

Chapter5

Phase Transformation

Part II

강의명: 기계재료공학 (MFA9009)

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Recap

- 상변태 과정
 - 핵생성 (균일/불균일 모델 비교) – 응고 모형.
 - 성장
 - 조밀/조대 조직이 발생 조건 비교
- 상변태 변태속도론
- 준안정 상태

Objectives and outlines

- 철 합금에서 나타나는 각각의 미세 구성 인자 (미세조직):
 - 미세 펄라이트 – fine pearlite
 - 조대 펄라이트 – coarse pearlite
 - 스페로이다이트 – spheroidite
 - 베이나이트 – bainite
 - 마텐사이트 – martensite
 - 템퍼링된 마텐사이트 – tempered martensite
- 미세 물질의 일반적인 기계적 특성
- 철과 탄소의 합금에 대한 ‘등온 상태도’에 따라 예상되는 미세 물질은?

철-탄소 합금에서 미세조직과 성질 변화

- 고체-고체 상변태가 우리가 집중적으로 살펴볼 상변태 형태.
- 열처리(temperature, time)에 따른 미세조직의 변화와, 그러한 변화에 기인하는 기계적 성질에 대해 살펴보겠다.
- 주로 철-탄소 binary system에 대한 논의

동온 변태도 - Eutectoid reaction

- Eutectoid transf. (Fe- Fe_3C system):

- For transf. to occur, must cool to below 727°C
(i.e., must “undercool”)

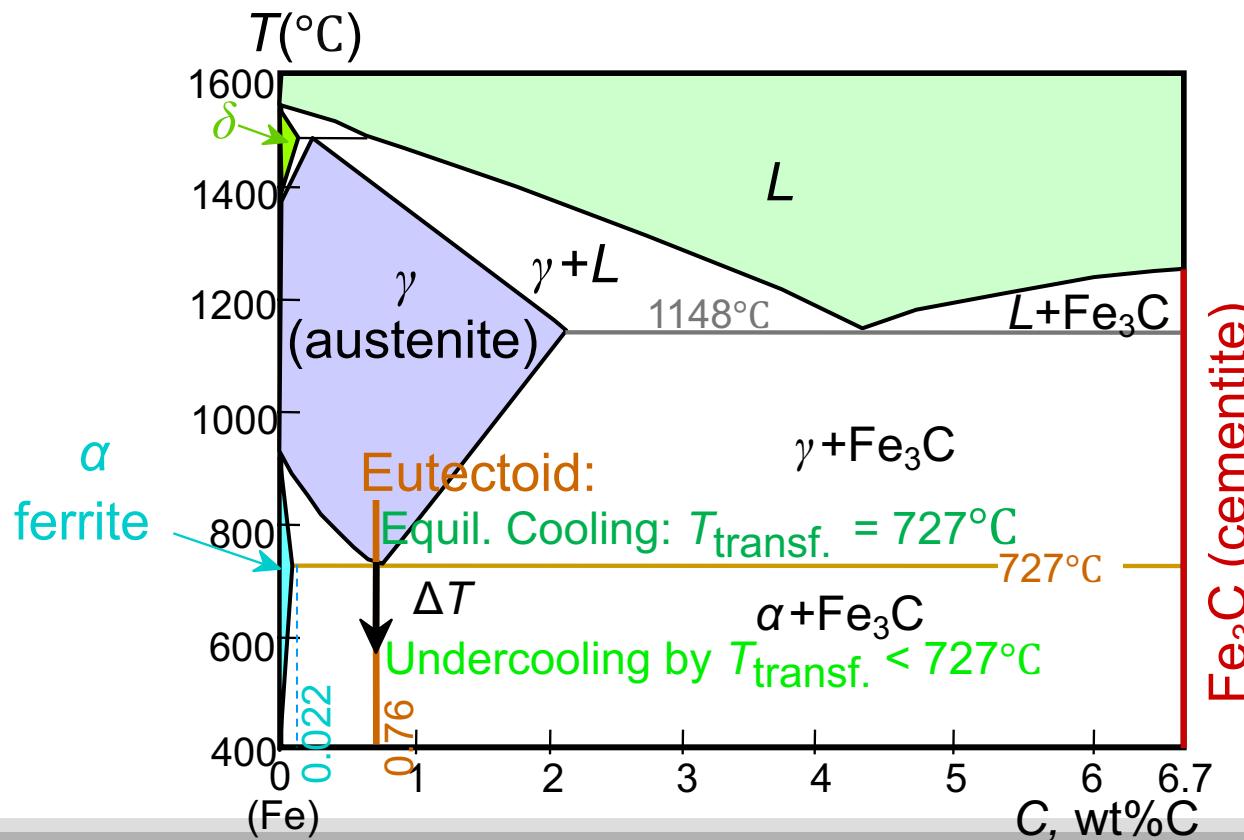
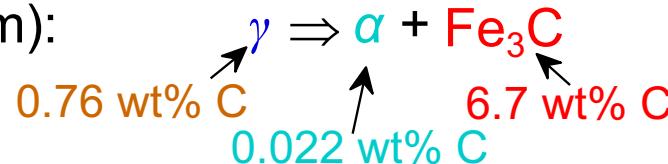
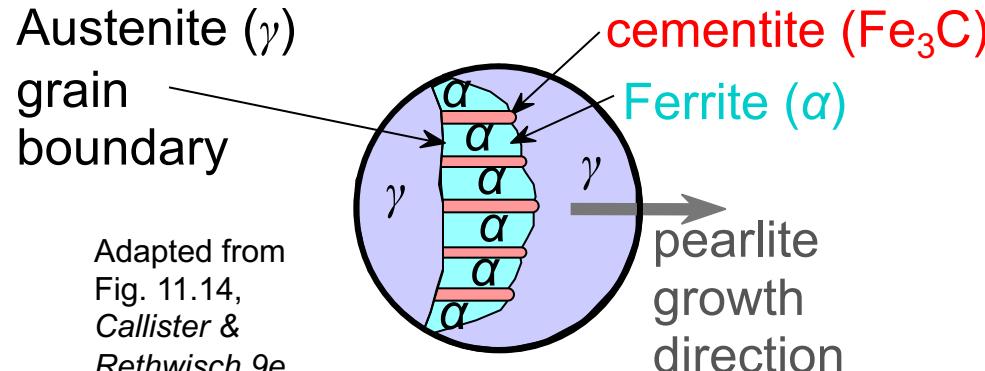


Fig. 11.23, Callister & Rethwisch 9e.

[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.]

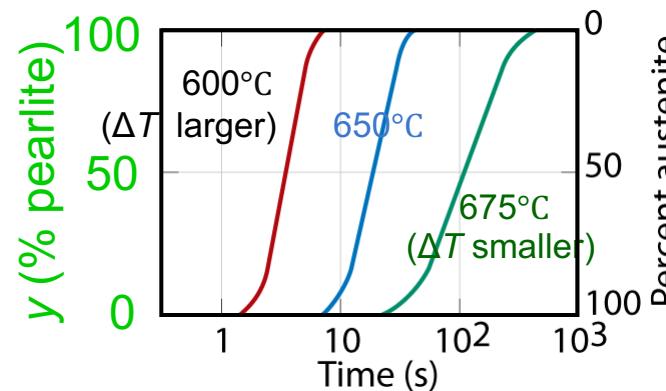
동온 변태도 - Eutectoid reaction

- Transformation of austenite to pearlite:



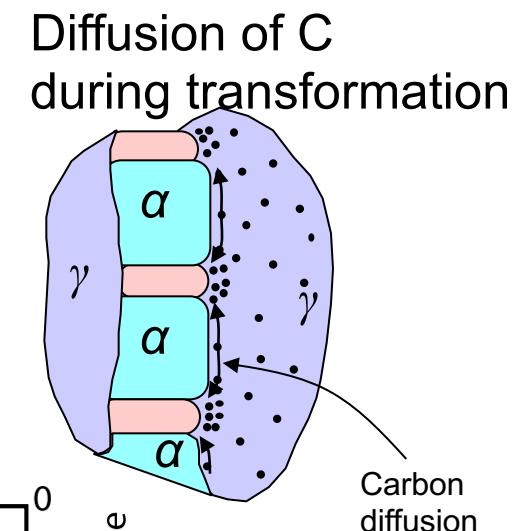
Adapted from
Fig. 11.14,
Callister &
Rethwisch 9e.

- For this transformation, rate increases with $[T_{\text{eutectoid}} - T]$ (i.e., ΔT).



Coarse pearlite → formed at higher temperatures – relatively soft

Fine pearlite → formed at lower temperatures – relatively hard



Adapted from
Fig. 12.12,
Callister &
Rethwisch 9e.

동온 변태도 - Eutectoid reaction

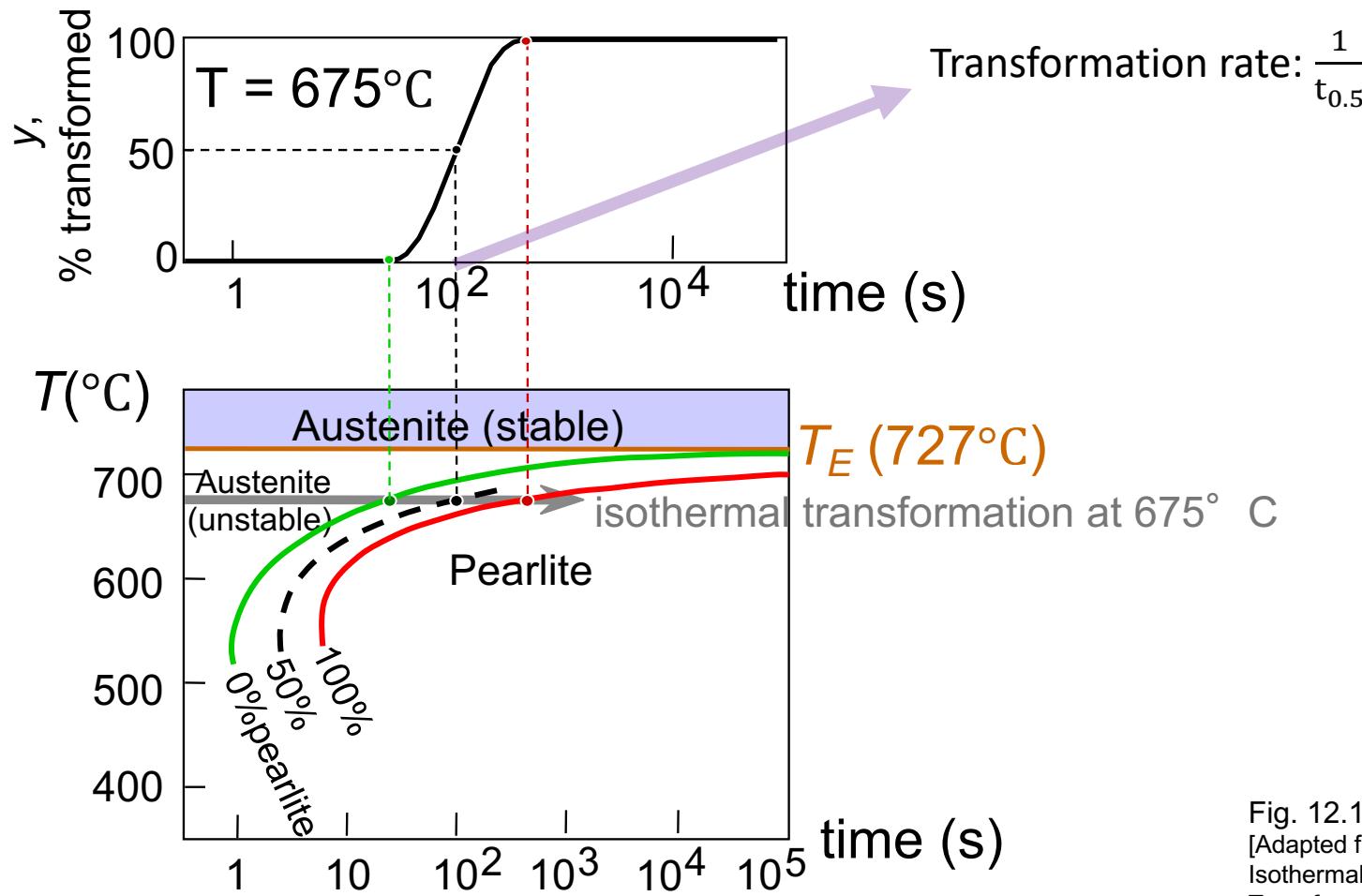


Fig. 12.13, Callister & Rethwisch 9e.
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등온 변태도 - Eutectoid reaction

- Eutectoid composition, $C_0 = 0.76 \text{ wt\% C}$
- Begin at $T > 727^\circ\text{C}$
- Rapidly cool to 625°C
- Hold $T (625^\circ\text{C})$ constant (isothermal treatment)

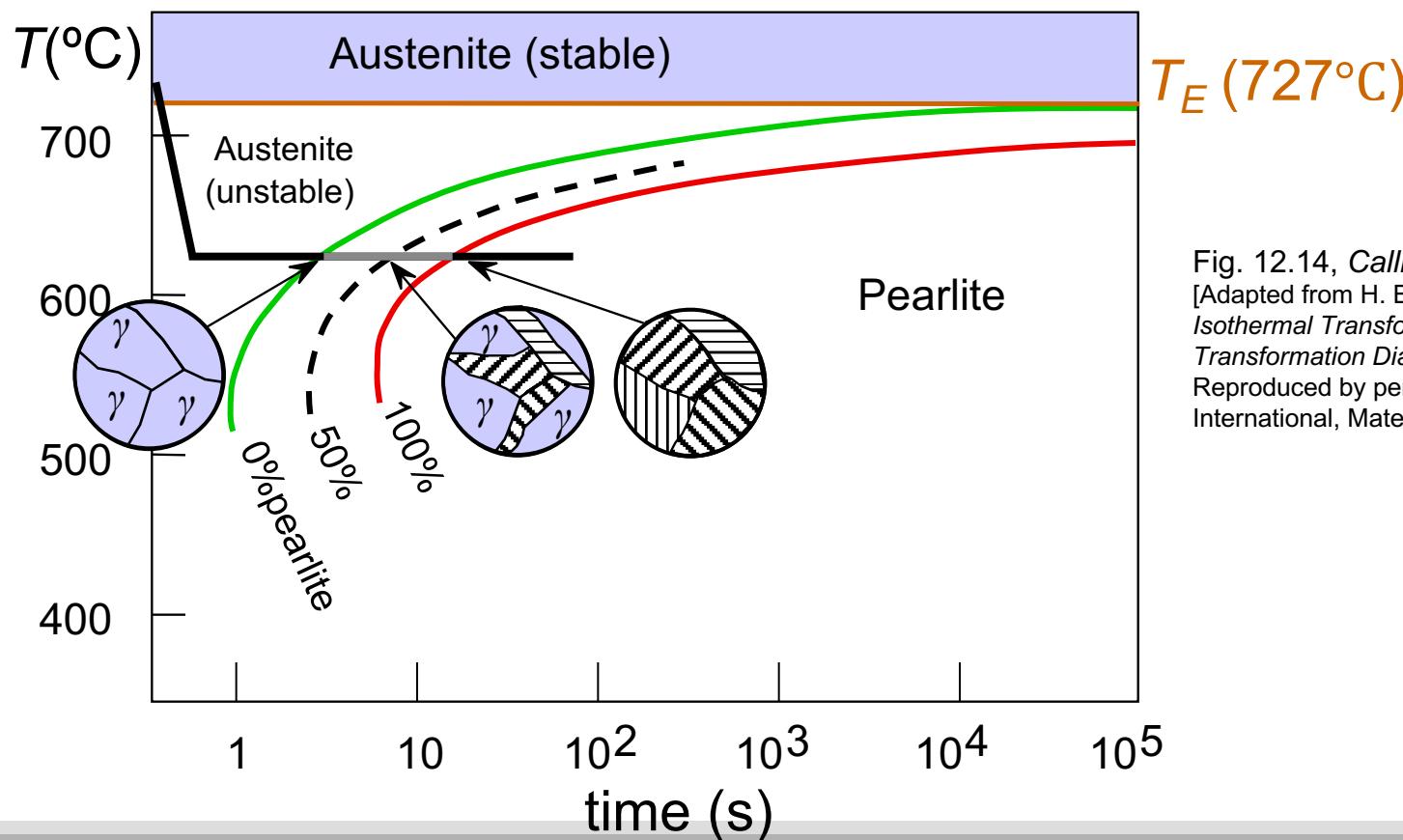
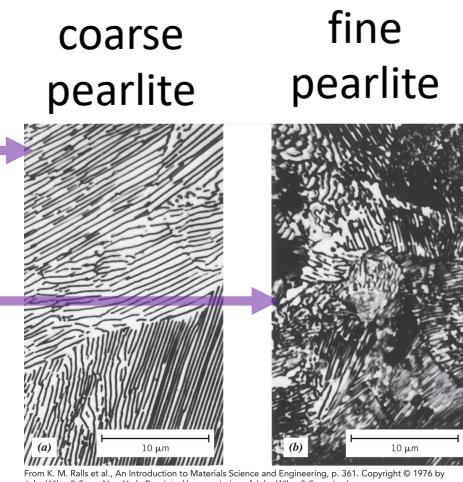
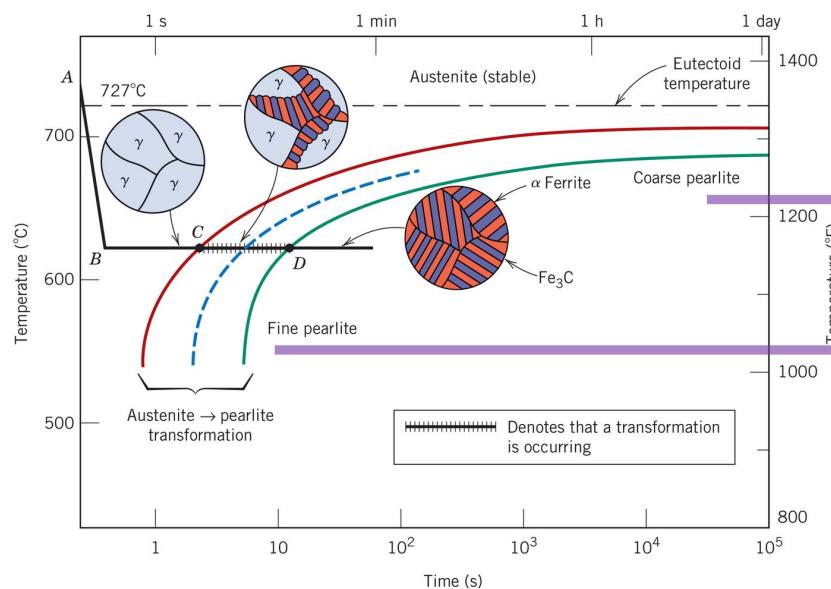
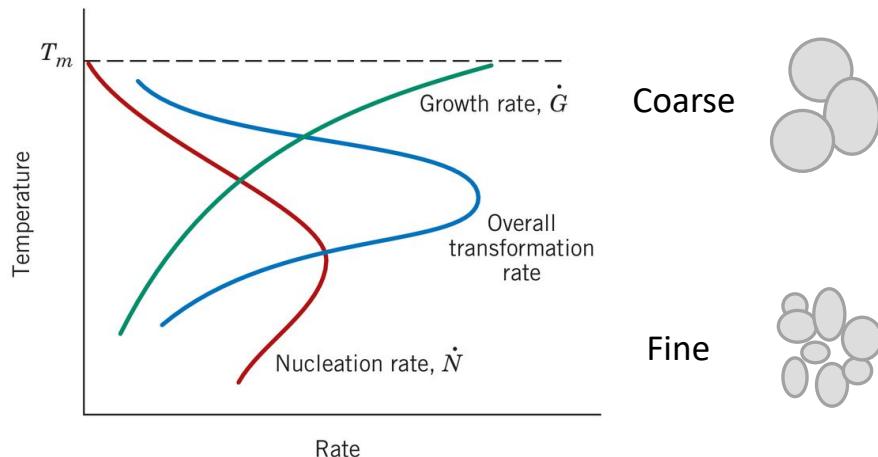


Fig. 12.14, Callister & Rethwisch 9e.
[Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, 1977.
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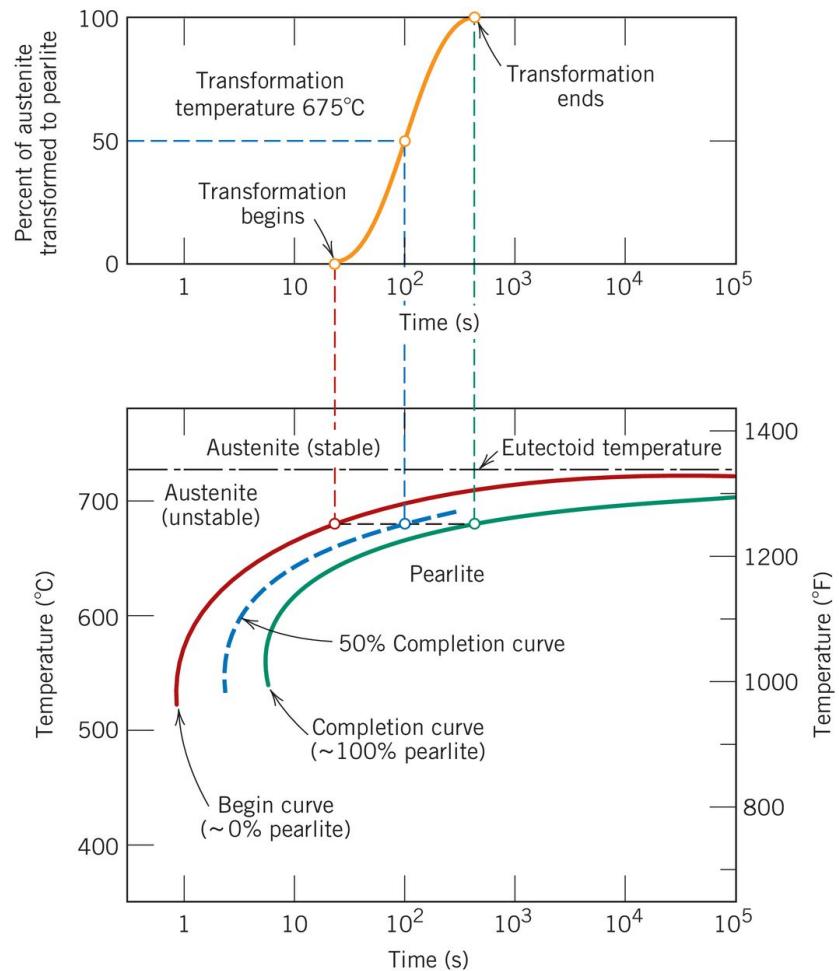
조대(coarse) pearlite, 미세(fine) pearlite



From K. M. Ralls et al., An Introduction to Materials Science and Engineering, p. 361. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

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Recap: 등온 변태도



Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, 1977. Reproduced by permission of ASM International, Materials Park, OH.

- 왼편의 diagram에는 몇가지 제약(constraint) 조건이 있음에 유의하자.
 - 해당 diagram은 특정 조성에만 유용하다. 즉 다른 조성(chemical composition)일 때는 다른 형태의 diagram으로 설명된다.
 - Transformation rate, 즉 변태속도(상변태에 소요되는 시간의 역수)는 온도에 따라 변한다. 등온변태도는 반응이 진행되는 동안 일정한 온도를 유지한 변태의 경우만을 대표한다.
 - 이렇게 일정한 온도를 유지한 상태에서의 상변태 정보를 표현하는 방법이기에 이와 같은 도식을 **등온 변태도** (isothermal transformation diagram) 또는 **시간-온도-변태곡선** (time-temperature-transformation curve; 줄여서 **TTT curve**)라고 한다.

동온 변태도 Non-eutectoid reaction

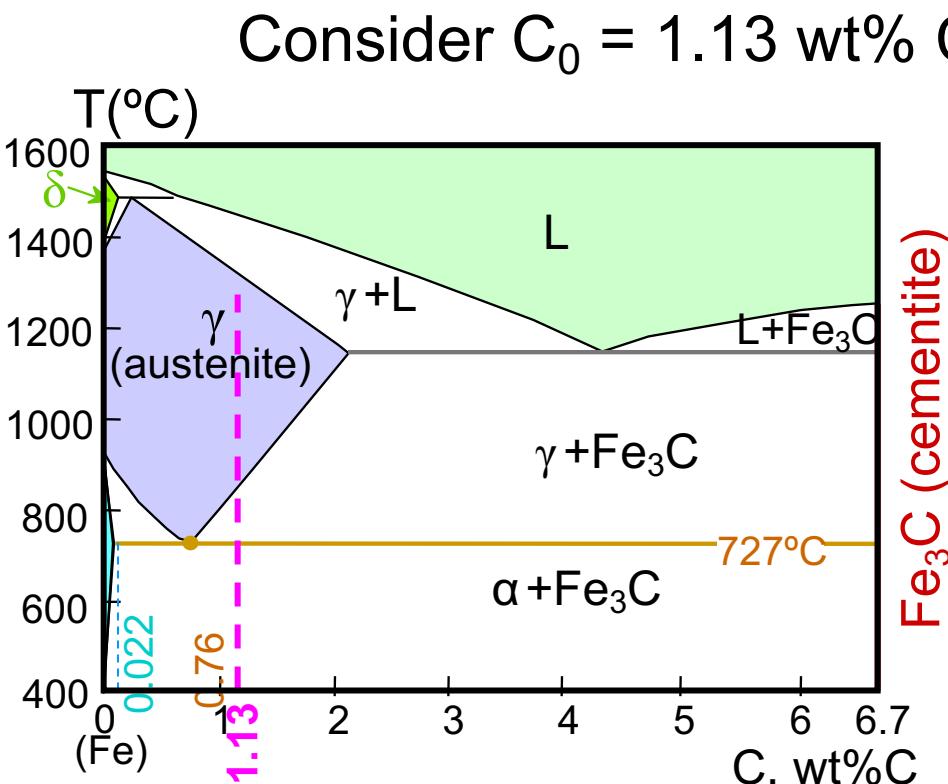


Fig. 11.23, Callister & Rethwisch 9e.

[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.]

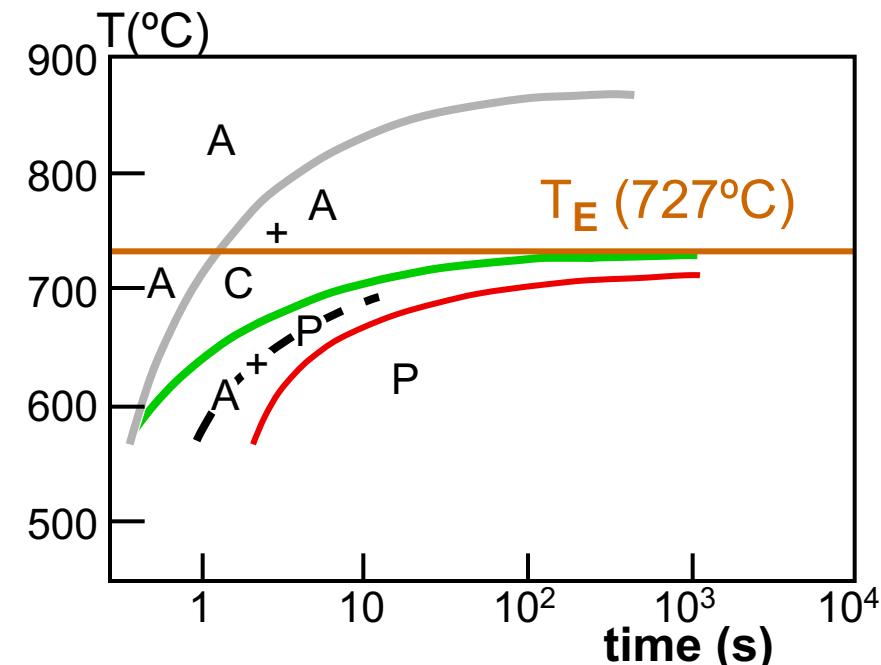


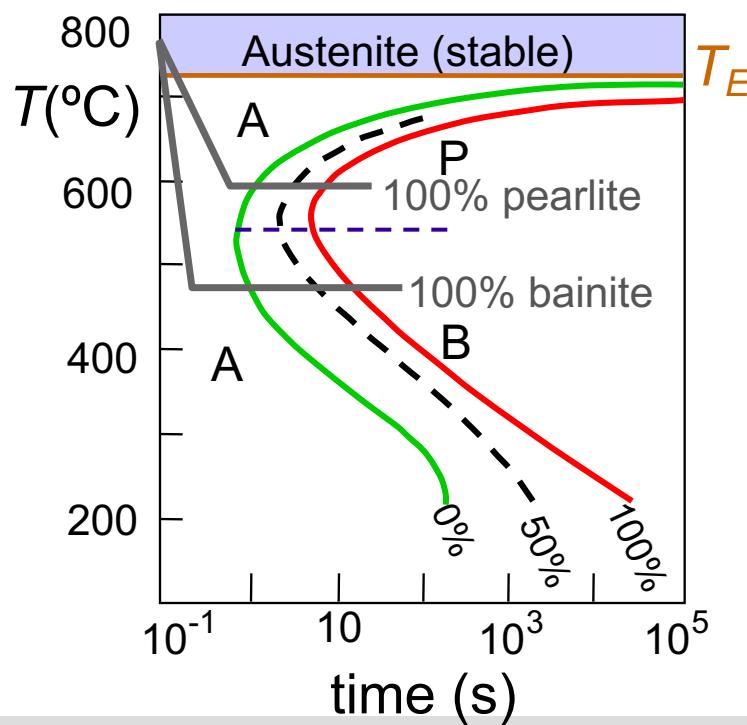
Fig. 12.16, Callister & Rethwisch 9e.

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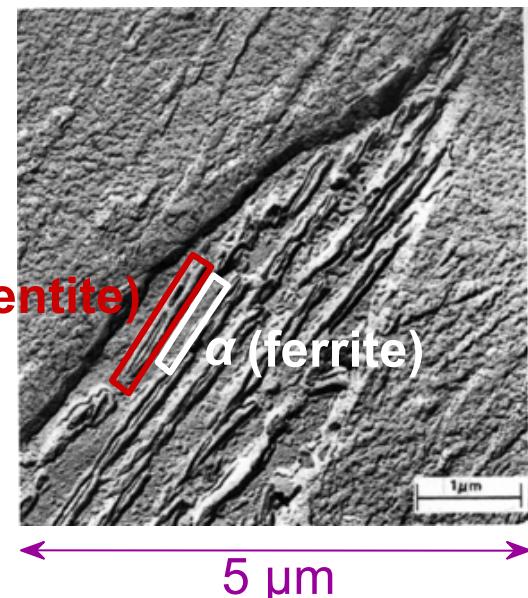
Hypereutectoid composition – proeutectoid cementite

Bainite: another Fe-Fe₃C transformation product

- Bainite:
 - elongated Fe₃C particles in α -ferrite matrix
 - diffusion controlled (diffusion 느림)
- Isothermal Transf. Diagram,
 $C_0 = 0.76 \text{ wt\% C}$

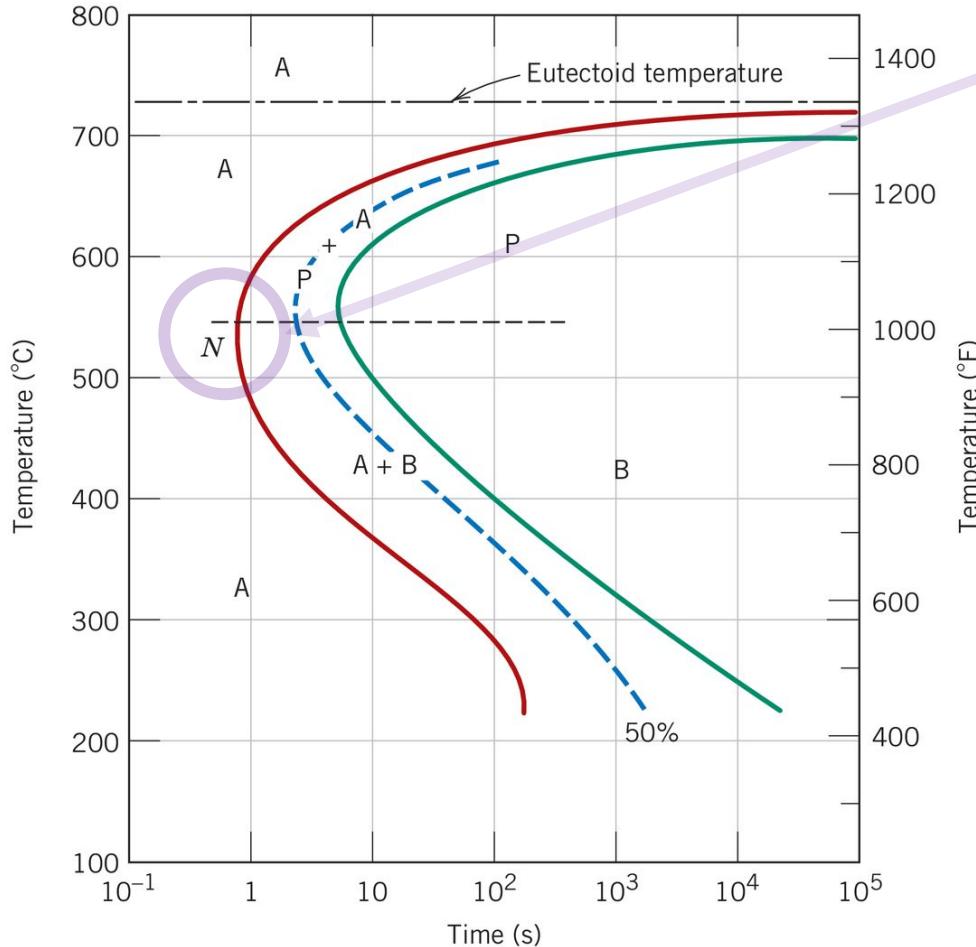


Bainite는 전자현미경으로만 분석이 가능할 정도로 미세하다.



베이나이트는 변태 온도에 따라 침상이나 판상 모양으로 형성 된다.

Bainite



Nose: 변태 속도가 최대인 점. 이를 기준으로 이하는 diffusion 속도가 nucleation에 비해 매우 느리다. 따라서 diffusion control

그 이상은 nuclei 생성이 느리다. 따라서 nucleation control.

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Spheroidite

- **Spheroidite:**
 - 구형의 Fe_3C particles가 α -ferrite 기지(matrix)에 박혀 있는 모습
 - Formation requires diffusion of carbon
 - bainite와 pearlite를 공석 온도 이하에서 오랫동안 열을 가해서.
 - Driving force – reduction of α -ferrite/ Fe_3C interfacial area

'구형'의 Fe_3C particle; 구형의 형태로 변하면서 부피당 interface를 줄인다.

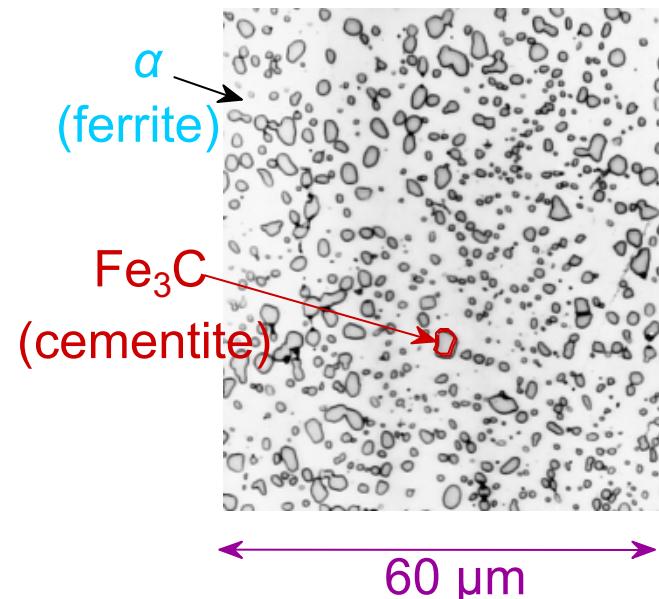
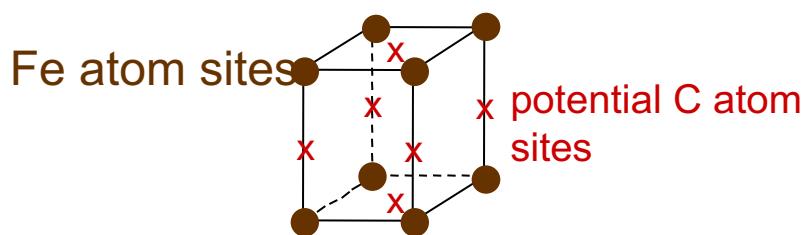


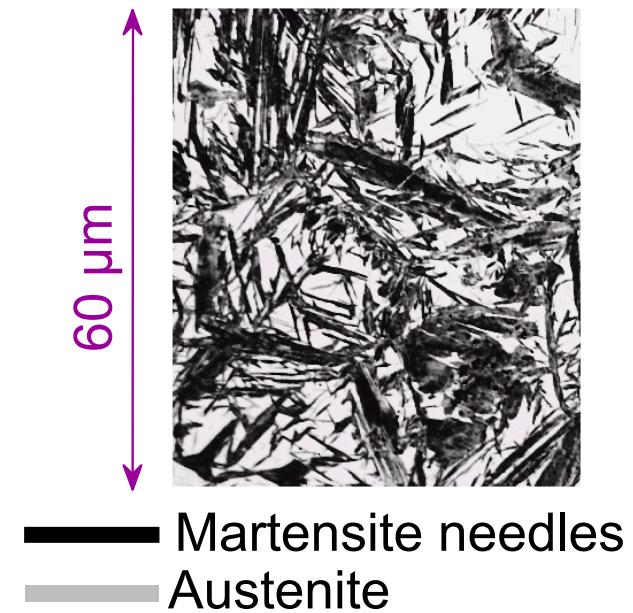
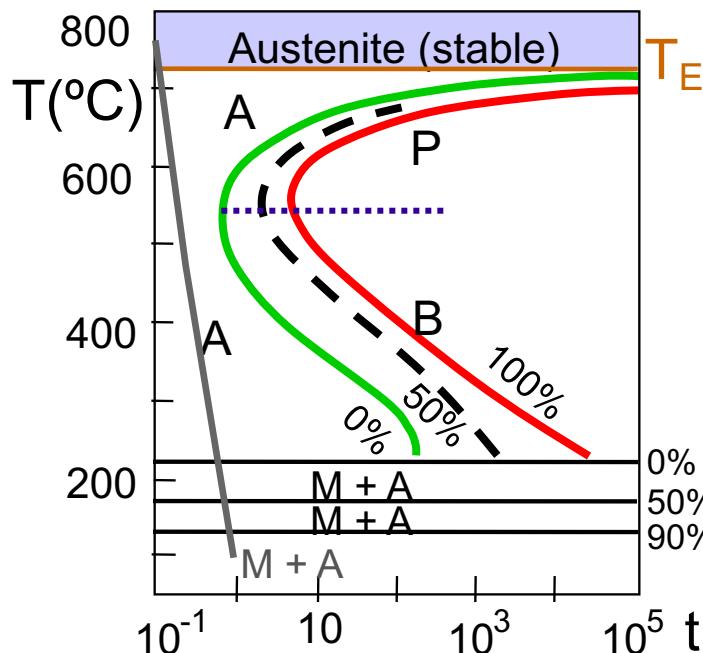
Fig. 12.19, Callister &
Rethwisch 9e.
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Martensite: a non-equilibrium transformation product

- **Martensite:** γ (FCC) to Martensite (BCT)



- Isothermal Transf. Diagram

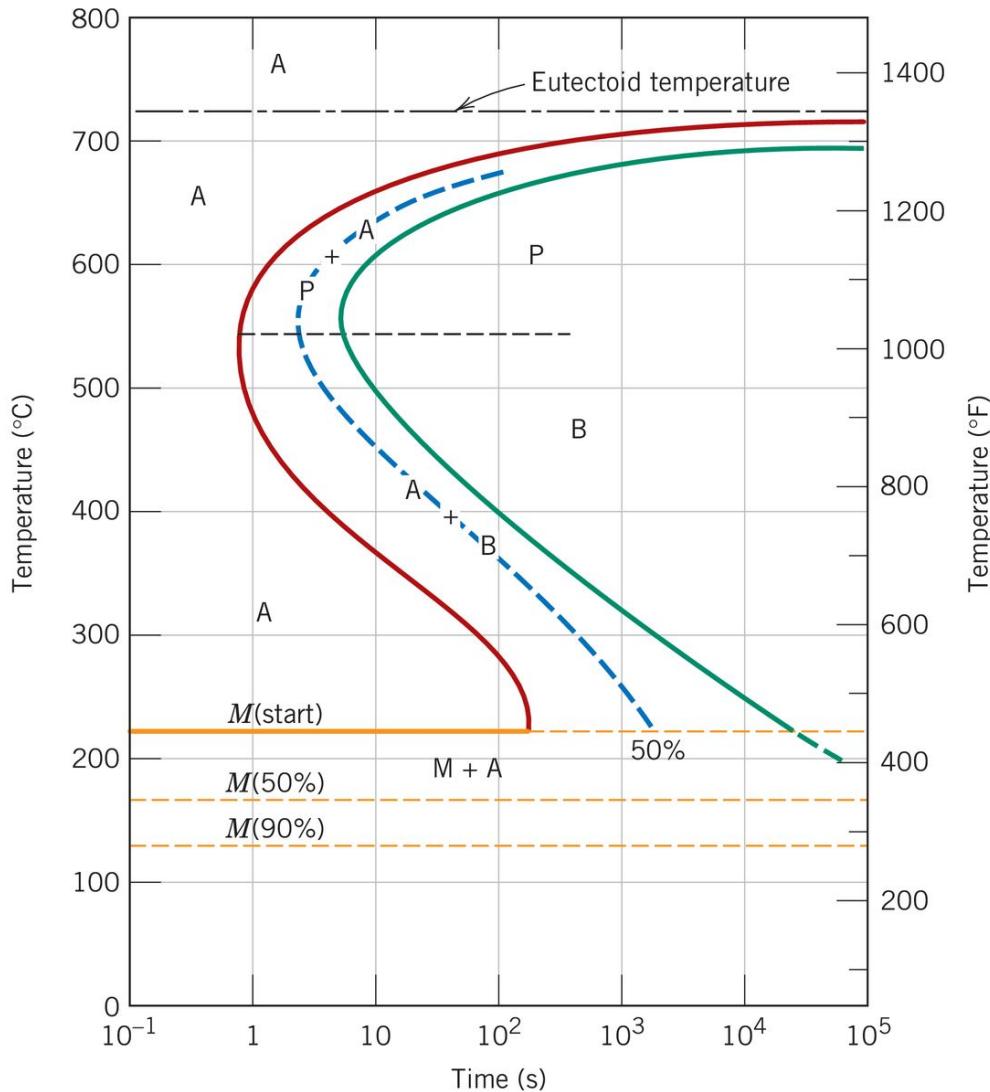


- • γ to martensite (M) transformation.
- Rapid! (**diffusionless, athermal transformation**)
- Amount of transformation depends only on T, to which γ is rapidly cooled

Quenching?

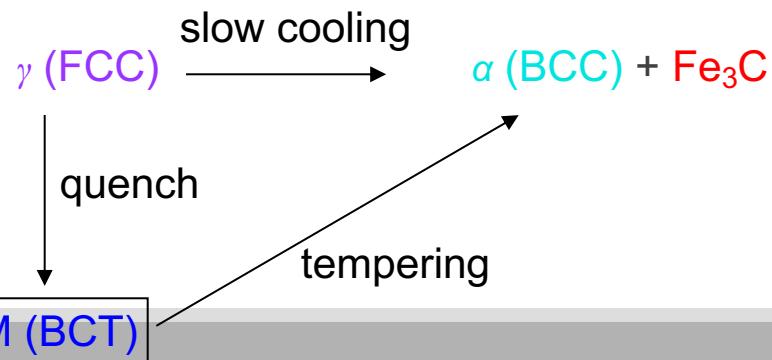


Martensite



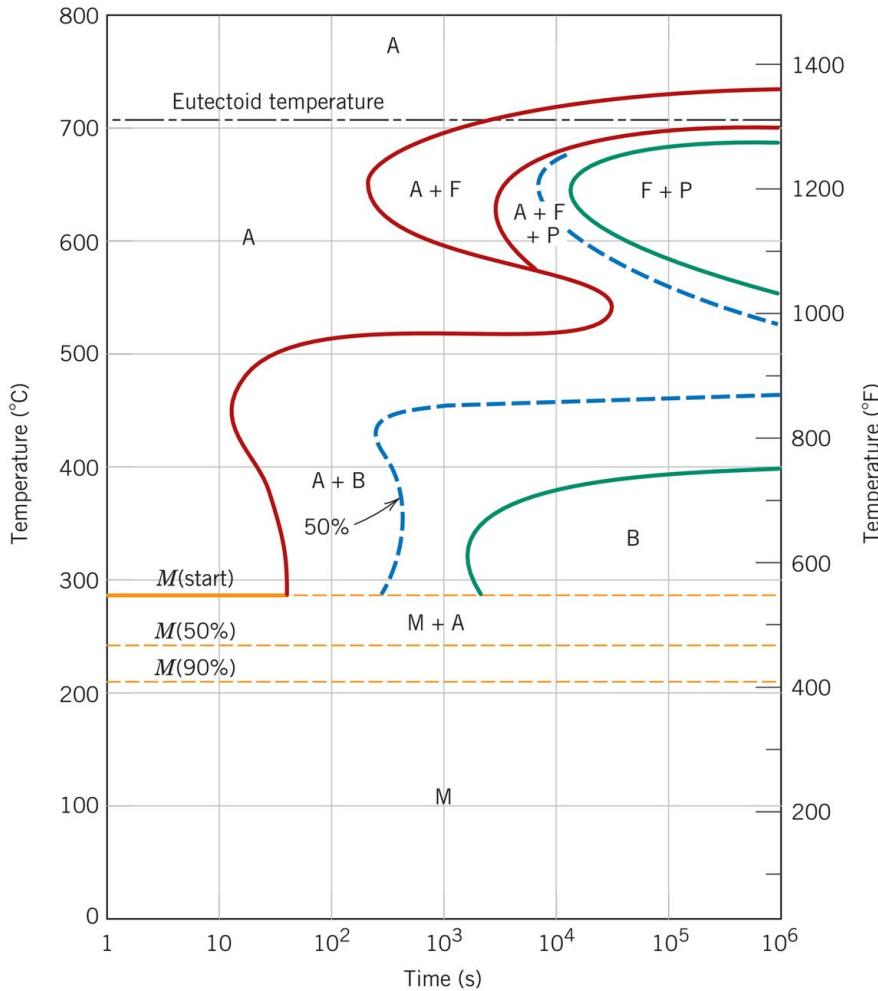
□ Martensite:
 Nucleation과 diffusion이 매우 빠르게 (음속만큼 빠르게) 발생. 시간에 무관하다 - 왼편에서 수평선으로 나타난 Ms temperature를 살펴보자. Ms T와 M(50%), M(90%) 경계는 시간에 무관하고 오직 급랭(quench)되는 온도만의 함수로 나타난다. 이러한 종류의 변태를 비열적 변태 (athermal transformation)이라고 한다 – 확산이 중요한 역할을 하는 (상)변태는 thermally activated (phase) transformation.

□ Martensite is a non-equilibrium phase:
 Martensite는 상온에서 평형상이 아니다. Ferrite+ Fe_3C 가 평형상. 하지만 상온에서 $\text{Martensite} \rightarrow \text{Ferrite} + \text{Fe}_3\text{C}$ 변태는 매우 느리다.



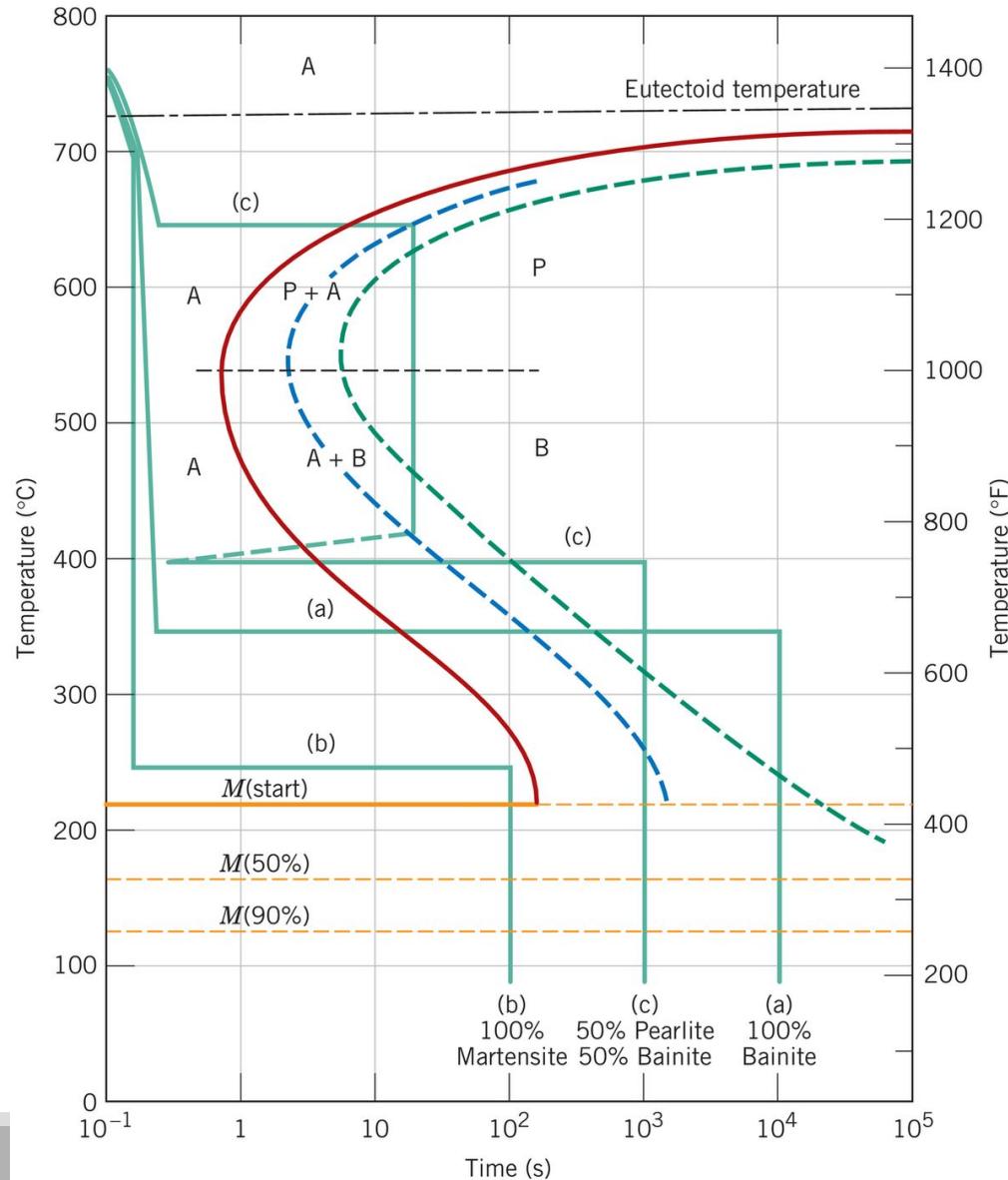
Alloying element의 영향

- 탄소 외의 다양한 합금 원소들이 변태도 내의 곡선 위치와 모양에 상당한 변화를 준다.
 - Austenite vs. Bainite nose의 shift.
 - Bainite nose의 분리



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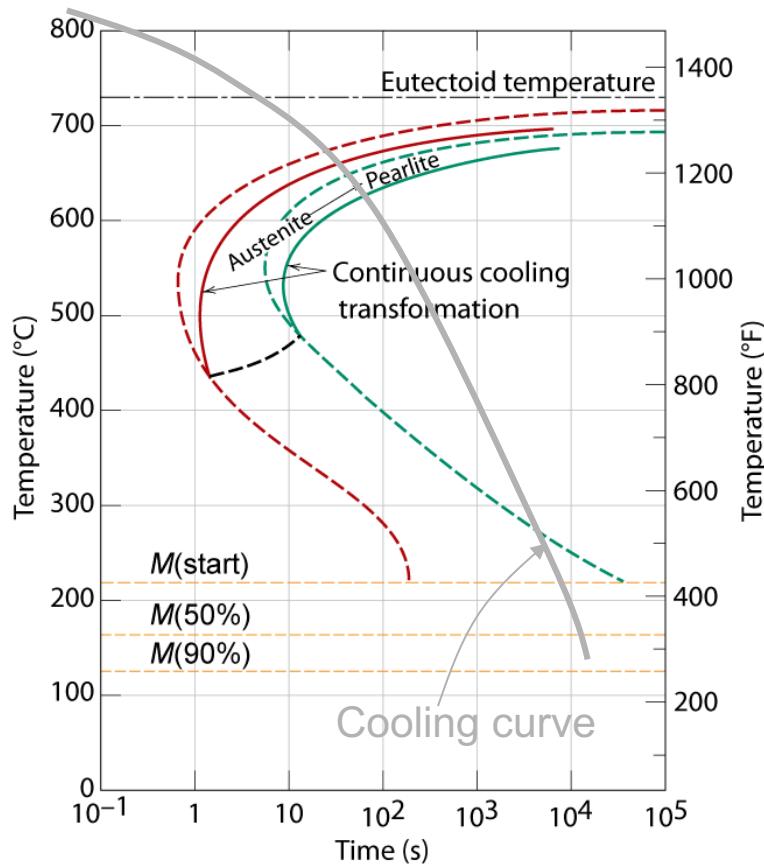
Ex 12.3



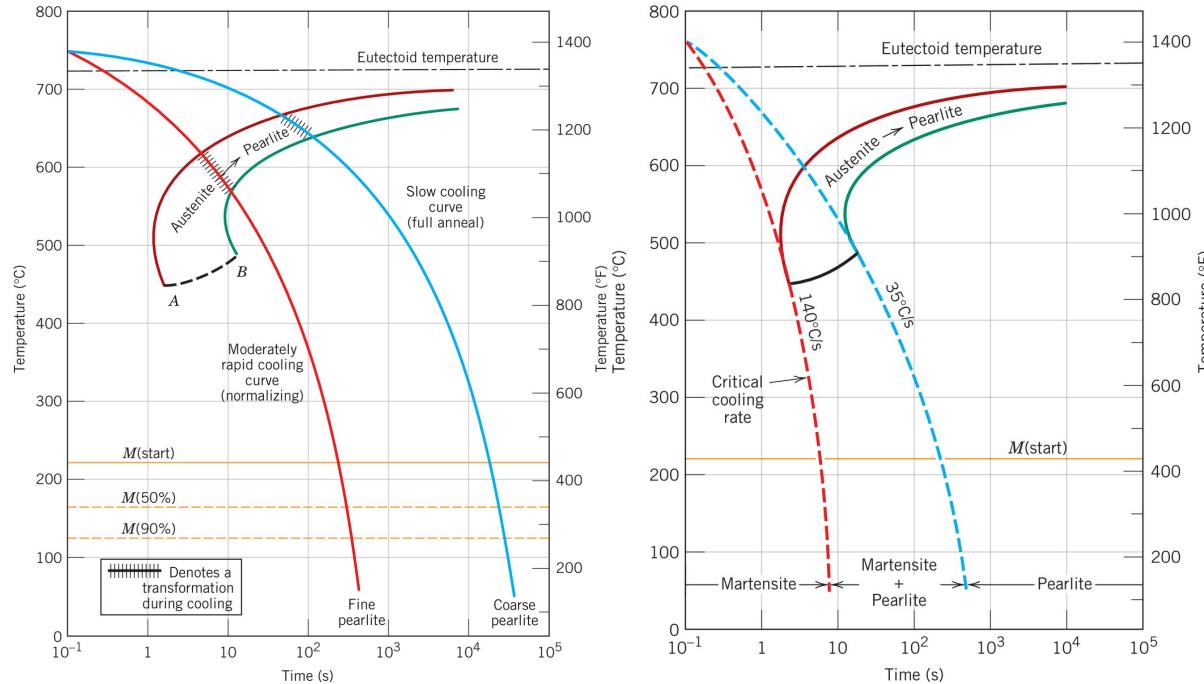
연속 냉각 변태도 (continuous cooling transformation diagrams)

TTT에서 사용한 방식의 온도/시간 변화를 실제 제조 공정에서 적용하기가 어려울 때가 있다. 대부분 강에서 열처리는 상온까지 '연속적인' 냉각을 한다. 등온 변태도는 연속적으로 냉각 상태에서는 사용이 불가 - 수정 되어야 한다.

- TTT → CCT
- 시간 지연
 - 낮은온도방향으로 shift



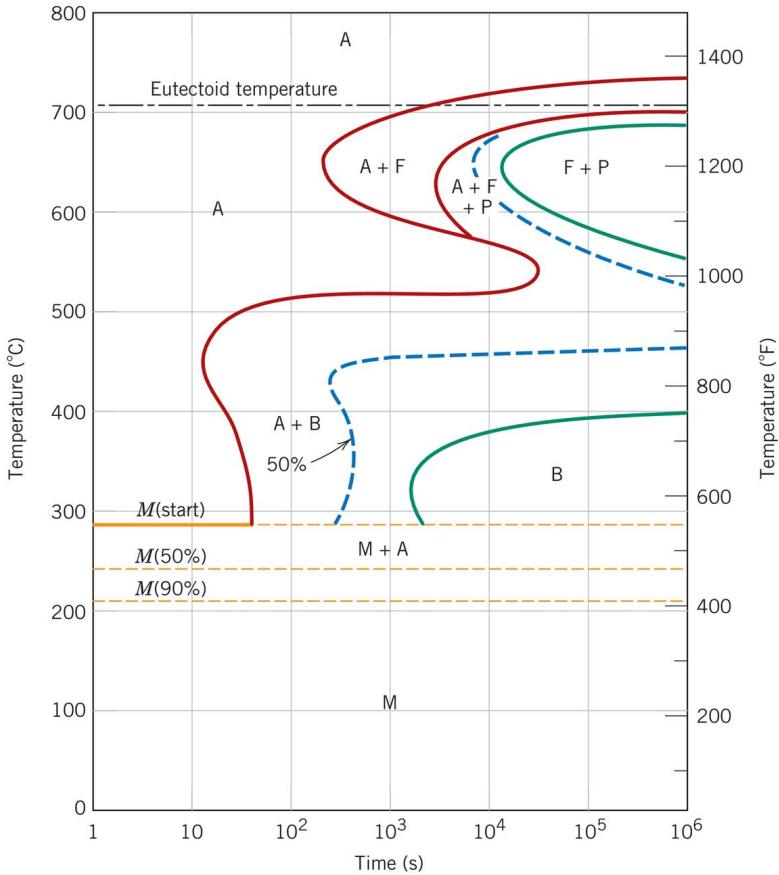
CCT



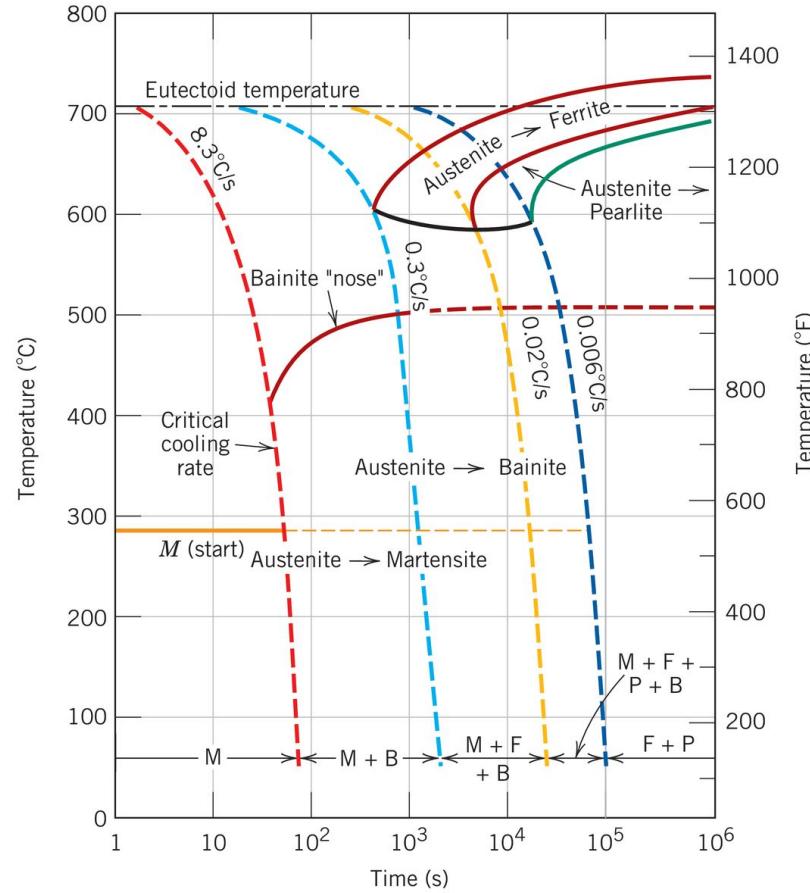
앞서, 합금원소들로 nose를 shift 할 수 있다는걸 배웠다. Nose 위치의 변화로 같은 냉각 속도라 하더라도 합금 원소의 영향으로 변태후 martensite의 양이 달라질 수 있다. (Hardenability)

Bainite는 일반적으로 등온 변태과정을 통해서만 얻어진다 – Nose에 냉각 곡선사이의 관계를 가지고 유추해보자.

TTT and CCT of 4030



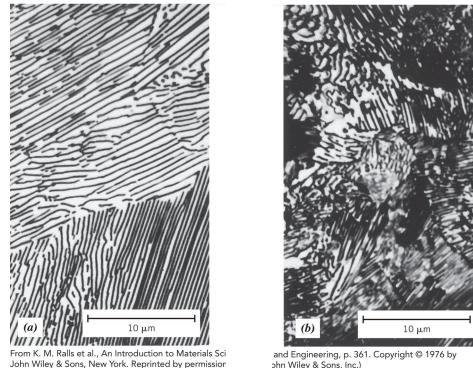
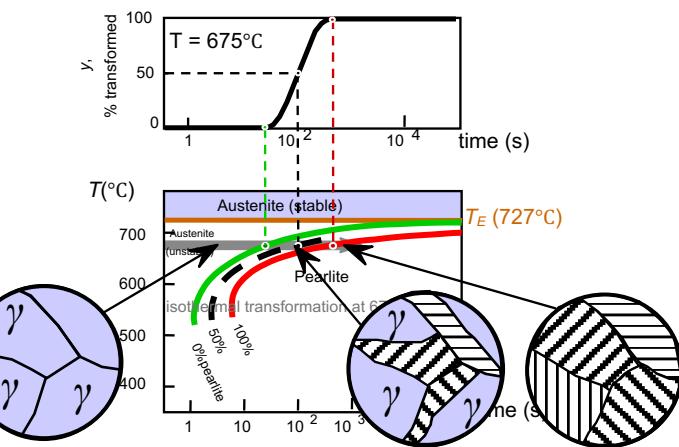
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Adapted from H. E. McGannon (Editor), *The Making, Shaping and Treating of Steel*, 9th edition, United States Steel Corporation, Pittsburgh, 1971, p. 1096.

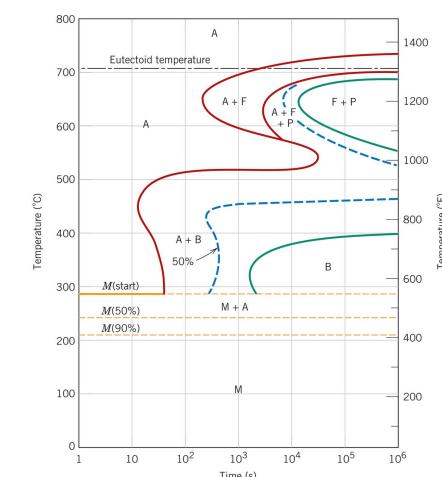
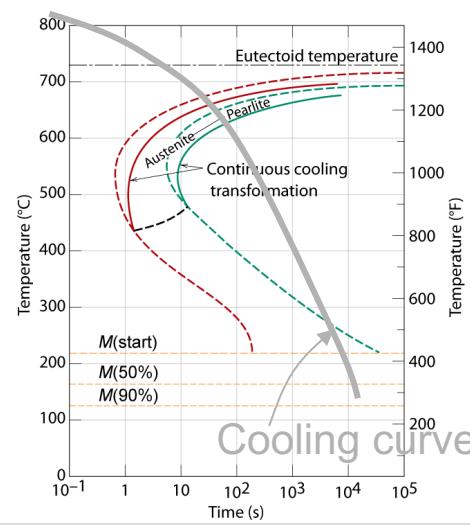
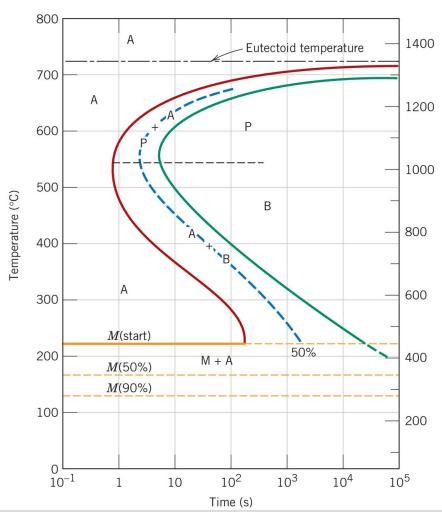
Recap

- 등온 변태도: γ -austenite \rightarrow α -Ferrite + Fe_3C eutectic reaction의 예로 살펴봄



조대
pearlite

미세
pearlite



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