Chapter 13. Types and Applications of Metals Ceramics, and Polymers

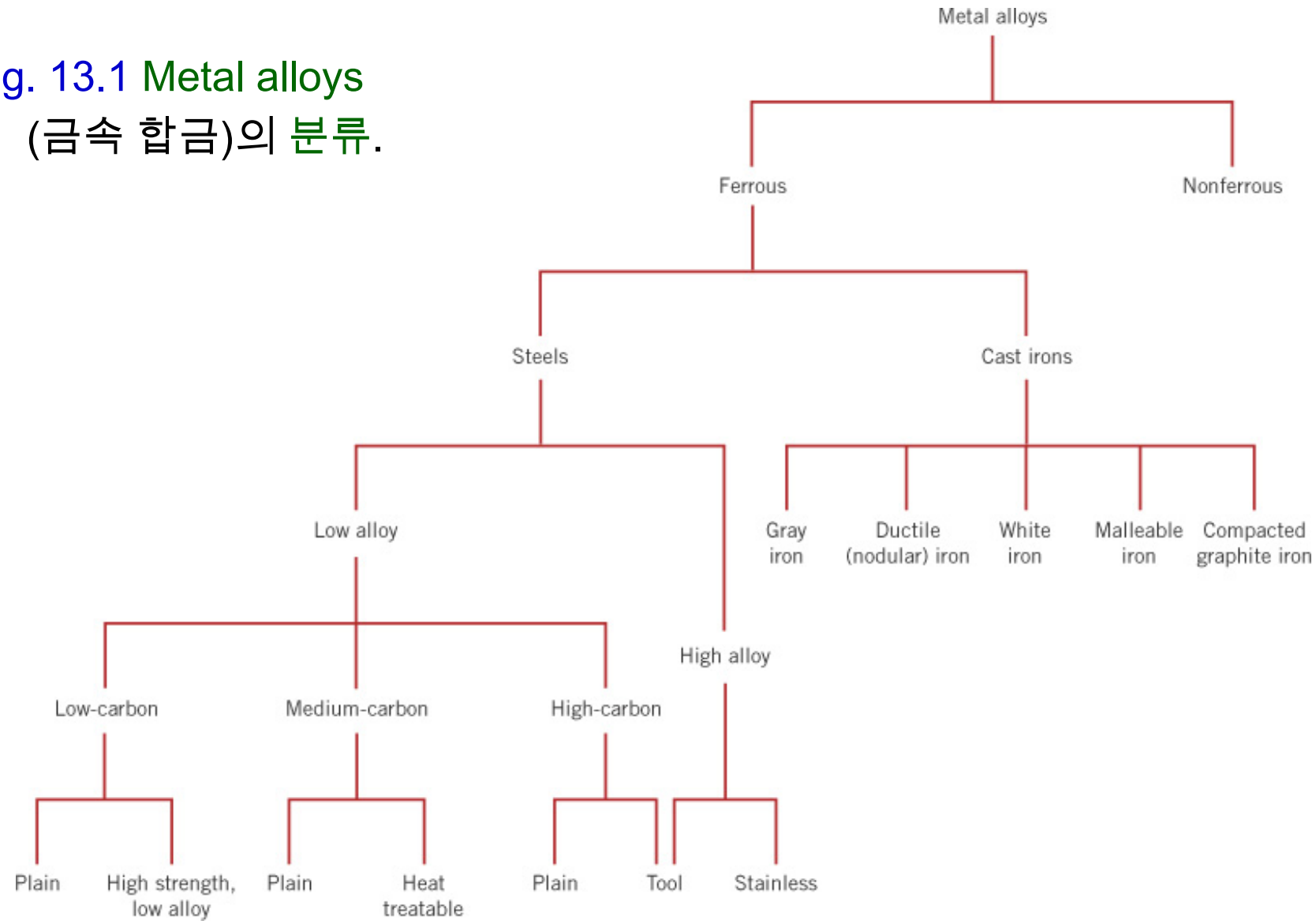
(금속, 세라믹, 고분자재료의 종류 및 응용)

Metal alloys, ceramics, polymeric materials

→ Ferrous alloys (철 합금), nonferrous alloys (비철 합금)

→ Steels (강), cast irons (주철)

Fig. 13.1 Metal alloys (금속 합금)의 분류.



Ferrous Alloys (철 합금)

Iron (철)

~ 금속 중 가장 널리 사용

1) 풍부히 존재

2) 비교적 쉽게 extraction (선광), refining (정련),
alloying (합금화) & fabrication (가공)

3) 다양한 기계적, 물리적 성질

단점: corrosion susceptibility (부식에 취약)

Steels (강)

Fe–C alloys + other alloying elements

→ C 함량이 기계적 성질에 큰 영향

Low-carbon steel (저탄소강)

Medium-carbon steel (중탄소강)

High-carbon steel (고탄소강)

Plain carbon steel (순탄소강) ~ C 이외의 다른 원소는 미량 함유

Alloy steel (합금 강) ~ 합금 원소를 특정 농도만큼 첨가

Low-Carbon Steels

: C 함량이 0.25 wt% 미만

Microstructure ~ Ferrite와 Pearlite 혼합 상으로 구성
(← 아공석(hypoeutectoid) 조성이므로)
Fe-Fe_3C 상평형도 참조 (Fig. 10.28)

특징: soft, weak but ductility & toughness ↑
machinable (기계가공성), weldable (용접성)
강 중에서 가장 저렴

용도: 차체, I-beam, 앵글 등 구조물, pipe, 다리, can 류

c.f.) High-strength, low-alloy steels (HSLA steels), 고강도 저합금강

: 저탄소강이면서 Cu, V, Ni, Mo 등 합금원소를 10% 함유

→ 순 저탄소강보다 강도, 경도, 내부식성 우수

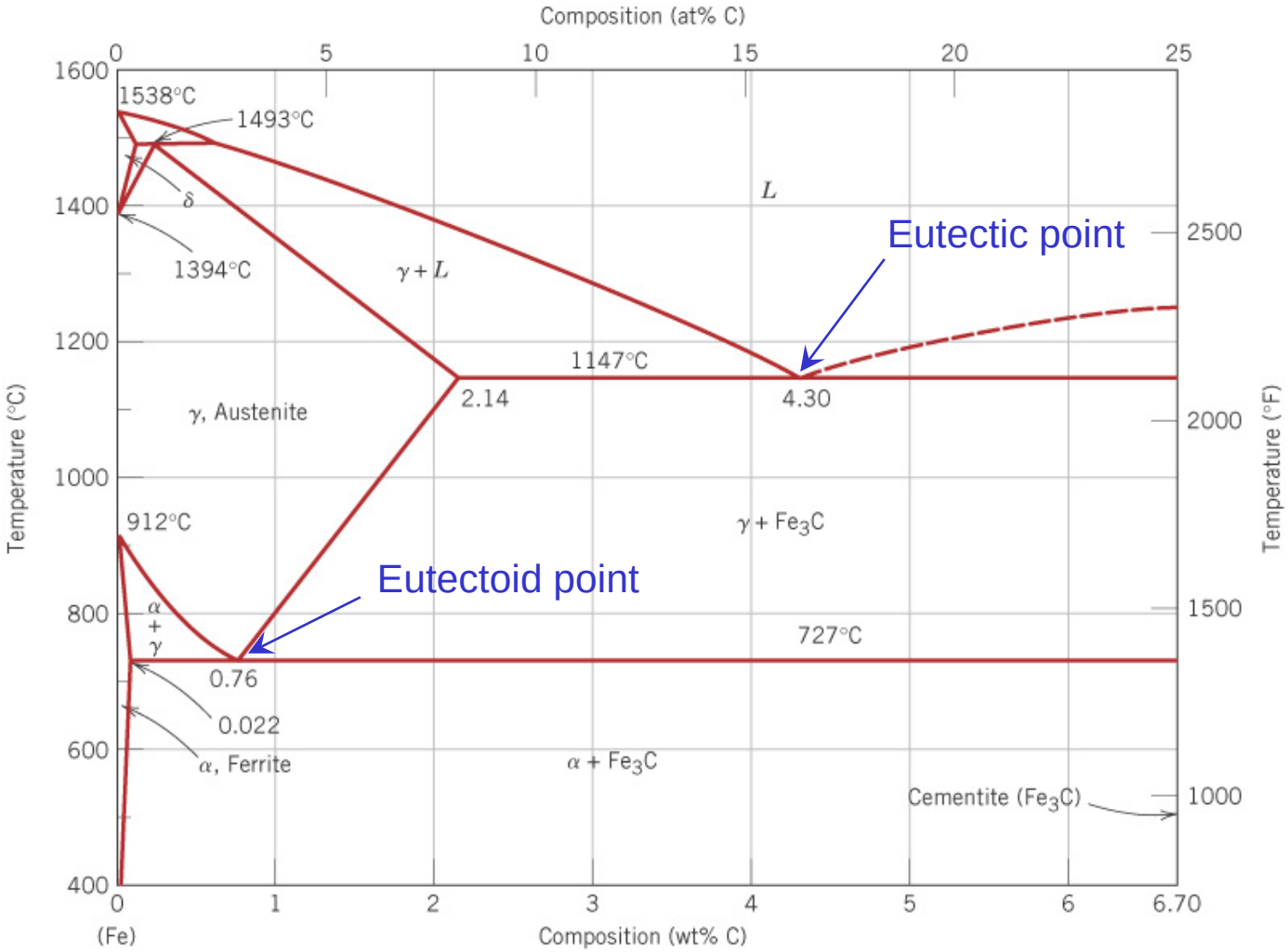


Fig. 10.28 Fe-Fe_3C 계의 상평형도.

Table 13.1b **Mechanical Characteristics of Hot-Rolled Material and Typical Applications for Various Plain Low-Carbon and High-Strength, Low-Alloy Steels**

AISI/SAE or ASTM Number	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Ductility [%EL in 50 mm (2 in.)]*	*Typical Applications*
		Plain Low-Carbon Steels		
1010	325 (47)	180 (26)	28	Automobile panels, nails, and wire
1020	380 (55)	210 (30)	25	Pipe; structural and sheet steel
A36	400 (58)	220 (32)	23	Structural (bridges and buildings)
A516 Grade 70	485 (70)	260 (38)	21	Low-temperature pressure vessels
		High-Strength, Low-Alloy Steels		
A440	435 (63)	290 (42)	21	Structures that are bolted or riveted
A633 Grade E	520 (75)	380 (55)	23	Structures used at low ambient temperatures
A656 Grade 1	655 (95)	552 (80)	15	Truck frames and railway cars

Medium-Carbon Steels

: C 함량이 0.25~0.6 wt% 미만

Microstructure ~ Tempered martensite
(austenitizing → quenching → tempering)

특징: 저탄소강에 비해 강도 ↑, 연성, 강인성 ↓

용도: 열차바퀴, 철로, 기어, 크랭크 축, 기계부품, 고강도 구조재

High-Carbon Steels

: C 함량이 0.6~1.4 wt%

Microstructure ~ Tempered martensite

특징: 탄소강 중에서 가장 강도, 경도 ↑, 연성 ↓

용도: 높은 내마모성이 요구되는 분야
(절삭공구, 칼날, 면도날, 톱날, 스프링)

Stainless Steels

: highly resistant to corrosion

주 합금원소 ~ Cr (적어도 11 wt% 이상), Mn, Ni, Mo

Microstructure ~ 주된 상에 따라 분류

- Ferritic stainless steels
- Austenitic stainless steels:
  - Cr 및 Ni 농도 가장 높음 (→ 내부식성 가장 강함)
  - 비자성 (nonmagnetic)
- Martensitic stainless steels

특징: 산화에 강함, 기계적 성질 우수 (높은 강도, 내부식성)
고온, 극한 환경에서 사용

용도: gas turbines, 고온 steam boilers, furnaces
비행기, 미사일, 원자력 발전 부품

Cast Irons (주철)

: C 함량이 2.14 wt% 이상 (보통 3~4.5 wt%)

용융온도 비교적 낮음 (1150~1300 °C)
very brittle → casting (주조)이 가장 일반적인 가공방법

C 농도가 높아 준안정상인 cementite가 상분리되어
ferrite 상 및 graphite 상을 형성하기도 함

$Fe_3C \rightarrow 3Fe\ (\alpha) + C$ → (Fig. 13.2)

Cementite Ferrite Graphite

1 wt% 이상의 Si 존재시 흑연 생성 촉진
& 냉각속도 느릴수록 C가 흑연상으로 존재

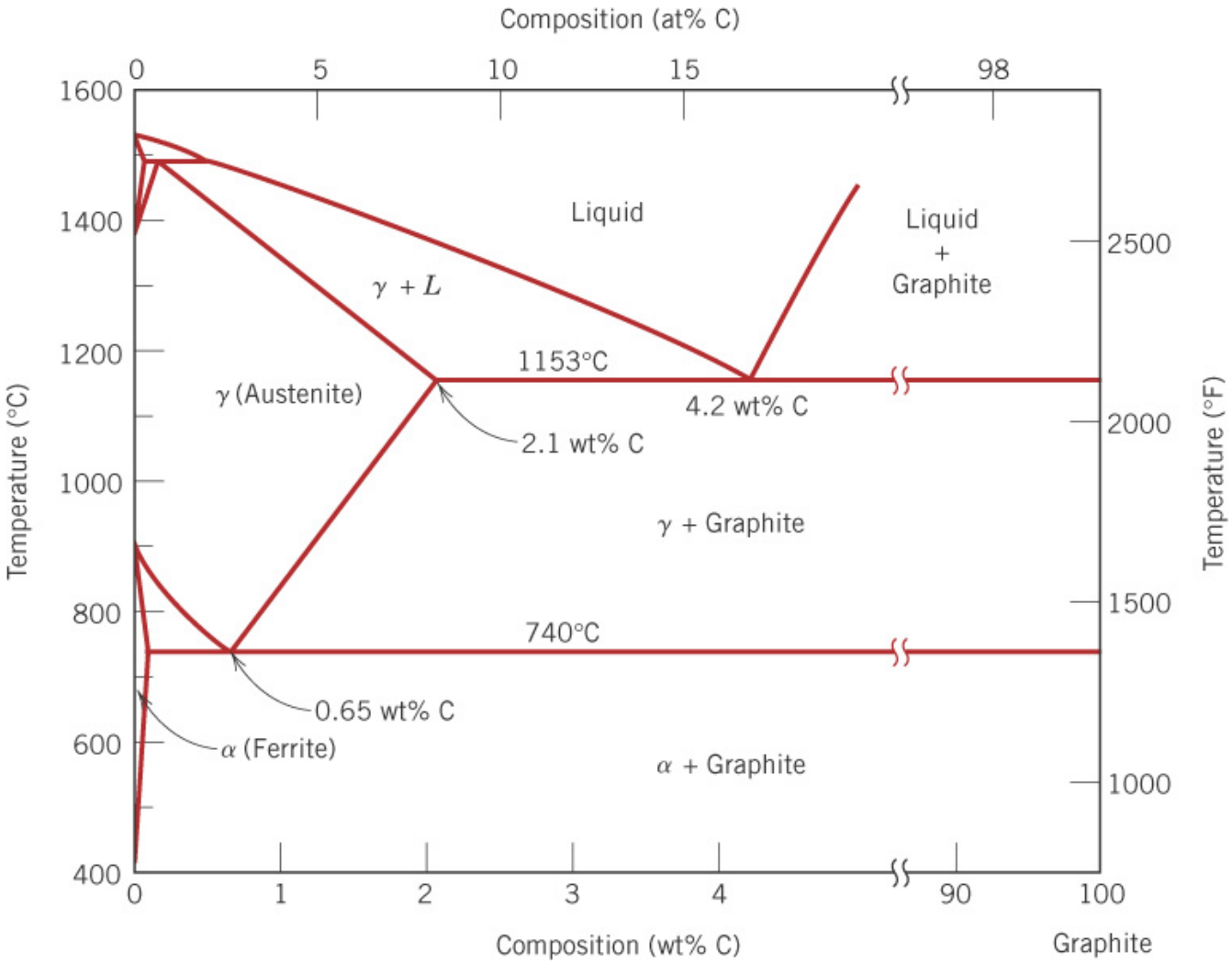


Fig. 13.2 준안정상 cementite 대신 안정상 graphite로 나타낸 Fe-C 상평형도.

Types of Cast Irons

: Gray (cast) iron, ductile iron, white (cast) iron
malleable iron, compacted graphite iron

1) Gray iron (회주철)

~ graphite flakes, weak & brittle in tension
stronger in compression, wear resistant
유동성 우수 → 주물 제조시 유리
금속재료중 가장 저렴, excellent vibrational damping

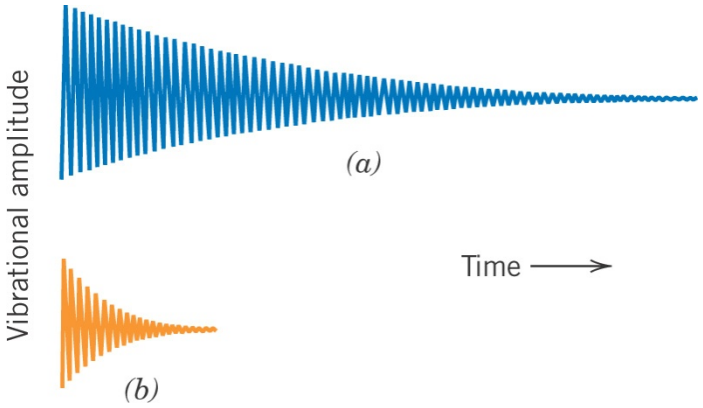


Fig. 13.4 진동흡수능의 비교:
(a) steel, (b) gray iron.

2) Ductile (or Nodular) iron (연주철 or 구상주철)

~ Mg & Ce을 첨가, 흑연상이 구상 형태

회주철보다 강도, 연성 ↑

3) White iron (백주철)

~ cementite와 pealite 상, 백색, very hard but brittle

4) Malleable iron (가단주철)

~ 장미꽃 형의 흑연상, 상대적으로 높은 강도 및 연성 우수

Heat-treated white iron at 800-900 ^{o}C

5) Compacted graphite iron (조밀 흑연 주철, CGI)

~ Si에 의해 흑연화 촉진된 주철

미세조직은 회주철과 연주철의 중간 형태

열전도도, 열충격 저항성, 고온 산화 저항성 ↑

← 미세구조와 기계적 성질은 조성 및 열처리가 결정

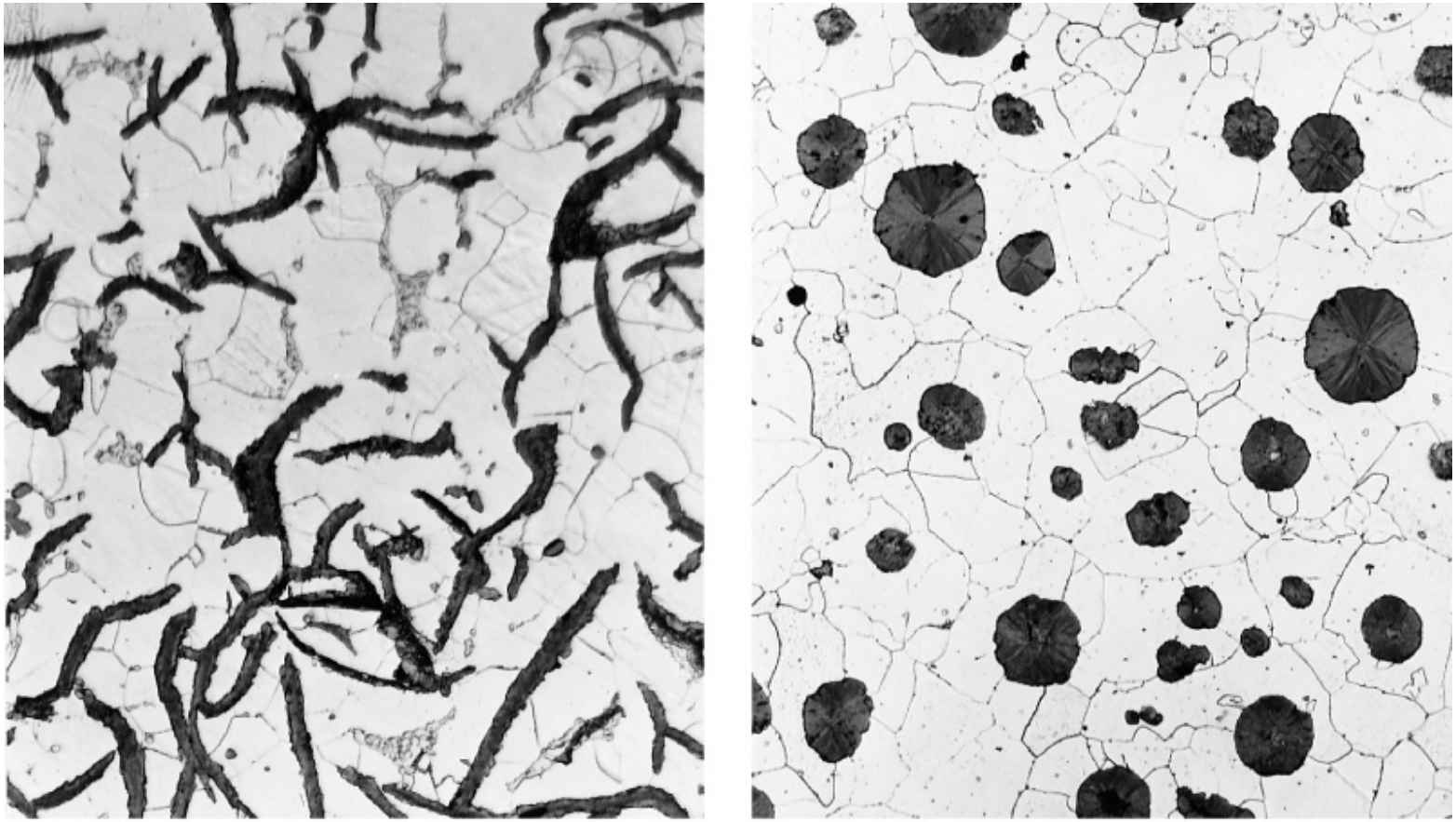
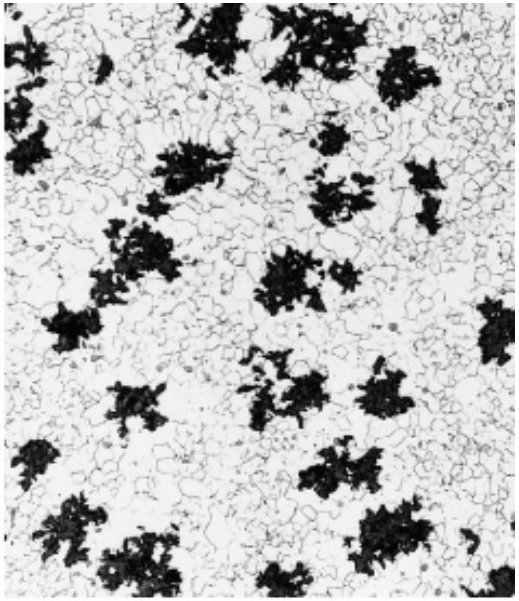
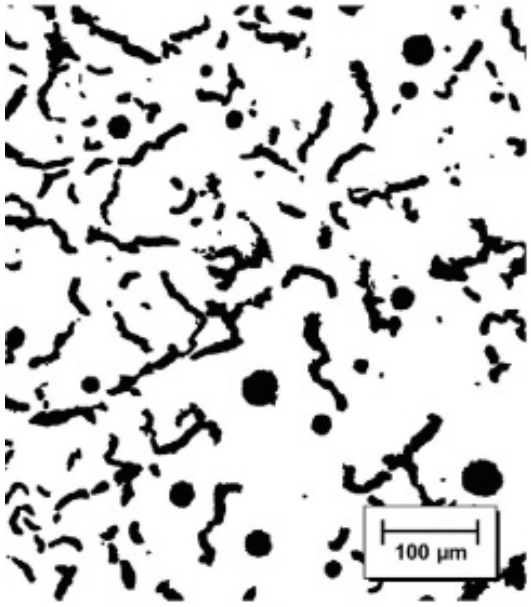


Fig. 13.3 (a) 회주철, (b) 연주철.

(c)



(d)



(e)

Fig. 13.3 (c) 백주철
(d) 가단주철
(e) 조밀 흑연 주철.

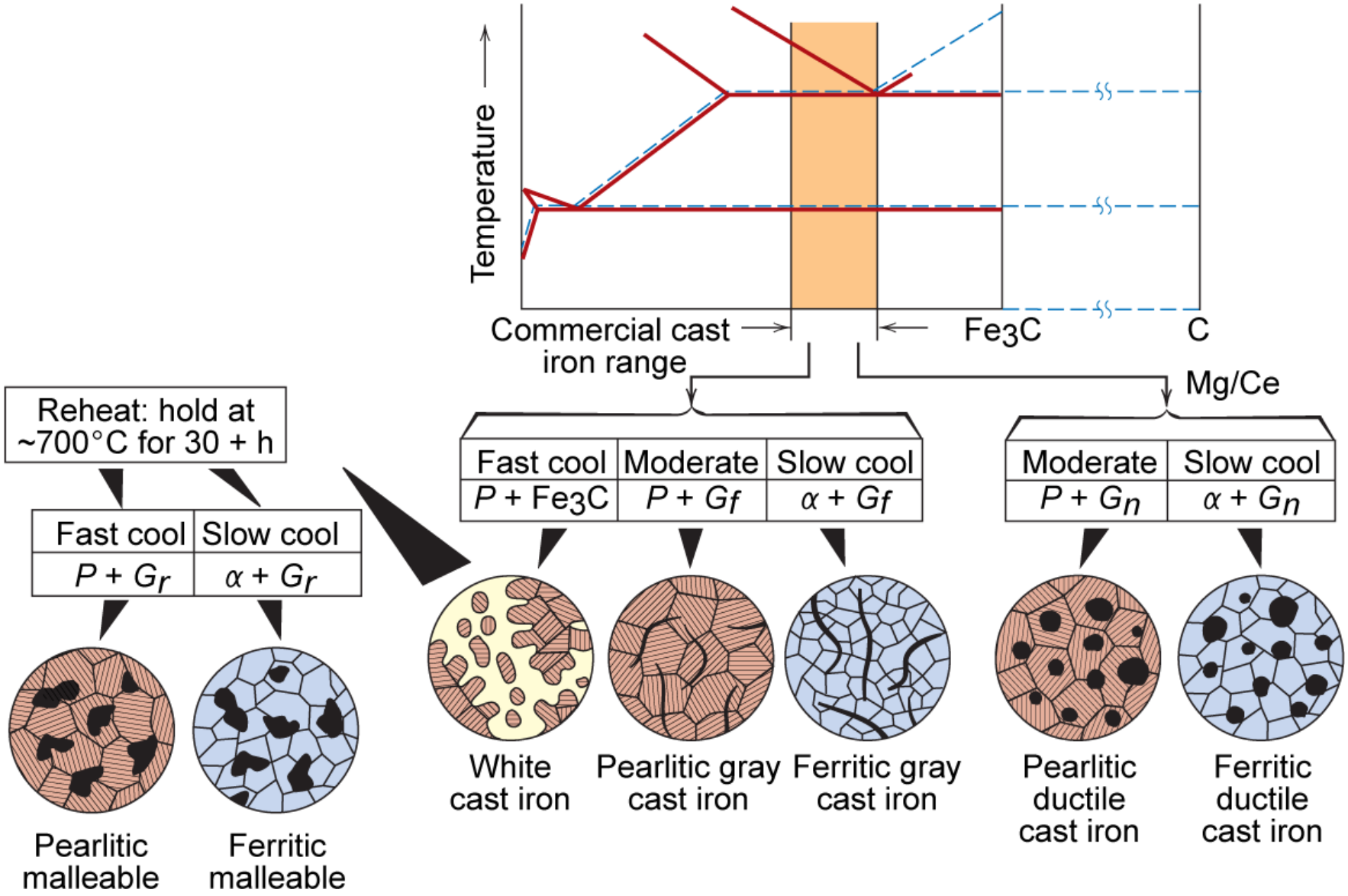


Fig. 13.5 주철의 Fe-C 상평형도와 열처리에 따른 미세구조.

Nonferrous Alloys (비철 합금)

Ferrous alloy의 단점:

- High density
- Low electrical conductivity
- Poor corrosion resistance

합금 가공 방식:

- Cast alloy (주조 합금) ~ too brittle, 소성 변형 어려운 재료
- Wrought alloy (단조 합금) ~ 소성 변형이 가능한 재료

Cu & Alloys

Copper ~ Soft & ductile, corrosion resistant
cold working (냉간가공)

Brass (황동) ~ Zn이 치환형 불순물로 첨가된 합금,
35 wt%까지 가능
FCC 결정구조, soft & ductile, 냉간 가공
의복 장식, cartridge case, 악기, radiator, 동전

Bronze (청동) ~ Sn, Al, Si, Ni 등을 첨가시킨 합금
Stronger than brass, 내부식성
Bearing, clutch disk, gears, springs, 용접봉

Al & Alloys

Aluminum ~ Low density (2.7 g/cm^3) ←→ Steel (7.9 g/cm^3)
전기 전도도 & 열전도도 ↑
내부식성, 연성 ↑
Al foil sheet 제조 가능, T_m = 660 ^{o}C, FCC

Cu, Mg, Si, Mn, Zn 등을 첨가하여 합금 → 고용체 강화

응용분야: 비행기 동체, 음료수 can, 버스 차체,
자동차 부품 (engine blocks, piston) 등

특수 Al 합금은 steel보다 specific strength ↑

Mg & Alloys

Magnesium ~ Low density (1.7 g/cm^3)

HCP 구조

상대적으로 연하고 탄성계수 ↓

상온 소성변형 어려움, 보통 hot working (열간 가공)

T_m = 651 ^{o}C, 비교적 불안정

Fine Mg powder ~ 쉽게 점화

Al, Zn, Mn 등을 첨가해 합금화

응용분야: 비행기, 미사일, 가방, 휴대장비, 자동차 부품

Audio-video-computer-communications 장비

(노트북, 캠코더, TV, 휴대폰)

Ti & Alloys

Titanium ~ ρ = 4.5 g/cm^3, T_m = 1668 ^{o}C (낮은 밀도, 높은 용융점)
인장강도, 비강도, 연성, 내부식성 ↑
비행기, 우주선, 인공뼈, 석유 화학산업

Refractory Metals (내화금속)

Nb, Mo, W, Ta (매우 높은 용융점, 2468 ~ 3410 ^{o}C)
금속 원자간 결합력, 강도, 경도, 내부식성 ↑
W의 용도: 필라멘트, X-선 관, 용접 전극

Noble Metals (귀금속)

Ag, Au, Pt, Pd, Rh, Ru, Ir, Os (물리적 특성이 유사한 8종 원소)
↳ 귀금속 중에서 흔함
: 산화와 부식에 강함, 고가, soft & ductile
금, 은 ~ 구리와 고용체 강화
백금 ~ 촉매로 사용, 고온 측정용 열전쌍 (thermocouple)

그 밖의 비철 합금

Ni & alloys ~ 알칼리 환경에서 내부식성 ↑
∴ 부식방지용 금속 표면

Pb, Sn & alloys ~ Soft & weak, T_m ↓, 내부식성 ↑

→ Can 내부 코팅 (steel과 식품과의 화학반응 억제), 양철

→ 납땜 재료 (Pb & Sn alloy)

Zn & alloys ~ T_m ↓, 화학반응성 ↑, 부식에 약함
Soft (100 ^oC 이상에서 전성 및 연성 우수)
주로 합금으로 사용

c.f.) Galvanized steel (아연도금강): 탄소강에 아연층을 도금한 강
→ Zn이 우선 산화되어 steel을 보호 (판재금속, 철망 → 함석)

Types of Ceramics (세라믹의 종류)

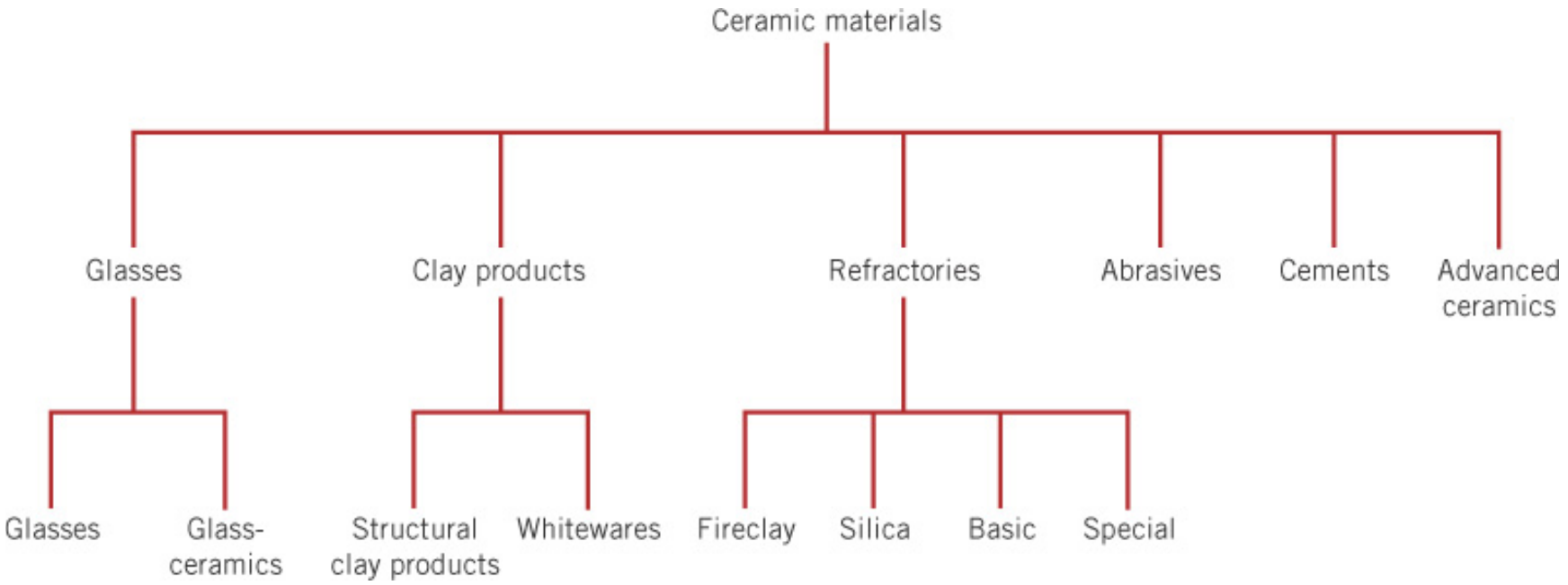


Fig. 13.7 응용면으로 분류한 세라믹 재료.

Glasses (유리)

- Noncrystalline silicates (비정질 규산염) ~ 주원료
  Na_2O, CaO, K_2O, Al_2O_3, B_2O_3 등 산화물 함유
  특징: Transparent & easily fabricated

Table 13.10 Compositions and Characteristics of Some of the Common Commercial Glasses

	Composition (wt%)						
Glass Type	*SiO_2*	*Na_2O*	*CaO*	*Al_2O_3*	*B_2O_3*	*Other*	*Characteristics and Applications*
Fused silica	>99.5						High melting temperature, very low coefficient of expansion (thermally shock resistant)
96% Silica (Vycor™)	96				4		Thermally shock and chemically resistant—laboratory ware
Borosilicate (Pyrex™)	81	3.5		2.5	13		Thermally shock and chemically resistant—ovenware
Container (soda–lime)	74	16	5	1		4MgO	Low melting temperature, easily worked, also durable
Fiberglass	55		16	15	10	4MgO	Easily drawn into fibers—glass–resin composites
Optical flint	54	1				37PbO, $8K_2O$	High density and high index of refraction—optical lenses
Glass–ceramic (Pyroceram™)	43.5	14		30	5.5	$6.5TiO_2$, $0.5As_2O_3$	Easily fabricated; strong; resists thermal shock—ovenware

Glass-Ceramics

Noncrystalline glass (비정질 유리)

고온 열처리

결정화 (crystallization) or

비유리화 (devitrification)

Glass-ceramics (미세 결정 구조의 다결정 재료)

강도, 열전도도, 열충격 저항 ↑ (열팽창 계수 ↓), 제조 간단

→ Ovenware, tableware, oven windows 등에 사용

Clay Products

저렴, 성형 용이, 고온 소성(firing)하면 강도 ↑

Structural clay products (구조용 점토 제품)
: 벽돌, 타일, 하수관

Whitewares (백자) ~ 소성후 흰색으로 변함
: 자기, 도기 식기류

Refractories (내화물)

가혹 환경에서도 불활성 상태 유지
고온에서 용융 or 분해 않음

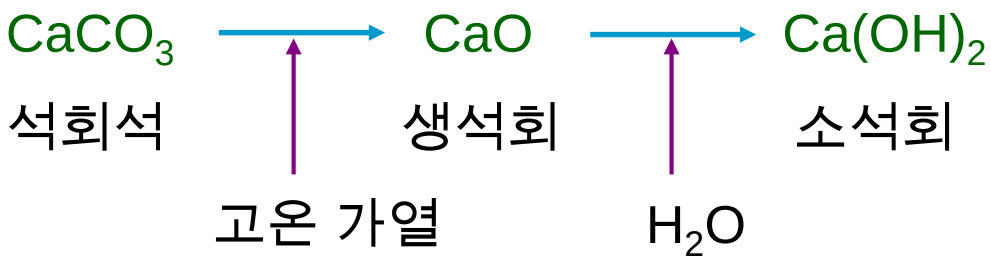
Thermal insulation (단열)

내화점토, Alumina (Al_2O_3), Silica (SiO_2), Zirconia (ZrO_2) 등

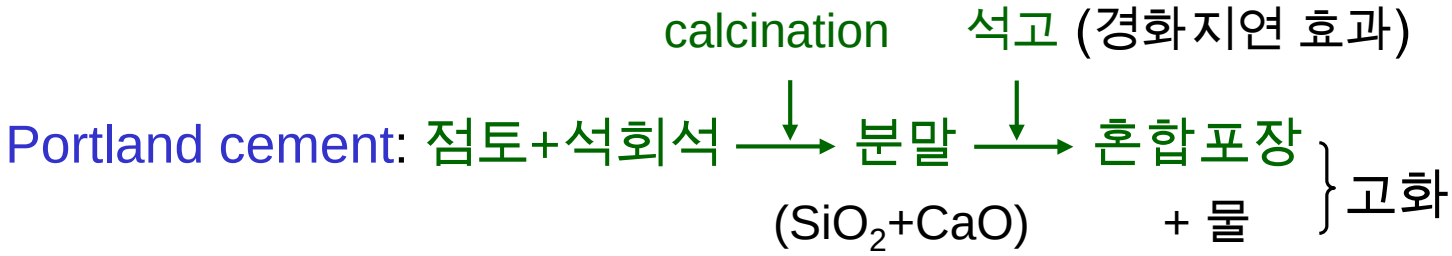
ex) Furnace linings, 유리제조, 금속 열처리, 발전소

Cements

← 점토, 석회석 ($CaCO_3$), 석고 ($CaSO_4$), 석회 (CaO) 등을 포함한 혼합물



물과 혼합하면 고착(setting) 후 경화됨



Types of Polymers (고분자재료의 종류)

Plastics (플라스틱), Elastomers (탄성체), Fibers (섬유)

Plastics

Thermoplastics (열가소성 고분자)

PE, PP, PVC, PS, PMMA, PA, ABS, PET

Thermosettings (열경화성 고분자)

Epoxies, Phenolics, Polyesters

종류와 성질이 다양함

Ex.) Optical transparency: PS, PMMA

Low friction coefficient: PTFE

(← 고온에서 내화학성 ↑)

Table 13.12 Trade Names, Characteristics, and Typical Applications for a Number of Plastic Materials

Material Type	*Trade Names*	*Major Application Characteristics*	*Typical Applications*
		Thermoplastics	
Acrylonitrile-butadiene-styrene (ABS)	Abson Cycolac Kralastic Lustran Novodur Tybrene	Outstanding strength and toughness, resistant to heat distortion; good electrical properties; flammable and soluble in some organic solvents	Refrigerator linings, lawn and garden equipment, toys, highway safety devices
Acrylics [poly(methyl methacrylate)]	Acrylite Diakon Lucite Plexiglas	Outstanding light transmission and resistance to weathering; only fair mechanical properties	Lenses, transparent aircraft enclosures, drafting equipment, outdoor signs
Fluorocarbons (PTFE or TFE)	Teflon Fluon Halar Hostaflon TF Neoflon	Chemically inert in almost all environments, excellent electrical properties; low coefficient of friction; may be used to 260°C (500°F); relatively weak and poor cold-flow properties	Anticorrosive seals, chemical pipes and valves, bearings, antiadhesive coatings, high-temperature electronic parts
Polyamides (nylons)	Nylon Baylon Durethan Herox Nomex Ultramid Zytel	Good mechanical strength, abrasion resistance, and toughness; low coefficient of friction; absorbs water and some other liquids	Bearings, gears, cams, bushings, handles, and jacketing for wires and cables
Polycarbonates	Calibre Iupilon Lexan Makrolon Merlon	Dimensionally stable; low water absorption; transparent; very good impact resistance and ductility; chemical resistance not outstanding	Safety helmets, lenses, light globes, base for photographic film
Polyethylenes	Alathon Alkathene Fortiflex Hi-fax Petrothene Rigidex Rotothene Zendel	Chemically resistant and electrically insulating; tough and relatively low coefficient of friction; low strength and poor resistance to weathering	Flexible bottles, toys, tumblers, battery parts, ice trays, film wrapping materials
Polypropylenes	Herculon Meraklon Moplen Poly-pro Pro-fax Propak Propathene	Resistant to heat distortion; excellent electrical properties and fatigue strength; chemically inert; relatively inexpensive; poor resistance to UV light	Sterilizable bottles, packaging film, TV cabinets, luggage
Polystyrenes	Carinex Dylene Hostyren Lustrex Styron Vestyron	Excellent electrical properties and optical clarity; good thermal and dimensional stability; relatively inexpensive	Wall tile, battery cases, toys, indoor lighting panels, appliance housings

(*Continued*)

Table 13.12 **Trade Names, Characteristics, and Typical Applications for a Number of Plastic Materials (*Continued*)**

Material Type	*Trade Names*	*Major Application Characteristics*	*Typical Applications*
Vinyls	Darvic Exon Geon Pliovic Saran Tygon Vista	Good low-cost, general-purpose materials; ordinarily rigid, but may be made flexible with plasticizers; often copolymerized; susceptible to heat distortion	Floor coverings, pipe, electrical wire insulation, garden hose, phonograph records
Polyesters (PET or PETE)	Celanar Dacron Eastapak Hylar Melinex Mylar Petra	One of the toughest of plastic films; excellent fatigue and tear strength, and resistance to humidity, acids, greases, oils, and solvents	Magnetic recording tapes, clothing, automotive tire cords, beverage containers
		Thermosetting Polymers	
Epoxies	Araldite Epikote Epon Epi-rez Lekutherm Lytex	Excellent combination of mechanical properties and corrosion resistance; dimensionally stable; good adhesion; relatively inexpensive; good electrical properties	Electrical moldings, sinks, adhesives, protective coatings, used with fiberglass laminates
Phenolics	Bakelite Amberol Arofene Durite Resinox	Excellent thermal stability to over 150°C (300°F); may be compounded with a large number of resins, fillers, etc.; inexpensive	Motor housings, telephones, auto distributors, electrical fixtures
Polyesters	Aropol Baygal Derakane Laminac Selectron	Excellent electrical properties and low cost; can be formulated for room- or high-temperature use; often fiber reinforced	Helmets, fiberglass boats, auto body components, chairs, fans

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Elastomers

SBR (Styrene-butadiene rubber)

~ 자동차 타이어

가황 고무 (TS, 마모, 인열 저항성 ↑)

Carbon black 첨가로 물성 더욱 향상

Silicone rubbers (실리콘계 고무)

~ -90 ^{o}C까지 높은 유연성 (flexibility) 유지

250 ^{o}C까지 안정성 (stability) 유지

내수성 ↑, 윤활유에 대한 저항성 ↑

Table 13.13 **Tabulation of Important Characteristics and Typical Applications for Five Commercial Elastomers**

Chemical Type	*Trade (Common) Names*	*Elongation (%)*	*Useful Temperature Range [°C (°F)]*	*Major Application Characteristics*	*Typical Applications*
Natural poly-isoprene	Natural rubber (NR)	500–760	−60 to 120 (−75 to 250)	Excellent physical properties; good resistance to cutting, gouging, and abrasion; low heat, ozone, and oil resistance; good electrical properties	Pneumatic tires and tubes; heels and soles; gaskets
Styrene-butadiene copolymer	GRS, Buna S (SBR)	450–500	−60 to 120 (−75 to 250)	Good physical properties; excellent abrasion resistance; not oil, ozone, or weather resistant; electrical properties good, but not outstanding	Same as natural rubber
Acrylonitrile-butadiene copolymer	Buna A, Nitrile (NBR)	400–600	−50 to 150 (−60 to 300)	Excellent resistance to vegetable, animal, and petroleum oils; poor low-temperature properties; electrical properties not outstanding	Gasoline, chemical, and oil hose; seals and O-rings; heels and soles
Chloroprene	Neoprene (CR)	100–800	−50 to 105 (−60 to 225)	Excellent ozone, heat, and weathering resistance; good oil resistance; excellent flame resistance; not as good in electrical applications as natural rubber	Wire and cable; chem. tank linings; belts, hoses, seals, and gaskets
Polysiloxane	Silicone (VMQ)	100–800	−115 to 315 (−175 to 600)	Excellent resistance to high and low temperatures; low strength; excellent electrical properties	High- and low-temperature insulation; seals, diaphragms; tubing for food and medical uses

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

Fibers

섬유의 조건:

length/diameter > 100

섬유는 가공중 stretching, twisting, shearing & abrasion 겪음

→ TS ↑, 탄성률 (E) ↑, 내마모성 ↑

(Polymer chain의 화학적 특성과 drawing 공정에 의해 가능)

MW ↑, 결정화도 ↑, 선형 사슬

→ 인장강도 ↑

의류로의 적합성은 열적 성질(T_g & T_m)에 의해 좌우

Miscellaneous Applications

Coatings ~ 재료의 표면에 도포하는 얇은 고분자 필름
paint, varnish, enamel, lacquer 등
To protect materials from corrosion or deterioration
To improve material's appearance
To provide electrical insulation

Adhesives ~ 두 고체재료의 표면을 결합시키는데 사용되는 물질
결합방식:
Mechanical ~ penetration into pores/crevices
Chemical ~ covalent or van der Waals bonding

Films ~ 식품 및 제품의 내용물 보호 및 포장 목적
low density, high flexibility, high tensile & tear strengths,
resistance to chemical/moisture attack, low gas permeability

Foams – 미세한 기공을 많이 포함하고 있는 플라스틱 재료

Advanced Polymeric Materials

Ultrahigh Molecular Weight Polyethylene (UHMWPE)

중량평균 분자량(M_w) ~ 4 x 10^6 g/mol

성질: high impact strength
- resistance to wear/abrasion
- low coefficient of friction
- self-lubricating surface
- very good chemical resistance
- outstanding sound/energy absorption
- excellent electrical insulation

활용: bullet-proof vests
- golf ball covers
- hip implants (acetabular cup)

Liquid Crystalline Polymers (액정 고분자, LCP)

: 액체 상태에서도 규칙적인 배열이 가능해 결정성을 보이는 고분자

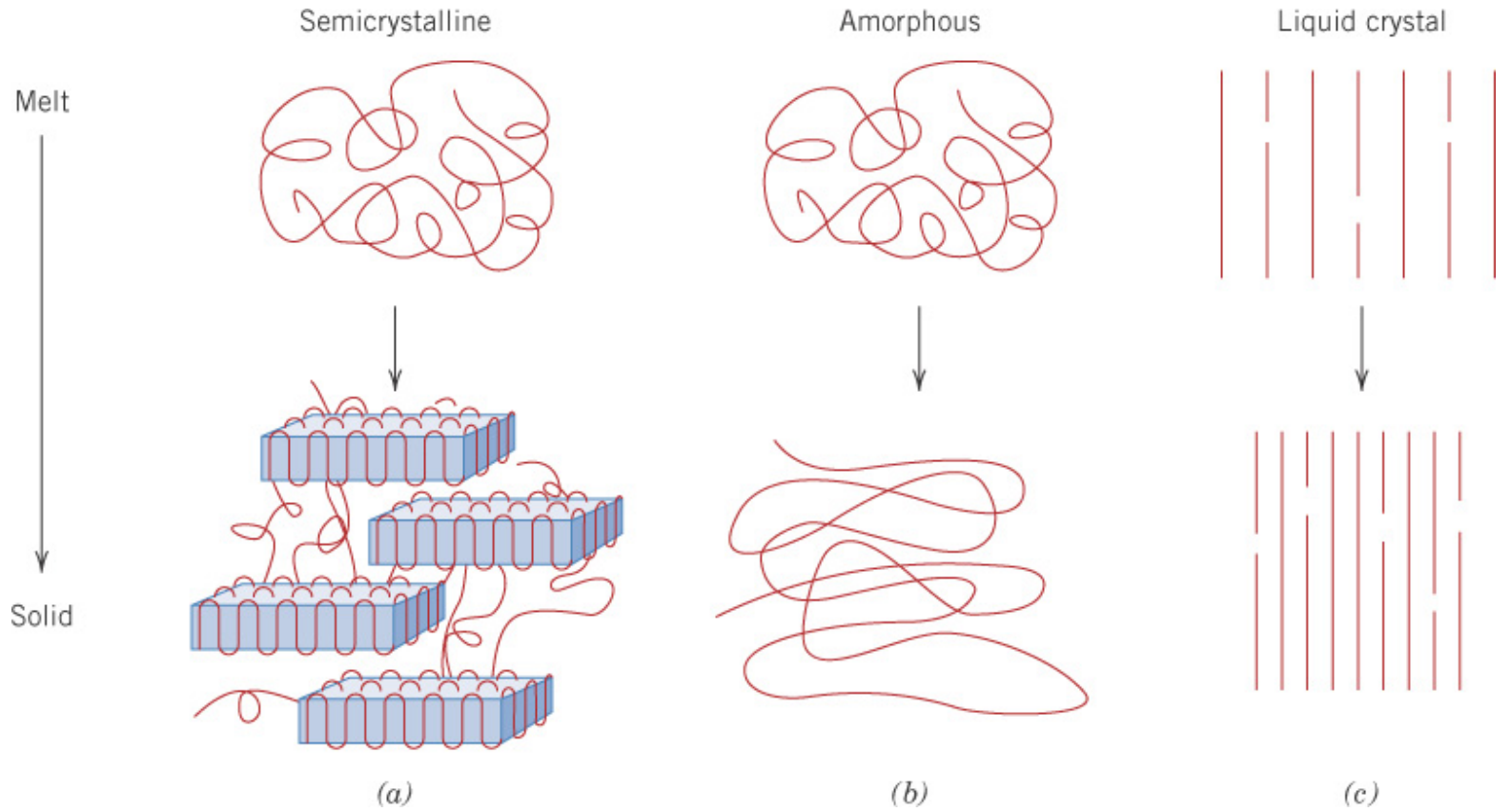

Fig. 13.12 용융상 및 고체상 고분자의 분자구조:
(a) 결정성 고분자, (b) 무정형 고분자, (c) 액정 고분자.

Thermoplastic Elastomers (열가소성 탄성체, TPE)

Styrene-butadiene block copolymer (스티렌 블록 공중합체)

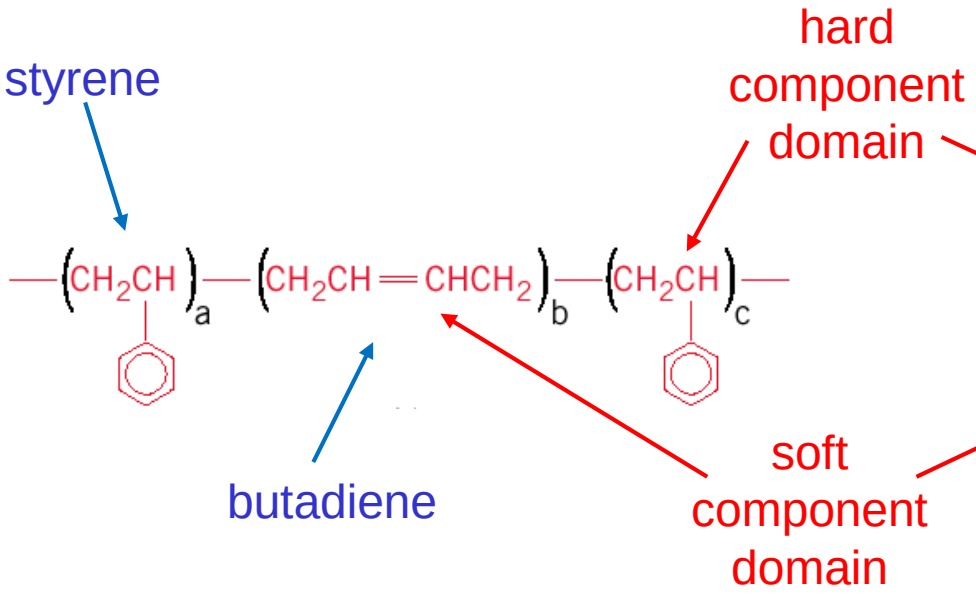

Fig. 13.13 Styrene-butadiene-styrene (S-B-S) 열가소성 탄성체의 구조식.

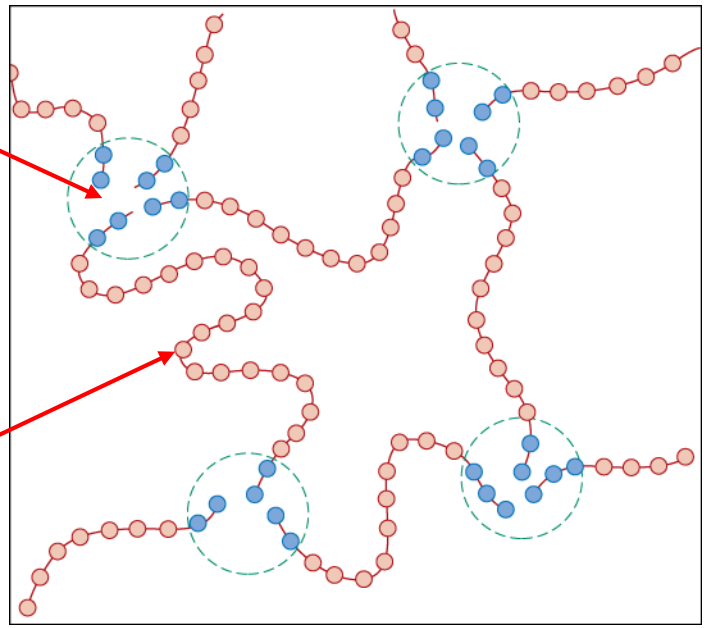

Fig. 13.14 S-B-S 열가소성 탄성체의 모식도.

(Probs.)

13.2, 13.4, 13.6, 13.12, 13.14, 13.21 & 13.23.