

Chapter 11. Phase Transformations (상변태)

Material properties depend on microstructures produced as a result of phase transformations.

* Classifications of phase transformations

1) Simple diffusion-dependent transformation

(no change in the number or composition)

ex) solidification of a pure metal & recrystallization

2) Diffusion-dependent transformation

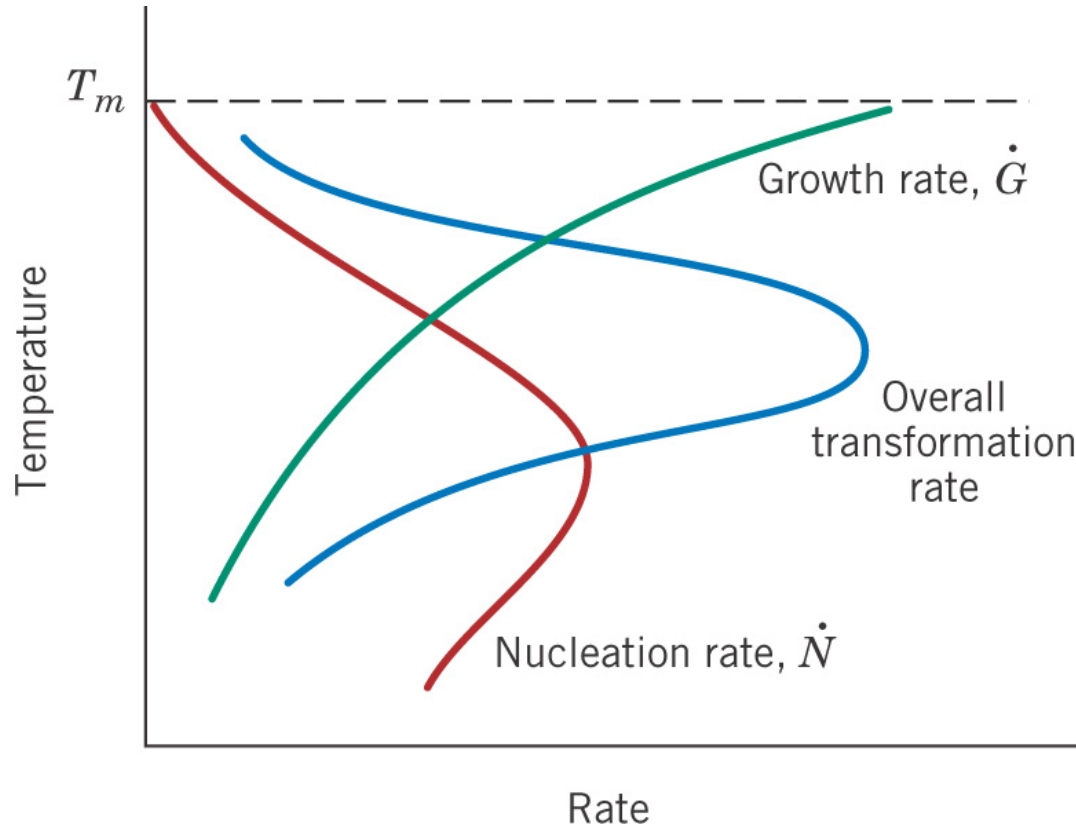
(change in the number or composition)

ex) eutectoid reaction

3) Diffusionless transformation (metastable phase)

ex) martensitic transformation in steel alloys

Transformation Rate vs. Temperature (온도에 따른 변태 속도)



T_m 부근의 온도:

핵생성 속도 느리고
성장속도 빠름

→ Coarse grain

낮은 온도:

핵생성 속도 빠르고
성장속도 느림

→ Fine grain

Fig. 11.8 온도에 따른 핵생성 속도, 성장 속도 및 총괄 변태 속도.

Transformation Rate vs. Time (온도에 따른 변태 시간)

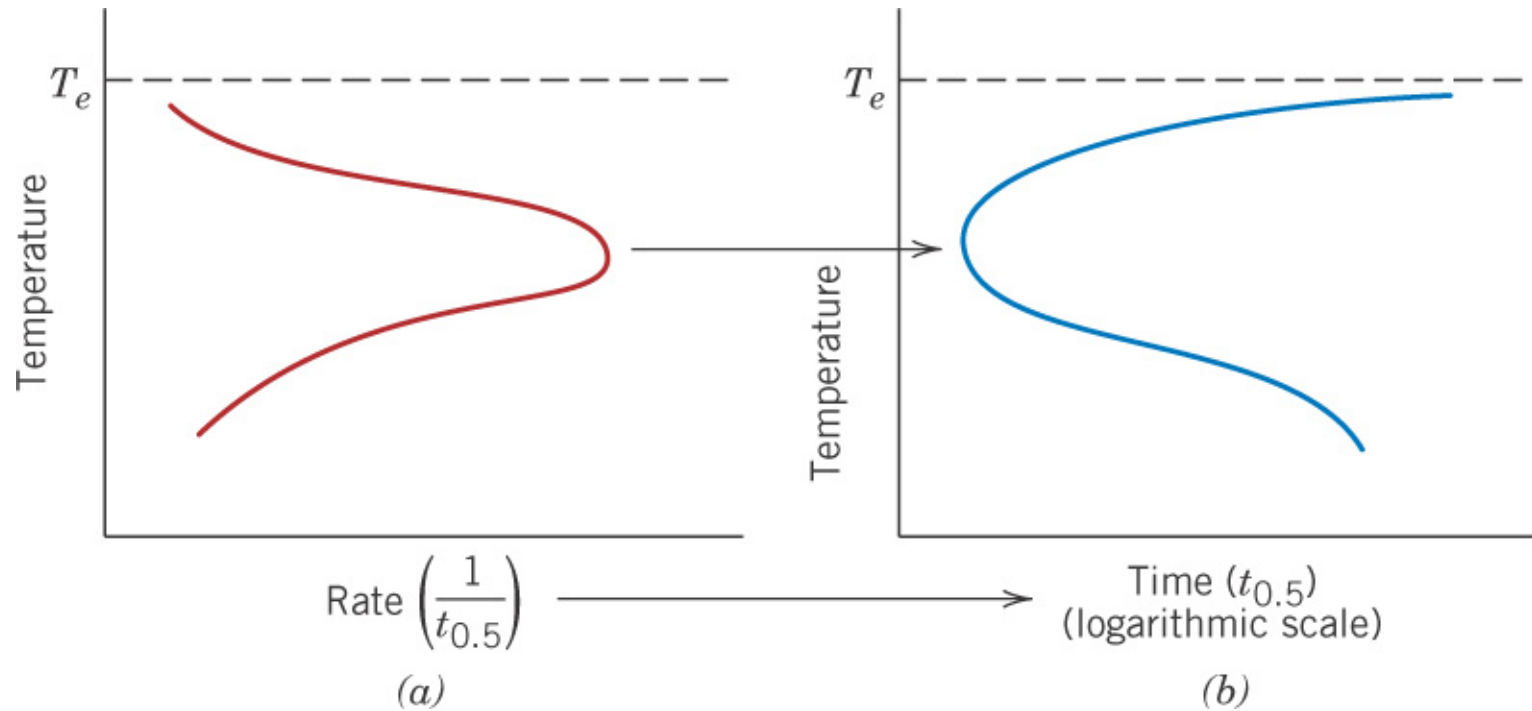
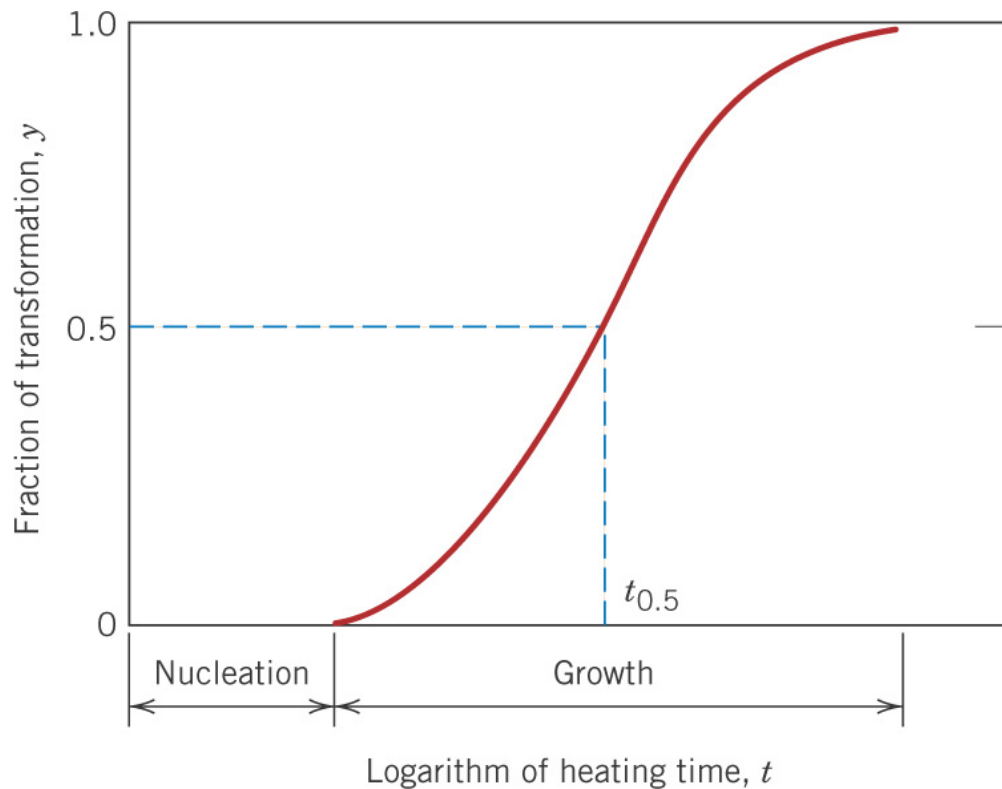


Fig. 11.9 (a) 온도에 따른 변태 속도, (b) 온도에 따른 변태 시간 그래프 개형.

Kinetics of Phase Transformation (상변태 속도론)

“Time dependence of rate”



Avrami equation ~시간(t)에
따른 변태 분율(y):

$$y = 1 - \exp(-kt^n)$$

k, n : 시간에 무관한 상수

Fig. 11.10 등은 조건에서
시간의 로그값에 대한
변태 분율.

Transformation rate (변태 속도)

~변태 분율이 0.5까지 도달한 시간의 역수: $\text{rate} = \frac{1}{t_{0.5}}$

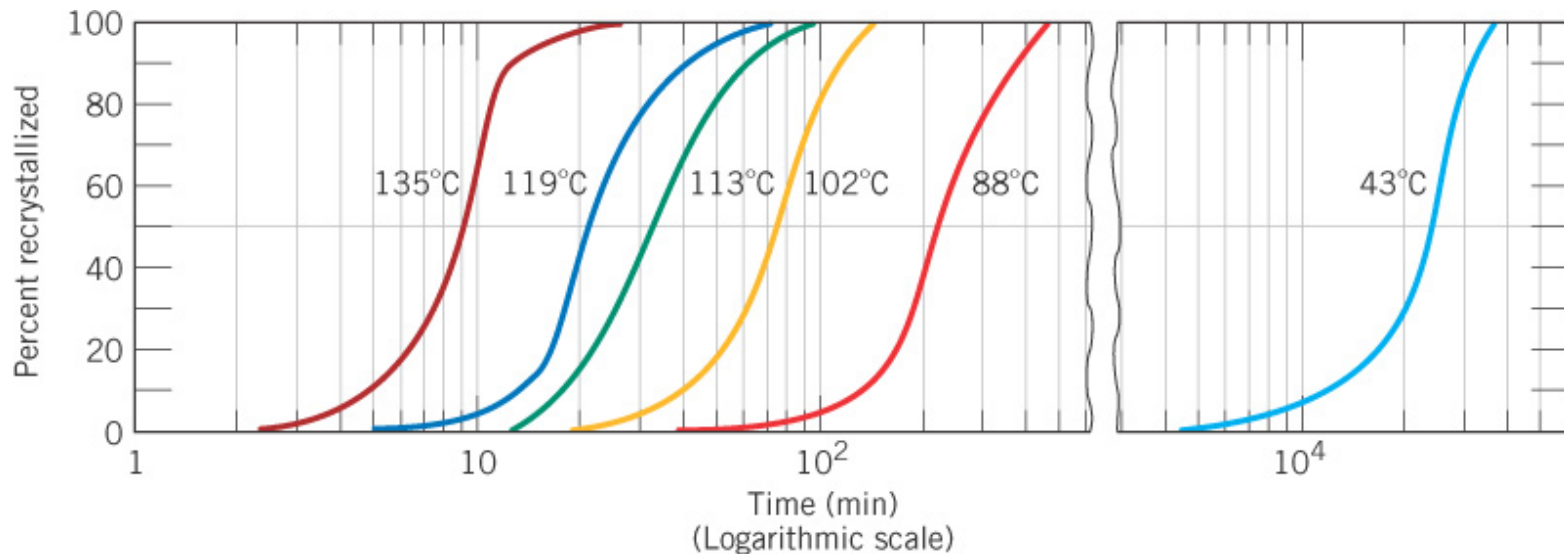


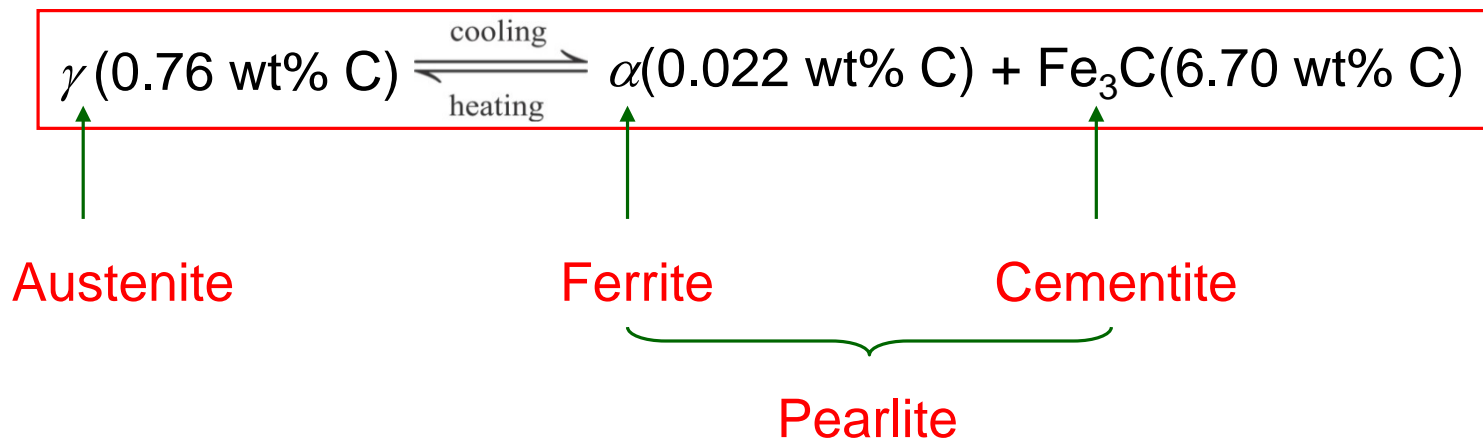
Fig. 11.11 Cu에 대한 시간의 로그값에 대한 재결정 백분율.

Microstructural & Property Changes in Fe-C Alloys (철-탄소 합금계에서 미세구조 및 성질의 변화)

Isothermal Transformation Diagrams (등온 변태도)

Pearlite (펄라이트)

Eutectoid reaction for Fe-Fe₃C system:



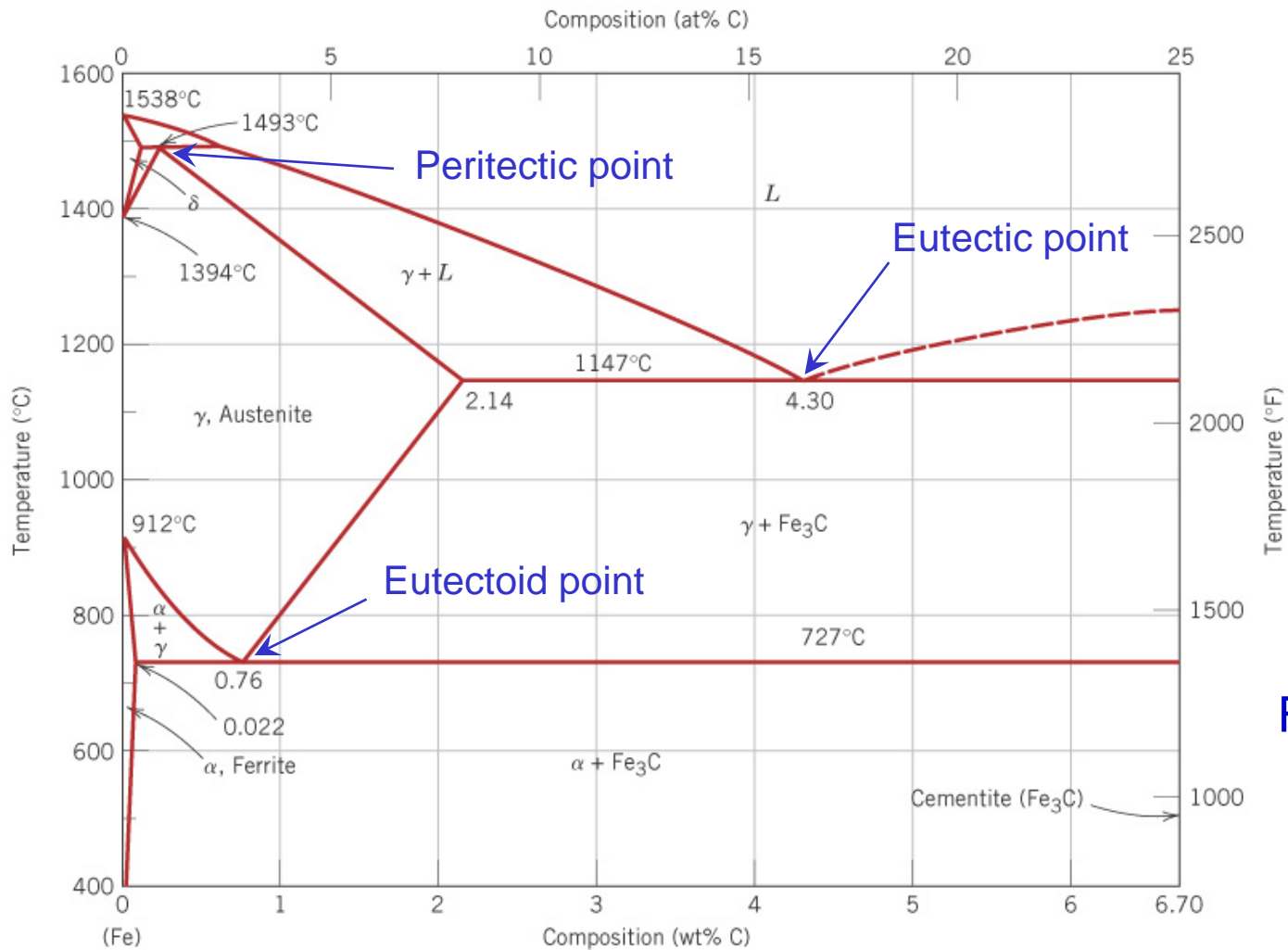
Iron-Iron Carbide (Fe-Fe₃C) Phase Diagram

Fig. 10.28 Fe-Fe₃C
계의 상평형도.

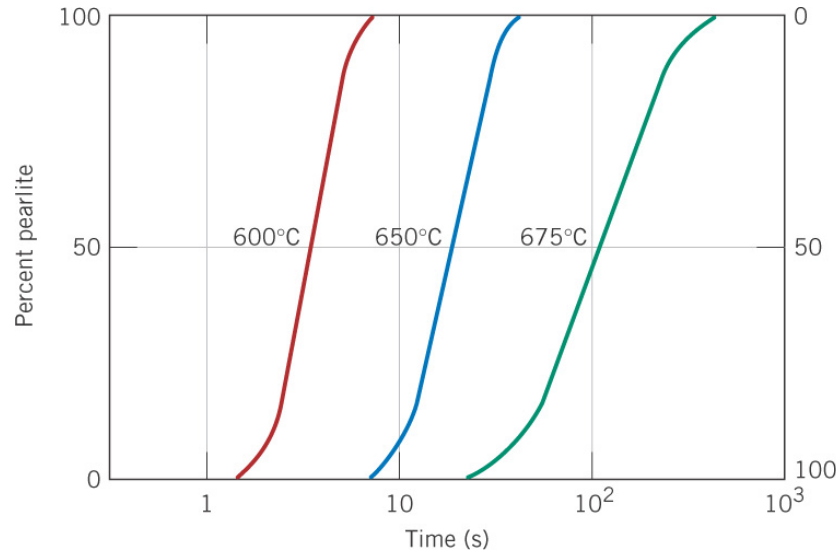


Fig. 11.12 공석 조성에서 austenite → pearlite 변태에 대한 시간에 대한 변태 백분율.

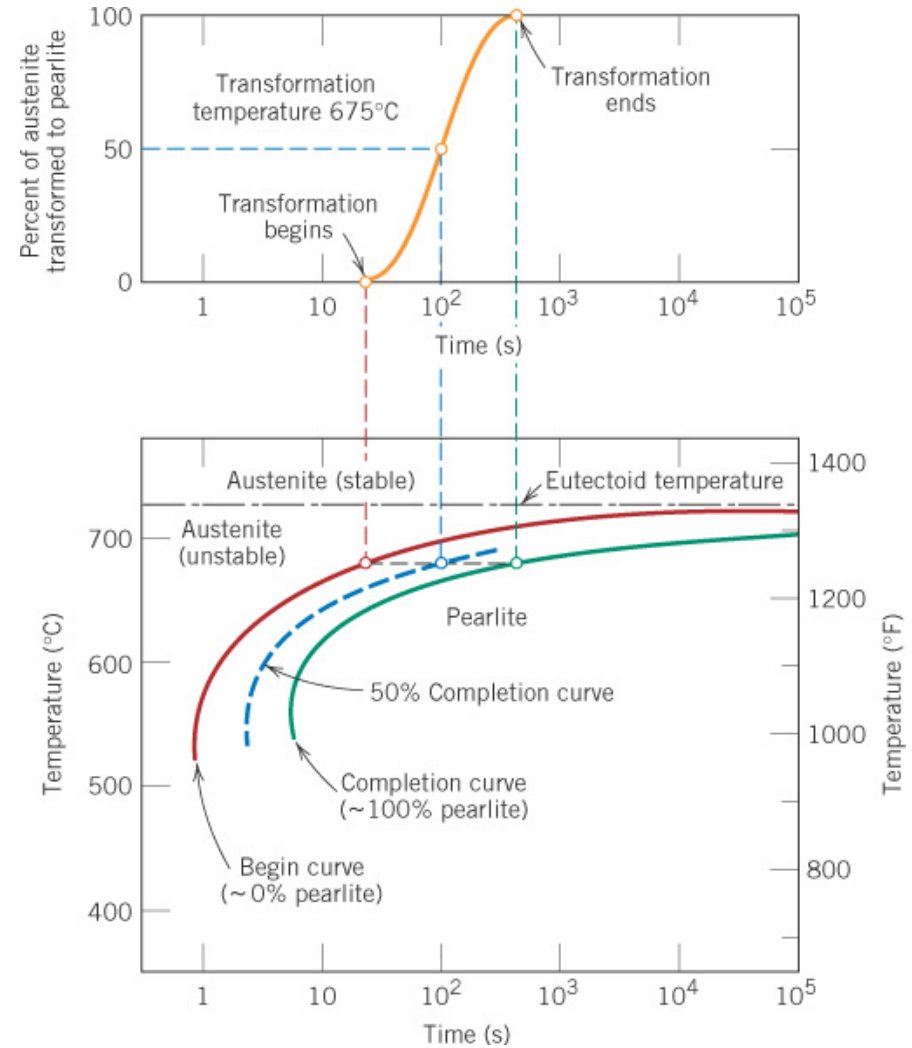


Fig. 11.13 시간에 대한 변태 백분율(위)로부터 등온변태도(아래)의 작성 예.

Isothermal transformation diagram (등온변태도) or T-T-T plot
or Time-temperature-transformation plot (시간-온도-변태 곡선)

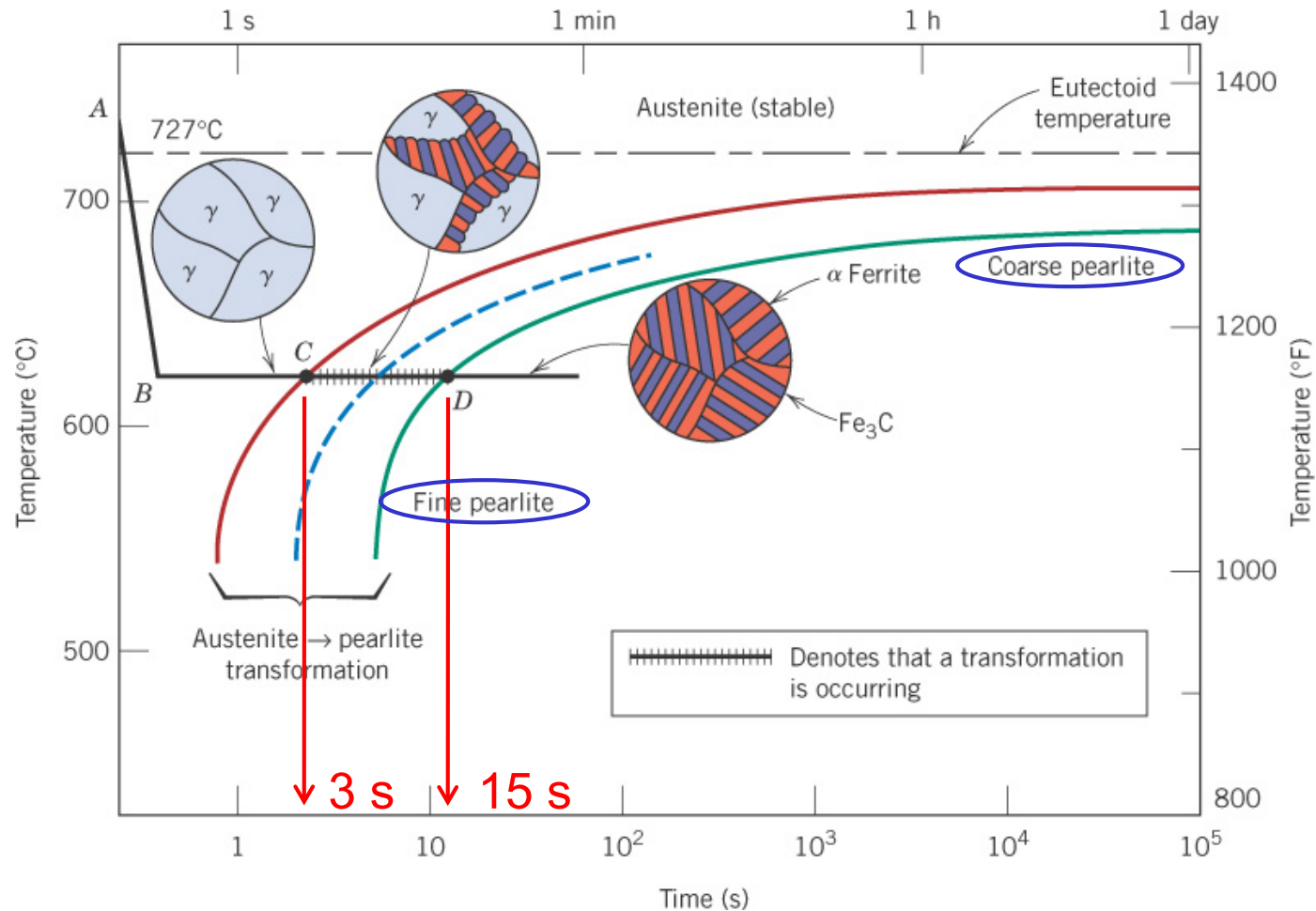


Fig. 11.14 공석 Fe-C 합금의 등온변태도와 열처리에 따른 미세구조.

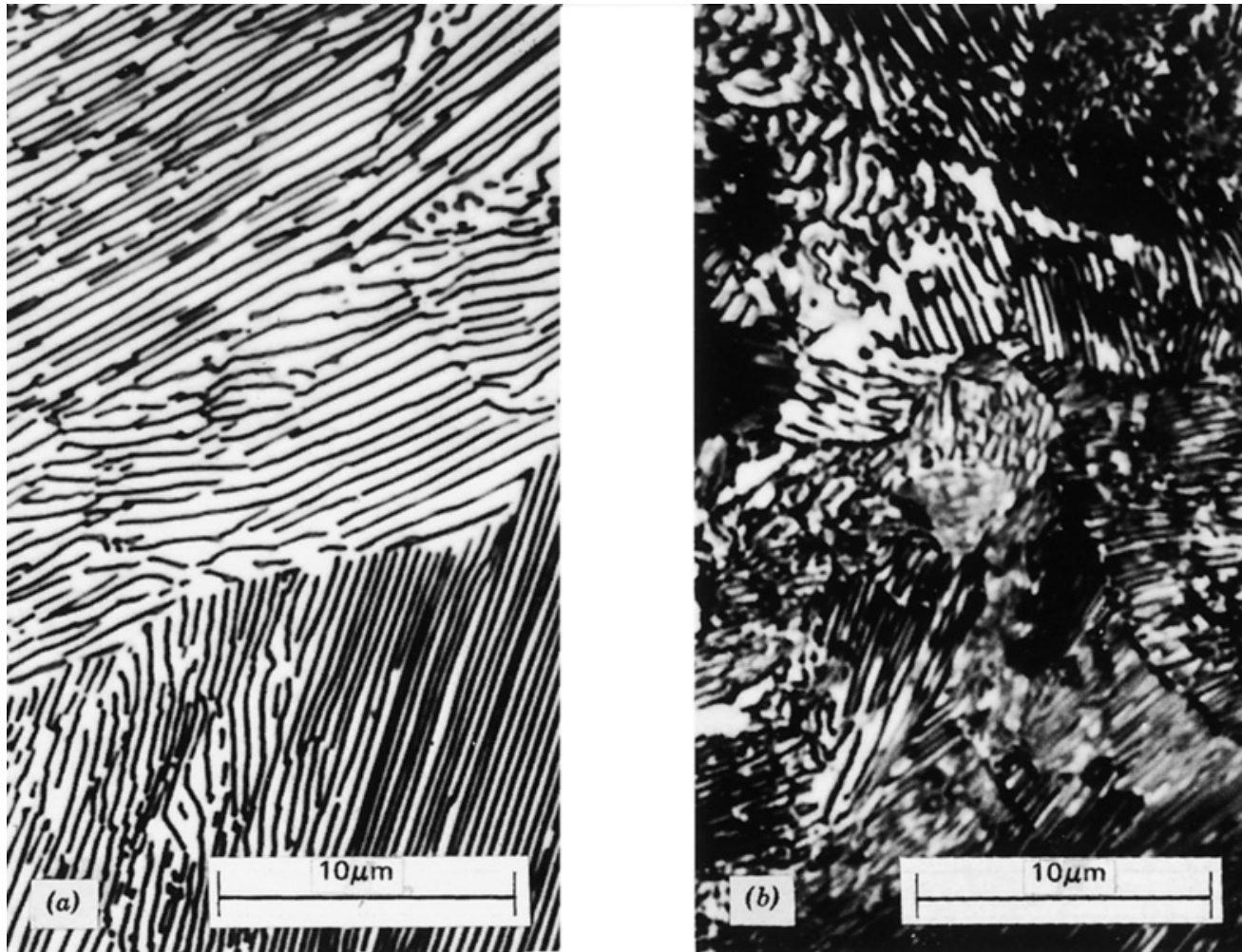


Fig. 11.15 (a) coarse pearlite (조대 펄라이트), (b) fine pearlite (미세 펄라이트) 현미경 사진.

Bainite (베이나이트) : Elongated Fe_3C particles in α -ferrite matrix
 Diffusion controlled (확산변태)
N(nose) 이하의 온도에서 형성

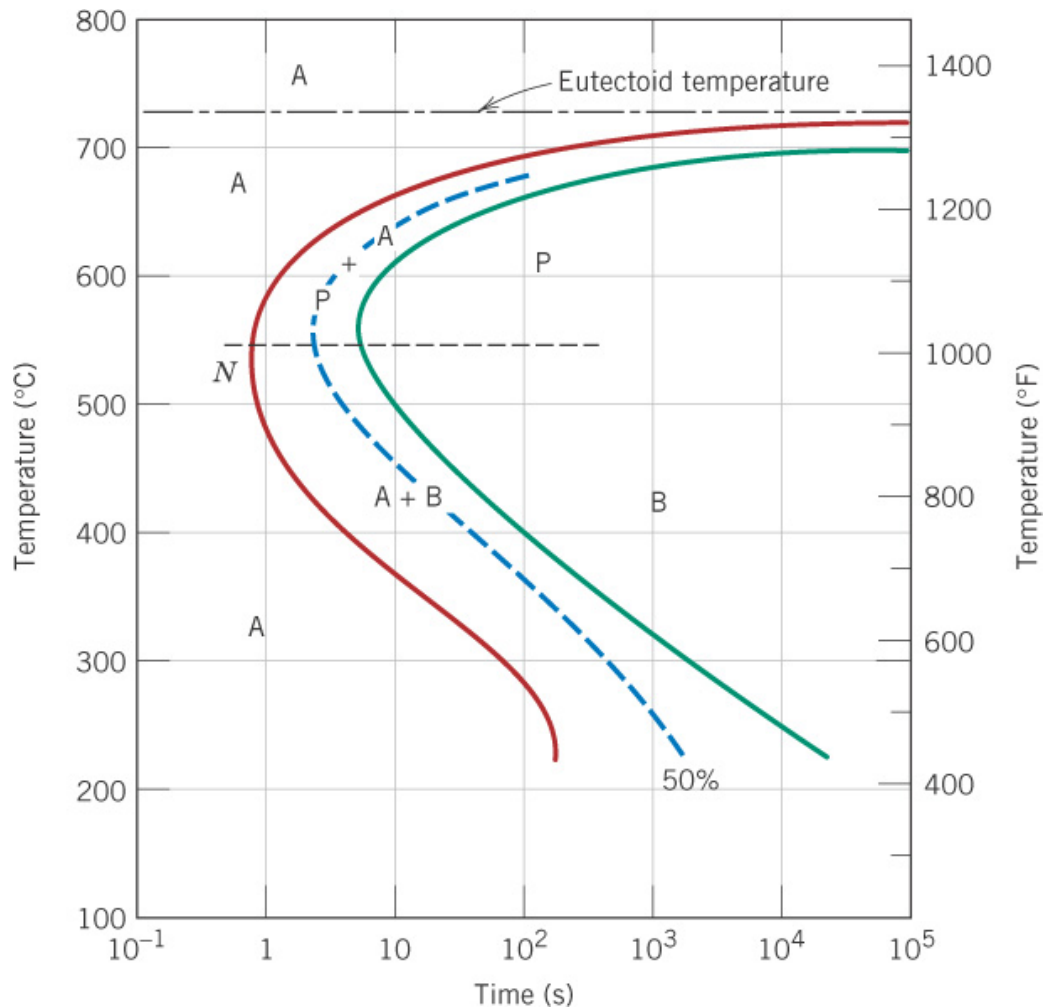


Fig. 11.18 공석조성 Fe-C alloy의 등온변태도.

- A: austenite**
(727 °C 이상의 고용체)
- P: pearlite**
(540~727 °C에서 형성)
- B: bainite**
(215~540 °C에서 형성).

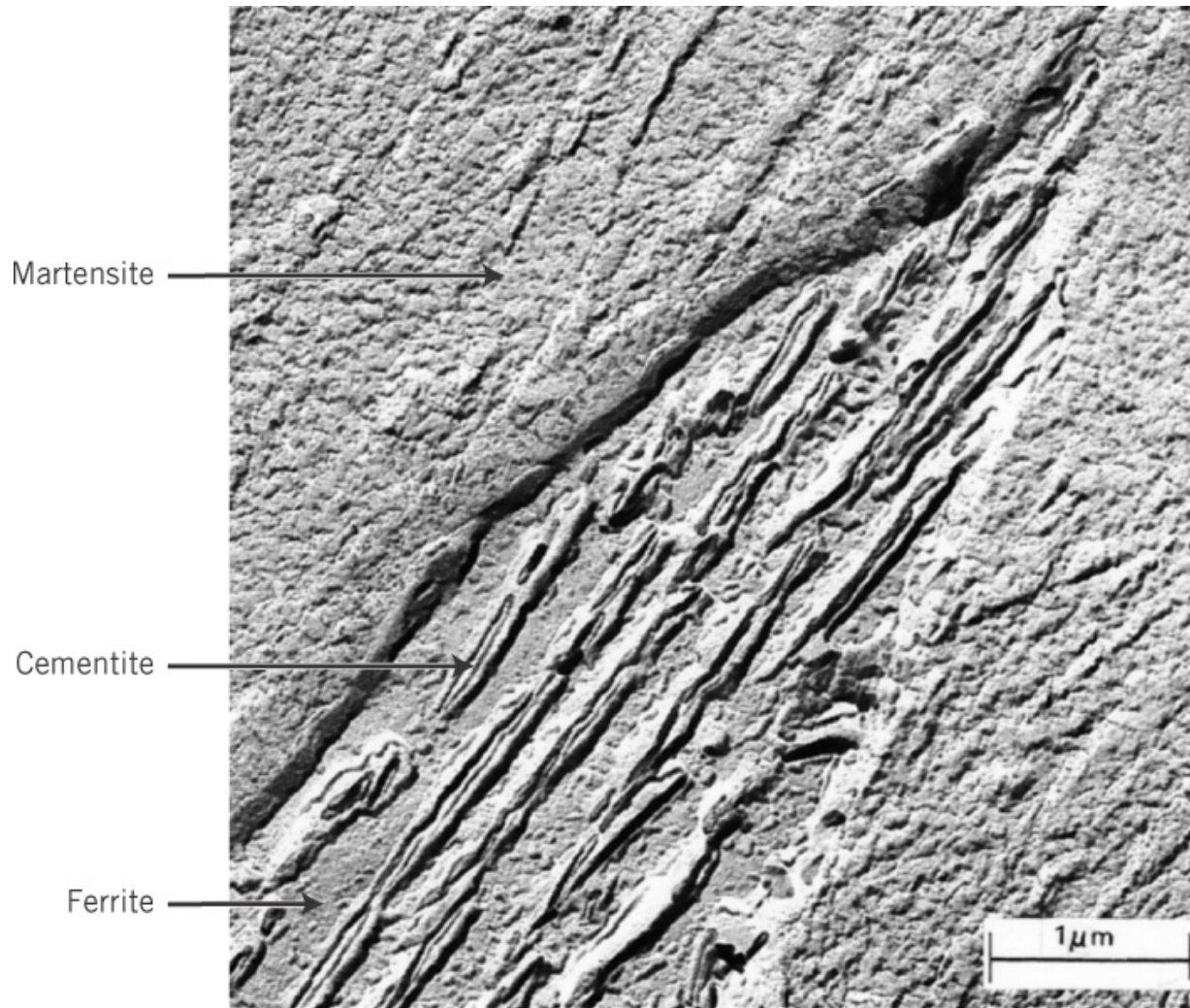


Fig. 11.17 Bainite 미세구조 현미경 사진.

Spheroidite (스페로이다이트)

Pearlite or bainite 강을 eutectoid 온도 이하에서 장시간 heat treatment할 경우 생성 (예, 700 °C에서 18-24 h 열처리)

Fe₃C 상이 입자 상으로 변환

Driving force – reduction of α -ferrite/Fe₃C interfacial area

α
(ferrite)

Fe₃C
(cementite)

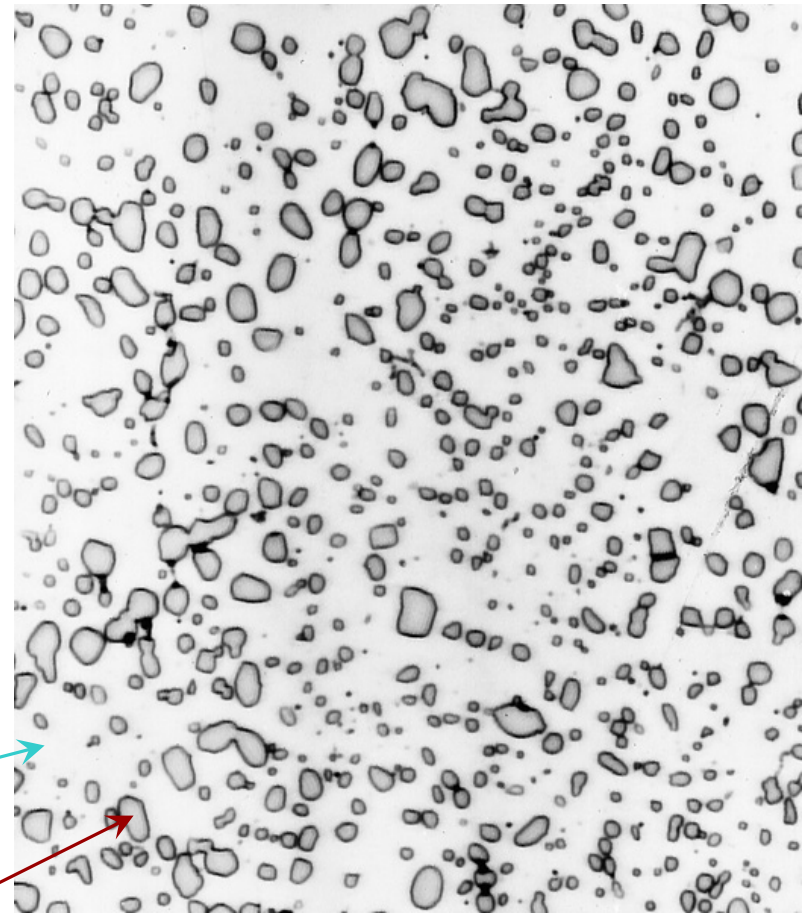


Fig. 11.19 Spheroidite 미세 구조 현미경 사진.

Martensite (마텐자이트)

Austenite 합금을 상온 근처로 quenching 할 경우 생성

Diffusionless transformation (무확산 변태)로 생긴 단일 상

FCC 구조의 austenite가 급랭될 때 Fe와 C의 원자가 재배열되어 BCT 구조로 순간적으로 바뀌어 생성 (시간에 무관)

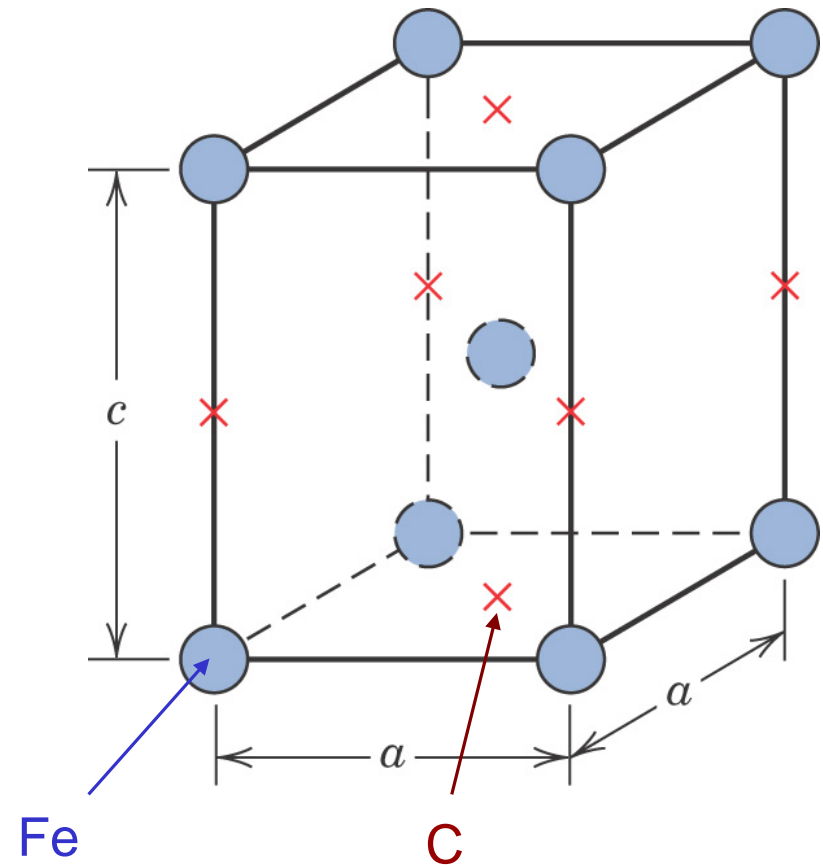


Fig. 11.21 Martensite의 unit cell (BCT: body-centered tetragonal).



Fig. 11.22 Martensite 미세구조 현미경 사진.

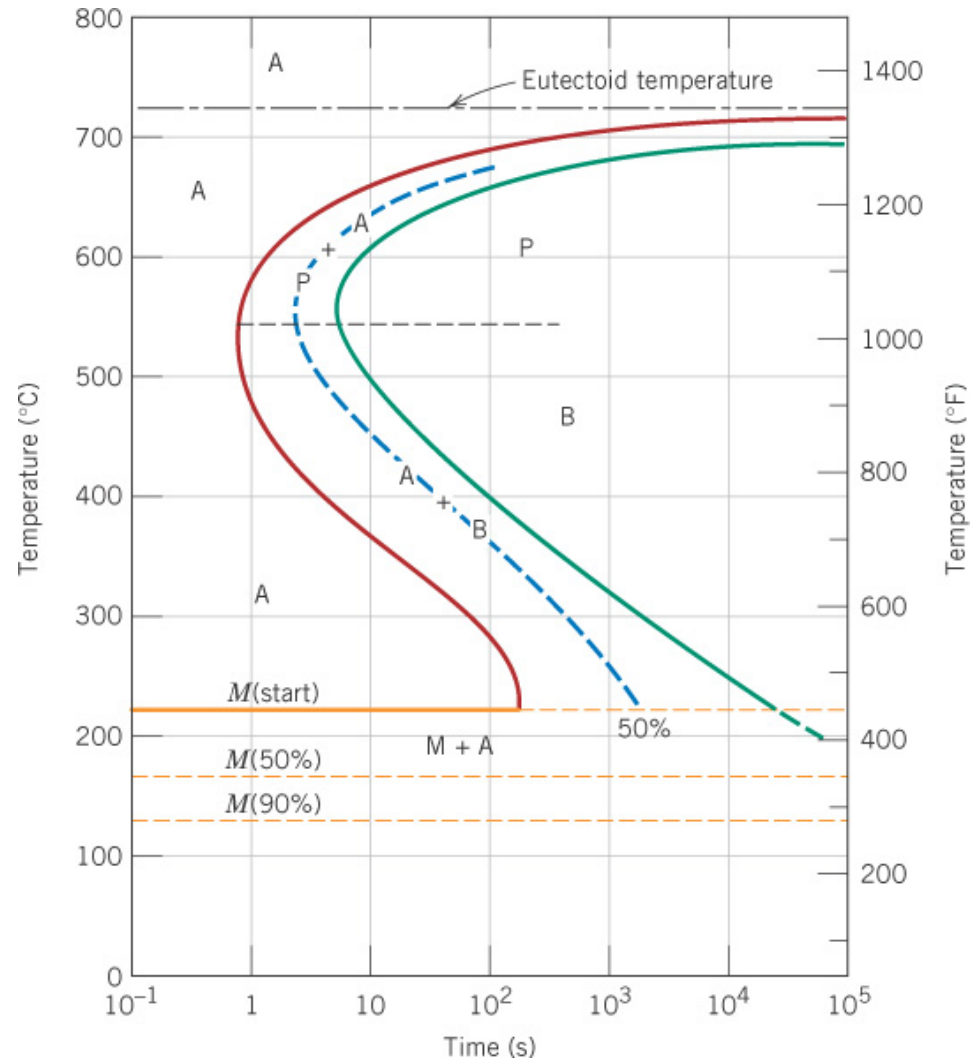
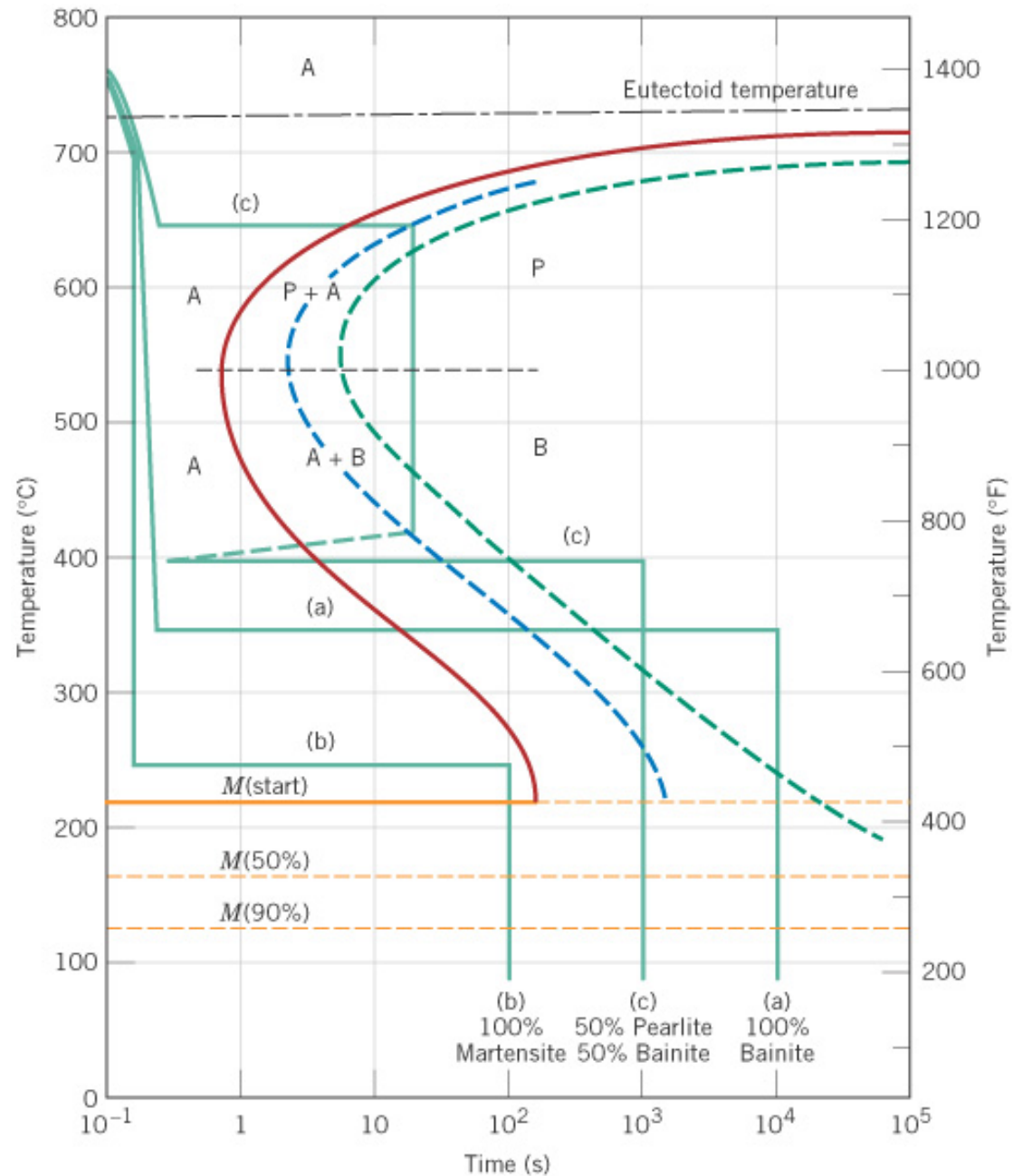


Fig. 11.23 공석조성 Fe-C 합금의 등온변태도.

Ex. 11.2) 세 가지
경우의 등온 열처리
리에 따른 미세구조
변화



Continuous cooling transformation diagram (연속냉각변태도)

→ Curves are shifted to longer times and lower temperatures.

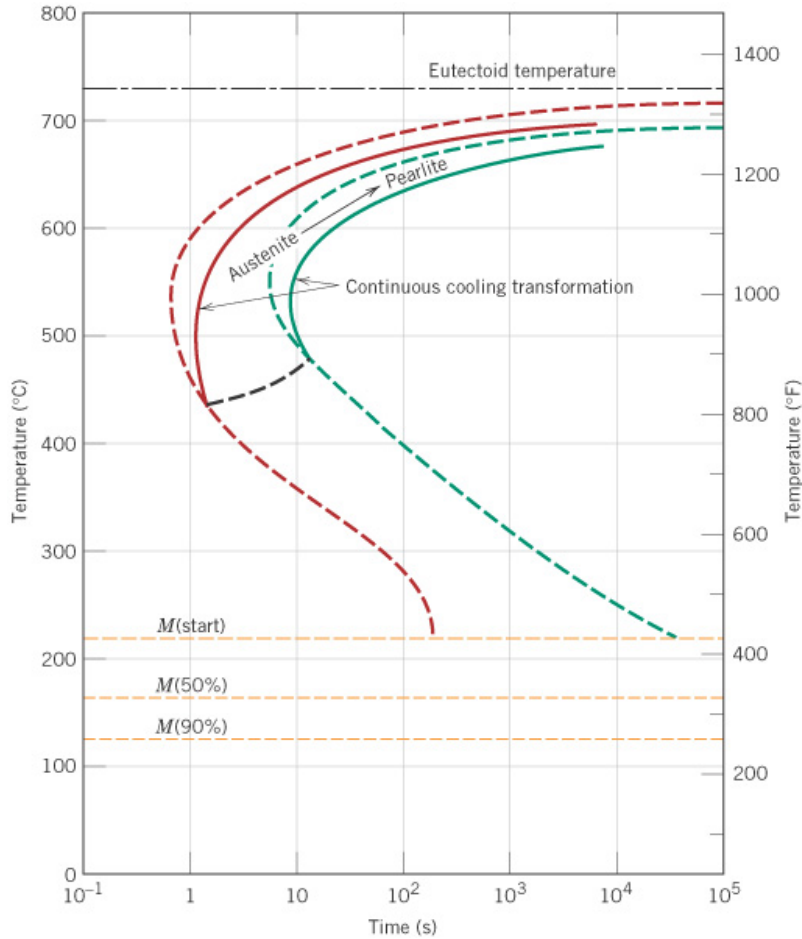


Fig. 11.26 공석 조성에서의 등온 변태도 및 연속냉각변태도.

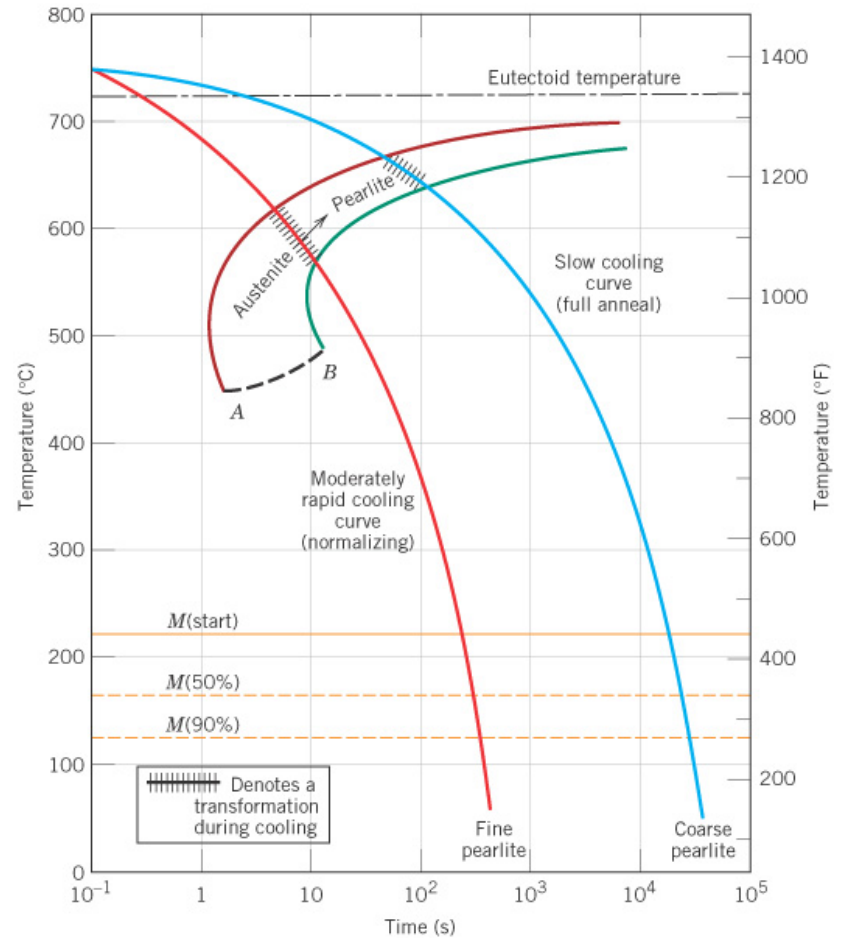


Fig. 11.27 연속냉각변태도 위에 그린 급랭과 서랭.

Mechanical Behavior of Fe-C Alloys (철-탄소 합금계의 기계적 성질)

Pearlite

Cementite: harder but more brittle than ferrite

Fine pearlite: harder and stronger than coarse pearlite

Spheroidite

Softest and weakest in steel alloys

Extremely ductile, much more than either fine or coarse pearlite

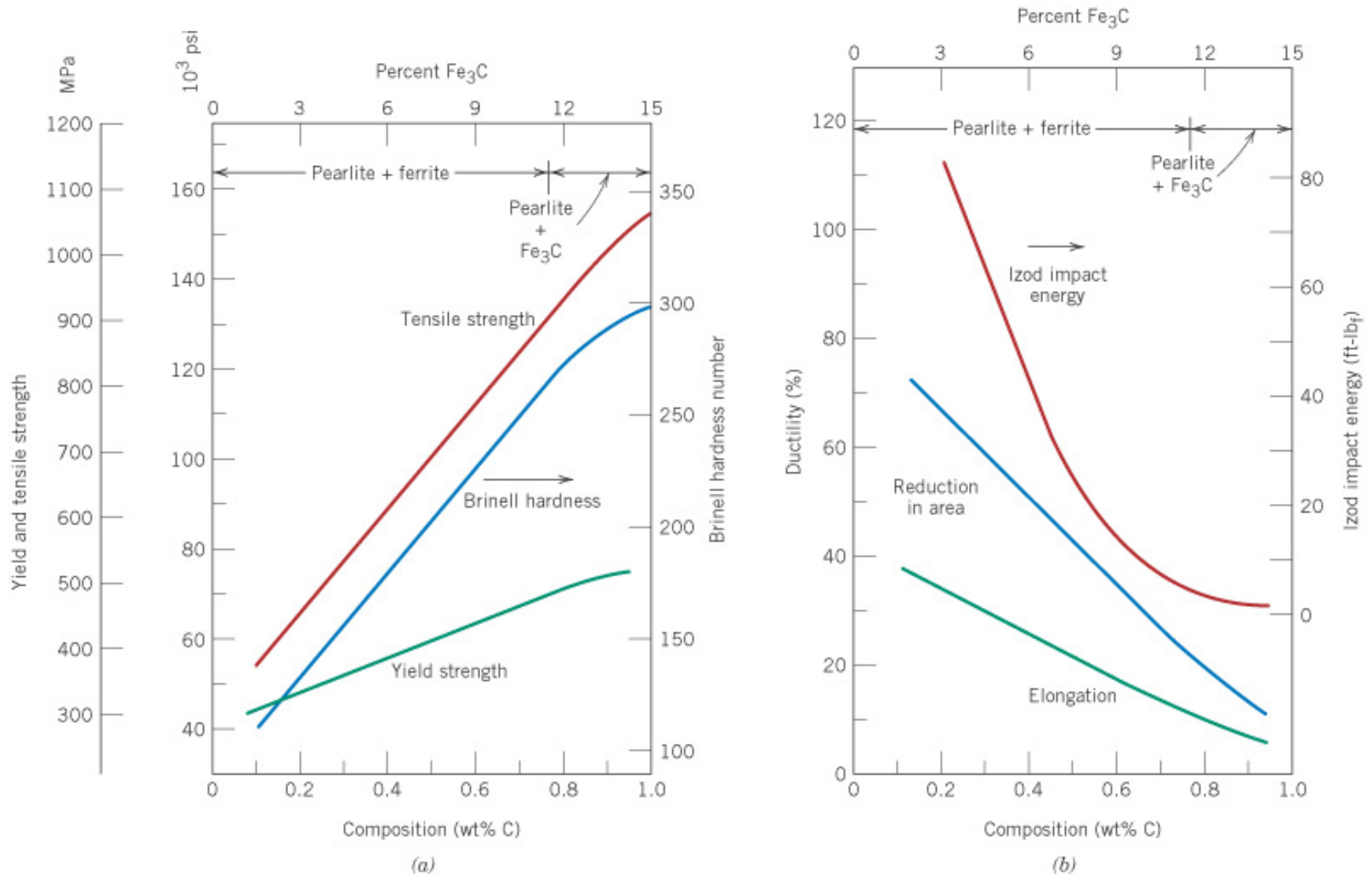


Fig. 11.30 순탄소강의 탄소 농도에 따른 기계적 성질.

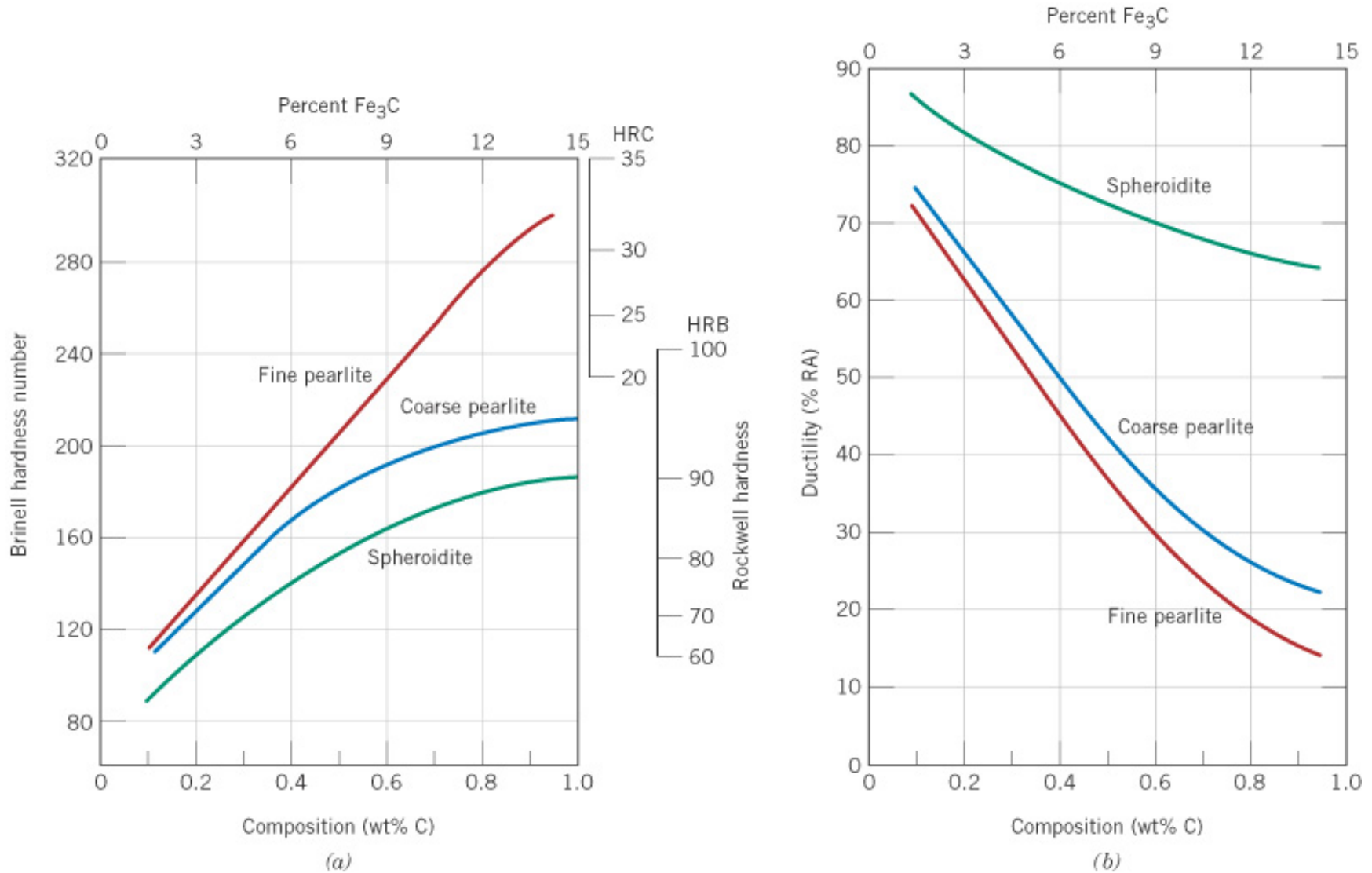


Fig. 11.31 순탄소강의 미세구조에 따른 기계적 성질: (a) 경도, (b) 연성.

Bainite

Fine structure,
stronger and harder
than pearlite

Desirable combination
of strength and
ductility

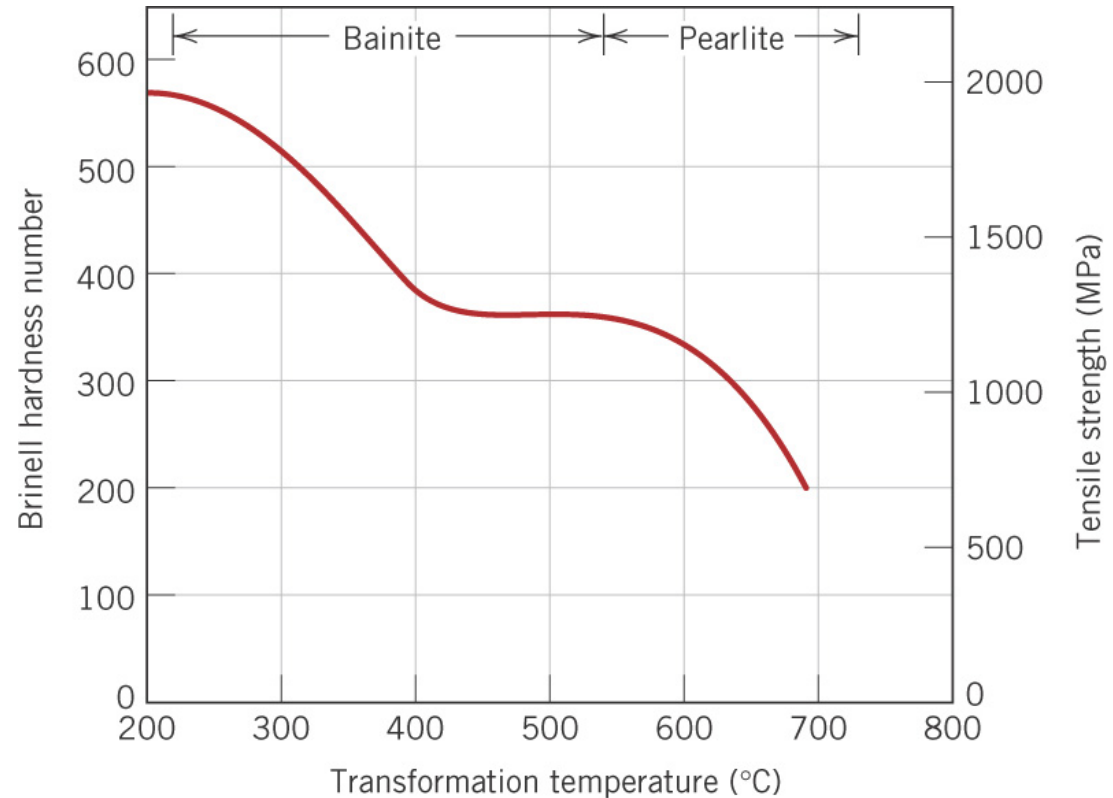


Fig. 11.32 공석조성의 Fe-C 합금에서 등온 변태온도에 따른 경도 및 인장강도.

Martensite

Hardest and strongest in steel alloys, but most brittle

← interstitial C atom이 dislocation motion을 막아주며

BCT 구조는 slip system이 적기 때문

0.5 wt% C 이상에서 급랭한 경우 internal stress 심각하여 crack 발생

Tempered martensite (템퍼링된 마텐자이트)

Tempering: 잔류응력 제거 및 연성 증가 위해 열처리 하는 것

단단하지만 취성인 martensite의 연성과 인성 증가 목적

보통 250~300 °C에서 열처리 후 200 °C에서 응력 제거

Martensite (BCT, 1 phase) → tempered martensite ($\alpha + \text{Fe}_3\text{C}$ phases)

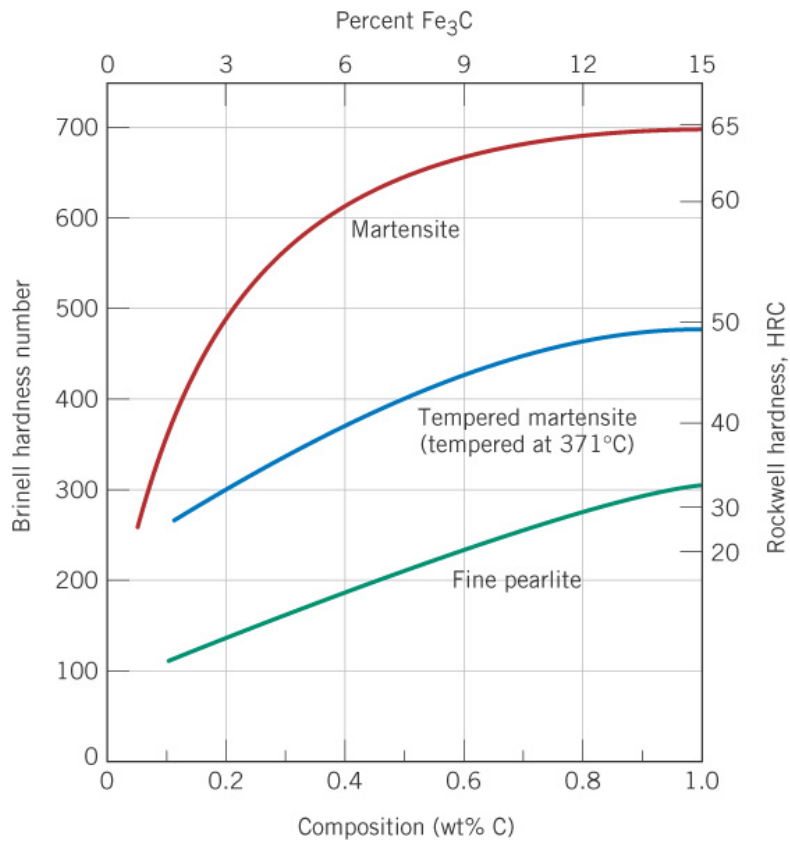


Fig. 11.33 Martensite, tempered martensite 및 pearlite의 탄소 농도에 따른 경도.

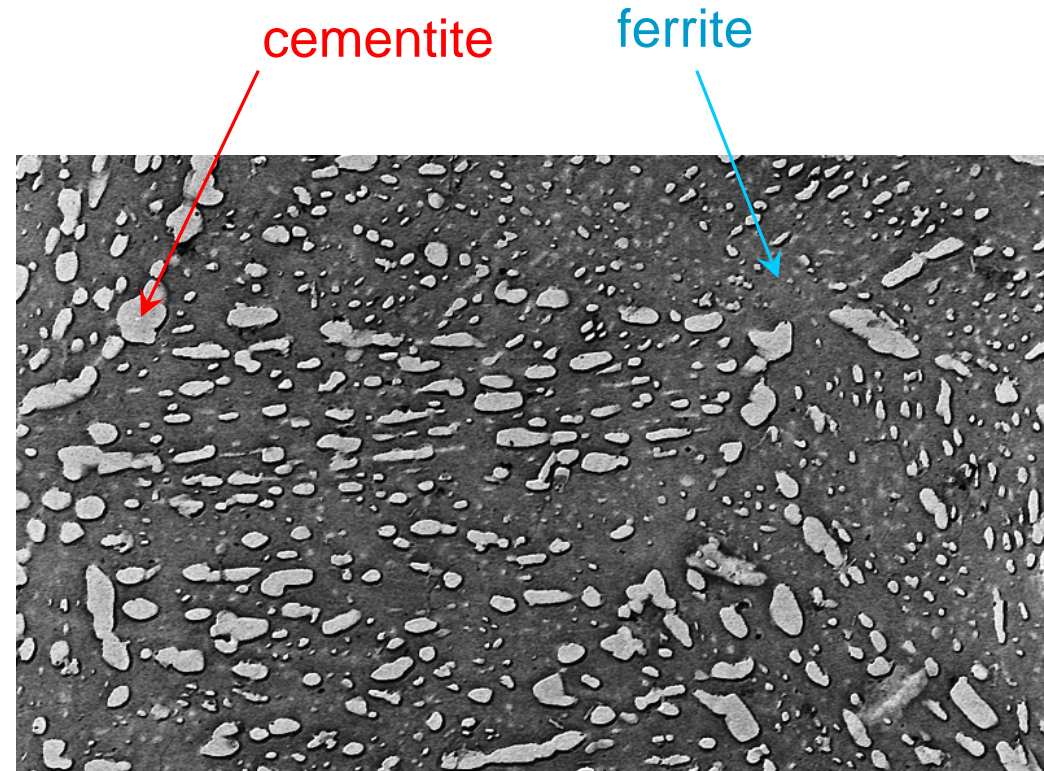


Fig. 11.34 Tempered martensite 의 현미경 사진.

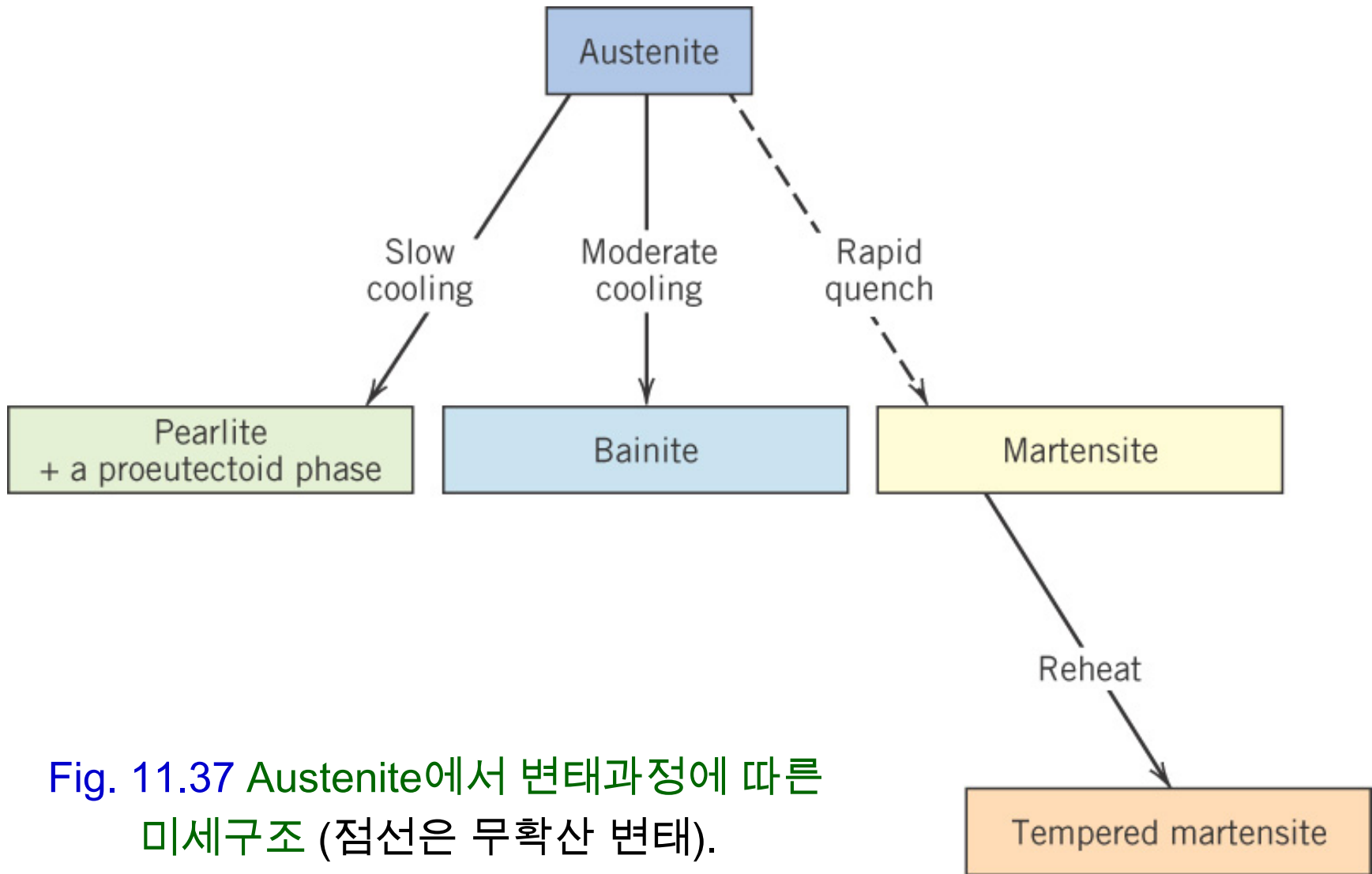
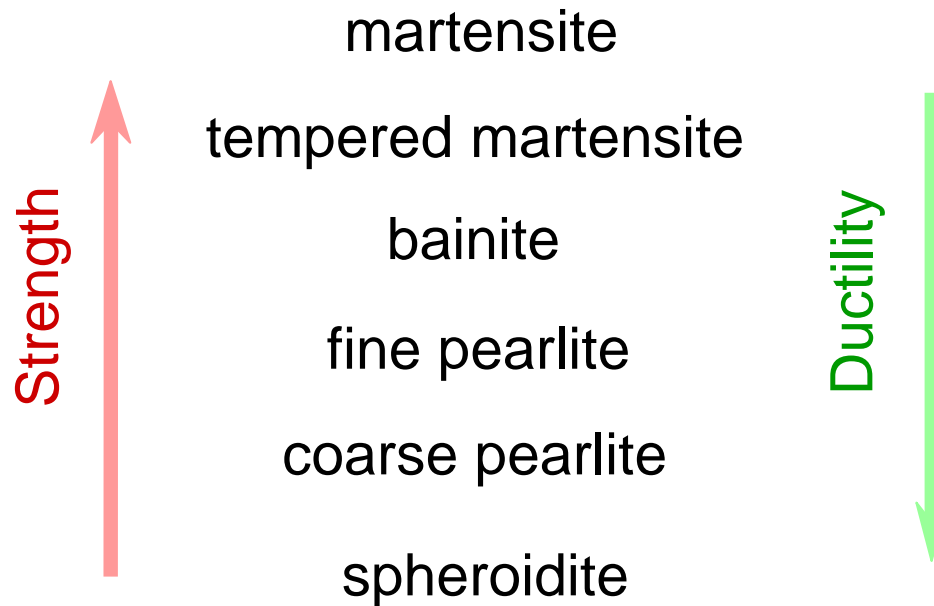


Fig. 11.37 Austenite에서 변태과정에 따른 미세구조 (점선은 무확산 변태).

Table 11.2 Summary of Microstructures and Mechanical Properties for Iron–Carbon Alloys

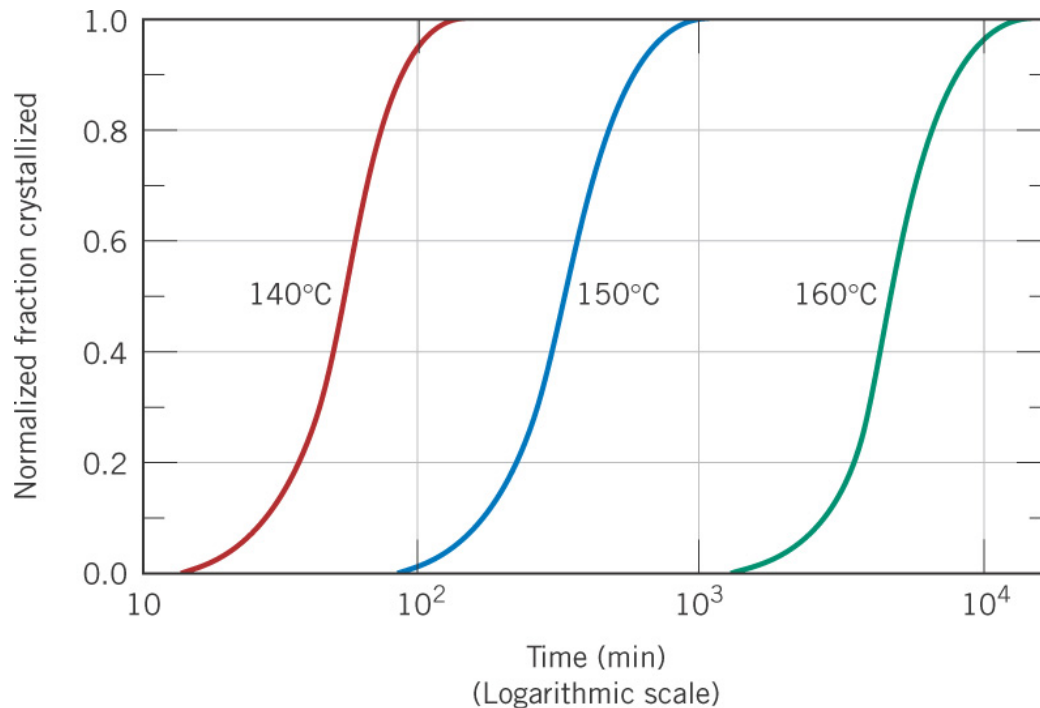
<i>Microconstituent</i>	<i>Phases Present</i>	<i>Arrangement of Phases</i>	<i>Mechanical Properties (Relative)</i>
Spheroidite	α Ferrite + Fe_3C	Relatively small Fe_3C sphere-like particles in an α -ferrite matrix	Soft and ductile
Coarse pearlite	α Ferrite + Fe_3C	Alternating layers of α ferrite and Fe_3C that are relatively thick	Harder and stronger than spheroidite, but not as ductile as spheroidite
Fine pearlite	α Ferrite + Fe_3C	Alternating layers of α ferrite and Fe_3C that are relatively thin	Harder and stronger than coarse pearlite, but not as ductile as coarse pearlite
Bainite	α Ferrite + Fe_3C	Very fine and elongated particles of Fe_3C in an α -ferrite matrix	Hardness and strength greater than fine pearlite; hardness less than martensite; ductility greater than martensite
Tempered martensite	α Ferrite + Fe_3C	Very small Fe_3C sphere-like particles in an α -ferrite matrix	Strong; not as hard as martensite, but much more ductile than martensite
Martensite	Body-centered tetragonal, single phase	Needle-shaped grains	Very hard and very brittle

General Trends of Mechanical Properties



Crystallization, Melting & Glass Transition Phenomena in Polymers (고분자재료에서의 결정화, 용융 및 유리전이 현상)

Crystallization



Avrami equation:

$$y = 1 - \exp(-kt^n)$$

Transformation rate:

$$\text{rate} = \frac{1}{t_{0.5}}$$

Fig. 11.46 Polypropylene의 시간에 따른 등온 결정화 분율.

Melting & Glass Transition Temperatures

(용융 온도 및 유리전이 온도)

Melting Temperature, T_m

~ 결정성 고체 고분자가 점성 액체로 바뀌는 온도

Glass Transition Temperature, T_g

~ 비정질 또는 반결정성 유리상 고분자가 고무상 고분자로 바뀌는 온도

Fig. 11.47 비결정질(A), 반결정질(B), 결정질(C) 고분자의 온도에 따른 비체적 거동.

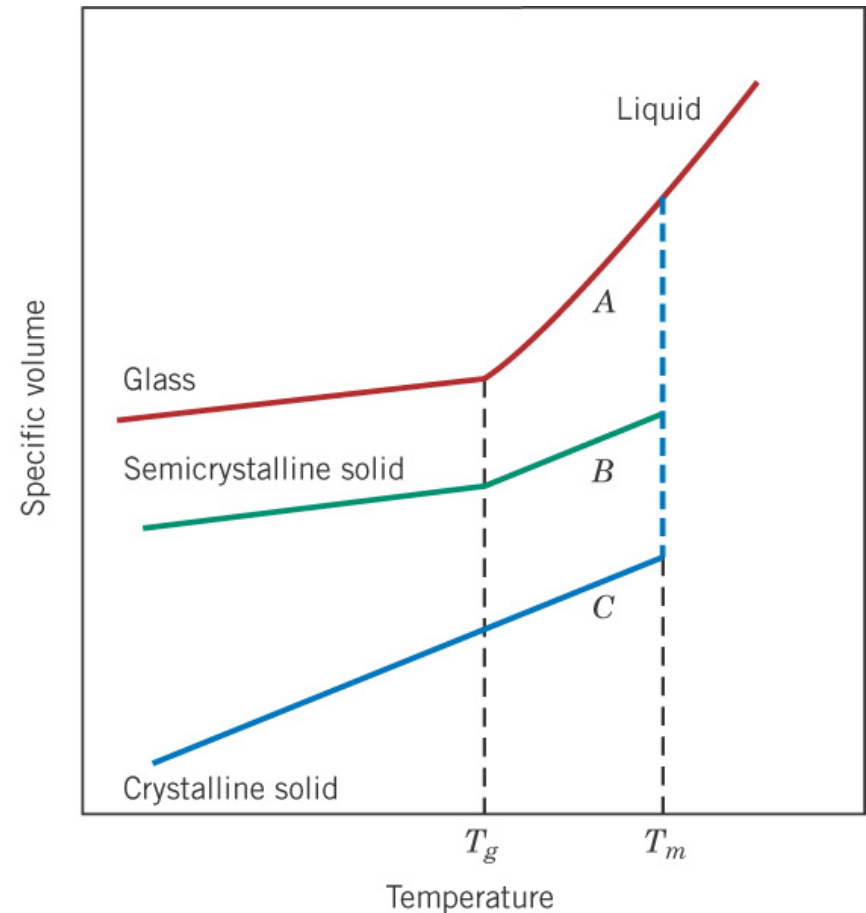


Table 11.3 Melting and Glass Transition Temperatures for Some of the More Common Polymeric Materials

<i>Material</i>	<i>Glass Transition Temperature</i> [°C (°F)]	<i>Melting Temperature</i> [°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)

Factors Affecting T_m & T_g (T_m 및 T_g 에 영향을 미치는 요소)

Both T_m & T_g increase with increasing chain stiffness.

Chain stiffness increases by the presence of

Bulky side groups (ex., PP vs. PS)

Polar groups (ex., PP vs. PVC)

Double bonds & aromatic groups in the backbone

T_g lies somewhere between 0.5 and 0.8 T_m (in Kelvin).

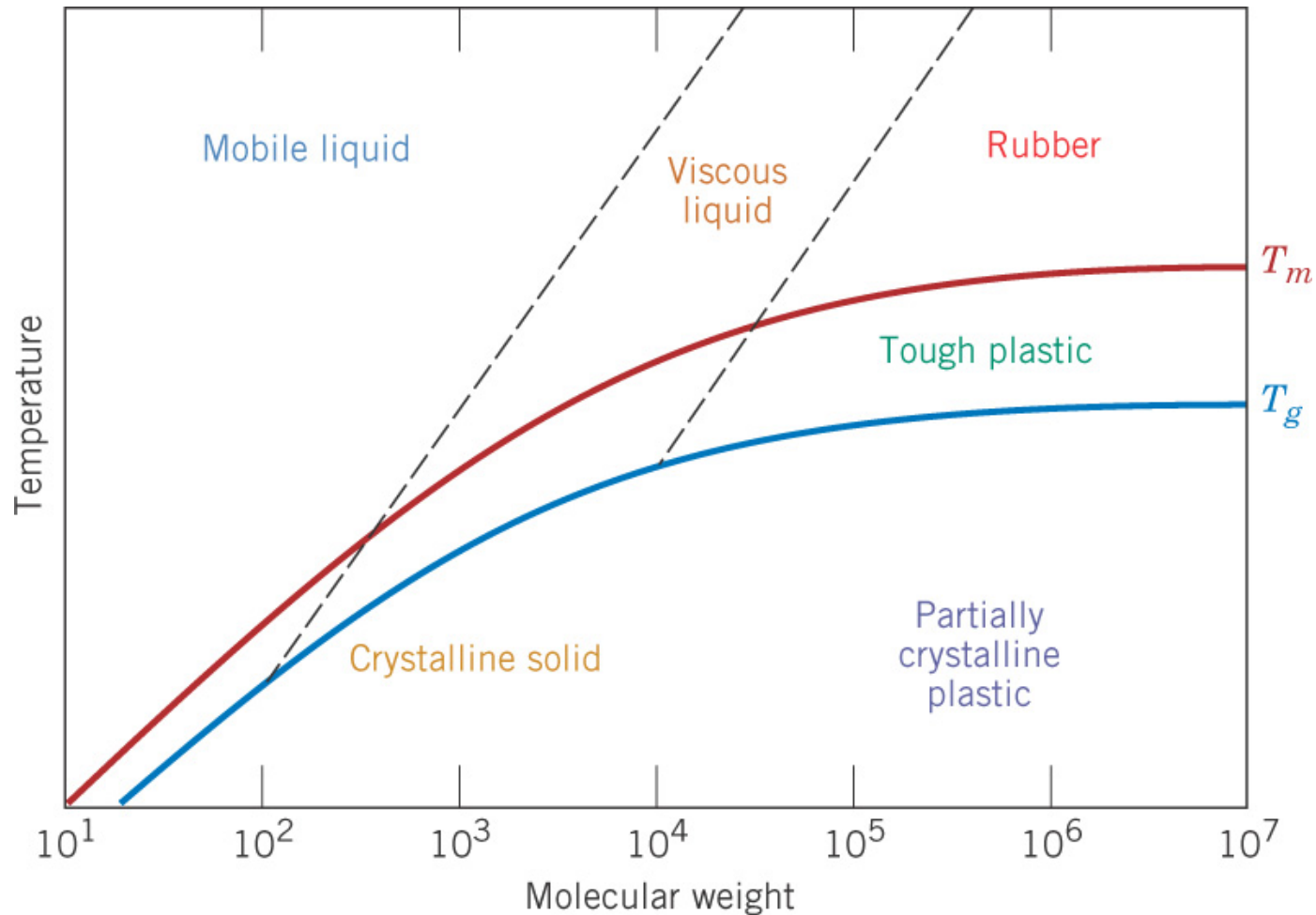


Fig. 11.48 분자량이 용융 온도 T_m , 유리전이 온도 T_g 및 고분자 성질에 미치는 영향.

(Probs.)

11.7, 11.9, 11.15, 11.18, 11.30, 11.32 & 11.44.