

Chapter5

Phase Transformation

Part II

강의명: 기계재료공학 (MFA9009)

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HOME PAGE: [HTTP://YOUNGUNG.GITHUB.IO](http://youngung.github.io)

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

등온 변태도 - Eutectoid reaction

- Eutectoid transf. (Fe-Fe₃C system):
- For transf. to occur, must cool to below 727°C (i.e., must “undercool”)

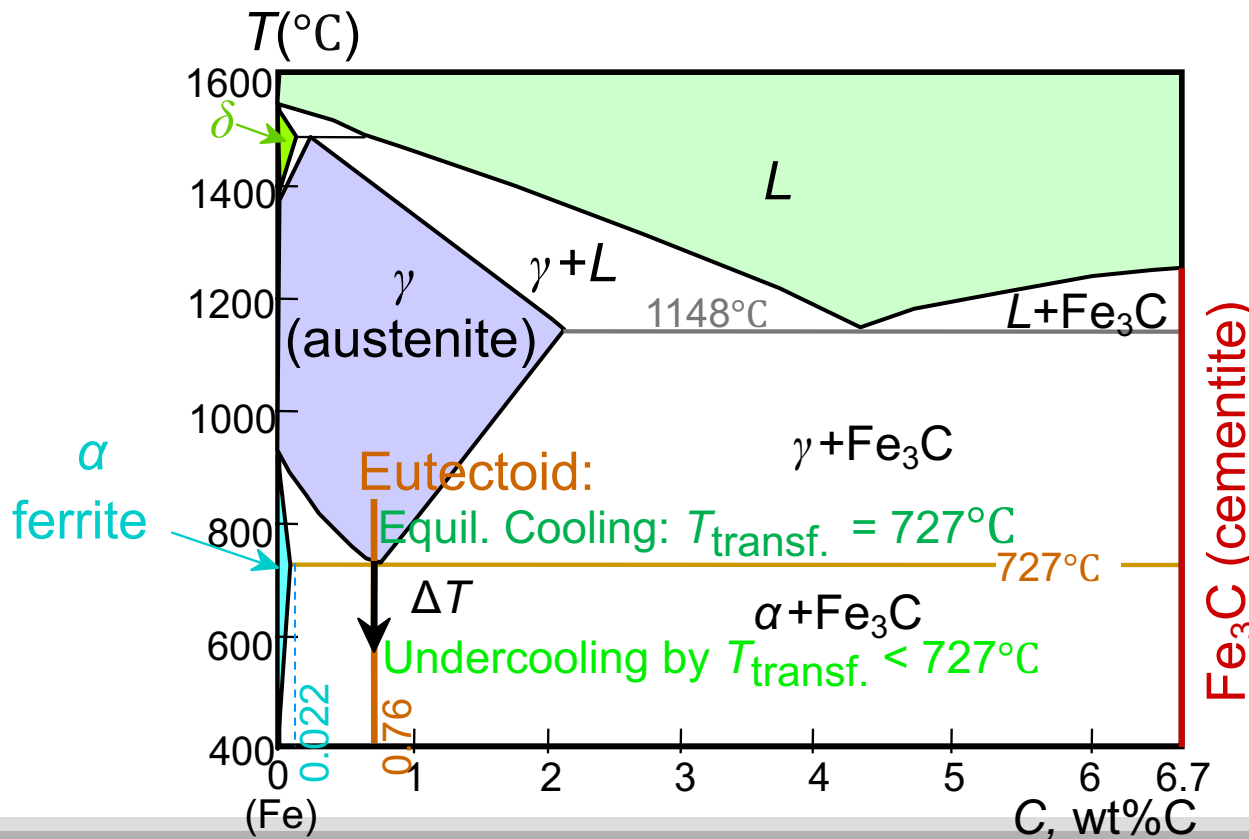
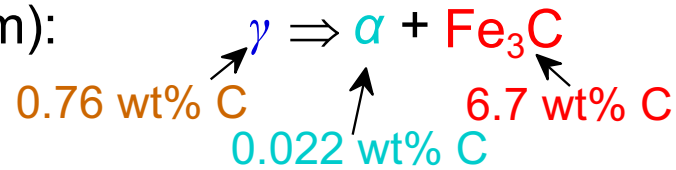
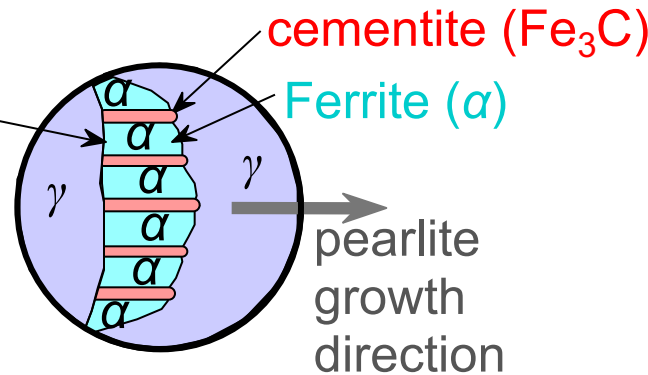


Fig. 11.23, Callister & Rethwisch 9e.
 [Adapted from Binary Alloy Phase Diagrams, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

등온 변태도 - Eutectoid reaction

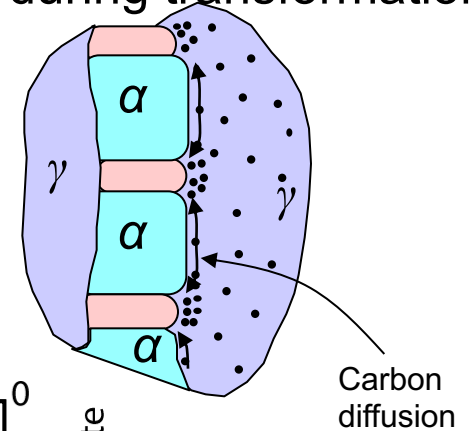
- Transformation of austenite to pearlite:

Austenite (γ)
grain
boundary



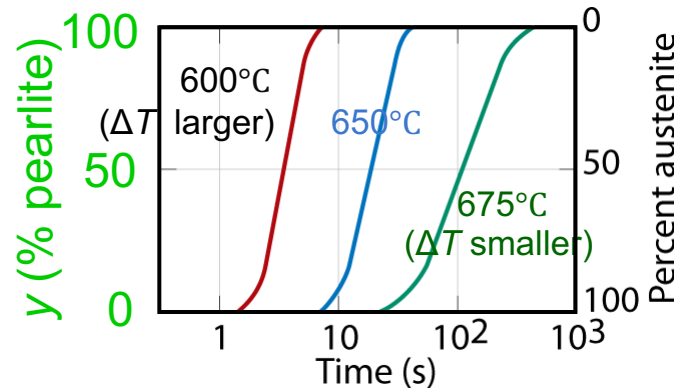
Adapted from
Fig. 11.14,
Callister &
Rethwisch 9e.

Diffusion of C
during transformation



Carbon
diffusion

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



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

Coarse pearlite → formed at higher temperatures – relatively soft

Fine pearlite → formed at lower temperatures – relatively hard

이온 변태도 - Eutectoid reaction

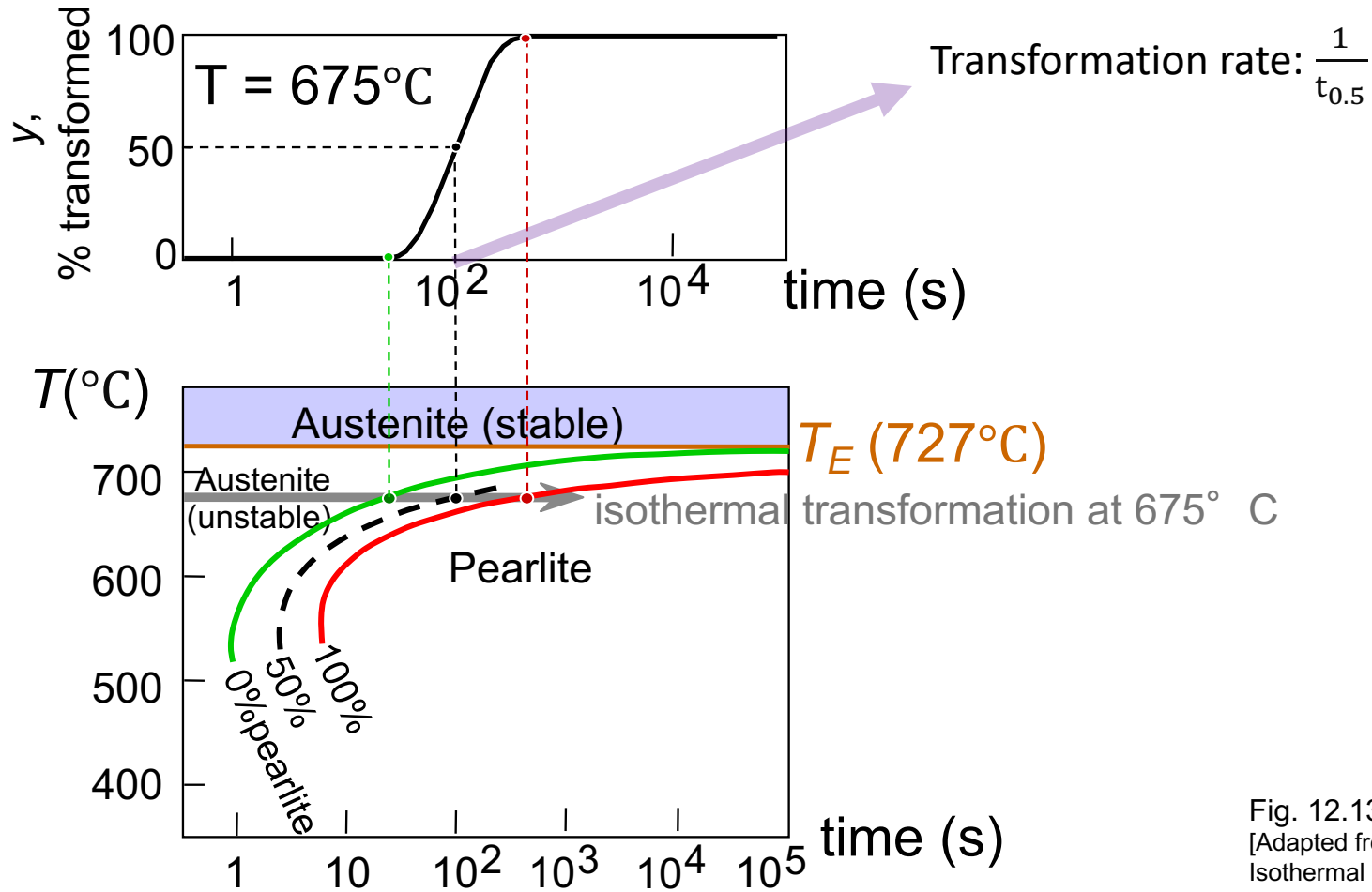


Fig. 12.13, *Callister & Rethwisch 9e*.
[Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, 1977.
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등온 변태도 - Eutectoid reaction

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

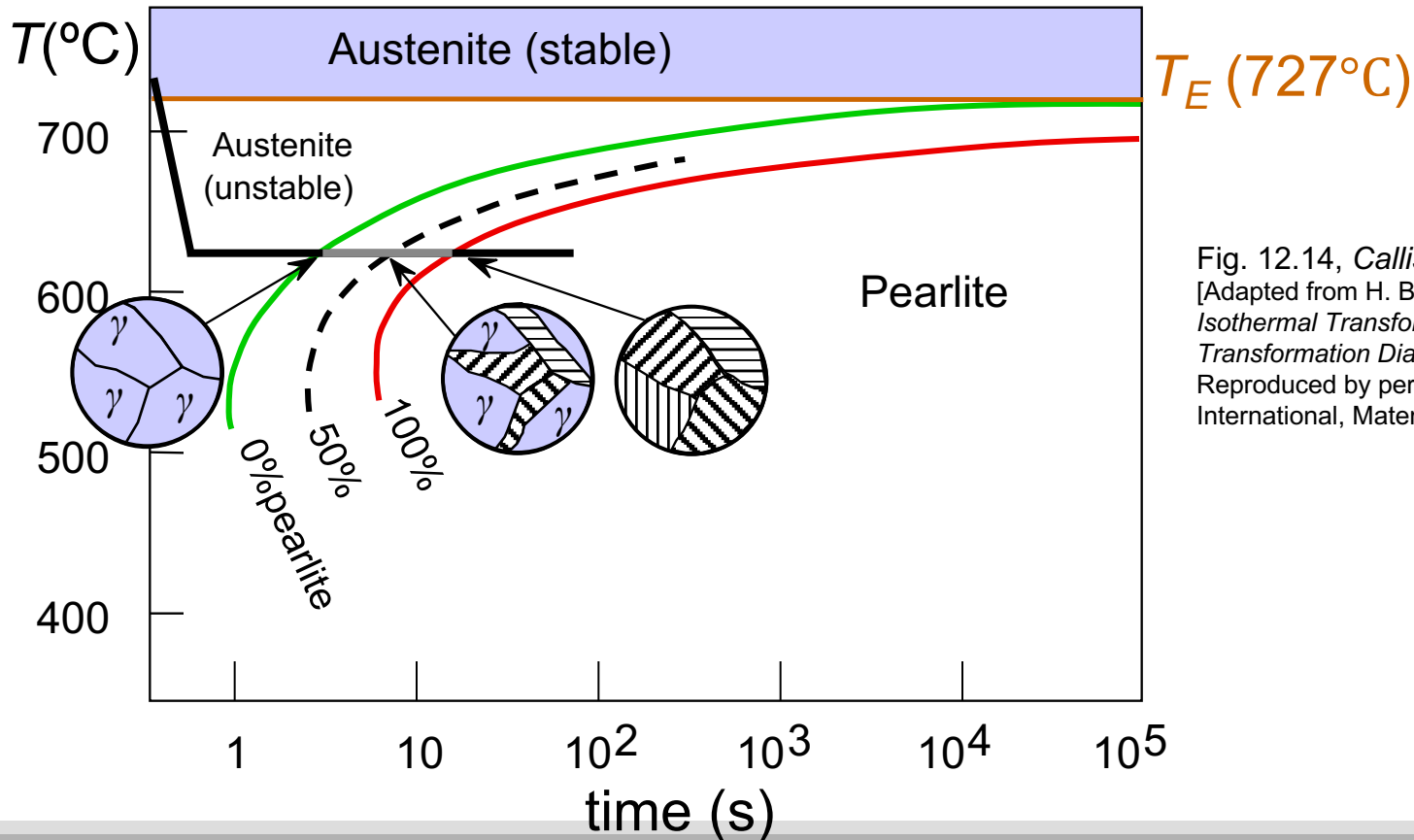
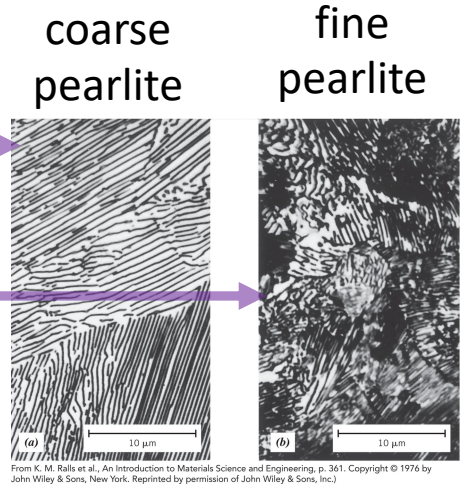
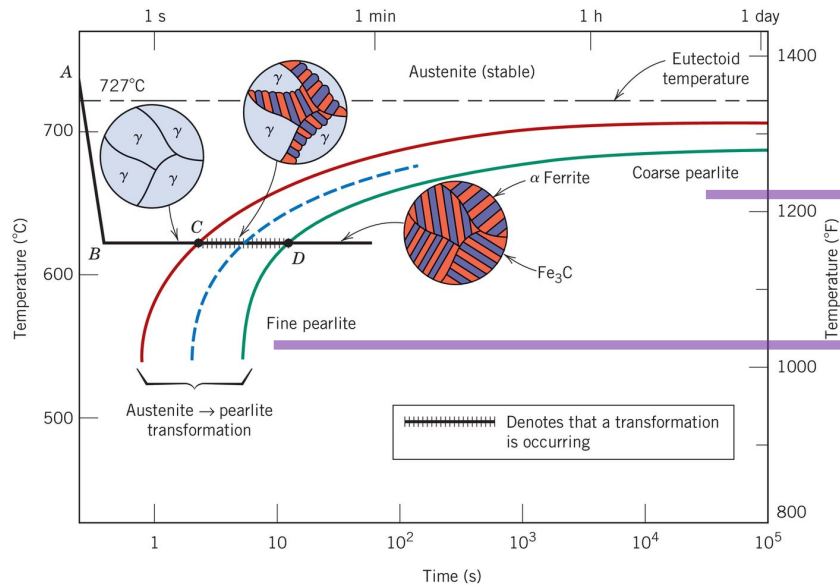
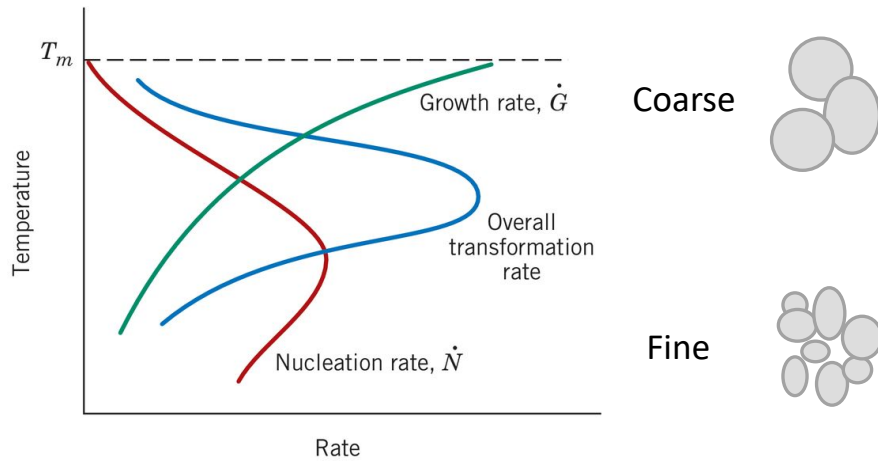


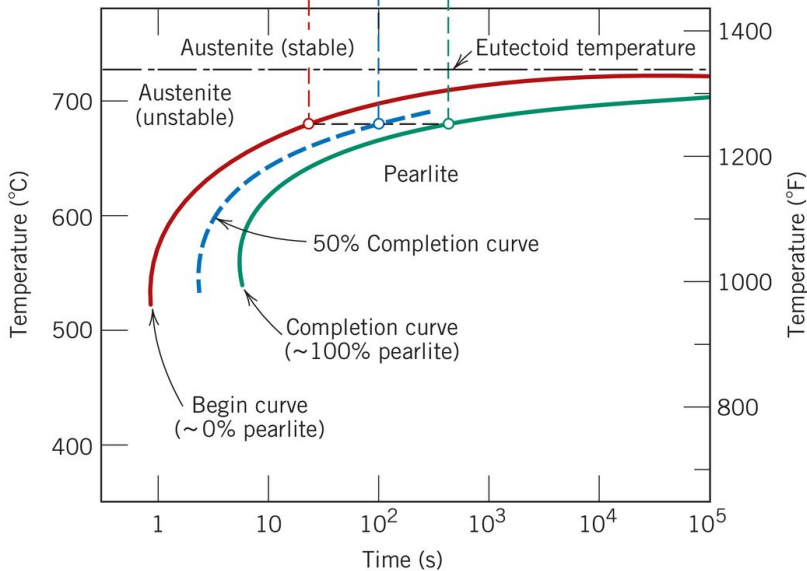
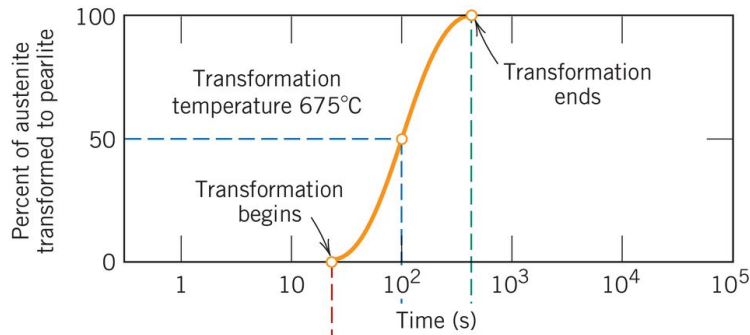
Fig. 12.14, Callister & Rethwisch 9e.
[Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, 1977.
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조대(coarse) pearlite, 미세 (fine) pearlite



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Recap: 등온 변태도



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- 원편의 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.

등온 변태도 Non-eutectoid reaction

Consider $C_0 = 1.13 \text{ wt\% C}$

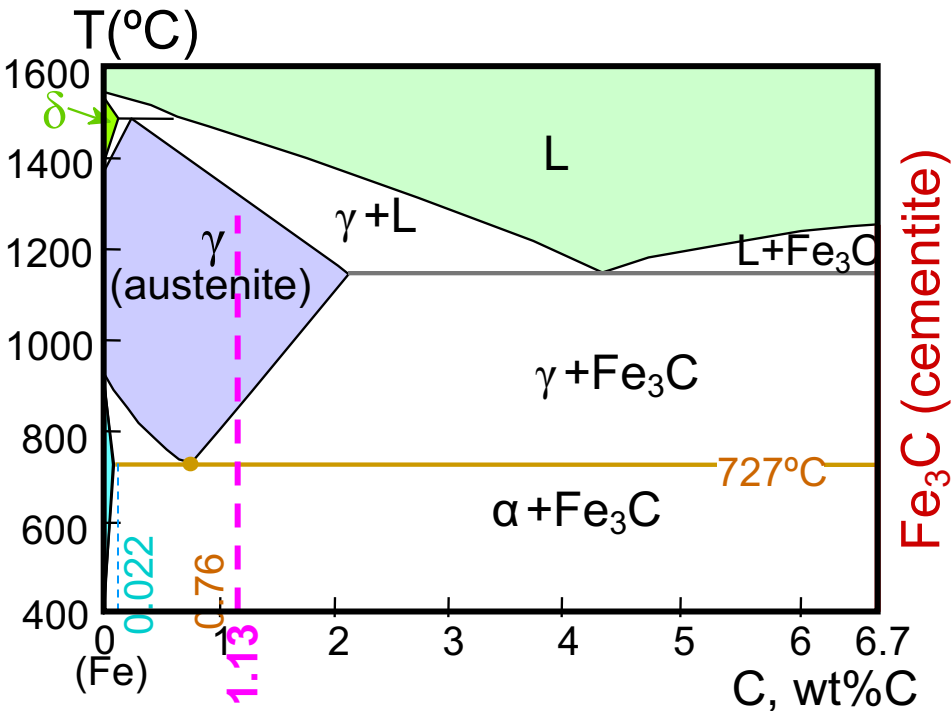


Fig. 11.23, Callister & Rethwisch 9e.
[Adapted from Binary Alloy Phase Diagrams, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

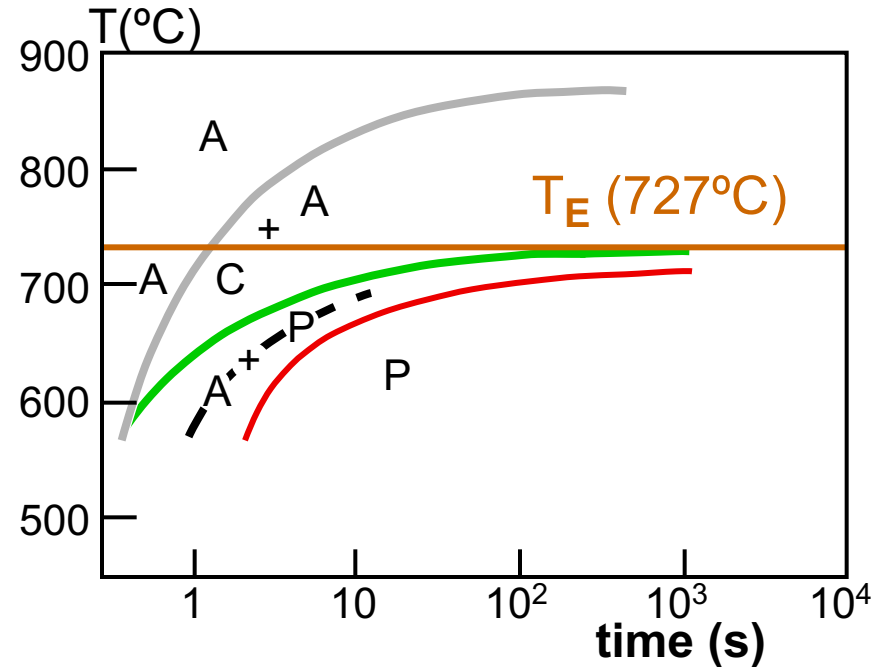
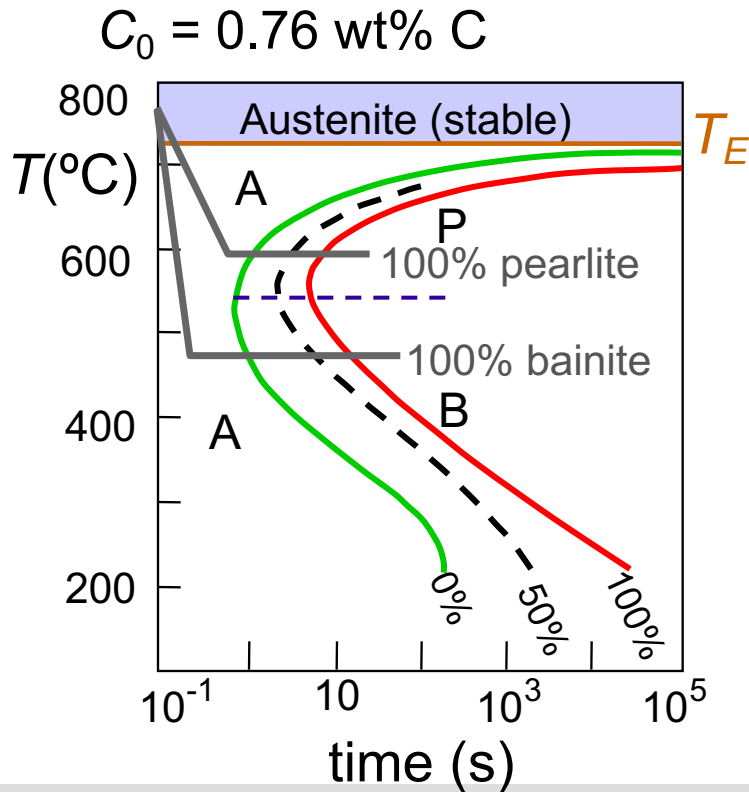


Fig. 12.16, Callister & Rethwisch 9e.
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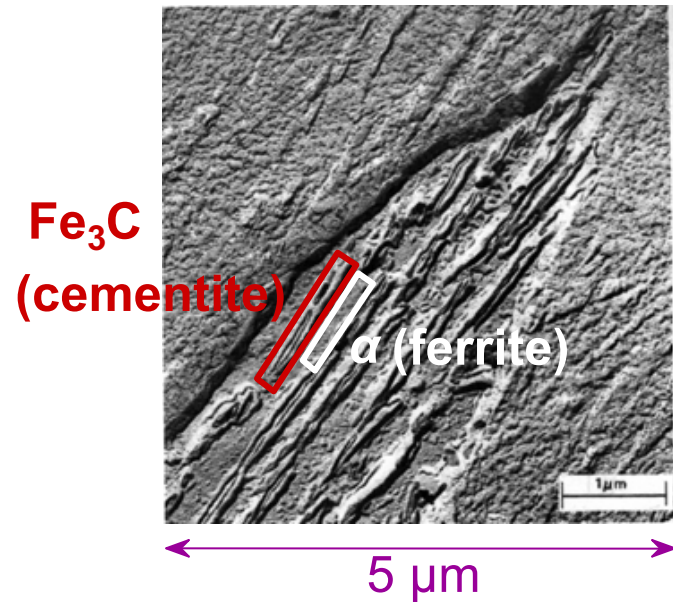
Hypereutectoid composition – proeutectoid cementite

Bainite: another Fe-Fe₃C transformation product

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

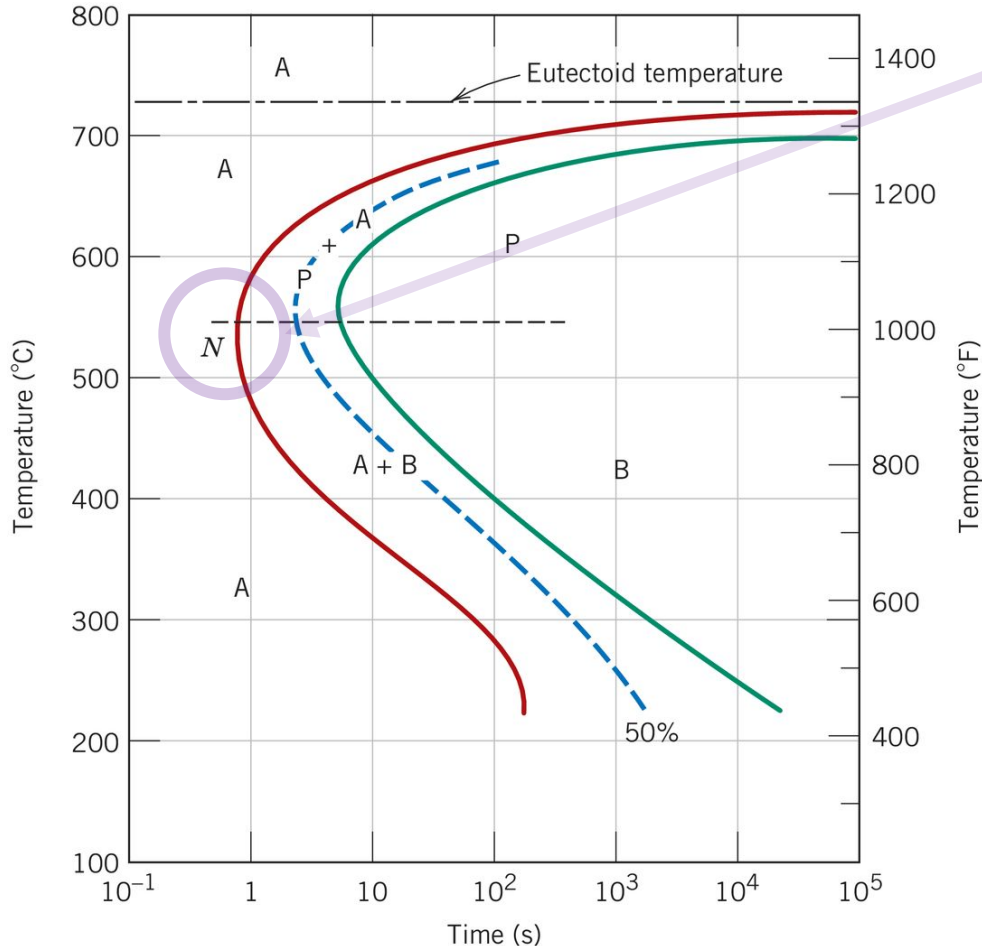


Bainite는 전자현미경으로만 분석이 가능할 정도로 미세하다.



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 particles 이 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.

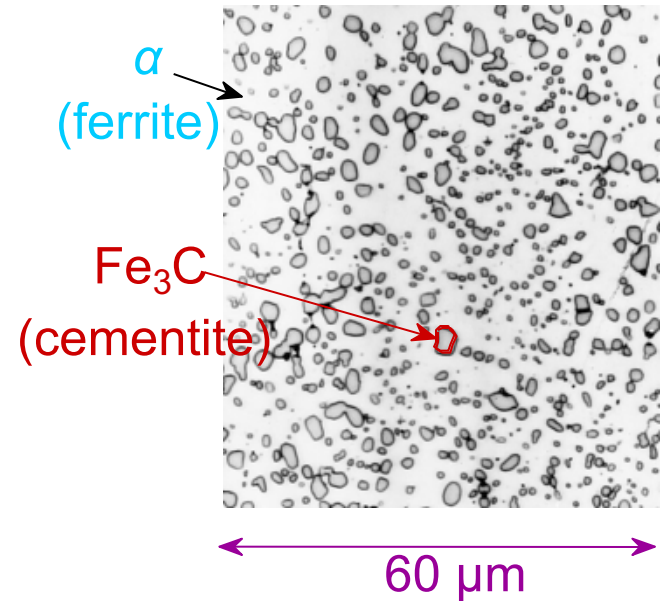
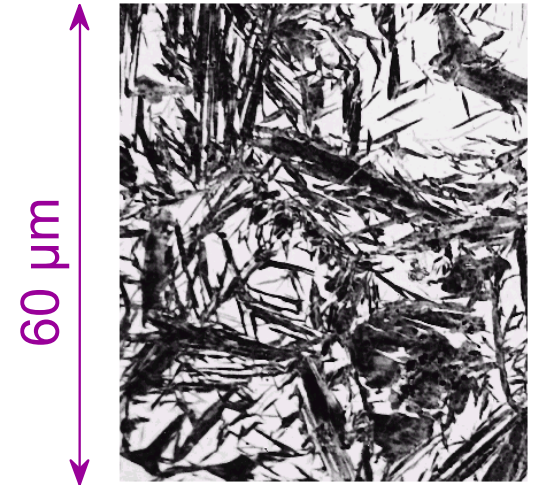
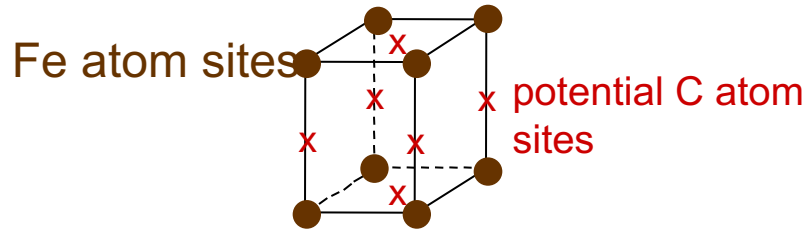


Fig. 12.19, Callister &
Rethwisch 9e.
(Copyright United States Steel
Corporation, 1971.)

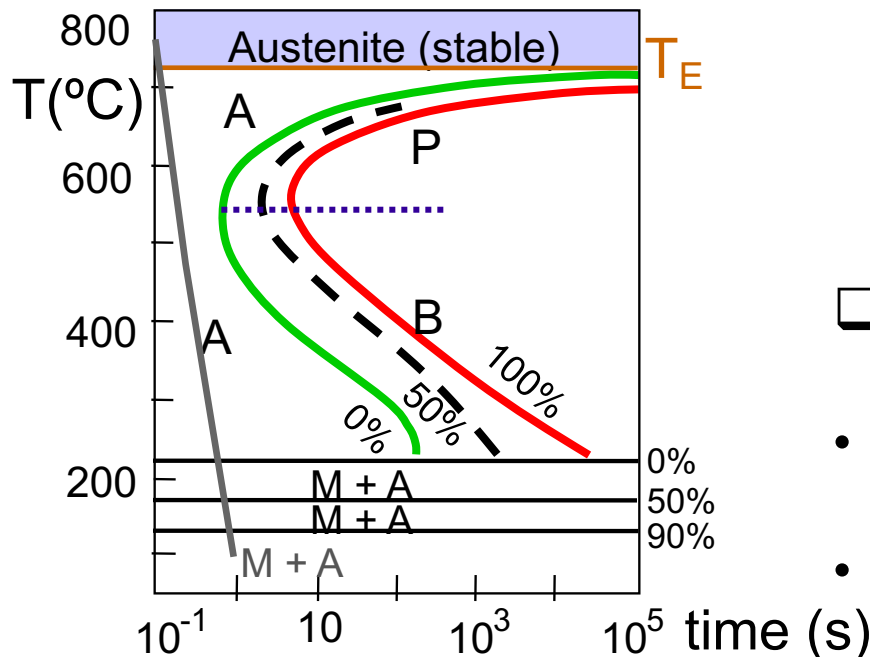
Martensite: a non-equilibrium transformation product

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



Martensite needles
 Austenite

- Isothermal Transf. Diagram

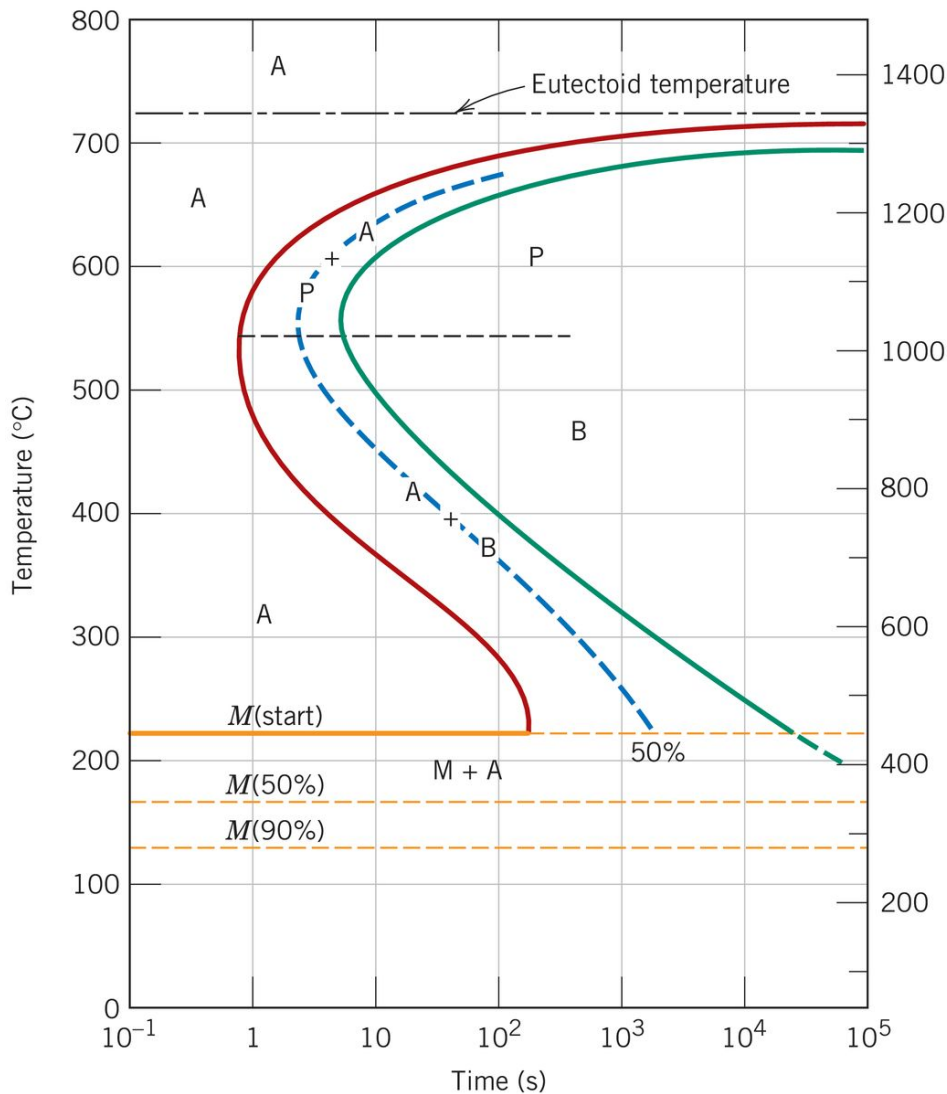


- • γ to martensite (M) transformation.
- Rapid! (**diffusionless, athermal transformation**)
- Amount of transformation depends only on T, to which γ is rapidly cooled

Quenching?



Martensite

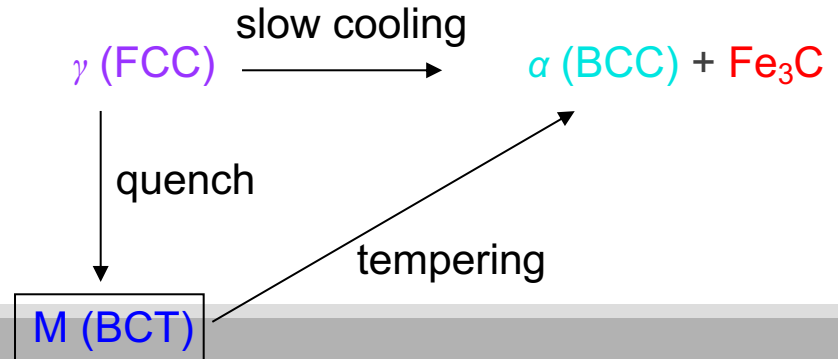


□ Martensite:

Nucleation과 diffusion이 매우 빠르게 (음속만큼 빠르게) 발생. 시간에 무관하다 - 왼편에서 수평선으로 나타난 Ms temperature를 살펴보자. Ms T.와 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:

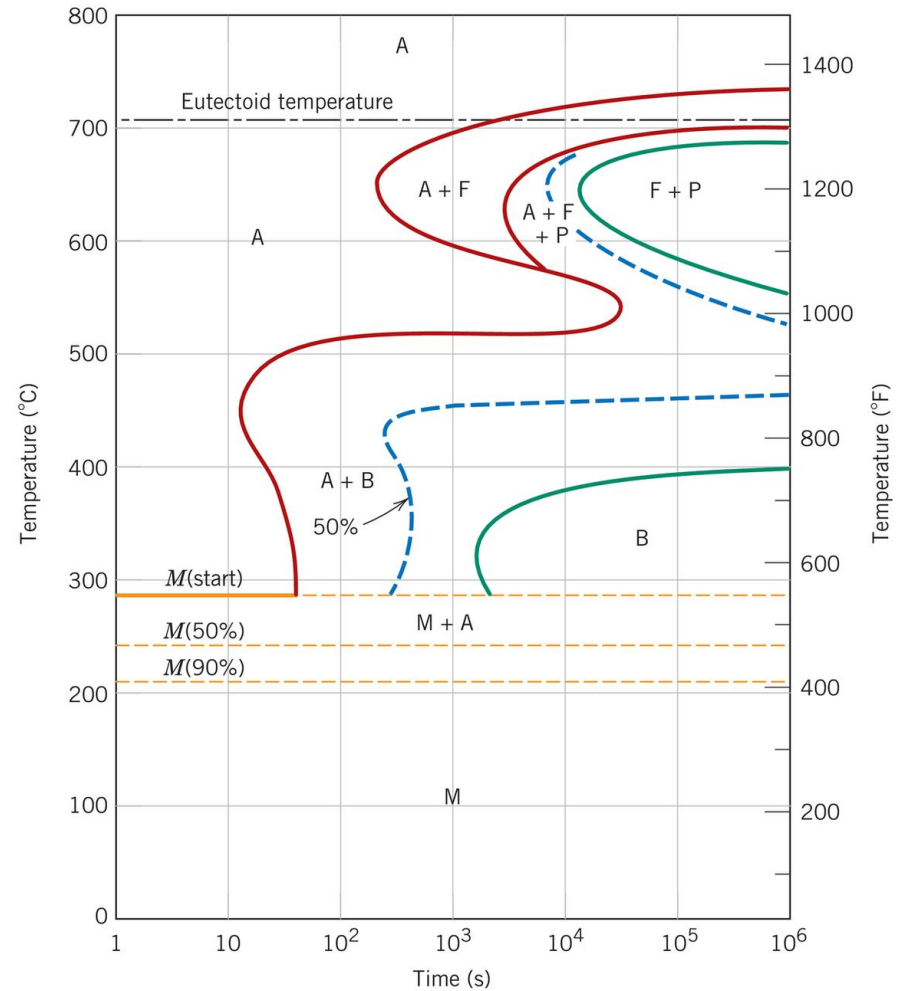
Martensite는 상온에서 평형상이 아니다. Ferrite+Fe₃C가 평형상. 하지만 상온에서 Martensite → Ferrite + Fe₃C 변태는 매우 느리다.



Alloying element의 영향

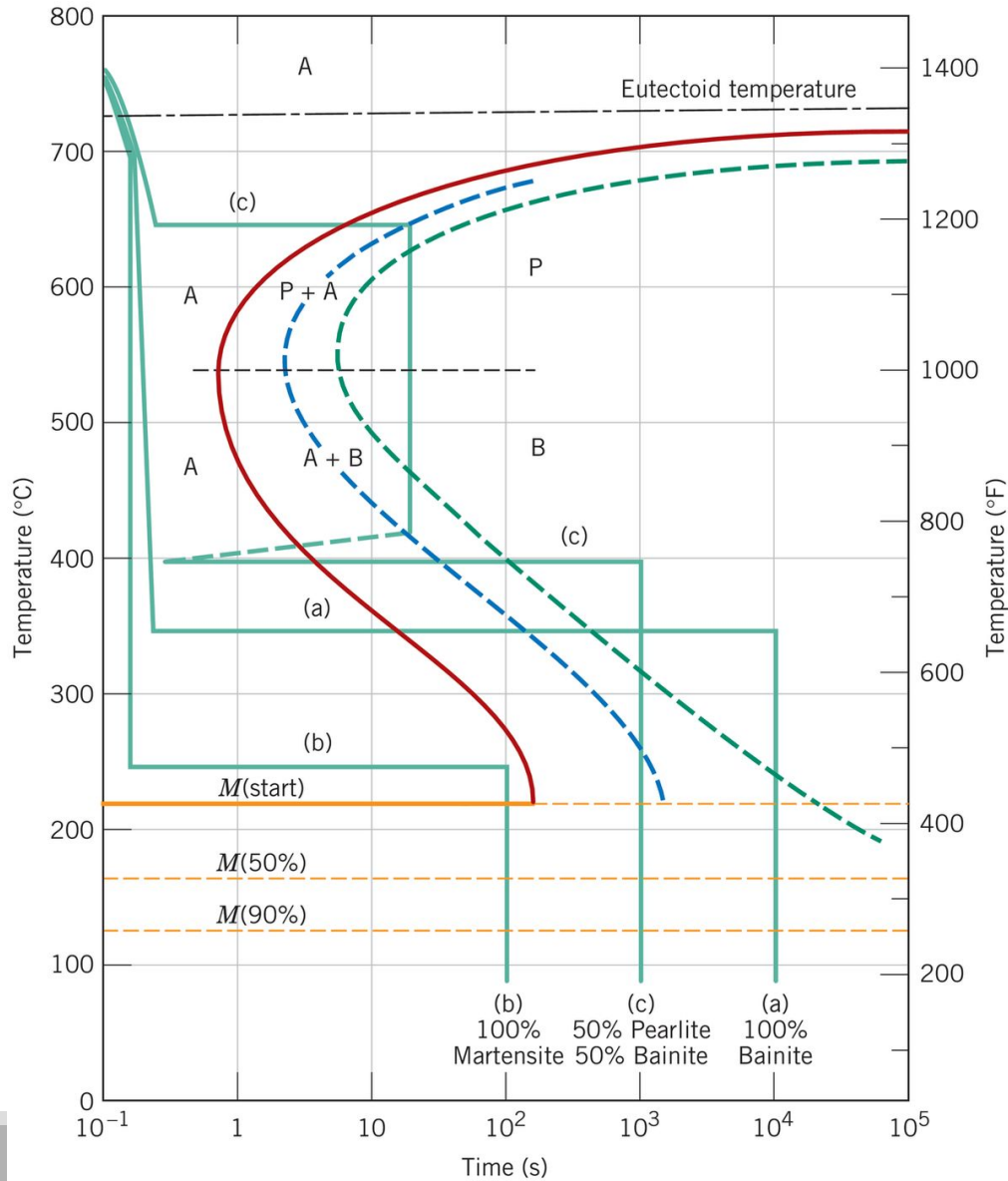
탄소 외의 다양한 합금 원소들이 변태도 내의 곡선 위치와 모양에 상당한 변화를 준다.

- Austenite vs. Bainite nose의 shift.
- Bainite nose의 분리



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Ex 12.3



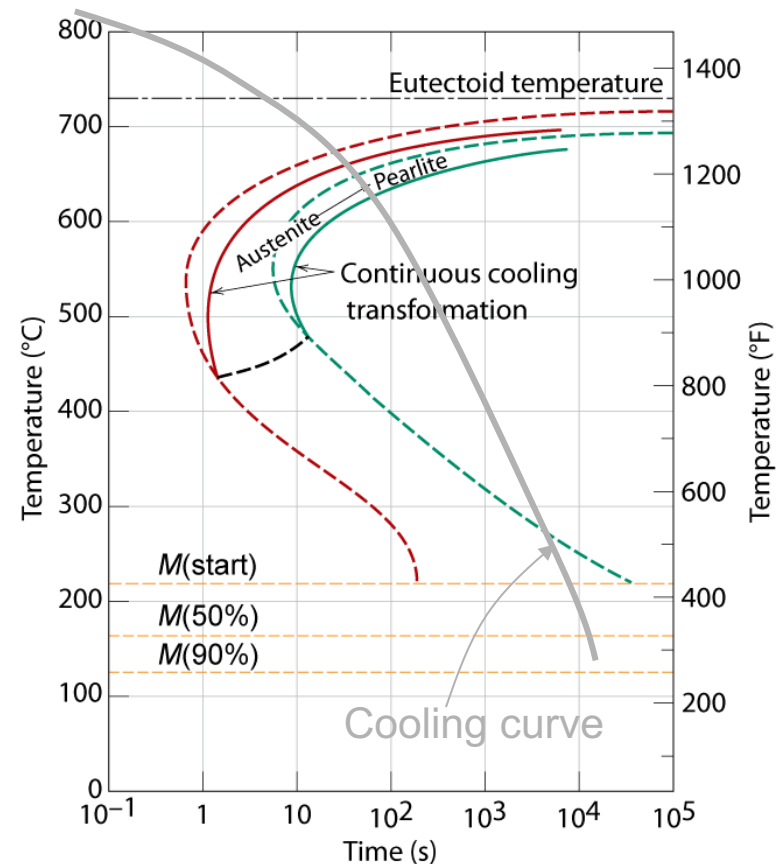
연속 냉각 변태도 (continuous cooling transformation diagrams)

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.

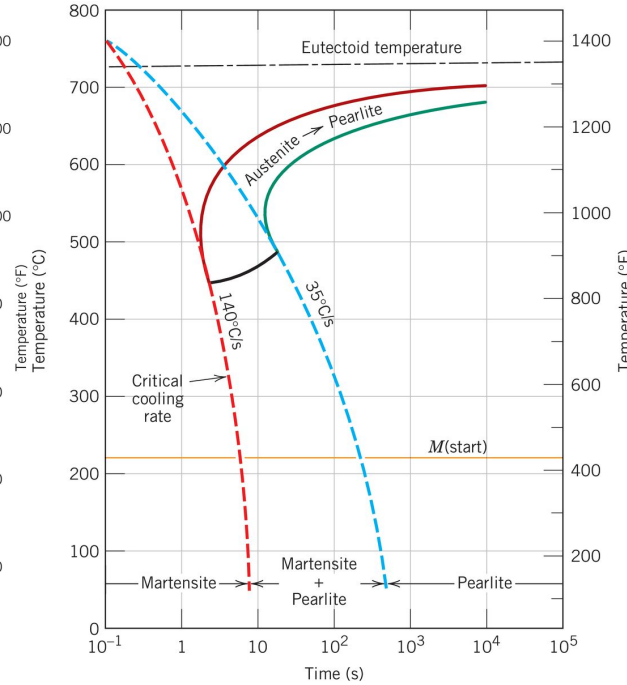
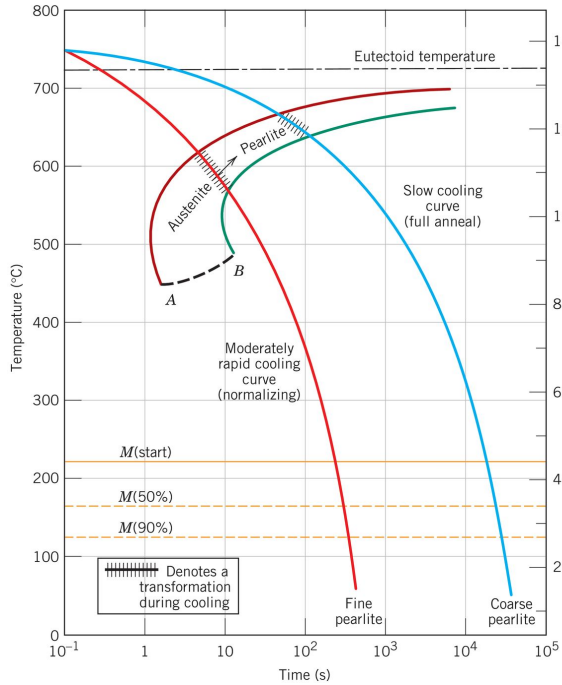
TTT → CCT

■ 시간 지연

■ 낮은 온도 방향으로 shift



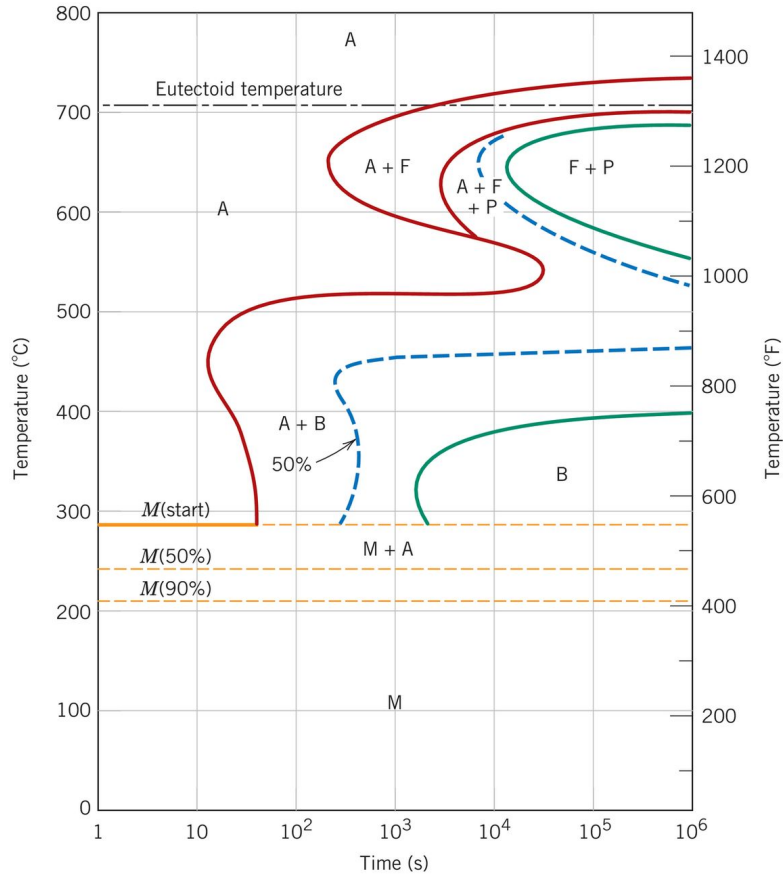
CCT



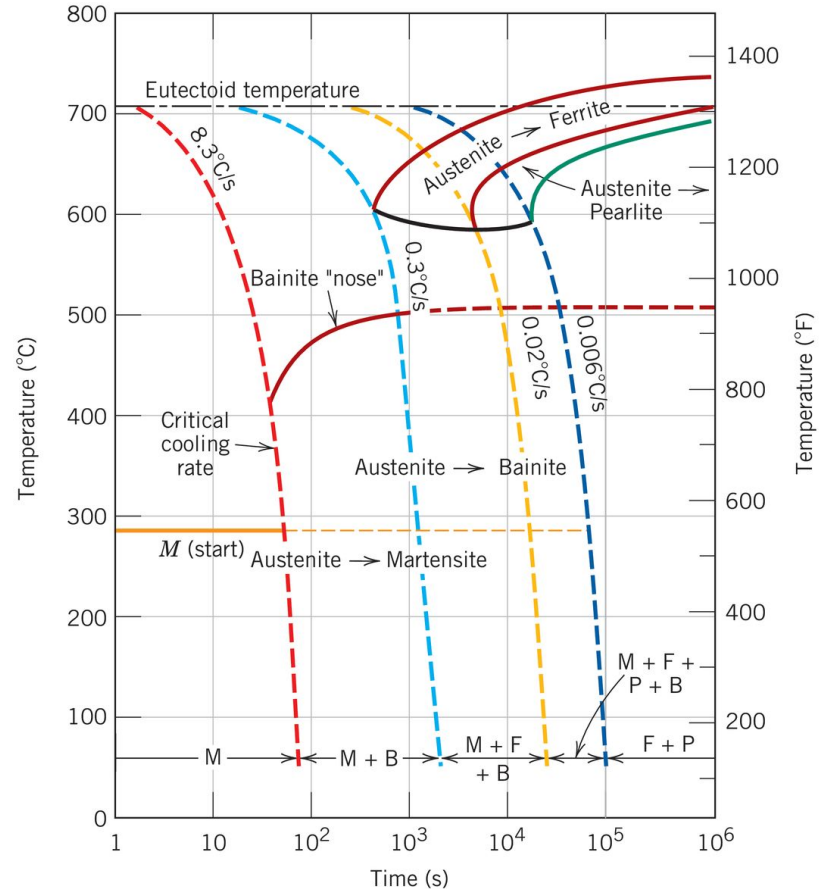
앞서, 합금원소들로 nose를 shift 할 수 있다는걸 배웠다. Nose 위치의 변화로 같은 냉각 속도라 하더라도 합금 원소의 영향으로 변태후 martensite의 량이 달라질 수 있다. (Hardenability)

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

TTT and CCT of 4030



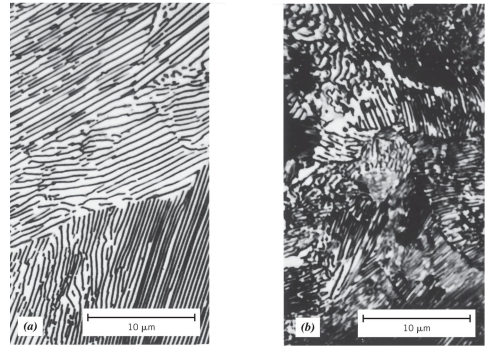
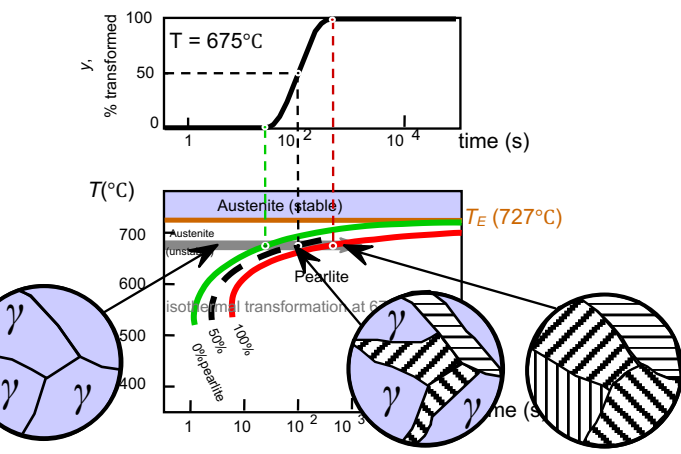
Adapted from H. Boyer (Editor), Atlas of Isothermal Transformation and Cooling Transformation Diagrams, 1977. Reproduced by permission of ASM International, Materials Park, OH.



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

Recap

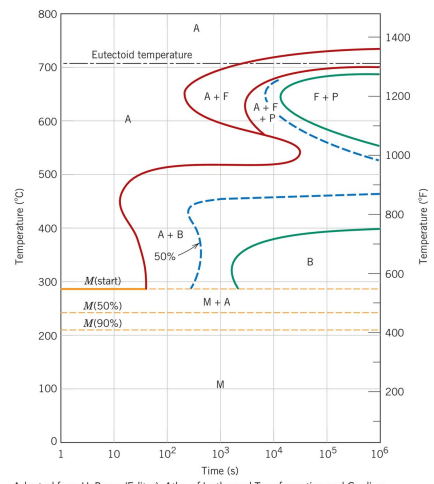
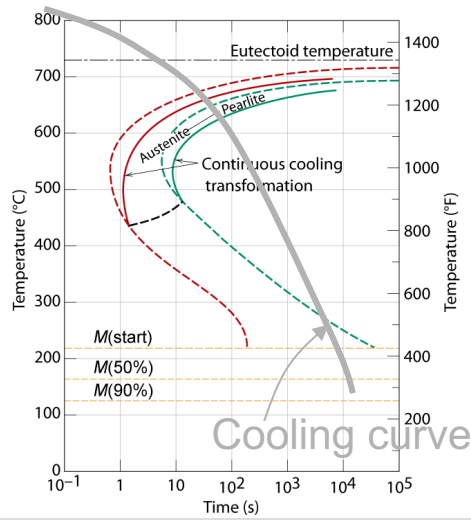
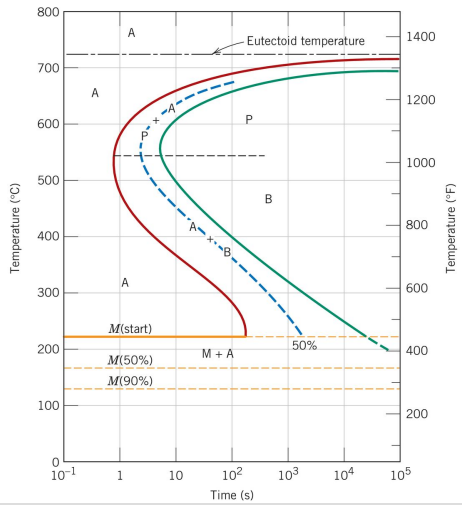
등온 변태도: γ -austenite \rightarrow α -Ferrite + Fe_3C eutectic reaction의 예로 살펴봄



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

조대 pearlite

미세 pearlite



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