

- **Al Alloys**

-**low ρ: 2.7 g/cm^3**

-Cu, Mg, Si, Mn, Zn additions

-solid sol. or precip. strengthened (struct. aircraft parts & packaging)

- **Mg Alloys**

-**very low ρ**: 1.7 g/cm^3

-ignites easily

-aircraft, missiles

- **Ti Alloys**

-relatively low *ρ*: 4.5 g/cm^3 vs 7.9 for steel

-reactive at high *T's*

-space applic.

- **Noble metals**

-Ag, Au, Pt

-oxid./corr. resistant

- **Refractory metals**

-**high melting *T's***

-Nb, Mo, W, Ta

Based on discussion and data provided in Chapter 13, *Callister & Rethwisch 9e.*

III. Advanced Engineering Alloys

a. Superalloys

b. Shape memory alloys

c. Quasicrytals

d. Bulk metallic glasses

e. High entropy alloys

...

* **Development strategy of completely new materials**

a. Alloyed pleasures: Multi-metallic cocktails

b. Synthesize metastable phases

Equilibrium conditions → Non-equilibrium conditions

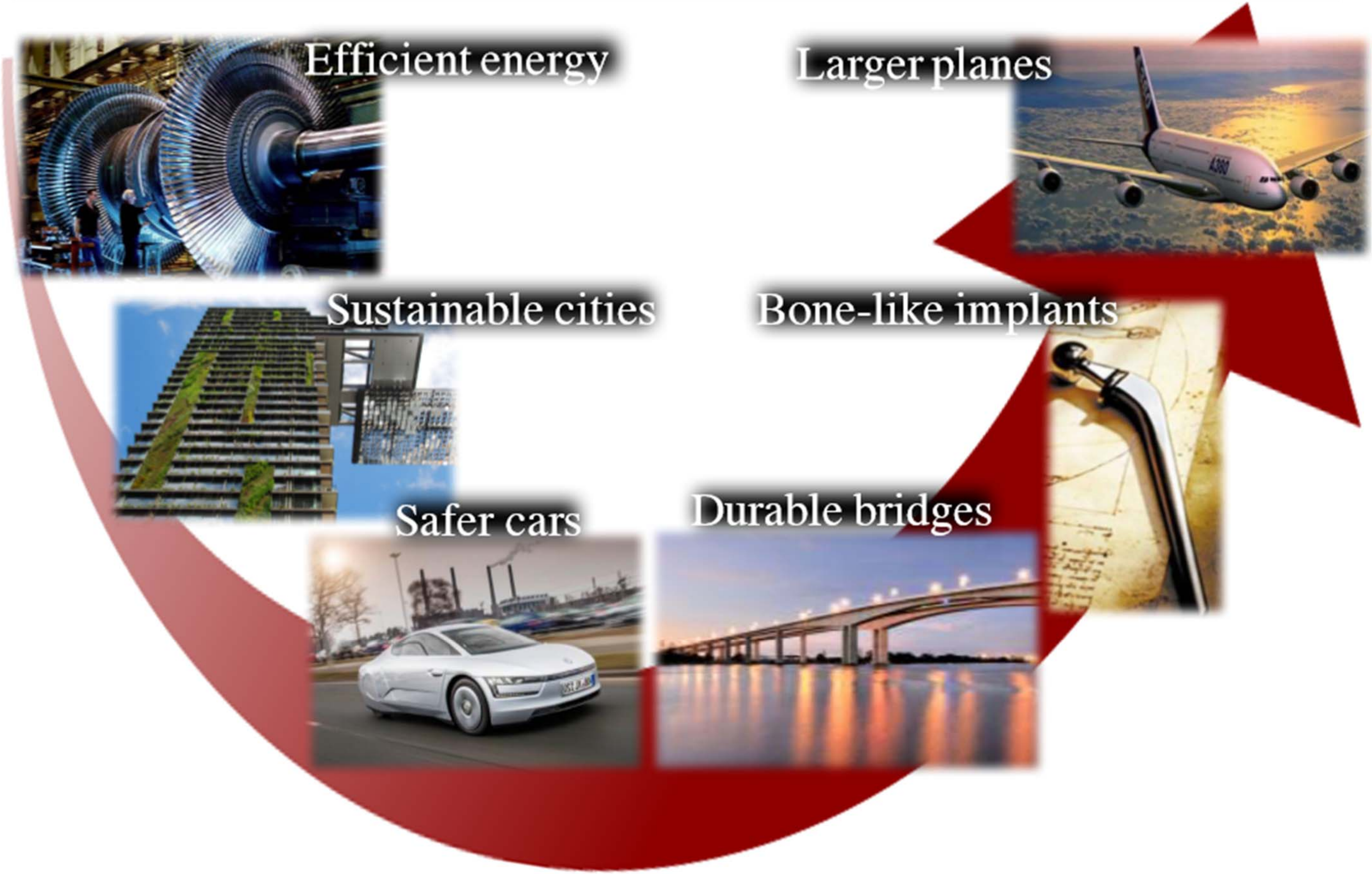
: non-equilibrium processing = “energize and quench” a material

TABLE 1.1

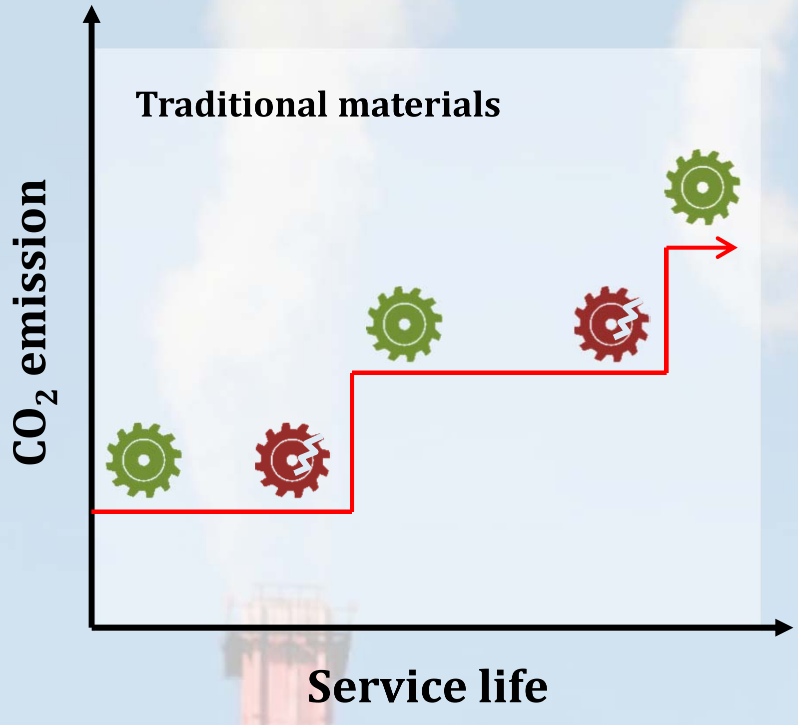
Departure from Equilibrium Achieved in Different Nonequilibrium Processing Methods

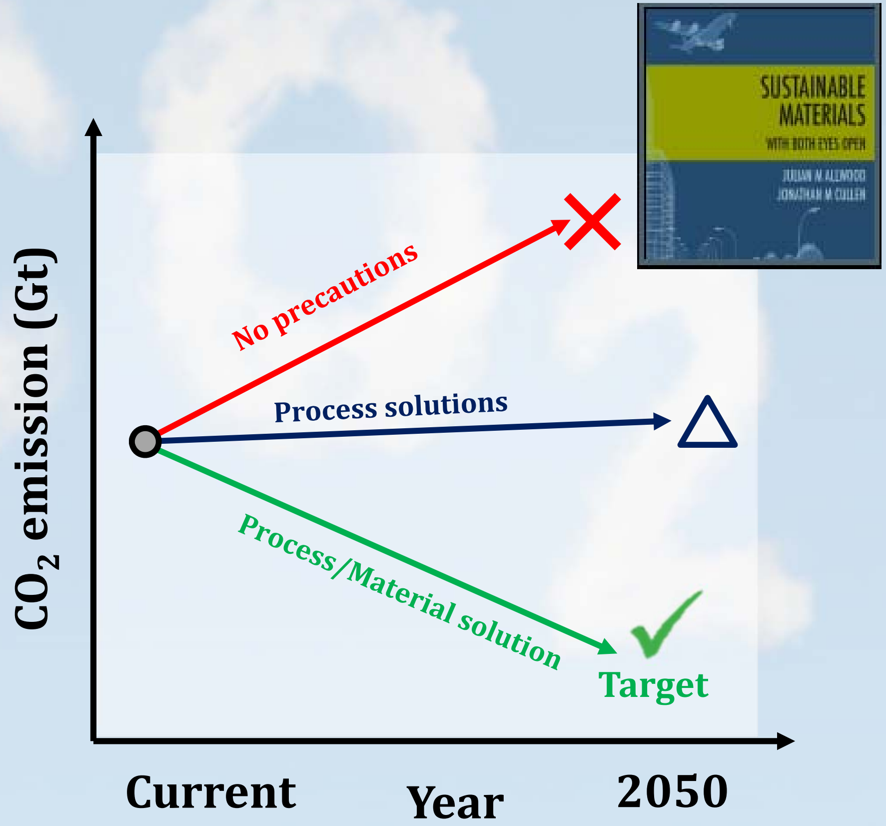
Technique	Effective Quench Rate ($K\ s^{-1}$), Ref. [25]	Maximum Departure from Equilibrium ($kJ\ mol^{-1}$) Ref. [28]	Maximum Departure from Equilibrium ($kJ\ mol^{-1}$) Refs. [29,30]
Solid-state quench	10^3	—	16
Rapid solidification processing	10^5–10^8	2–3	24
Mechanical alloying	—	30	30
Mechanical cold work	—	—	1
Irradiation/ion implantation	10^{12}	—	30
Condensation from vapor	10^{12}	—	160

Still design-for-properties, to enable new technologies



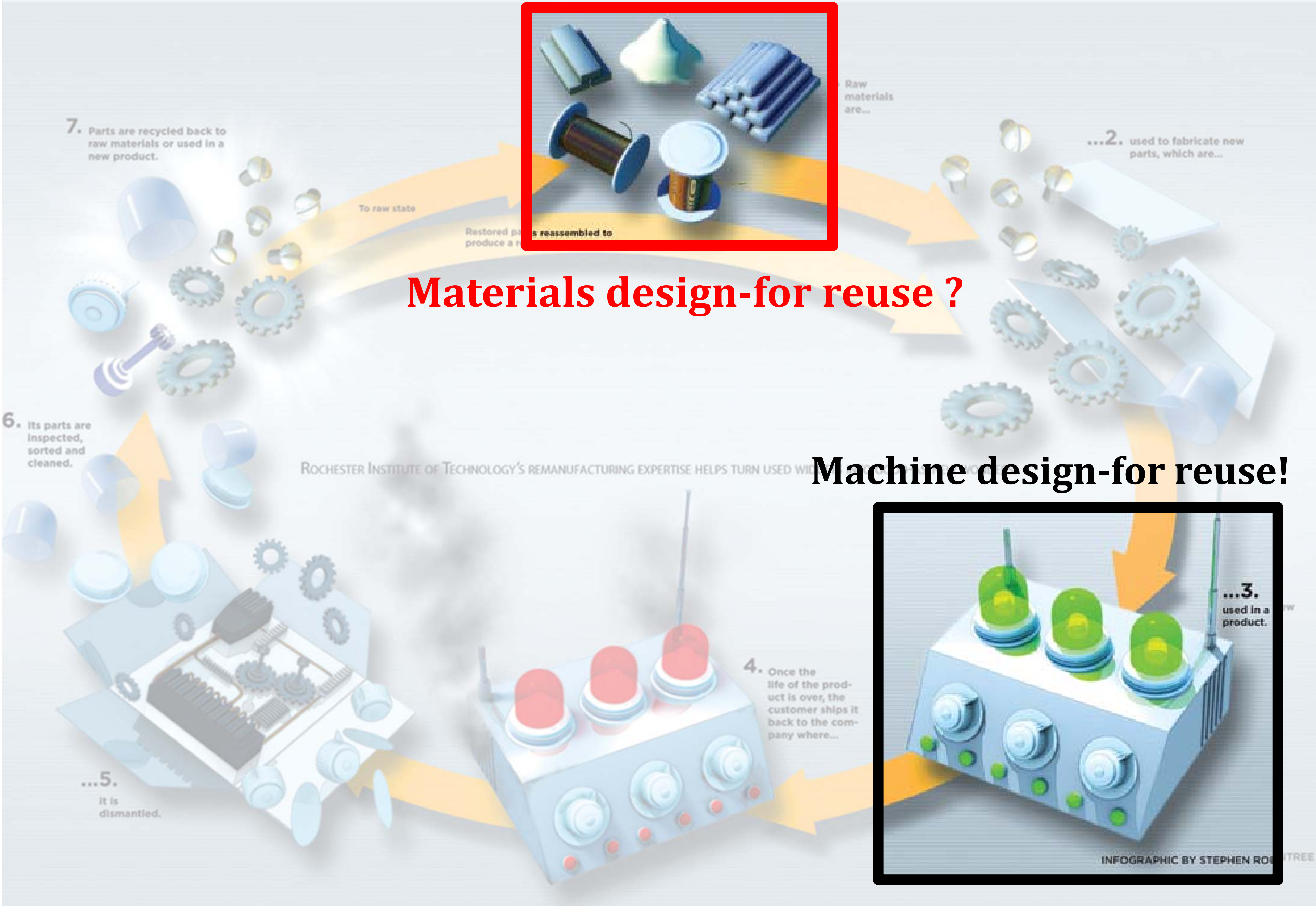
New challenges : *Less use, Extend lifetime, Reuse!*





Extend lifetime, where possible, *Reuse!*

Remanufacturing : Machine design-for-reuse!



Materials design-for reuse ?

Machine design-for reuse!

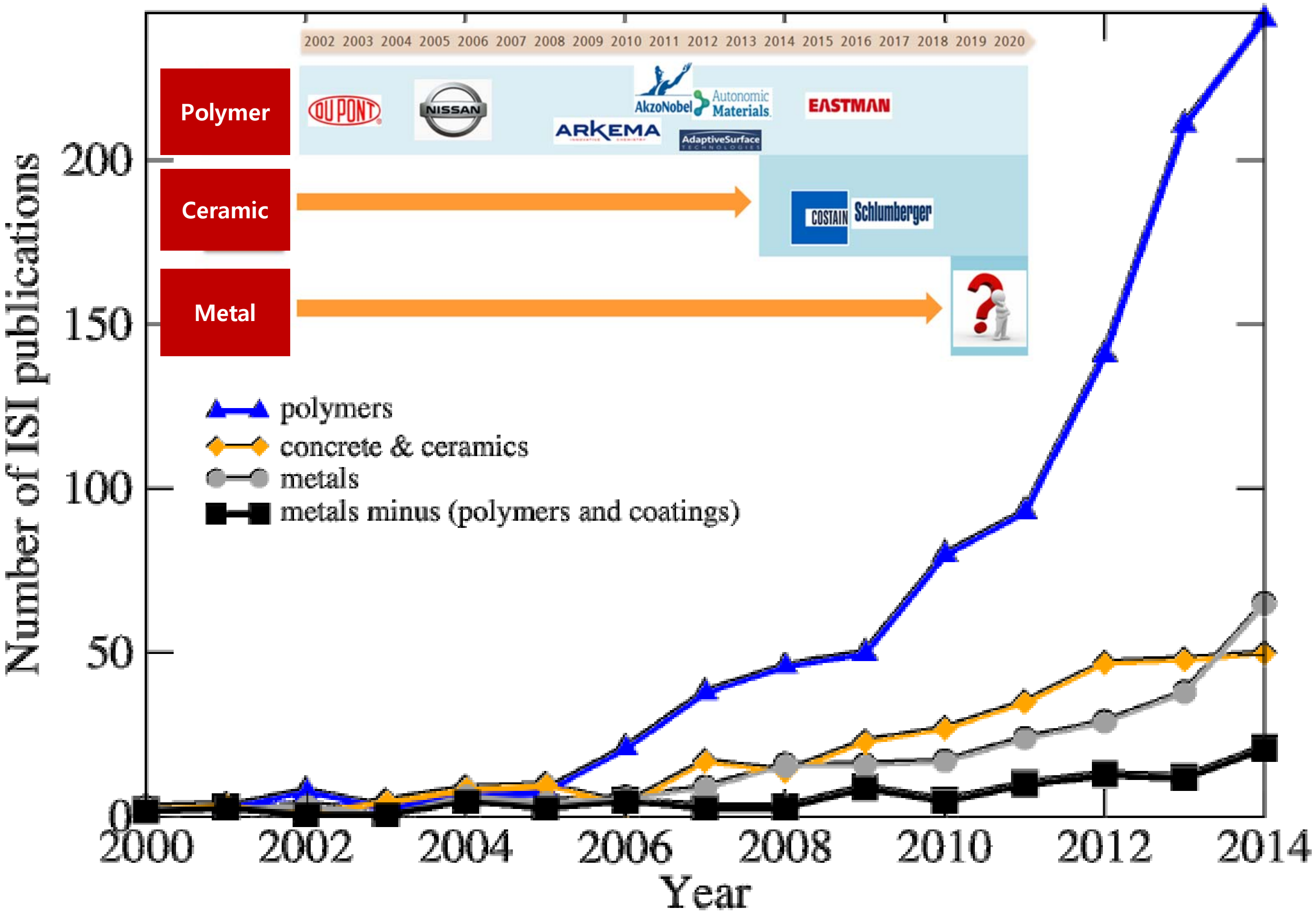
Materials design for reuse

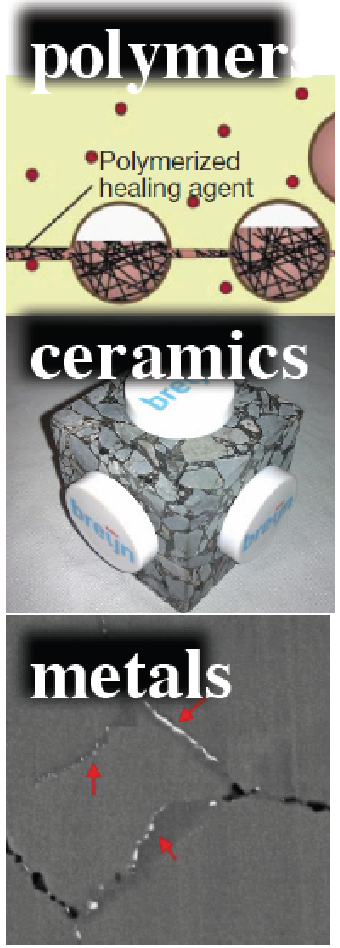
Damage process is incremental, and often local → repair opportunity

Two damage repair options possible:

- The metal autonomously repair damage → ***Self-healing***
- Damage is repaired by an external treatment → ***Resetting***

Self Healing New paradigm for structural material development





- Transformation kinetics in metals are slow at room temperature!

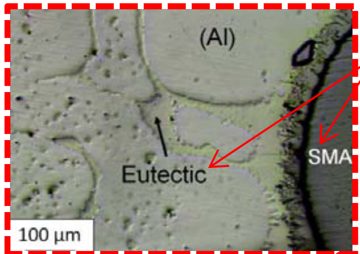
Commercialized self-healing polymer

Healing agent's movement and reaction occurs even with small energy at room temperature

Self-healing metals   Current technical level

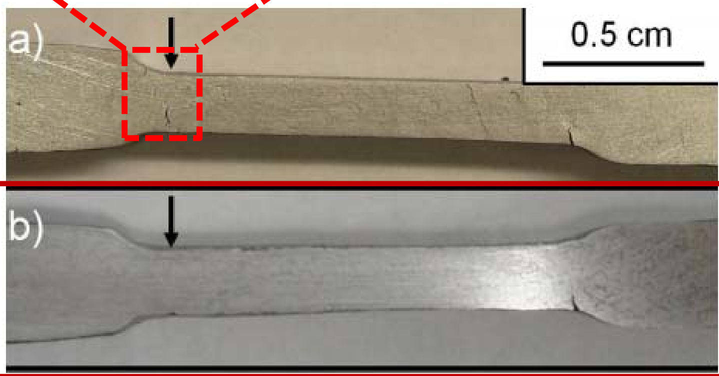
Prevention of microcrack propagation via healing agent

Al-3at% Si composite reinforced with 2 vol% NITI SMA wire



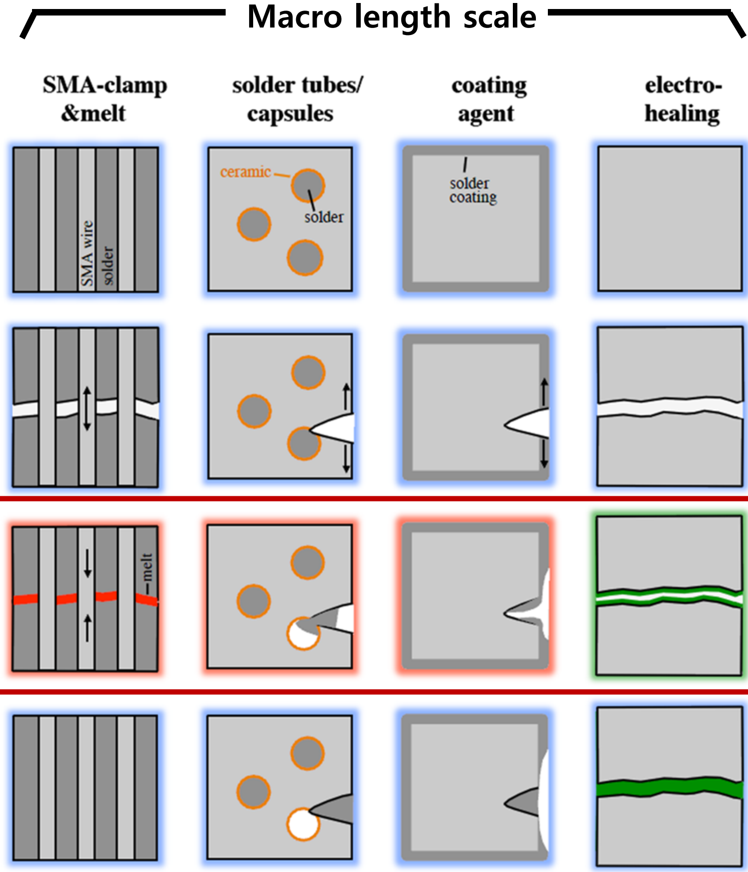
a. Healing agent
(ex. SMA wire etc.)

CT scan of VHP dogbone



heating

Grabowski & Tasan, Self-healing Metals (2016).



Heating or E field

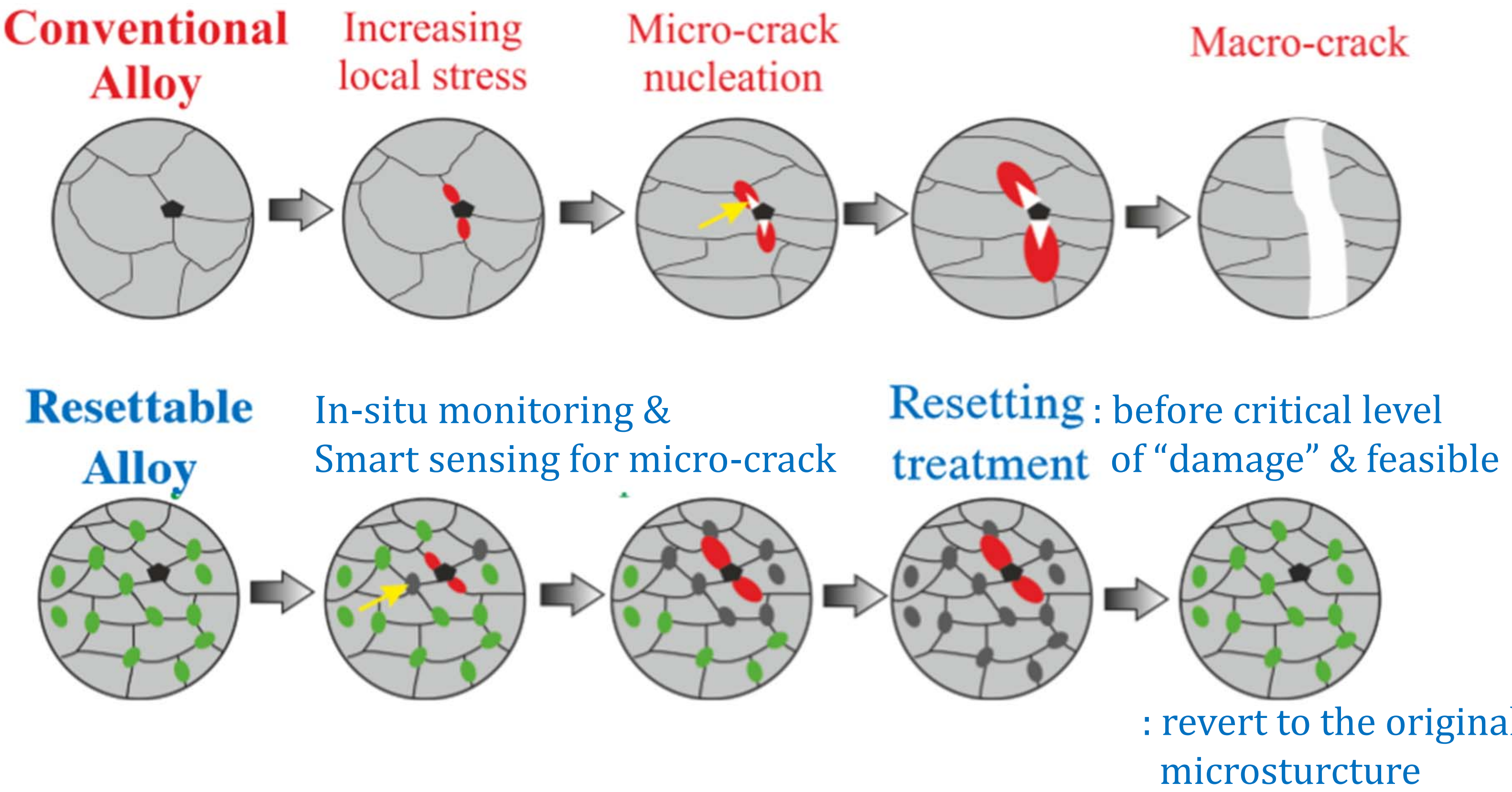
b. Healing Treatment & **c. Local melting**
(ex. Aging, electro pulse etc.) (ex. Eutectic phase, Sn etc.)

➡ **Prevention of Macroscale crack propagation**

For metals, restrictive thermodynamic / kinetic driving force for self-healing at RT!

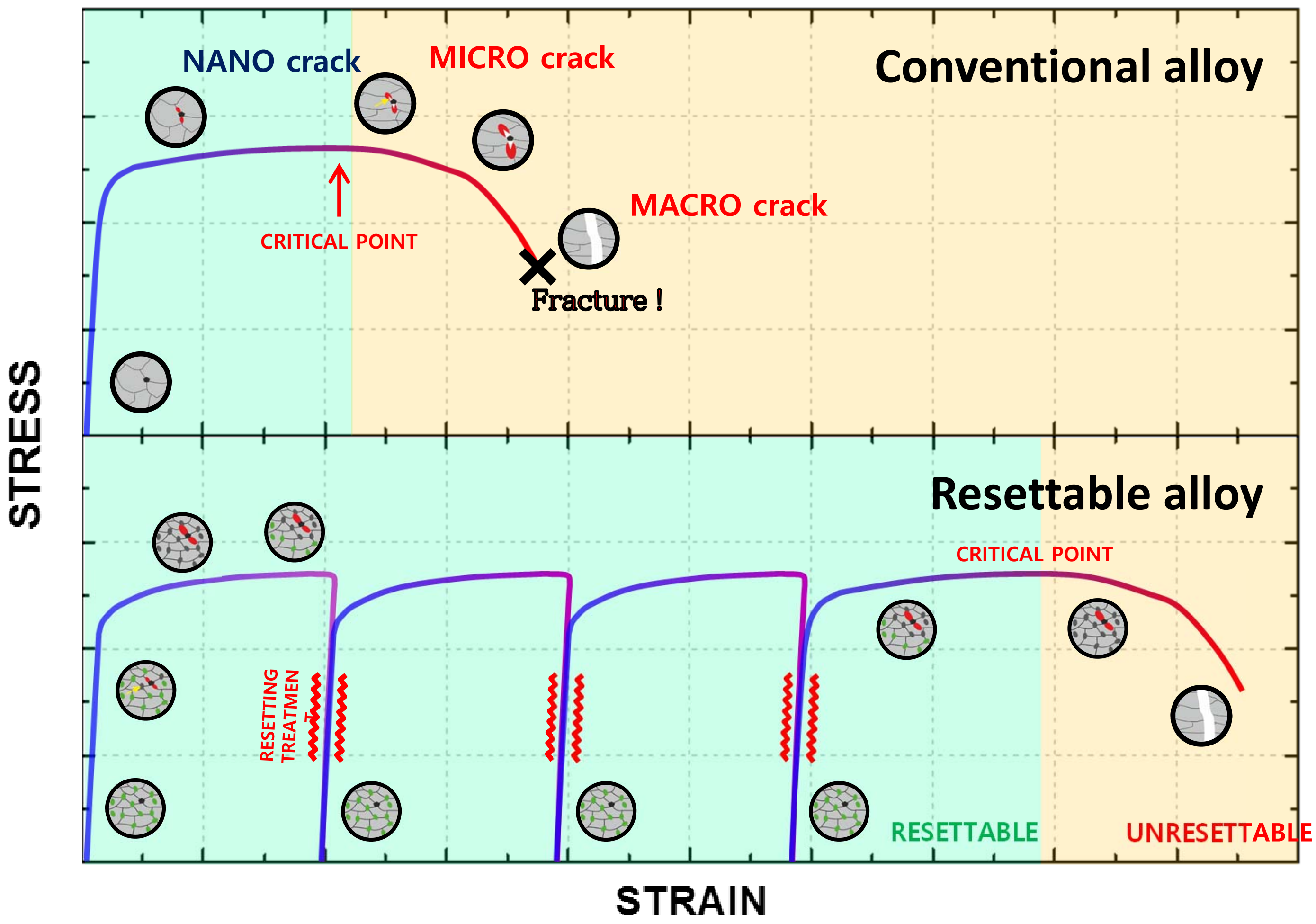
Self-healing metals vs Resettable alloys

- self-healing: "*autonomic closure of micro-cracks*"
- resetting: "*non-autonomic retrieval of crack-arresting ability*"



Different failure mechanisms require different resetting strategies

New challenges : *Resettable alloys!*



Resetting treatment 를 통해 초기 미세구조로 회복 가능한 Resettable alloy!

Urgent need for mission change:

Materials design-for-“properties” & “reuse”

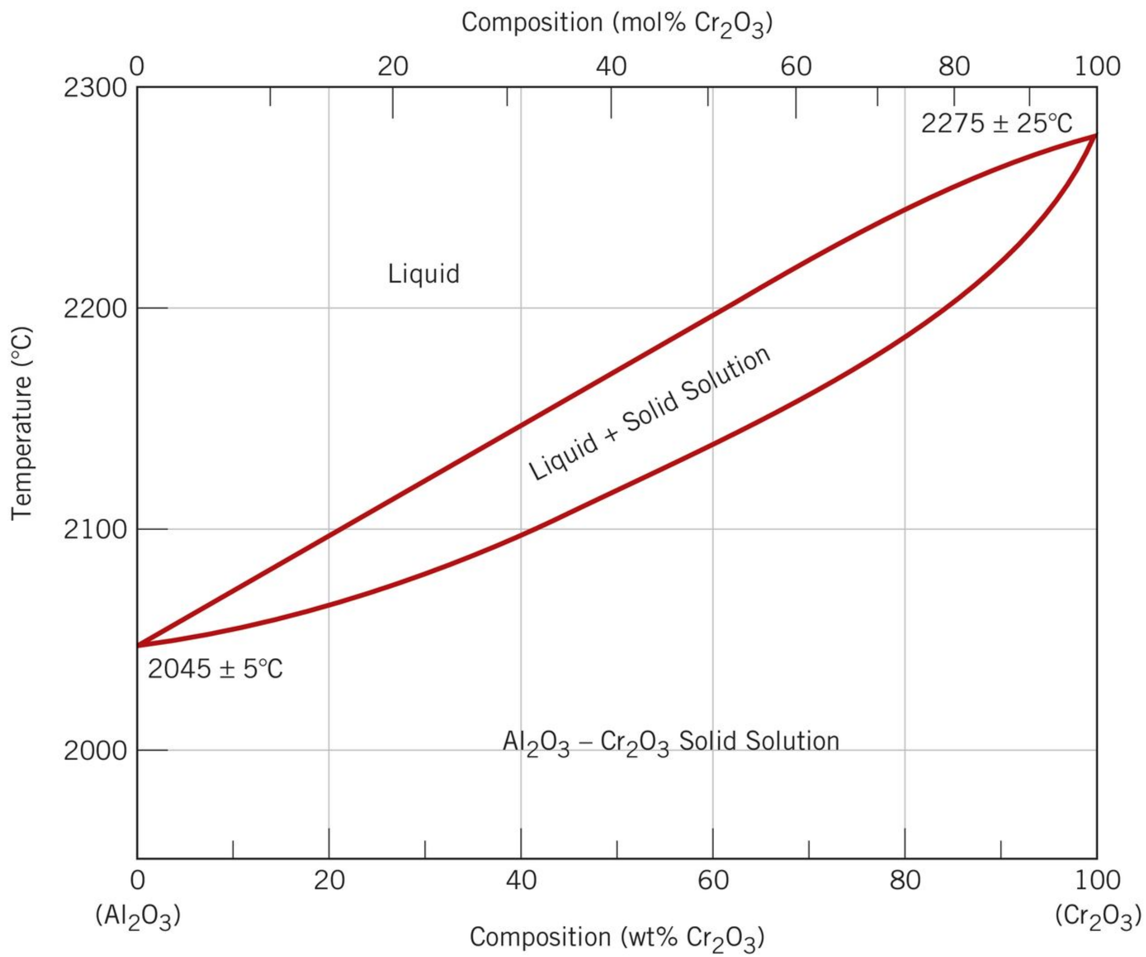
Chapter 14: Properties and Applications of Ceramics

ISSUES TO ADDRESS...

- In what ways are **ceramic phase diagrams** different from phase diagrams for metals?
- How are the **mechanical properties of ceramics** measured, and how do they differ from those for metals?
- How do we **classify ceramics**?
- What are **some applications of ceramics**?

I. Ceramic Phase Diagrams

a. Al_2O_3- Ca_2O_3diagram: complete solid solution

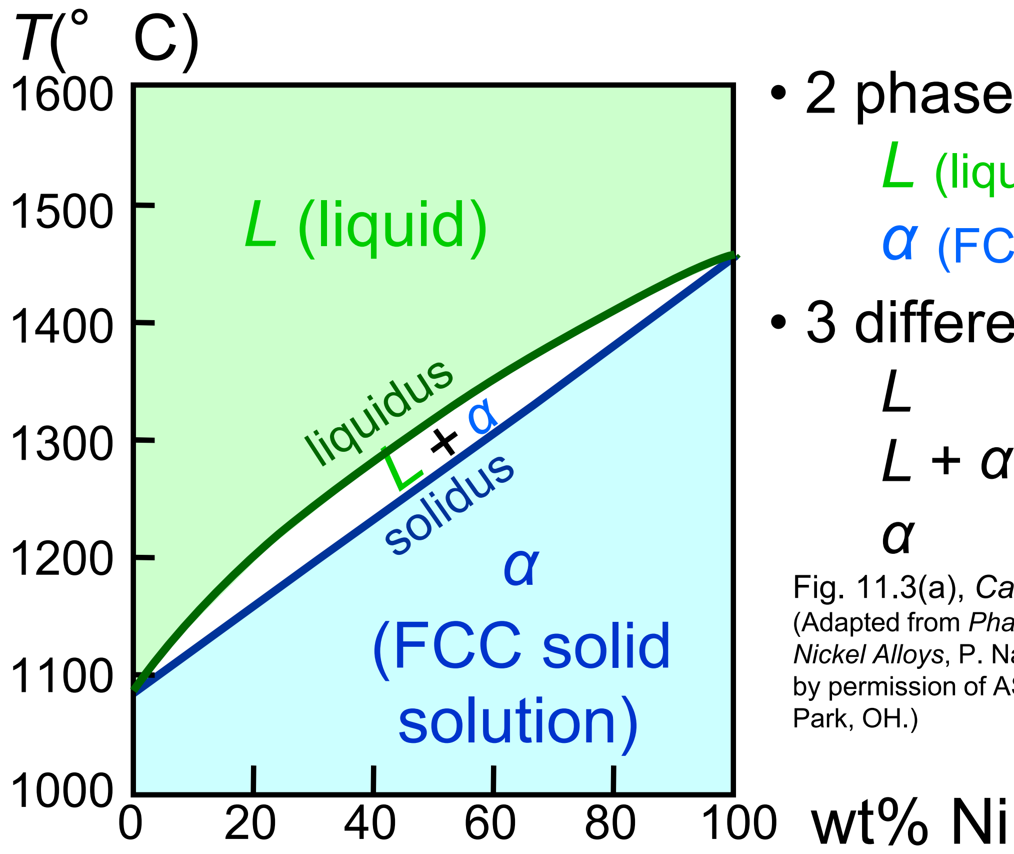


Adapted from E. N. Bunting, "Phase Equilibria in the System Cr2O3–Al2O3," Bur. Standards J. Research, 6, 1931, p. 948.

Isomorphous Binary Phase Diagram

- Indicate phases as a function of *T*, *C*, and *P*.
- For this course:
  - binary systems: just 2 components (Cu and Ni).
  - independent variables: *T* and *C* (*P* = 1 atm is almost always used).

Phase Diagram for Cu-Ni system

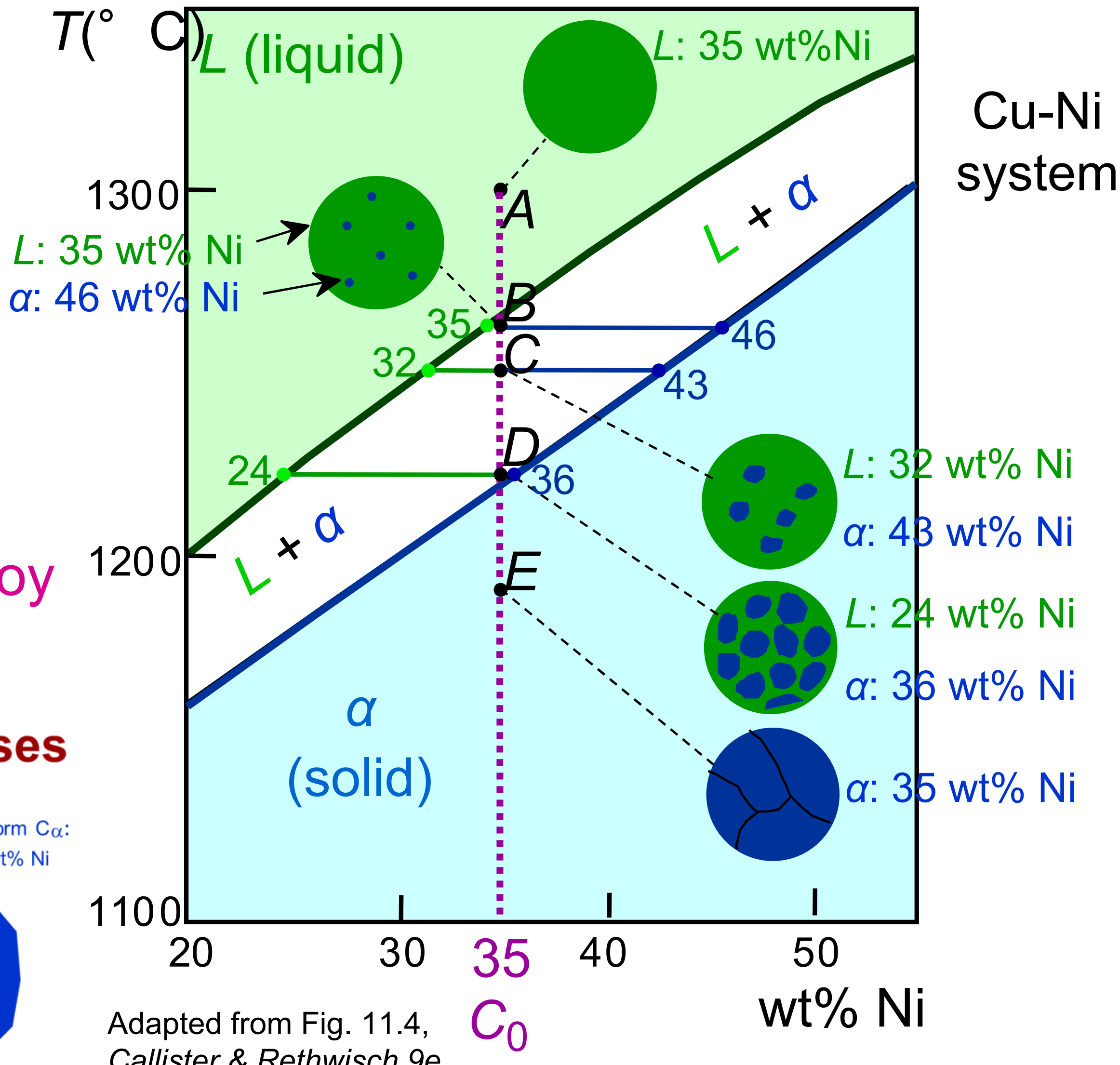


- 2 phases:
  - *L* (liquid)
  - *α* (FCC solid solution)
- 3 different phase fields:
  - *L*
  - *L* + *α*
  - *α*

Fig. 11.3(a), *Callister & Rethwisch 9e.* (Adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

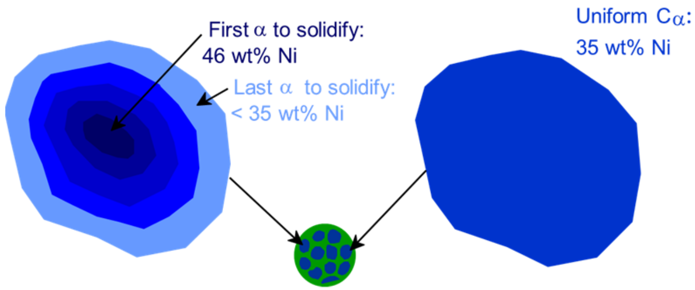
Cooling of a Cu-Ni Alloy

- Phase diagram: Cu-Ni system.
- Consider microstuctural changes that accompany the cooling of a C_0 = 35 wt% Ni alloy



Adapted from Fig. 11.4, *Callister & Rethwisch 9e.*

- Cored vs Equilibrium Phases



Ceramic Phase Diagrams

b. $MgO-Al_2O_3$ diagram: Eutectic system

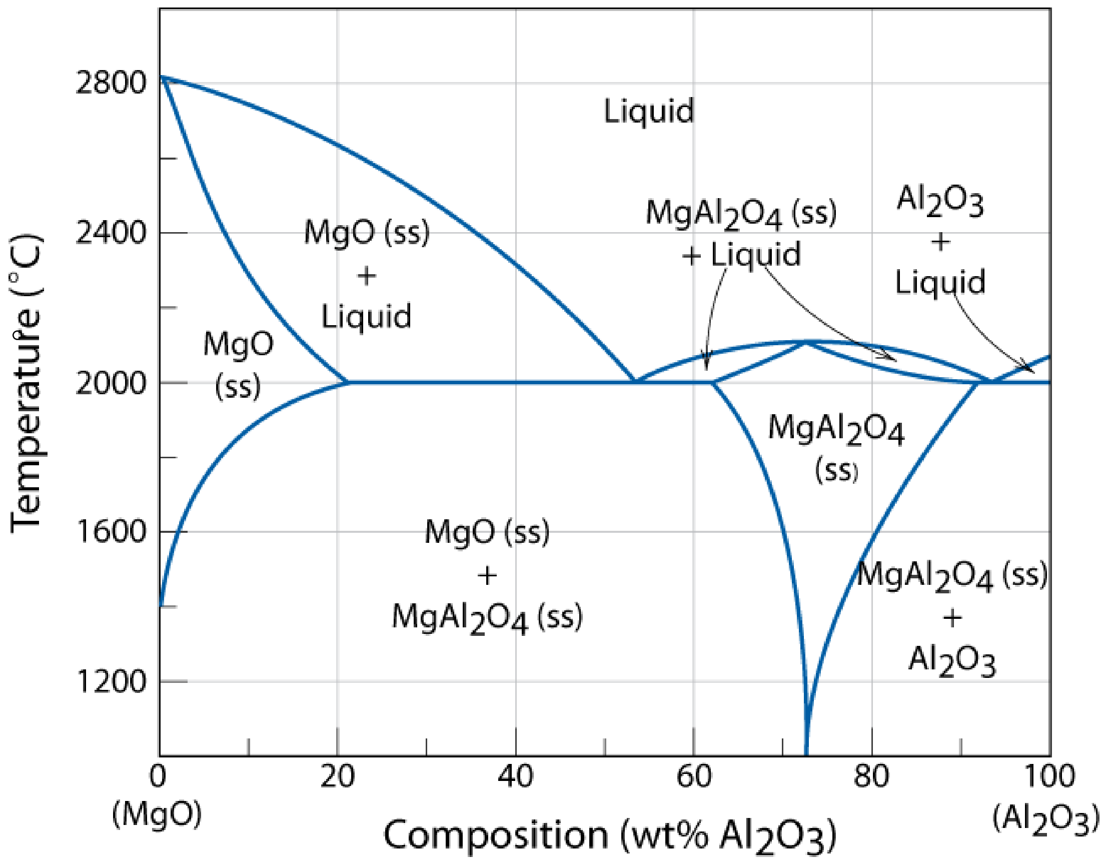


Fig. 14.2, Callister & Rethwisch 9e.
[Adapted from B. Hallstedt, "Thermodynamic Assessment of the System $MgO–Al_2O_3$," J. Am. Ceram. Soc., 75[6], 1502 (1992). Reprinted by permission of the American Ceramic Society.]

$MgAl_2O_4$ (or $MgO-Al_2O_3$) Spinel: 중간상 - 고용체

Eutectic Systems

- For alloy of composition $C_0 = C_E$
- Result: Eutectic microstructure (lamellar structure)
  -- alternating layers (lamellae) of *α* and *β* phases.

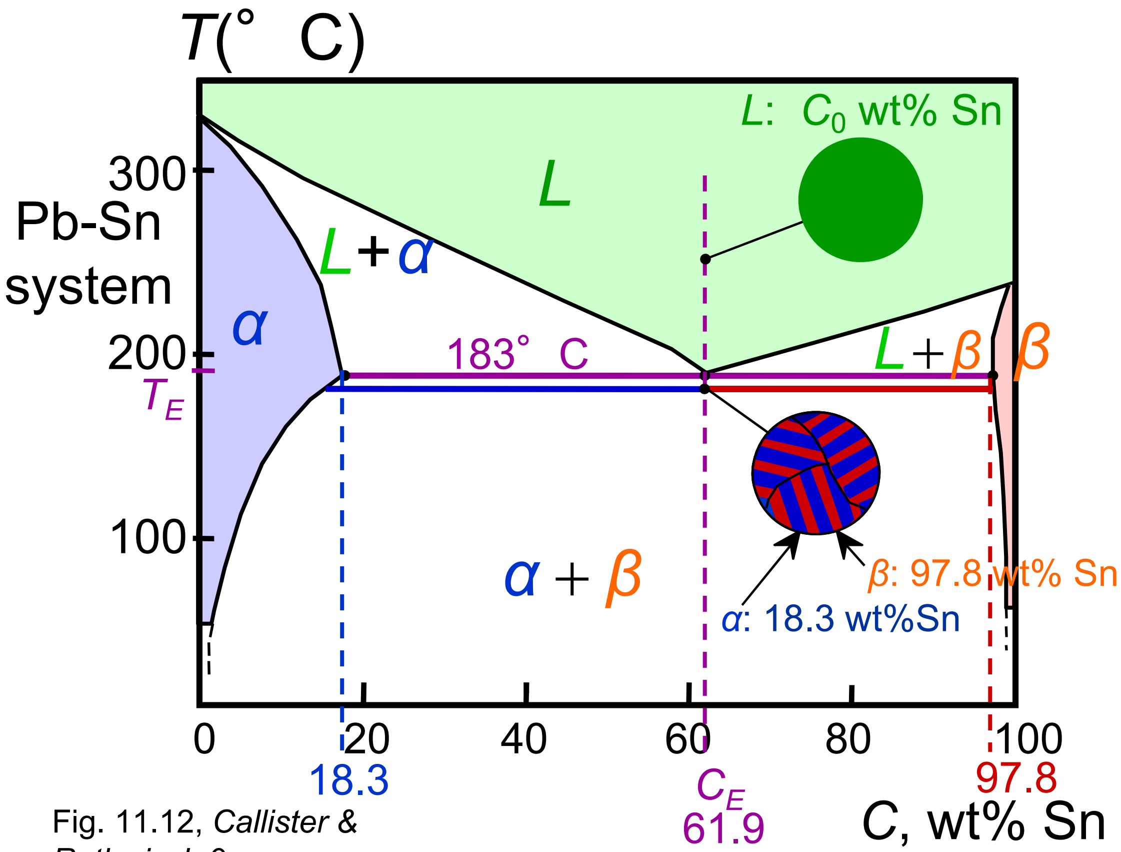


Fig. 11.12, *Callister & Rethwisch 9e.*

Micrograph of Pb-Sn eutectic microstructure

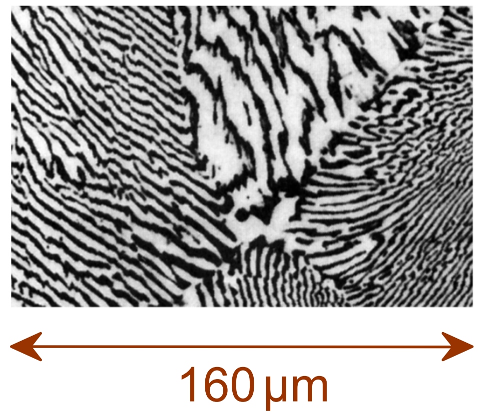


Fig. 11.13, *Callister & Rethwisch 9e.*
(From *Metals Handbook*, 9th edition, Vol. 9, *Metallography and Microstructures*, 1985. Reproduced by permission of ASM International, Materials Park, OH.)

Ceramic Phase Diagrams

c. ZrO_2-CaO diagram: Eutectic system

T ↔ Z 커다란 부피변화
: 재료내 균열 야기

→ CaO 첨가

→ Cubic phase 안정화

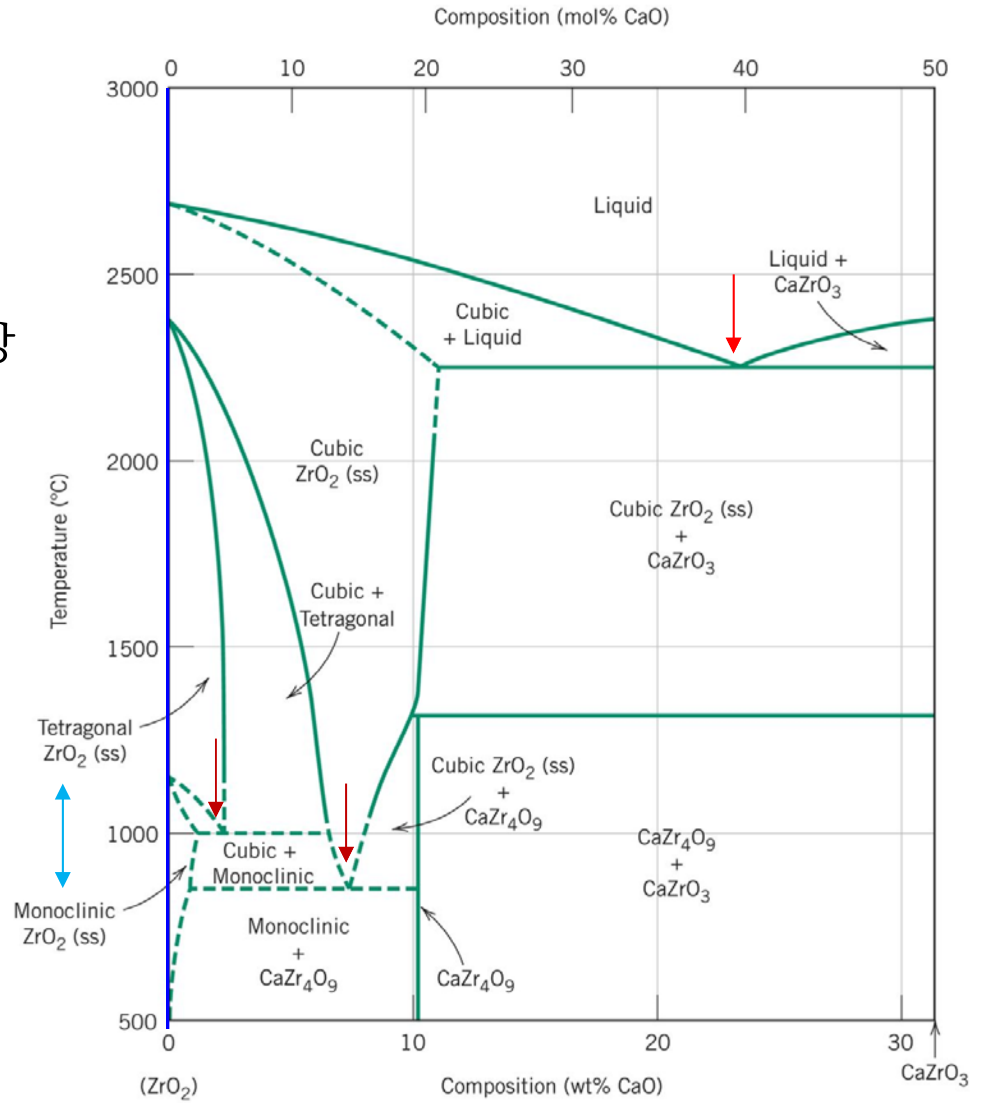
→ Cubic + Tetragonal 상 공존 냉각 조건에 따라 상온에서도 유지되도록 함

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

→ Y2O3, MgO 도 안정화제

→ 함량 증가시 Cubic이 상온까지 안정화

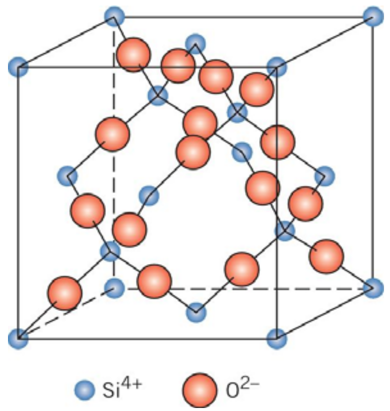
→ 완전 안정화 지르코니아



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.

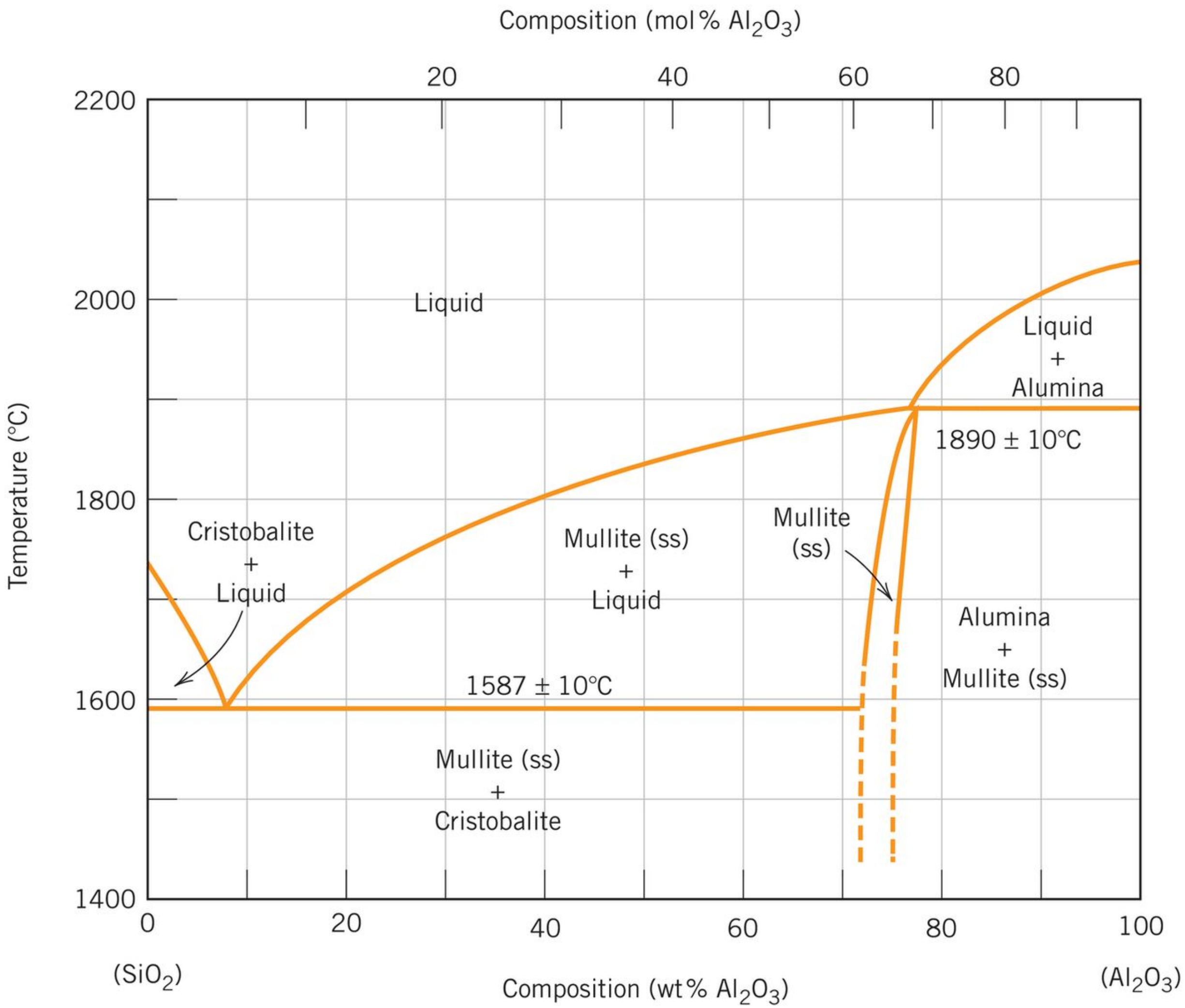
Ceramic Phase Diagrams

d. SiO_2-Al_2O_3 diagram: 대표적 내화세라믹 재료



Cristobalite
Figure 4.11

Mullite
$3Al_2O_3$-$2SiO_2$



Adapted from F. J. Klug, S. Prochazka, and R. H. Doremus, "Alumina–Silica Phase Diagram in the Mullite Region," J. Am. Ceram. Soc., 70[10], 758 (1987). Reprinted by permission of the American Ceramic Society.

Ceramic Phase Diagrams

b. $MgO-Al_2O_3$ diagram: Eutectic system

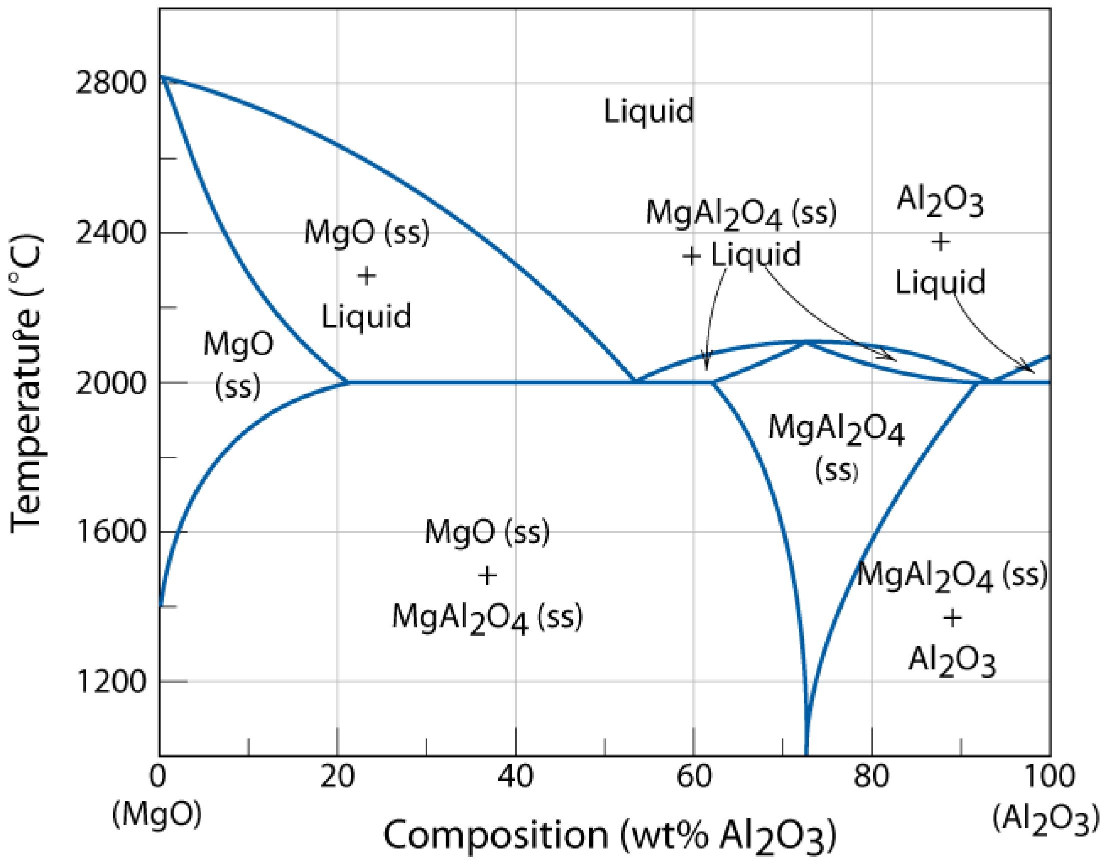


Fig. 14.2, Callister & Rethwisch 9e.
[Adapted from B. Hallstedt, "Thermodynamic Assessment of the System $MgO–Al_2O_3$," J. Am. Ceram. Soc., 75[6], 1502 (1992). Reprinted by permission of the American Ceramic Society.]

$MgAl_2O_4$ (or $MgO-Al_2O_3$) Spinel: 중간상 - 고용체

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?

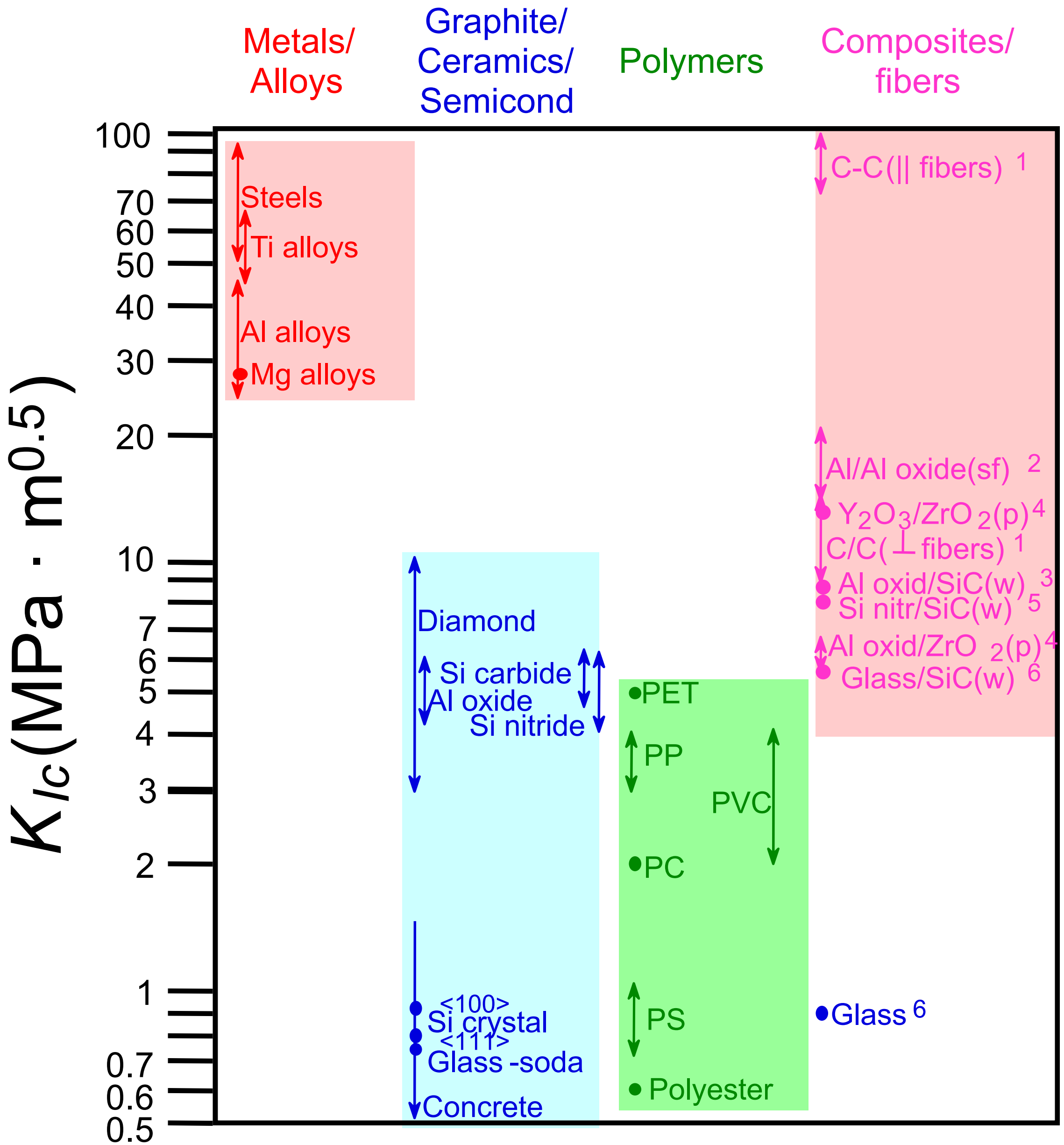
- Consider **mechanism of deformation**
  - **In crystalline, by dislocation motion**
  - In highly ionic solids, dislocation motion is difficult
    - few slip systems
    - resistance to motion of ions of like charge (e.g., anions) past one another

Fracture Toughness

균열이 존재할 때 취성 파괴에 대한 재료의 저항 정도 나타냄

$$K_c = Y\sigma\sqrt{\pi a}$$

$$(= MPa\sqrt{m})$$



대체로 얇은 판에 있어 **K$_c$값은 시편 두께에 따라** 변한다. <u>시편의 두께가</u> 균열 크기보다 <u>매우 크면</u> K$_c$ 값은 시편 두께의 영향을 받지 않으며, 이를 **평면 변형률(plane strain)상태**라고 한다. 이러한 두꺼운 시편에서의 **K$_c$값을 평면 변형률 파괴 인성(plane strain fracture toughness) K$_{Ic}$**라 함.

Based on data in Table B5,
Callister 7e.

$$K_c = Y\sigma\sqrt{\pi a}$$

$$(= MPa\sqrt{m})$$

* 우측항 값이 K_{Ic} 보다 작아도 **어떤 환경의 정적 응력하**에서 세라믹 재료 파괴

= **Static Fatigue or delayed fracture**

→대기 중 습기의 영향으로 균열 선단에서
응력부식 파괴가 발생

→정적 피로 강도 표시는 (응력 + 시간)

* **세라믹 재료의 파괴강도** 왼쪽과 같은
분포를 나타냄_결함의 존재확률로 설명

단, 압축 응력에서는 결함에 의해 응력
증폭의 효과가 없어 세라믹에서의
강도가 인장에서보다 압축이 10배정도 큼

→ 세라믹의 파괴강도는 표면에 잔류 압축
응력을 부가하여 상당히 증가시킬 수 있음
열 템퍼링 (Thermal tempering)

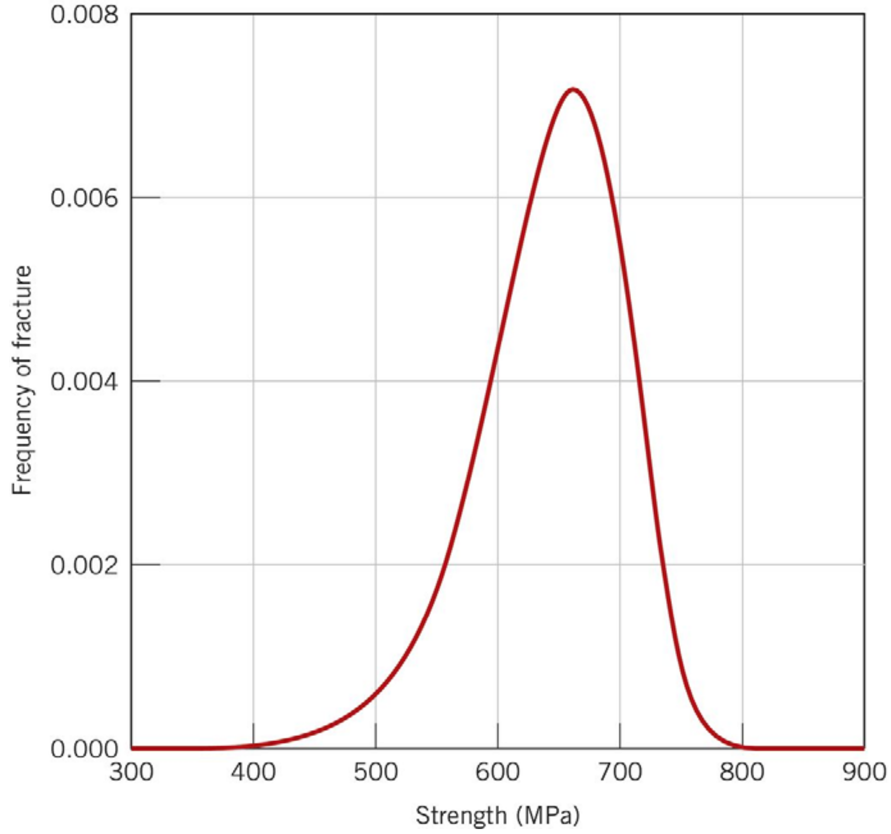
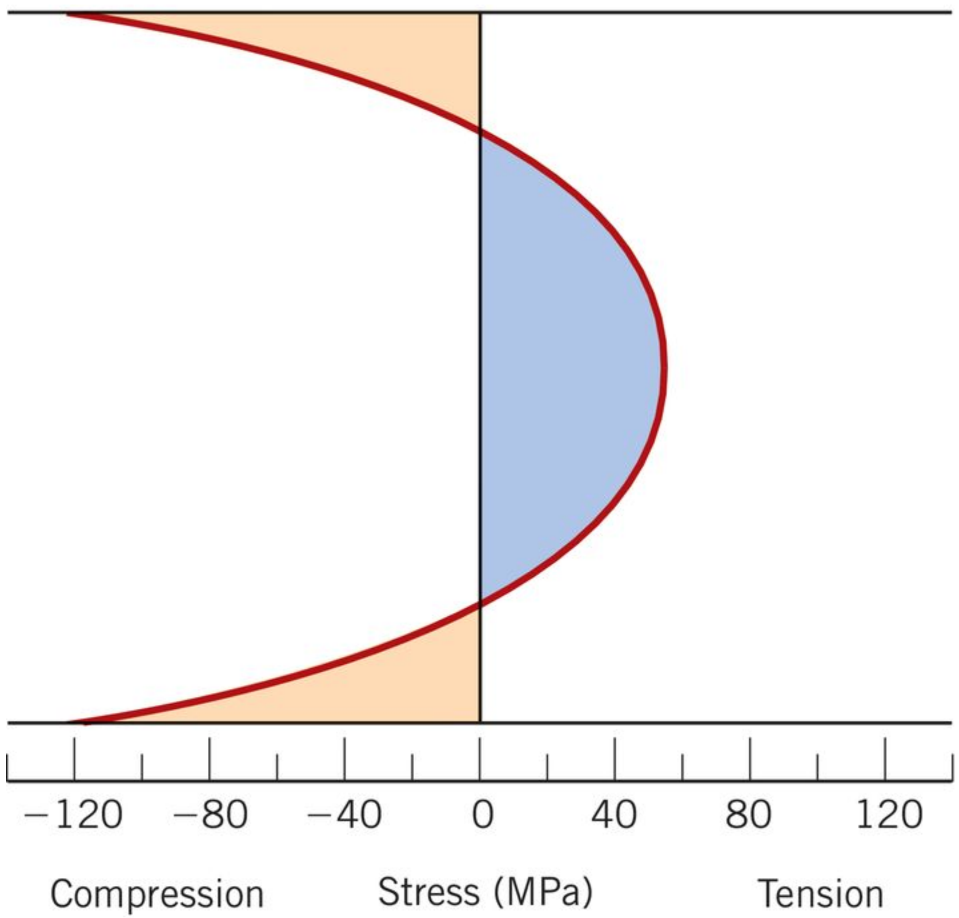


Figure 14.5 질화규소 재료에서 측정된 파괴강도의 분포 빈도

Figure 17.27 유리판 단면의 상온 잔류응력 분포

: 공기 제트나 기름욕 (oil bath) 내에서 상온까지 냉각
  표면과 내부의 냉각 속도가 상이하기 때문에 잔류응력 발생



* 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

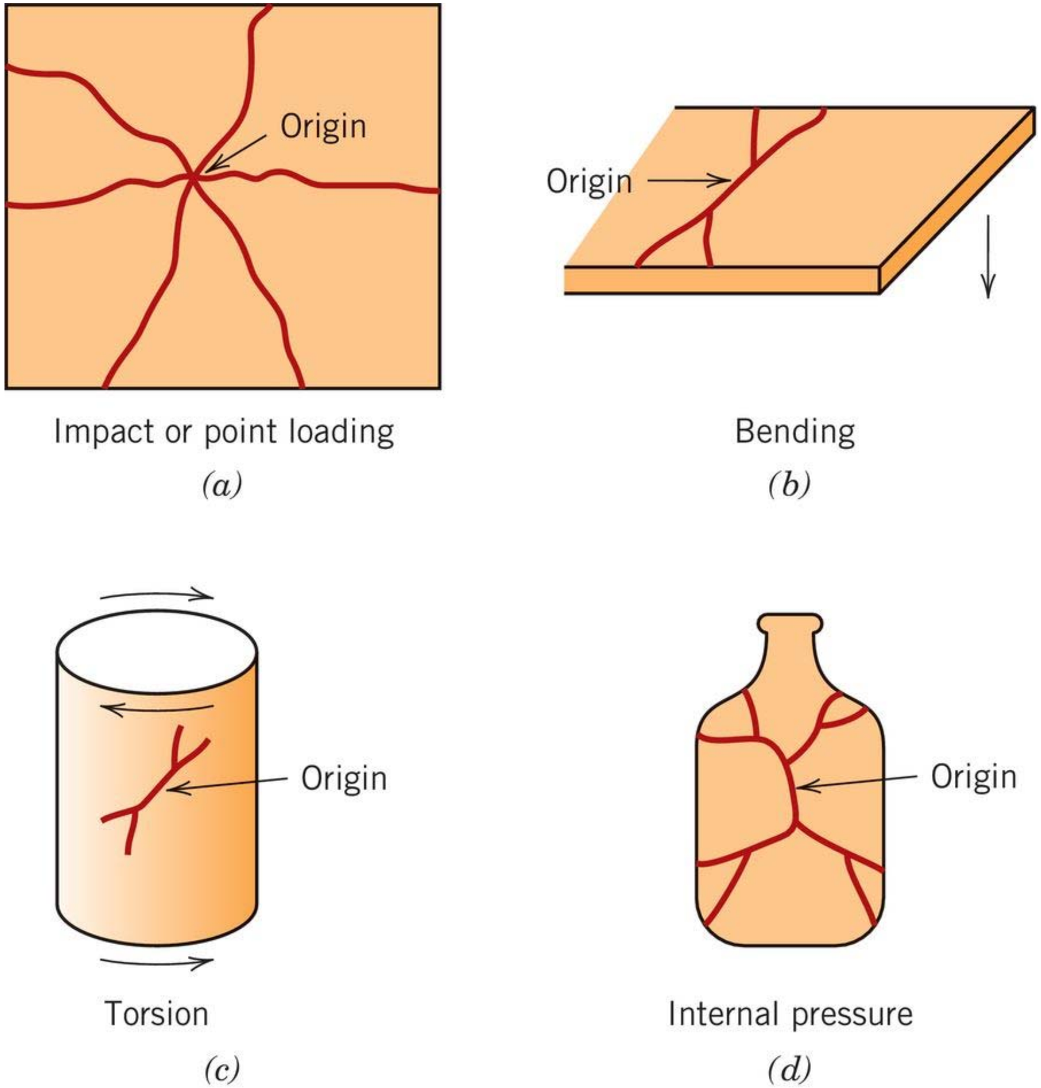


Figure 14.6 취성 세라믹에서 일반적인 네 종류의 하중 인가 조건에서 인가된 응력 패턴에 따른 생성되는 **균열의 기원 및 형상의 모식도**

* 세라믹의 파면

b. 파단면 (Fractography)

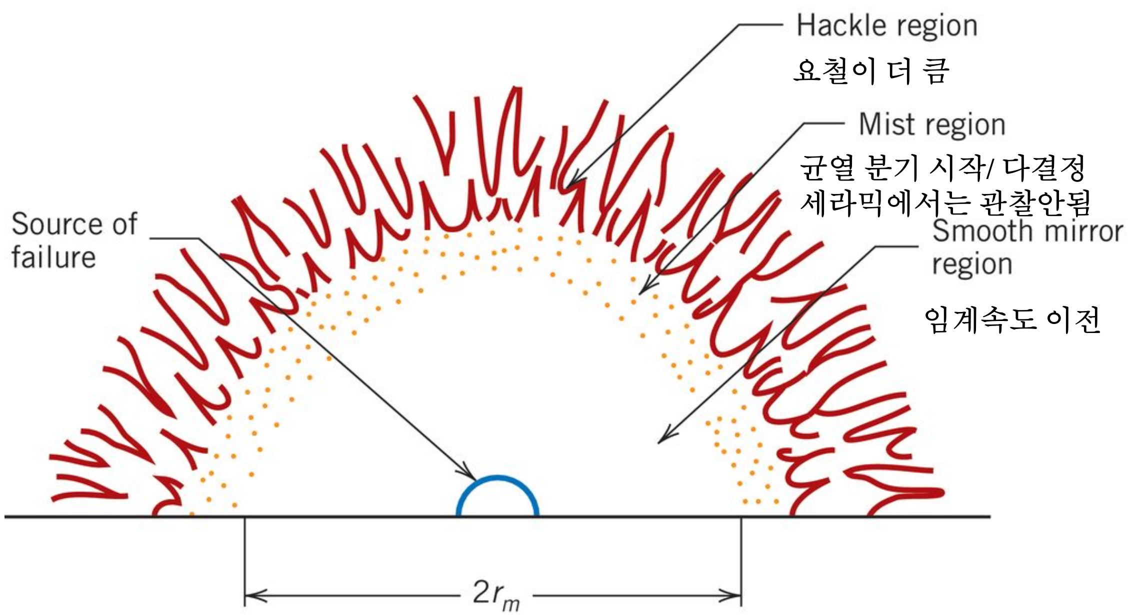
균열이 전파하는 동안
재료의 미세구조, 응력,
발생된 탄성파 등과
상호작용을 하며
파단면에 특정한 특징을 유발

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.

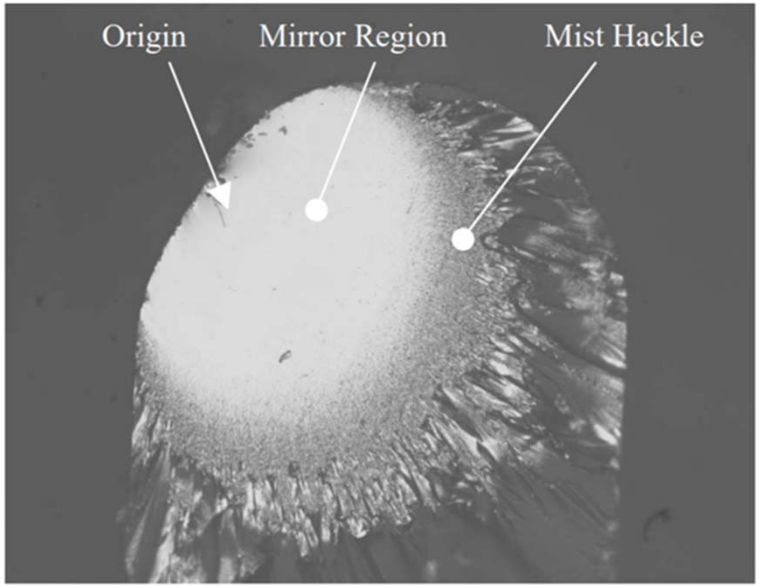
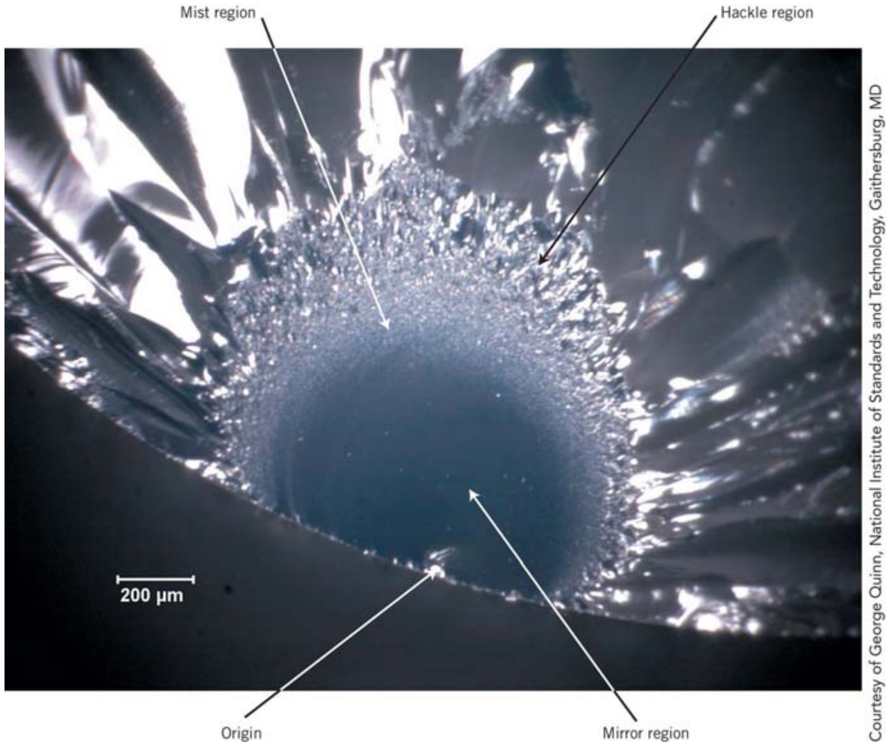
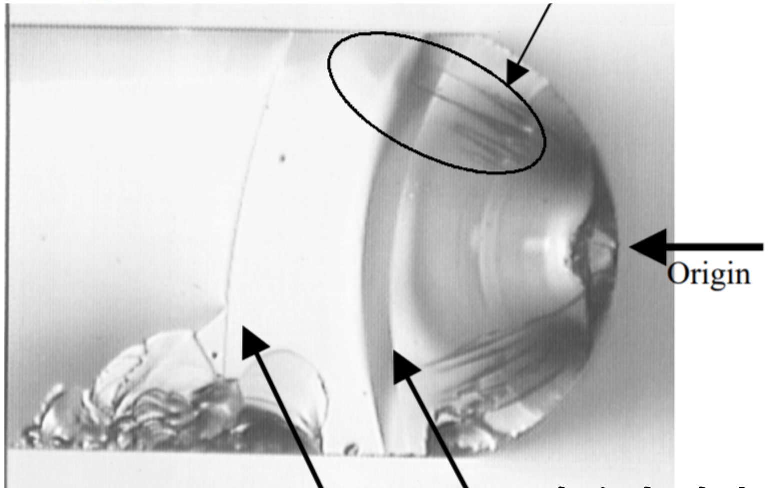


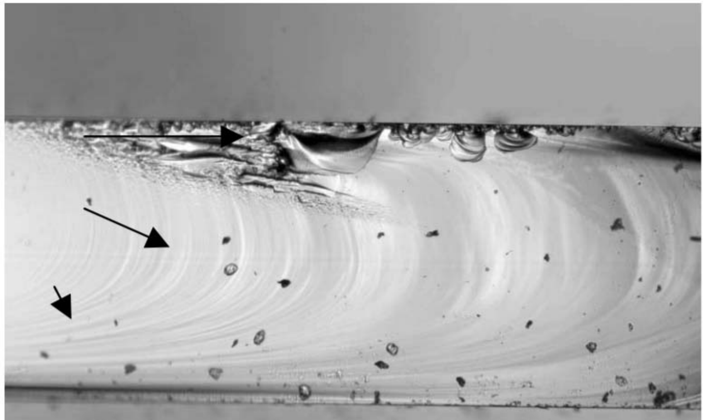
Fig. 6 Fracture surface around origin. Origin is surrounded with mirror region, which is covered with mist Hackle mark. Failure stress can be estimated using radius of the mirror region.





파단시 생성되는 탄성(음)파와 균열 선단과 상호작용으로 발생

Fig. 10 Fracture surface around origin. Radial Hackle marks, symmetrical Wallner lines with Arrest lines are existed

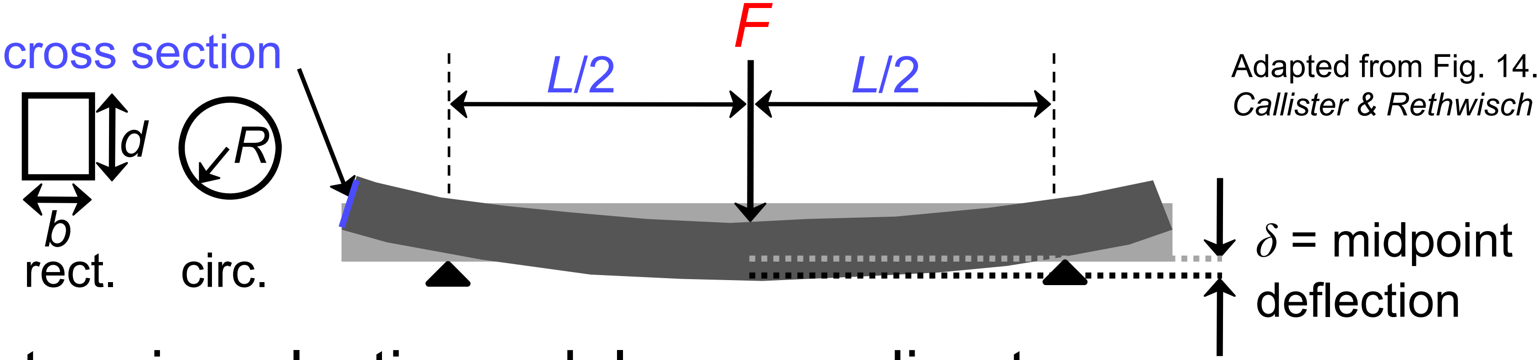


: 응력 분포 및 균열의 전파방향에 대한 정보제공

Fig. 4 Secondary Wallner lines created by crack propagation with bending stress. Cracks run left to right (arrow mark).

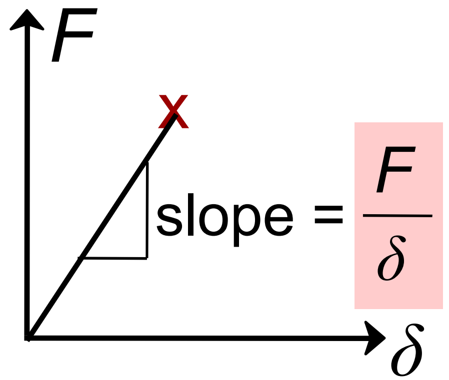
Flexural Tests – Measurement of Elastic Modulus

- Room T behavior is usually elastic, with brittle failure.
- 3-Point Bend Testing often used.
  -- tensile tests are difficult for brittle materials.



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

- Determine elastic modulus according to:



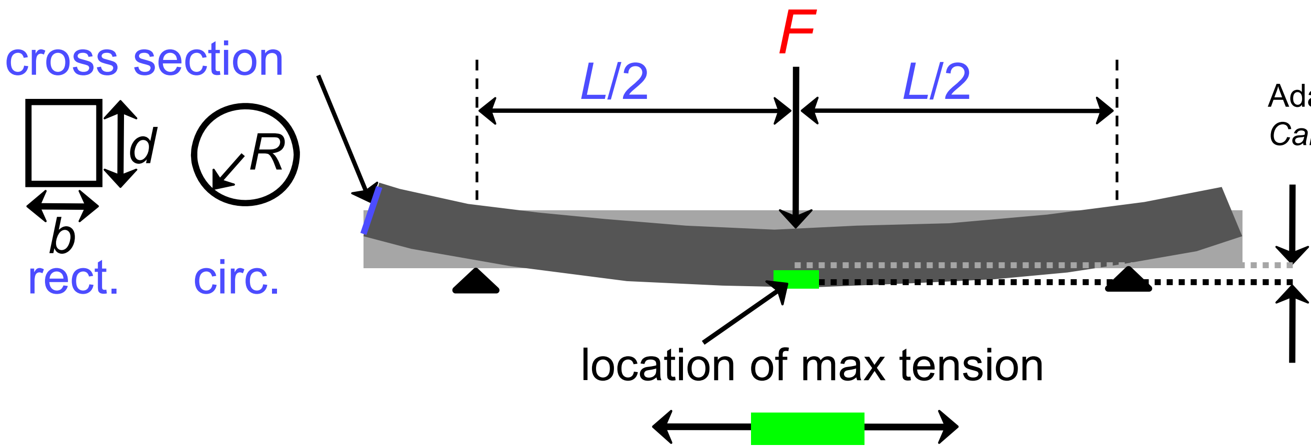
linear-elastic behavior

$$E = \frac{F}{\delta}\frac{L^3}{4bd^3} \quad \text{(rect. cross section)}$$

$$E = \frac{F}{\delta}\frac{L^3}{12\pi R^4} \quad \text{(circ. cross section)}$$

Flexural Tests – Measurement of Flexural Strength

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



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

- Flexural strength:

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

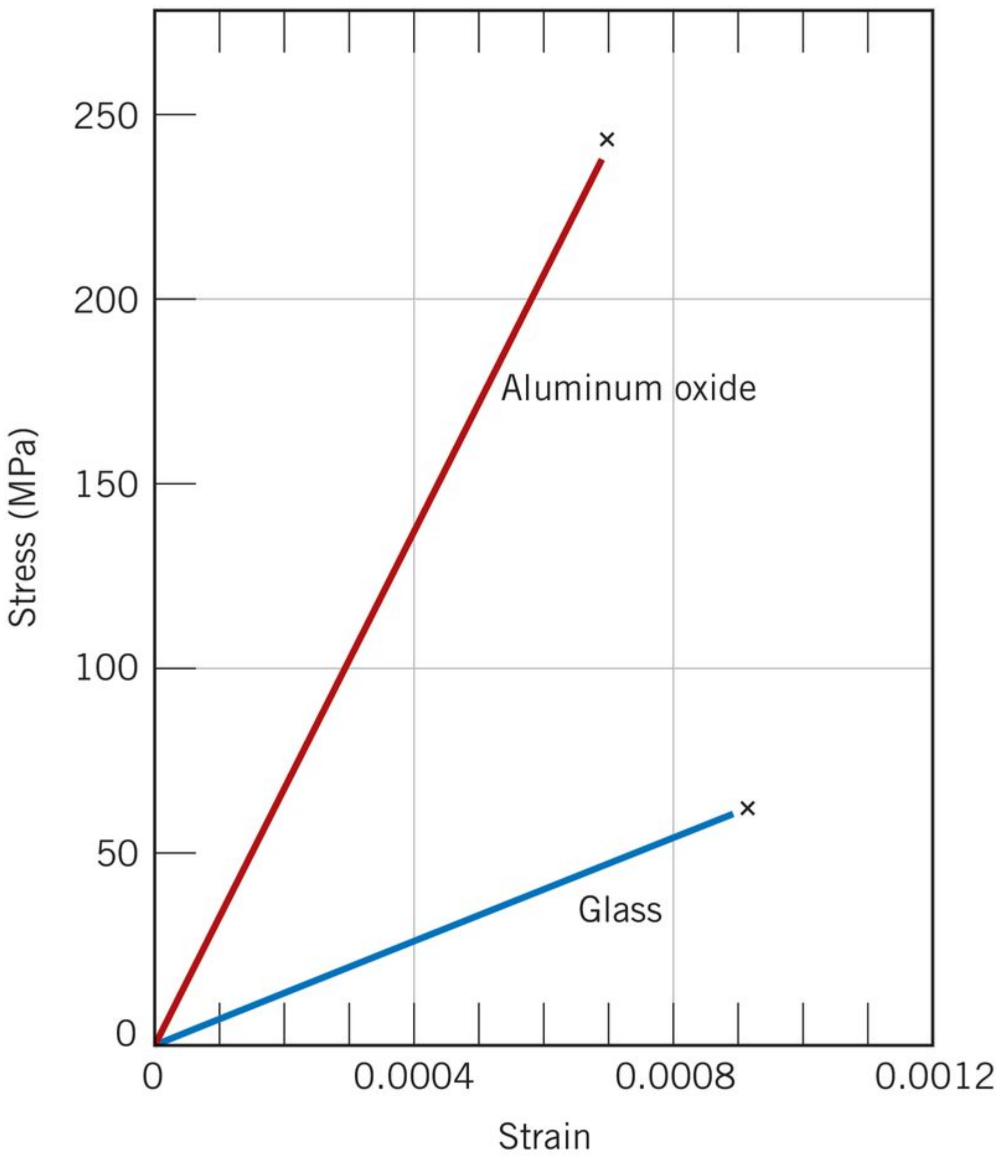
$$\sigma_{fs} = \frac{F_f L}{\pi R^3} \quad \text{(circ. cross section)}$$

- 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.*

Figure 14.10 알루미나와 유리의 응력 변형률 거동_ 탄성거동
세라믹의 탄성계수 = 70 ~ 500 GPa 범위 금속보다 약간 높음



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

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

단위: P (poise) or Pa·s

1P=1dyne·s/cm^2, 1 Pa·s=1N·s/m^2

10 P (poise) = 1 Pa·s

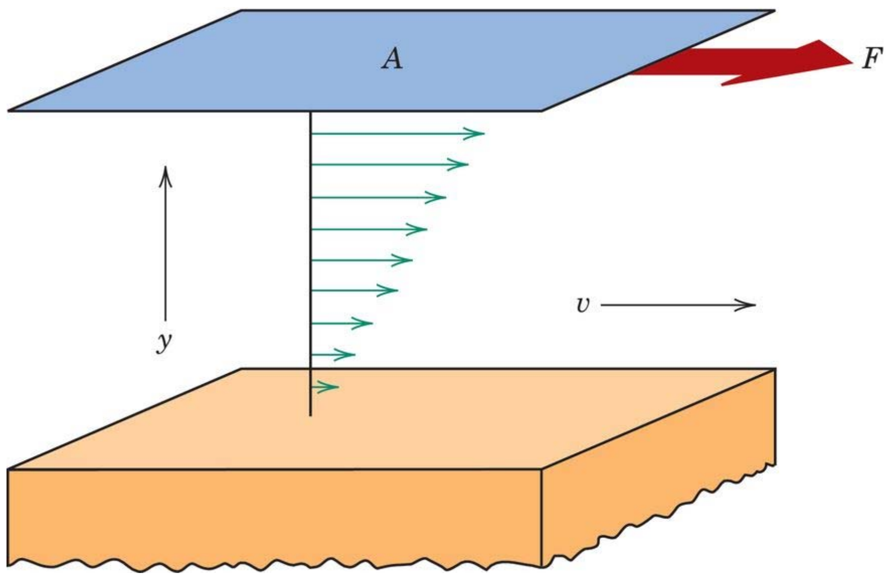
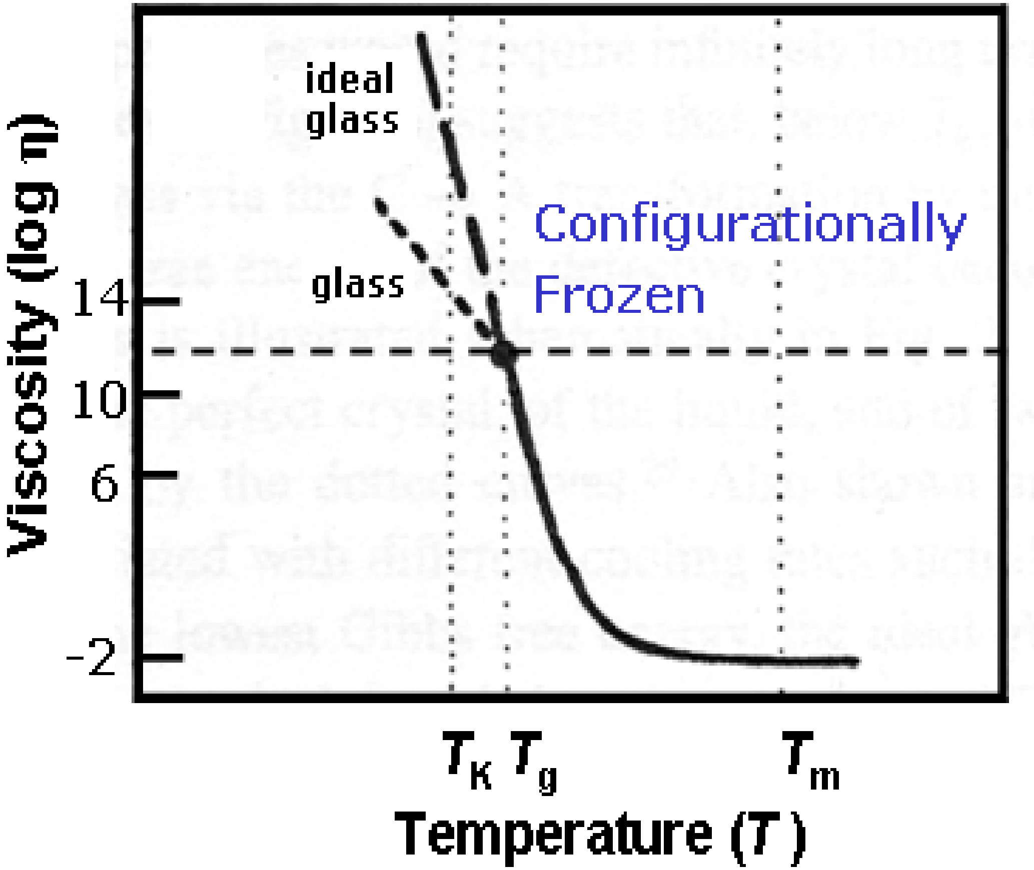


Figure 14.11 가해진 전단응력에 대한 액체와 유리의 점성유동의 모식도

Glass : undercooled liquid with high viscosity

The higher the structural relaxation, the closer it moves toward a "true" glass.



A solid is a materials whose viscosity exceeds $10^{14.6}$ centiPoise (10^{12} Pa s)

cf) liquid ~*10^{-2} poise*

14.9 기타 기계적 고려사항

a. 탄성계수의 기공도 의존성: $E = E_0(1 - 1.9P + 0.9P^2)$

P (기공의 부피분율)↑ → E↓

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

기공은 (1) 하중이 가해지는 면적을 감소시킴 (2) 응력집중자 역할

P **가 파단 계수를 지수함수적으로 감소시킴 ex) 10% 기공, 강도 50%이상 감소**

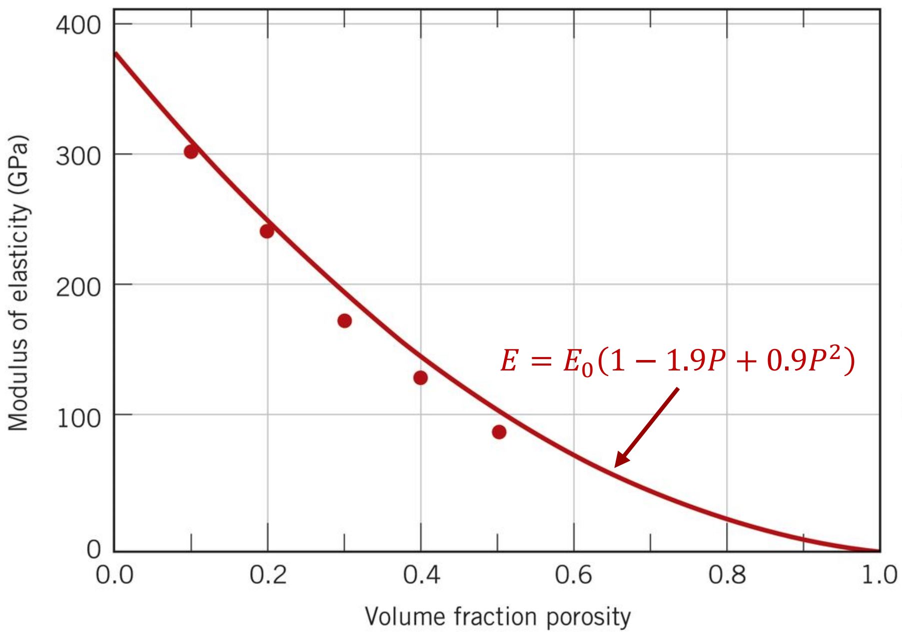


Figure 14.12

상온에서 알루미나의 탄성 계수에 미치는 기공의 영향

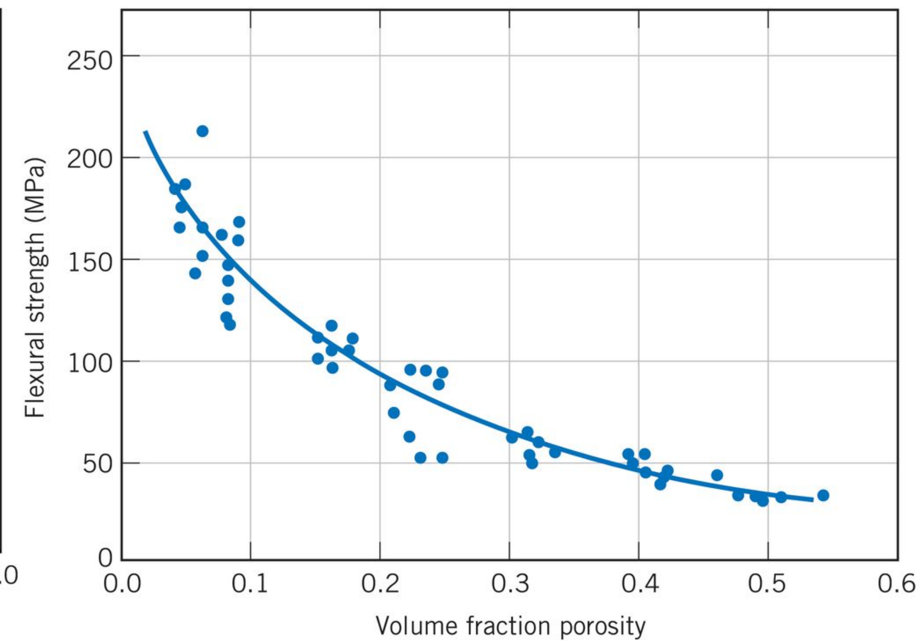


Figure 14.13

상온에서 알루미나의 굴곡강도에 미치는 기공의 영향

c. 경도 : 경도가 가장 높은 재료들이 세라믹 재료에 속함

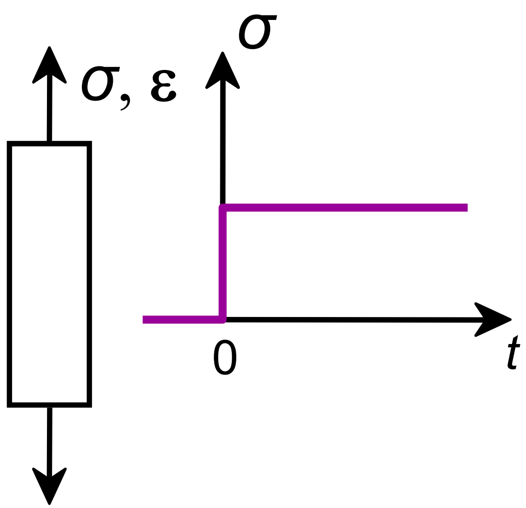
- 세라믹 재료는 압입시 쉽게 균열이 발생하여 정확한 경도를 측정하기 어려움 따라서, 균열을 심하게 유발하는 구형 압입자 [로크웰 Rockwell 경도 시험기와 브린넬 Brinell 경도시험기]가 사용되지 않고 피라미드형 압입자인 비커스 Vickers 와 누프 Knoop 법 (취성이 매우 심한 경우)이 주로 사용됨.

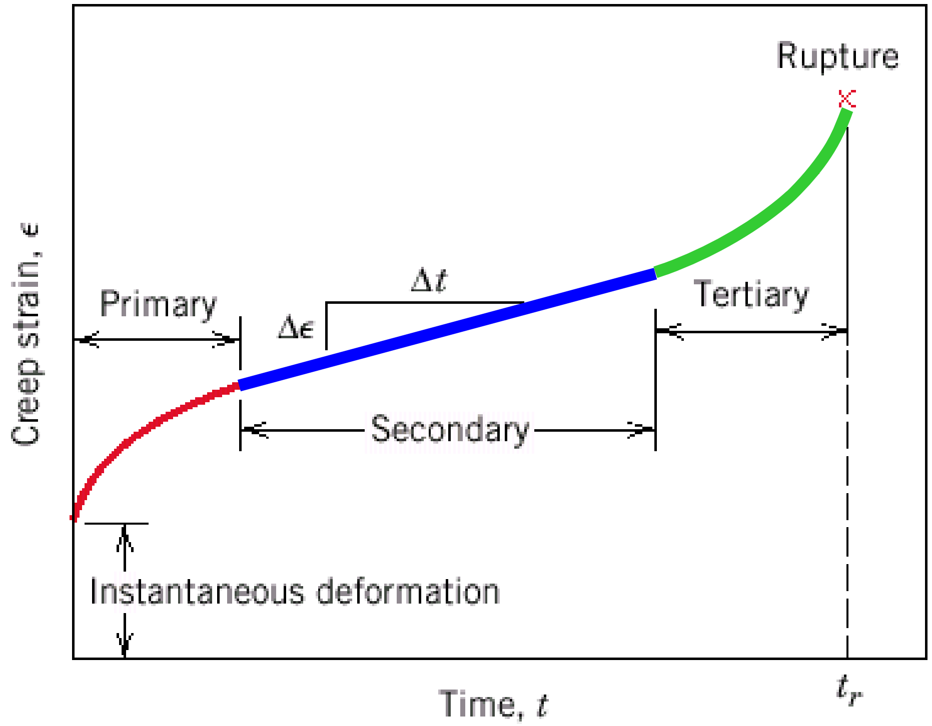
Table 14.2 Vickers (and Knoop) Hardnesses for Eight Ceramic Materials

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	—	

Creep

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





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

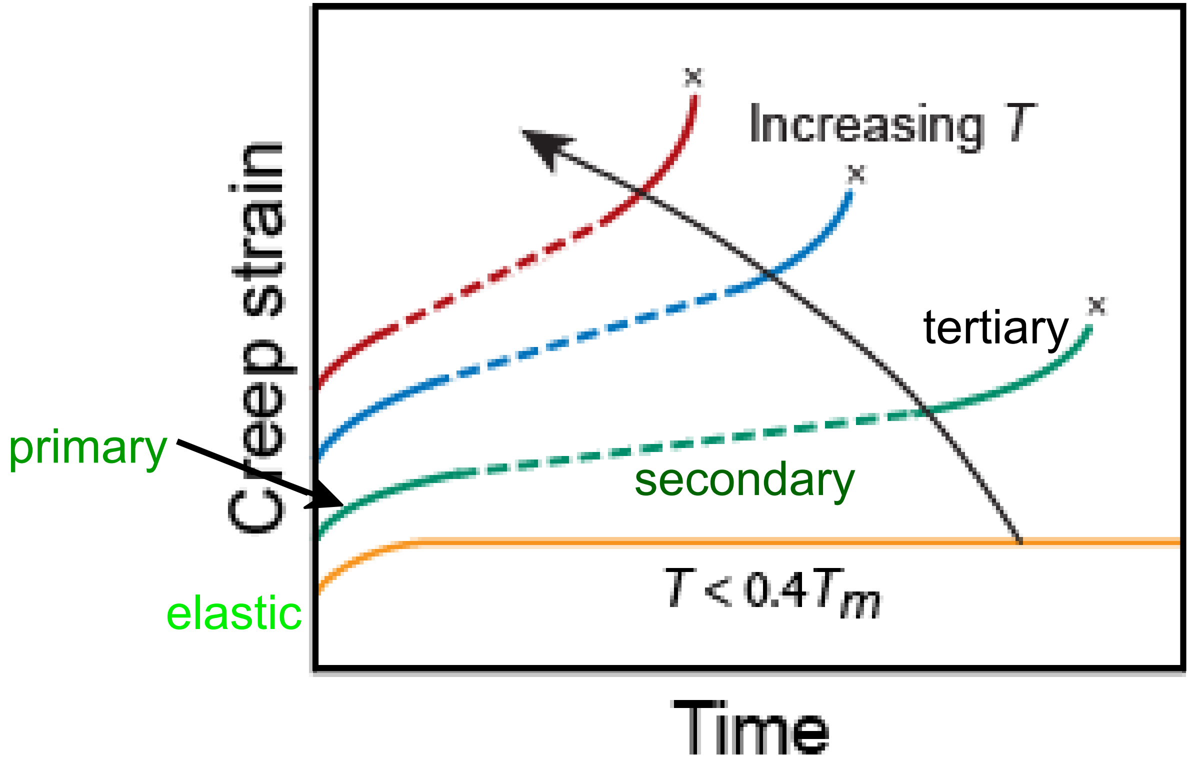
Primary Creep: slope (creep rate) decreases with time.

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.

Creep: Temperature Dependence

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



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

d. 세라믹 재료의 크리프는 T_m이 금속보다 상대적으로 커서 좀더 높은 온도에서 발생

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
- **Advanced ceramics**
  - -engine rotors valves bearings
  - -sensors

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

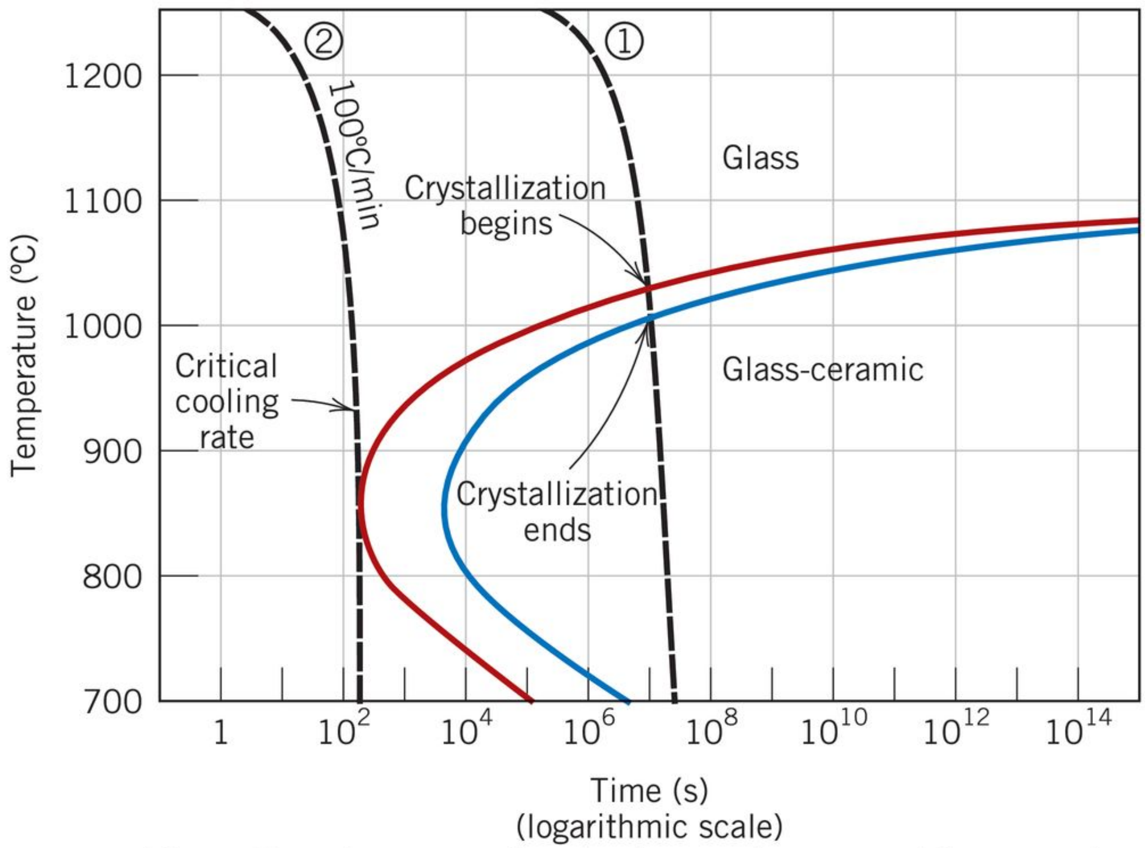
Figure 14.14 용도에 따라 분류한 세라믹 재료

a. Glass (유리): SiO_2 (Silicate) + CaO, Na_2O, K_2O 및 Al_2O_3 등 포함

Glass-ceramic:

다결정 재료

대부분 유리질의 핵생성 촉진을 위해 핵 생성제 (대부분 산화 티탄) 첨가 → C curve 왼쪽으로 이동



Reprinted from Glass: Science and Technology, Vol. 1, D. R. Uhlmann and N. J. Kreidl (Editors), "The Formation of Glasses," p. 22, copyright 1983, with permission from Elsevier.

Figure 14.15 루나 유리의 결정화 반응에 대한 연속냉각 변태곡선

b. 점토 제품: Structural clay products (벽돌, 타일, 하수구 파이프 등)과
Whitewares (백자=도자기, 식기, 접시, 화장실 도기 등)

c. 내화물 (Refractory ceramic):

(1) 가혹한 분위기하 불활성상태 유지, (2) 고온에서 용융되거나 분해되지 않음, (3) 열차폐 가능

Table 14.4 Compositions of Five Common Ceramic Refractory Materials

	Composition (wt%)							Apparent Porosity (%)
Refractory Type	Al_2O_3	SiO_2	MgO	Cr_2O_3	Fe_2O_3	CaO	TiO_2	
Fireclay	25–45	70–50	0–1		0–1	0–1	1–2	10–25
High-alumina fireclay	90–50	10–45	0–1		0–1	0–1	1–4	18–25
Silica	0.2	96.3	0.6			2.2		25
Periclase	1.0	3.0	90.0	0.3	3.0	2.5		22
Periclase–chrome ore	9.0	5.0	73.0	8.2	2.0	2.2		21

Source: From W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics*, 2nd edition. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

d. 연마재 (Abrasive ceramic):

상대적으로 연한재료를 마무, 연마, 절삭하는데 사용
인조 또는 천연 다이아몬드 (비쌈), 탄화규소, WC, 산화 알루미늄, 실리카 모래

- Cutting tools:
  -- for grinding glass, tungsten, carbide, ceramics
  -- for cutting Si wafers
  -- for oil drilling

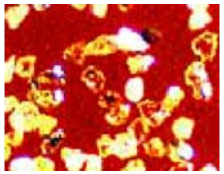
* manufactured single crystal or polycrystalline diamonds in a metal or resin matrix.

* polycrystalline diamonds resharpen by microfracturing along cleavage planes.

oil drill bits

blades

Single crystal diamonds



polycrystalline diamonds in a resin matrix.

- Sandpaper 등 코팅된 연마재 혹은 기름과 물에 혼합된 연마재 등

e. 시멘트 (cement): 포틀랜드 시멘트, 석고 (수성), 석회석 (비수성) _ 재료성분 중 일부가 결합제로 작용 → 화학적으로 결합

f. 탄소재료: 탄소의 동질이상체 (다이아몬드, 흑연, 탄소섬유)

Table 14.5 Properties of Diamond, Graphite, and Carbon (for Fibers)

Property	*Material*			
		Graphite		
	Diamond	*In-Plane*	*Out-of-Plane*	*Carbon (Fibers)*
Density (g/cm^3)	3.51	2.26		1.78–2.15
Modulus of elasticity (GPa)	700–1200	350	36.5	230–725[a]
Strength (MPa)	1050	2500	—	1500–4500[a]
Thermal Conductivity (W/m·K)	2000–2500	1960	6.0	11–70[a]
Coefficient, Thermal Expansion (10^{-6} K^{-1})	0.11–1.2	−1	+29	−0.5–−0.6[a] 7–10[b]
Electrical Resistivity (Ω·m)	10^{11}–10^{14}	1.4×10^{-5}	1×10^{-2}	9.5×10^{-6}–17×10^{-6}

[a]Longitudinal fiber direction.

[b]Transverse (radial) fiber direction.

g. Advanced Ceramics:

세라믹의 독특한 전기적, 자기적, 광학정 성질 활용
→ 내연기관, 터빈 엔진, 전자패키징, 절단용구 그리고 에너지 변환 저장 및 발전에 사용 (제19, 21, 22장 참고)

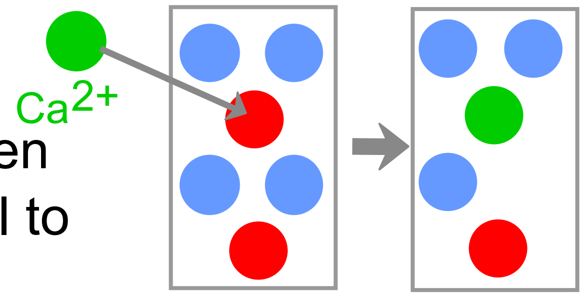
Ex. (1) Materials for Automobile Engines

- Advantages:
  - Operate at high temperatures – high efficiencies
  - Low frictional losses
  - Operate without a cooling system
  - Lower weights than current engines
- Disadvantages:
  - Ceramic materials are brittle
  - Difficult to remove internal voids (that weaken structures)
  - Ceramic parts are difficult to form and machine

- Potential candidate materials: Si_3N_4, SiC, & ZrO_2
- Possible engine parts: engine block & piston coatings

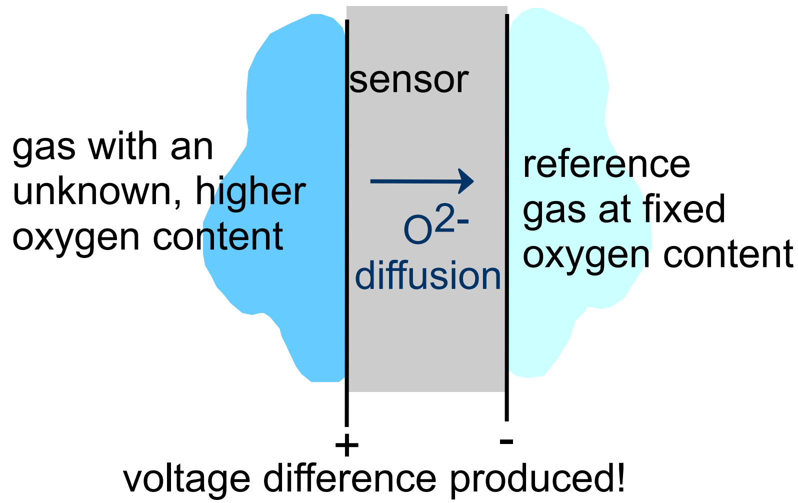
(2) Ceramics Application: Sensors

- Example: ZrO_2 as an oxygen sensor
- Principle: Increase diffusion rate of oxygen to produce rapid response of sensor signal to change in oxygen concentration



A substituting Ca^{2+} ion removes a Zr^{4+} ion and an O^{2-} ion.

- Approach:
  Add Ca impurity to ZrO_2:
  -- increases O^{2-} vacancies
  -- increases O^{2-} diffusion rate
- Operation:
  -- voltage difference produced when O^{2-} ions diffuse from the external surface through the sensor to the reference gas surface.
  -- magnitude of voltage difference $\propto$ partial pressure of oxygen at the external surface



(3) Nanocarbons

- Fullerenes – spherical cluster of 60 carbon atoms, C_{60}
  - Like a soccer ball
- Carbon nanotubes – sheet of graphite rolled into a tube
  - Ends capped with fullerene hemispheres

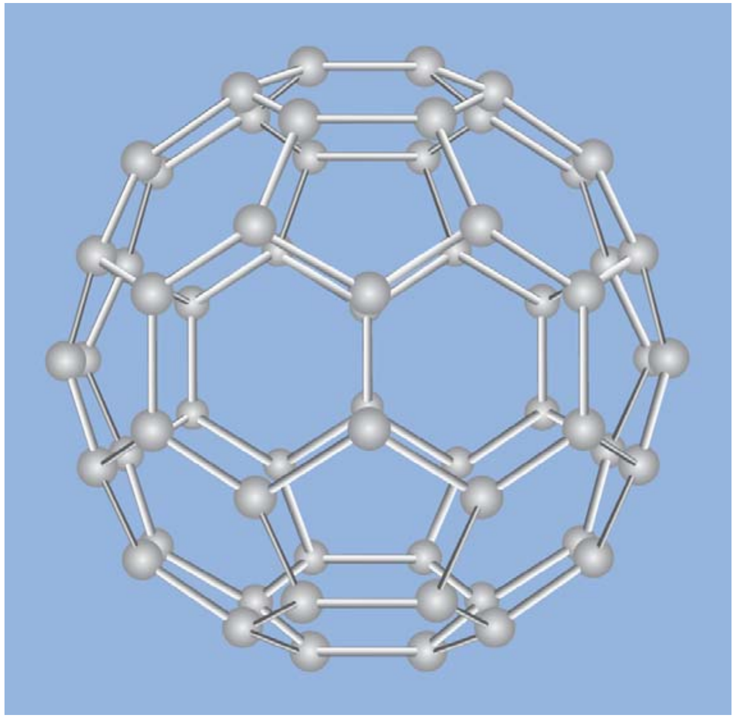


Fig. 14.20, *Callister & Rethwisch 9e.*

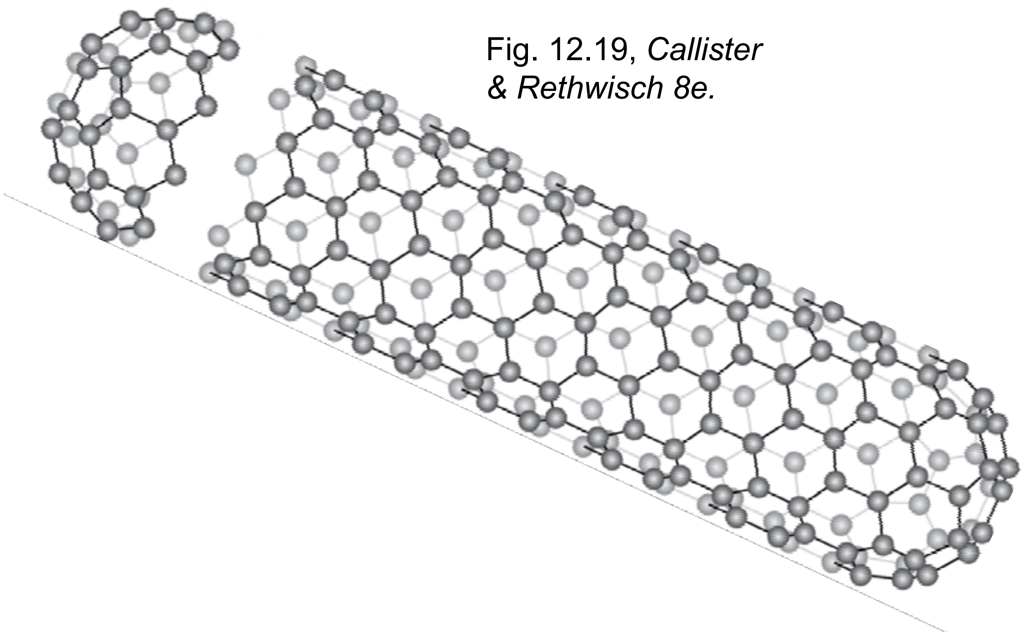


Fig. 12.19, *Callister & Rethwisch 8e.*

Nanocarbons (cont.)

- Graphene – single-atomic-layer of graphite
  - composed of hexagonally sp^2 bonded carbon atoms

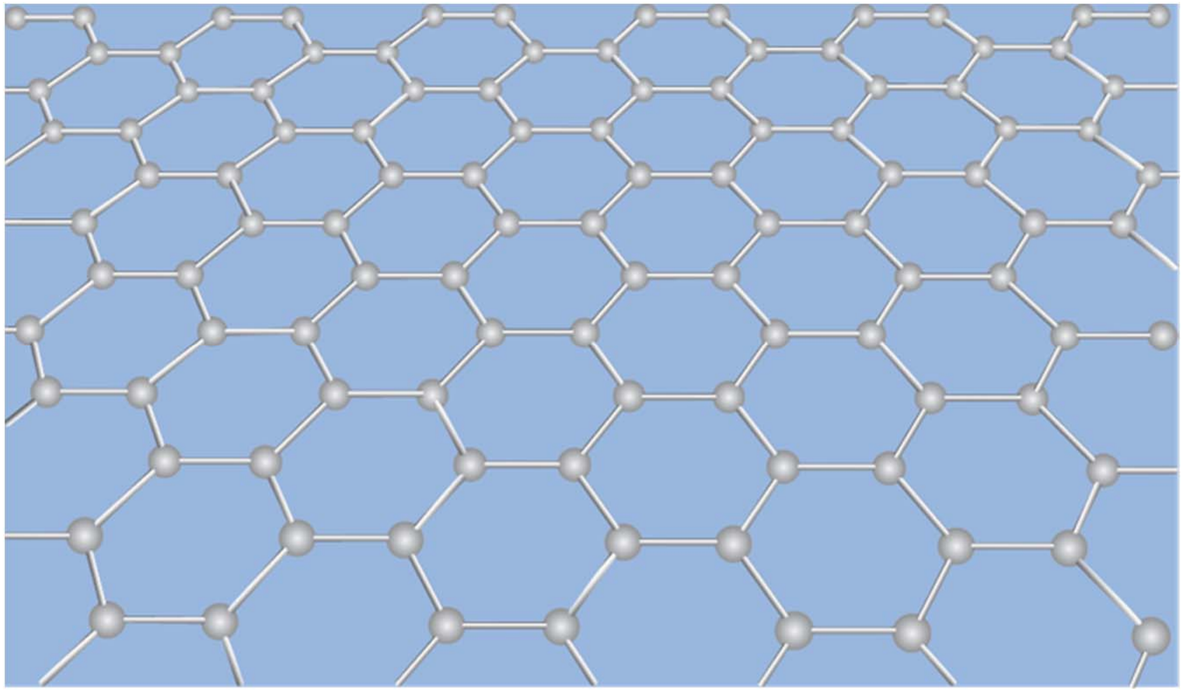


Fig. 14.22, *Callister & Rethwisch 9e.*

Summary

- Room-temperature mechanical behavior – flexural tests
  - -- linear-elastic; measurement of elastic modulus
  - -- brittle fracture; measurement of flexural modulus

- Categories of ceramics:
  - -- glasses
  - -- refractories
  - -- advanced ceramics
  - -- clay products
  - -- cements