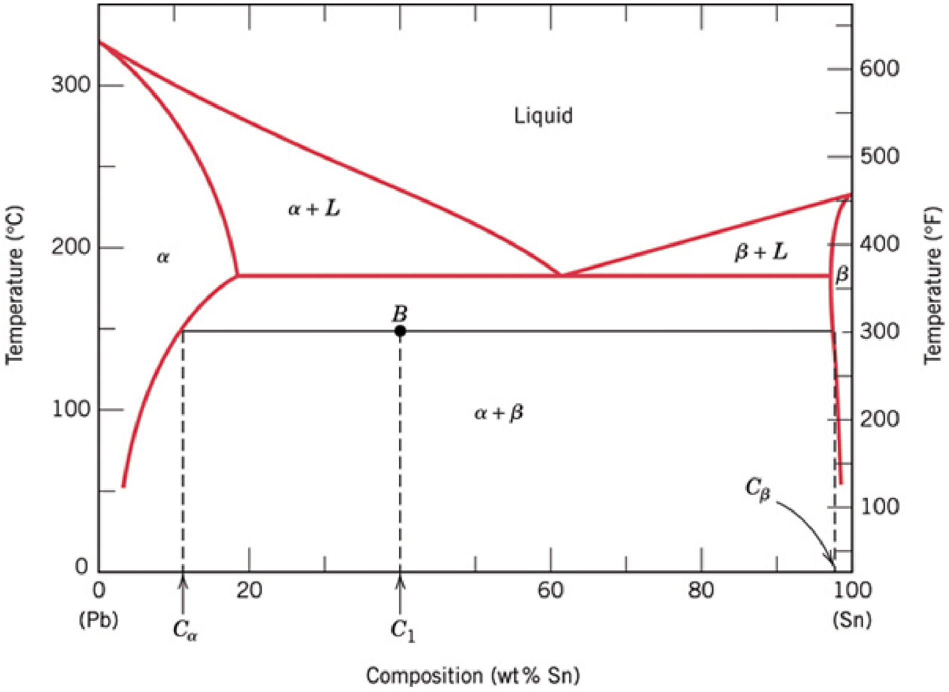
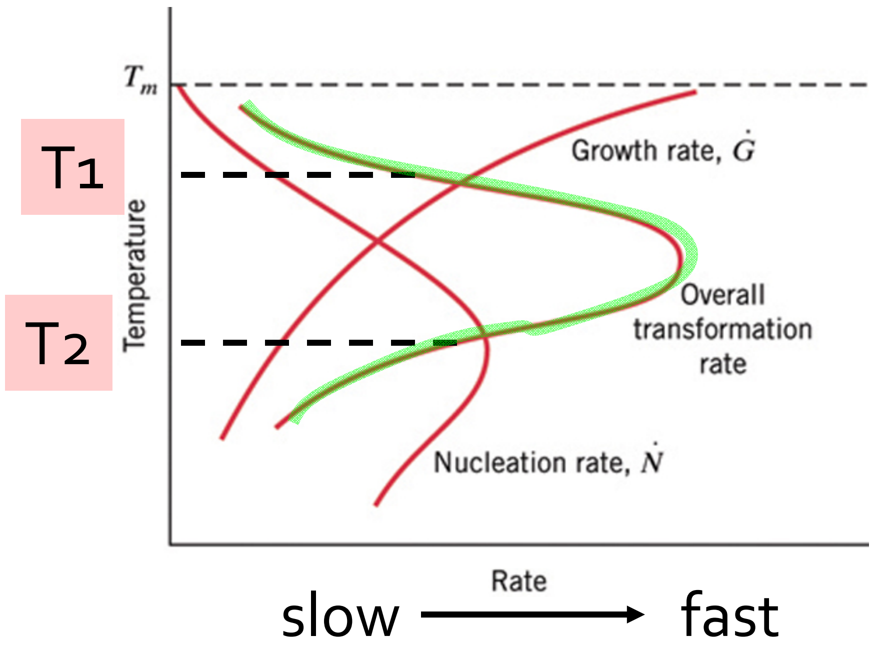
Chapter 11
Phase Transformations
Time Temperature Transformations
Continuous Cooling Transformations
Precipitation Hardening

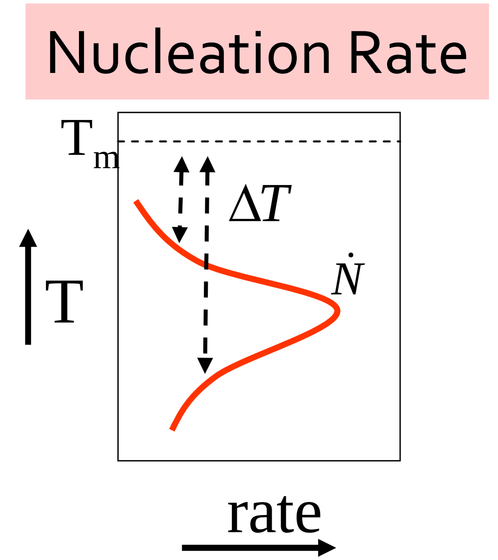
Chapter 11 – Phase Transformations

- Phase Diagram tells us….?
- Solid state transformations - diffusion dependent. (T and t)
- Phase transformation study allows prediction of reasonably attainable microstructure
  - Properties depend on microstructure



Phase transformation rate - Temperature dependence





Why this shape?

Final Microstructure depends on T of transformation

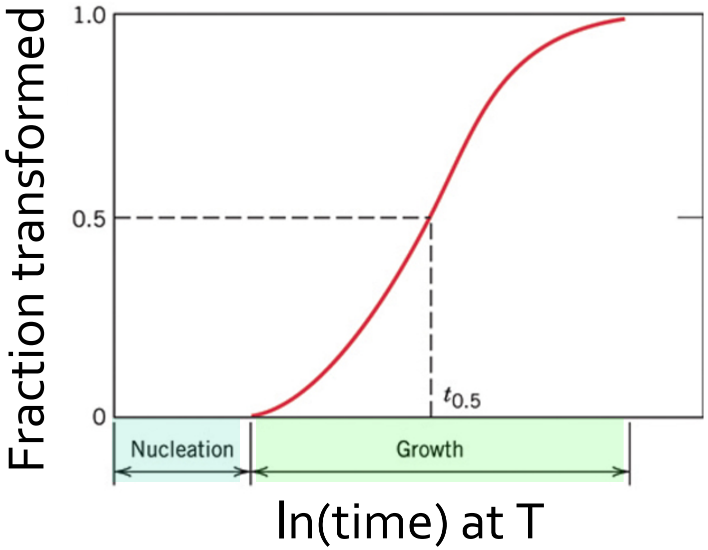
1. Solidification
2. Solid state precipitation

When is transformation complete?

When does transformation stop?

Rate vs. % transformed

Phase transformation rate - Time dependence (kinetics)



Transformation rate changes over time – driving force diminishes

Why? - Consider case of precipitation of 2nd phase from solid solution

Curve described by Avrami eqn.

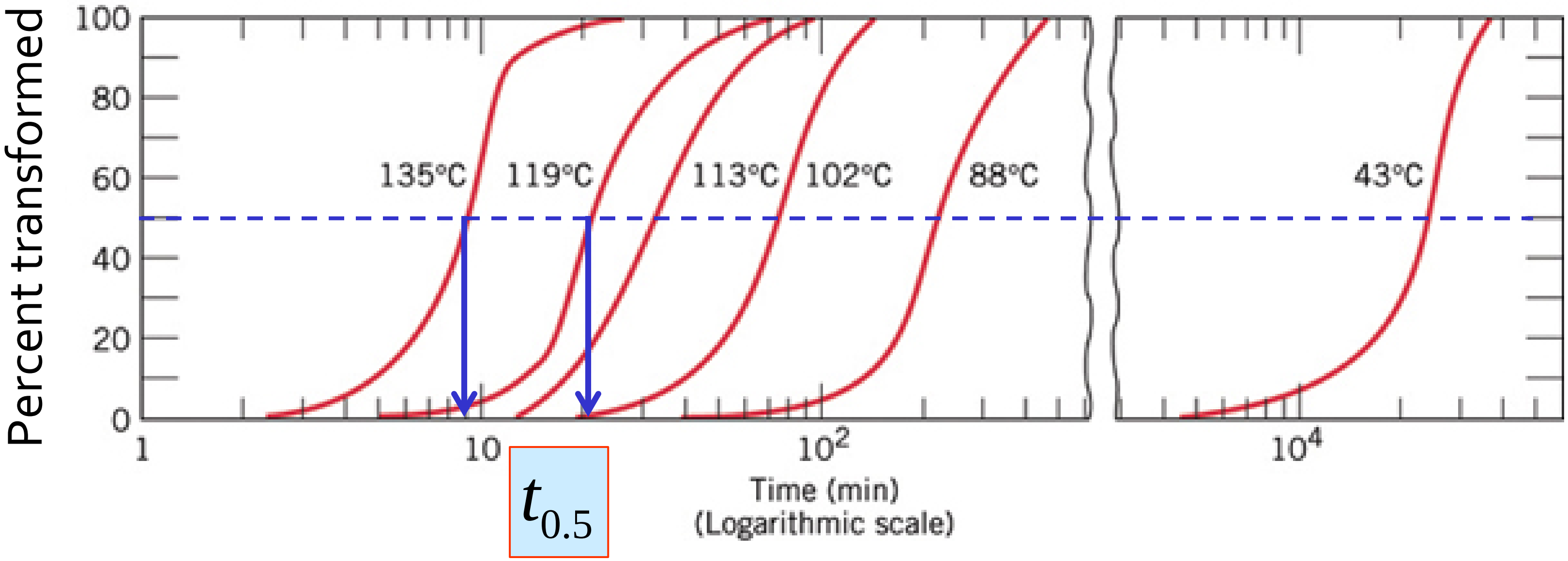
$$y = 1 - \exp(-kt^n)$$

k and *n* are constant for given T and transformation

By Definition:
Transformation rate

$$\frac{1}{t_{0.5}}$$

Transformation rate: Time and Temp effect



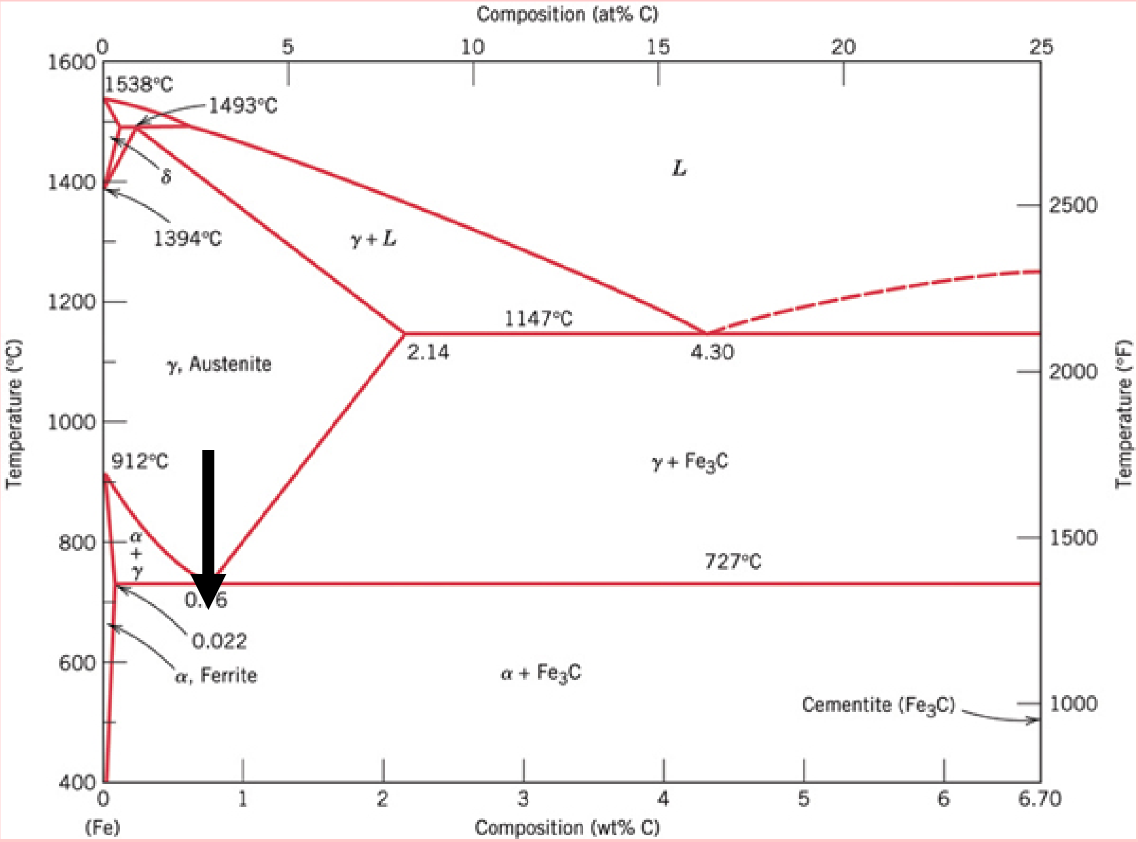
Transformation rate = $\dfrac{1}{t_{0.5}}$

Temp(°C)	Transformation rate (min^{-1})
135	1/9
88	1/210

Fe-C TTT diagrams

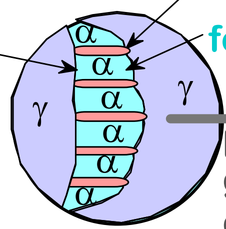
TRANSFORMATIONS & UNDERCOOLING

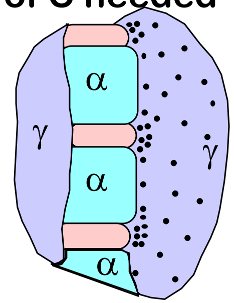
- **Eutectoid transf. (Fe-C System):** $\gamma \Rightarrow \alpha + Fe_3C$
  - 0.77wt%C (γ), 0.022wt%C (α), 6.7wt%C (Fe_3C)
- **Can make it occur at:**
  - **...727°C (cool it slowly)**
  - **...below 727°C ("undercool" it!)**

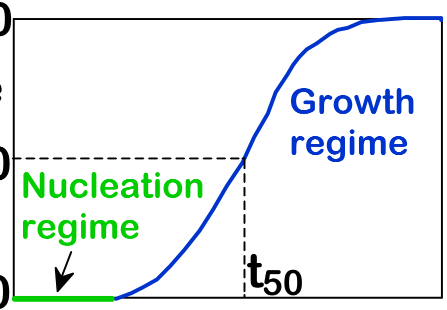


EUTECTOID TRANSFORMATION RATE ~ ΔT

- **Growth of pearlite from austenite:**





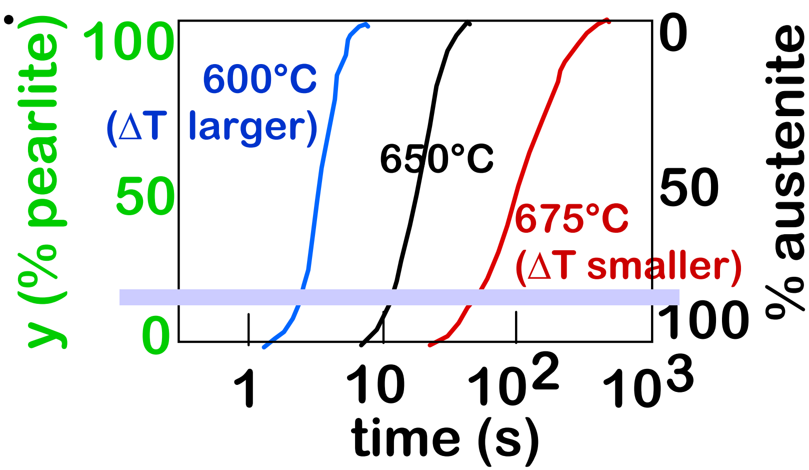


at given temp, T_1

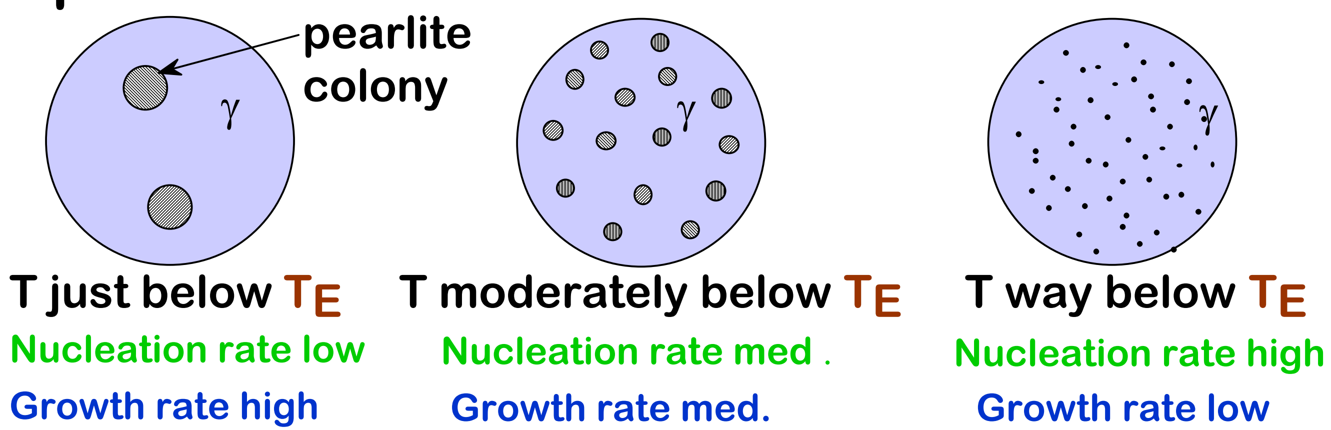
Adapted from Fig. 10.3, *Callister 6e.*

NUCLEATION AND GROWTH

- **Reaction rate is a result of nucleation and growth of crystals.**



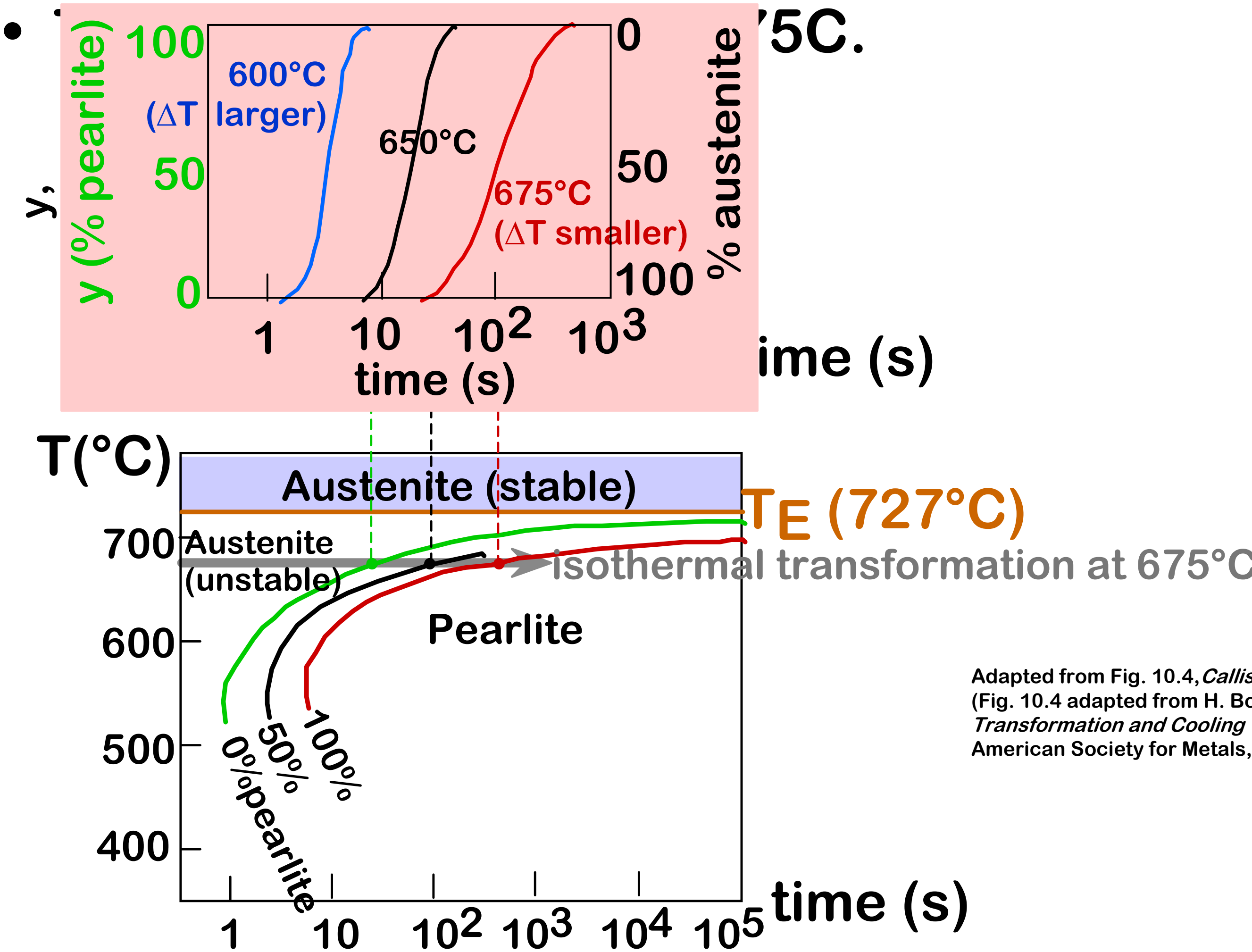
- **Examples:**



At 15% transformed.

ISOTHERMAL TRANSFORMATION DIAGRAMS

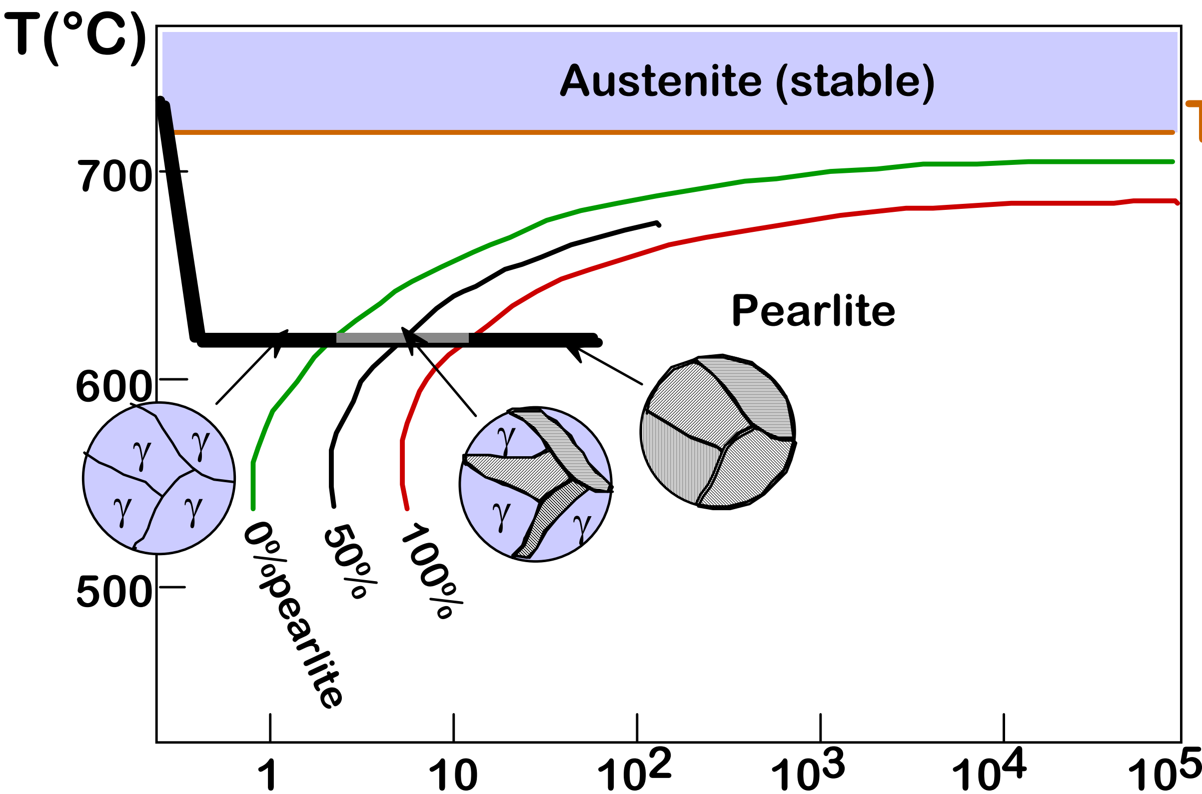
- Fe-C system, $C_o = 0.77wt\%C$
- T[illegible] 75C.



Adapted from Fig. 10.4, *Callister 6e*.
(Fig. 10.4 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1977, p. 369.)

EX: COOLING HISTORY Fe-C SYSTEM

- **Eutectoid composition, C_o = 0.77wt%C**
- **Begin at T > 727C**
- **Rapidly cool to 625C and hold isothermally.**

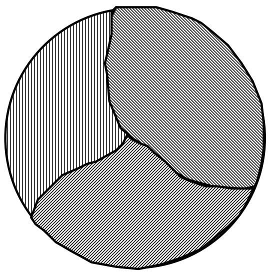


Adapted from Fig. 10.5, *Callister 6e*. (Fig. 10.5 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1997, p. 28.)

PEARLITE MORPHOLOGY

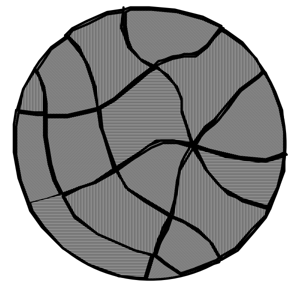
Two cases:

- **T_{transf} just below T_E**



- Smaller ΔT: colonies are larger

- **T_{transf} well below T_E**



- Larger ΔT: colonies are smaller

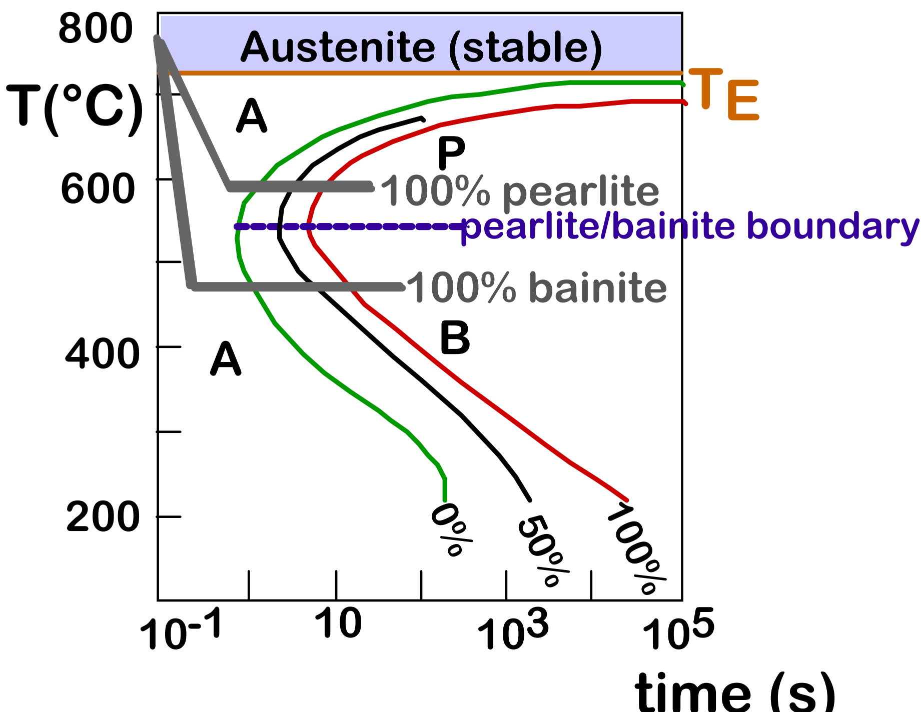
HigherT: diffusion is faster
Pearlite is coarser ← interface energy → Pearlite is finer.

Lower T: diffusion is slower

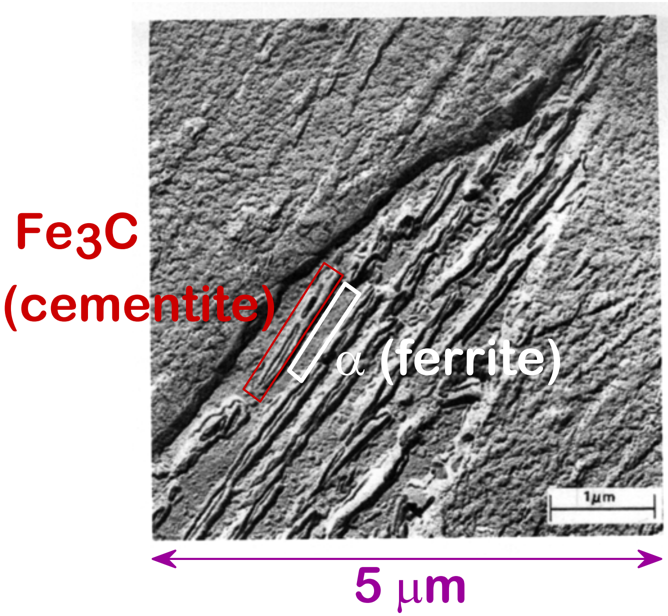
10μm

OTHER TRANSFORMATION PRODUCTS: Fe-C

- **Bainite:**
  - **--α lathes (strips) with long rods of Fe_3C**
  - **--diffusion controlled.**
- **Isothermal Transf. Diagram**



Adapted from Fig. 10.9, *Callister 6e.*
(Fig. 10.9 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1997, p. 28.)

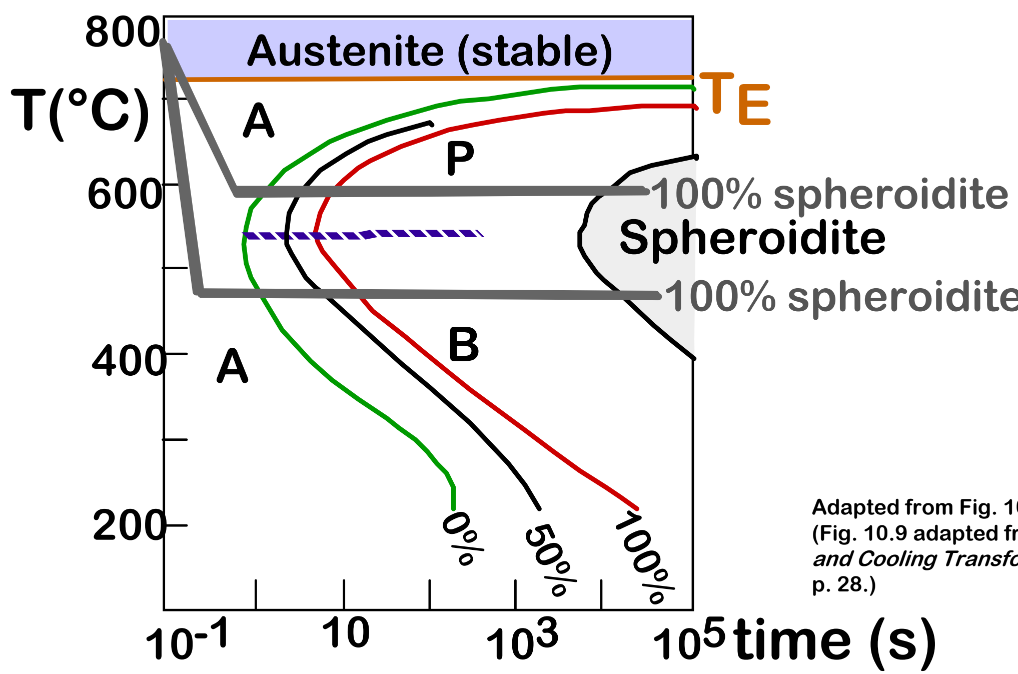


(Adapted from Fig. 10.8, *Callister, 6e*. (Fig. 10.8 from *Metals Handbook*, 8th ed.,
Vol. 8, *Metallography, Structures, and Phase Diagrams*,
American Society for Metals, Materials Park, OH, 1973.)

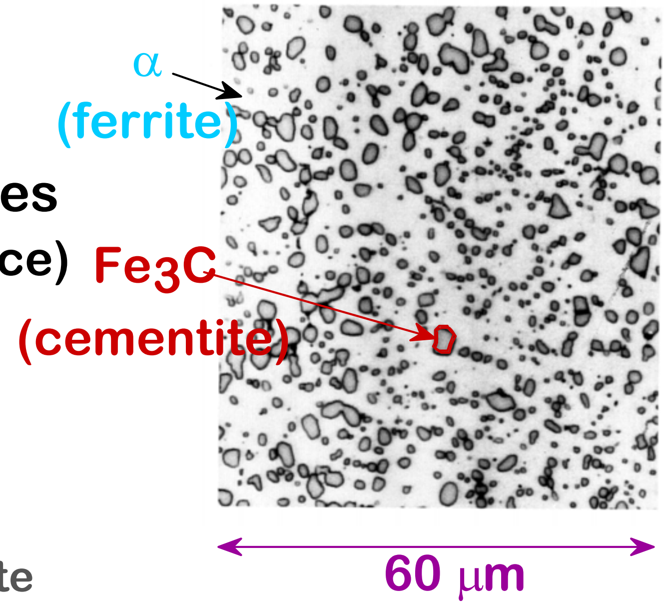
Micrograph scale difference

Fe-C SYSTEM - Spheroidite

- **Spheroidite:**
  - **--α crystals with spherical Fe_3C**
  - **--diffusion dependent.**
  - **--heat bainite or pearlite for long times**
  - **--reduces interfacial area (driving force)**
- **Isothermal Transf. Diagram**



Adapted from Fig. 10.9, *Callister 6e.*
(Fig. 10.9 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1997, p. 28.)

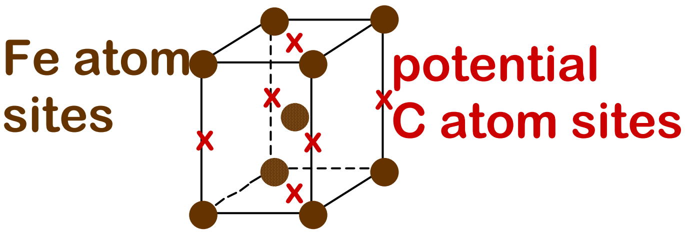


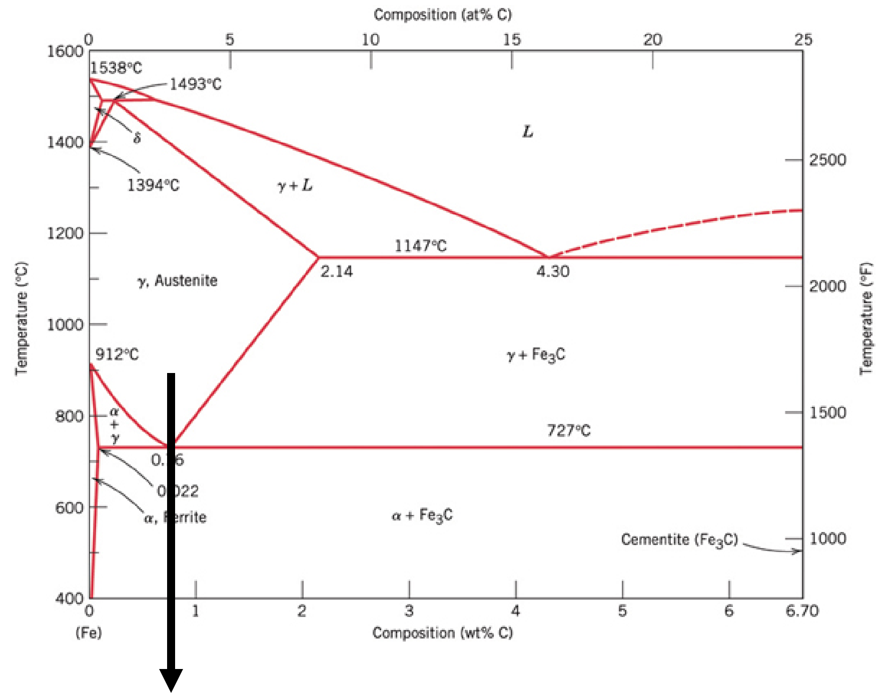
(Adapted from Fig. 10.10, *Callister, 6e.* (Fig. 10.10 copyright United States Steel Corporation, 1971.)

Fe-C SYSTEM: Martensitic transformation

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

(involves single atom jumps)





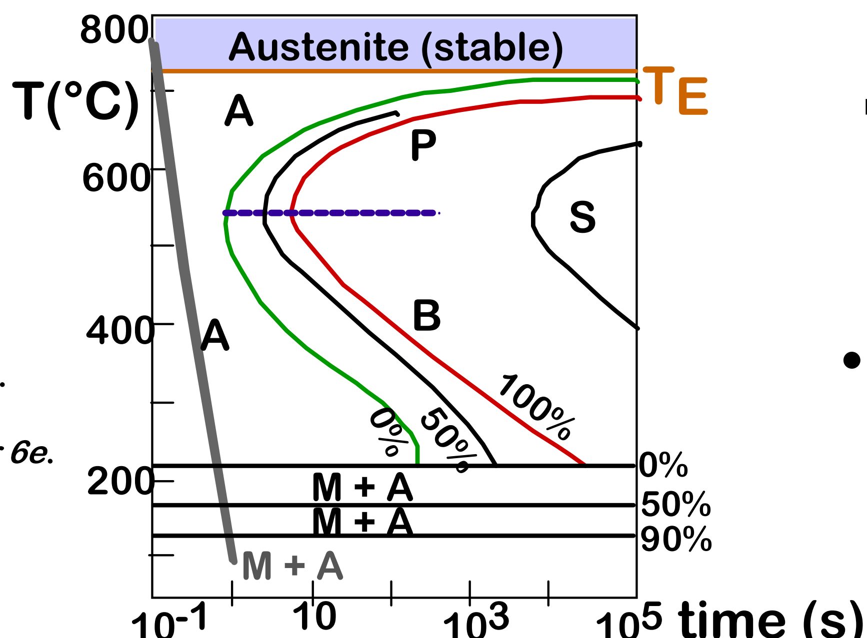
- Occurs when Austenite rapidly cooled to room temp.
- Supersaturated solid solution
  - C stays in interstitial sites
  - No diffusion during transformation
  - Very unstable

Unique properties – very brittle

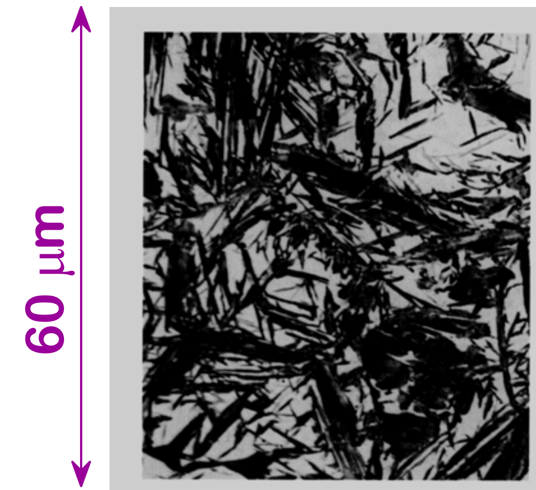
Fe-C SYSTEM - Martensite

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

- **Isothermal Transf. Diagram**



Adapted from Fig. 10.13, *Callister 6e.*



Martentite needles
Austenite

(Adapted from Fig. 10.12, *Callister, 6e*. (Fig. 10.12 courtesy United States Steel Corporation.)

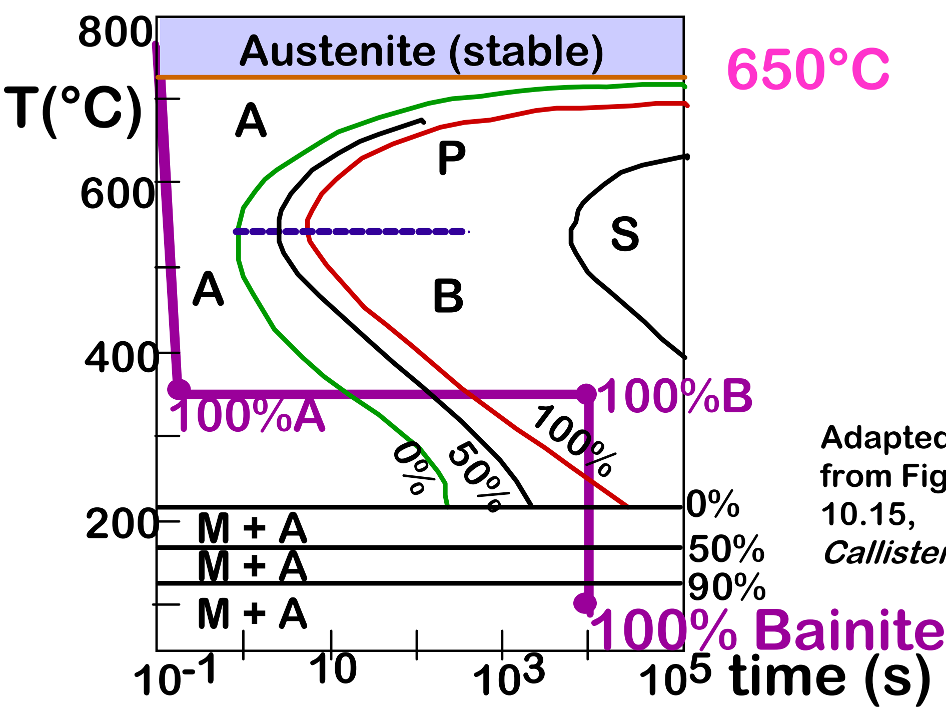
- **γ to M transformation..**
  -- is rapid!
  -- % transf. depends on T only.
  -- remaining material is retained Austenite

COOLING EX: Fe-C SYSTEM (1)

- $C_o = C_{eutectoid}$
- Three histories...

Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
350°C	10^4s	T_{room}		
250°C	10^2s	T_{room}		
650°C	20s	400°C	10^3s	T_{room}

Case I



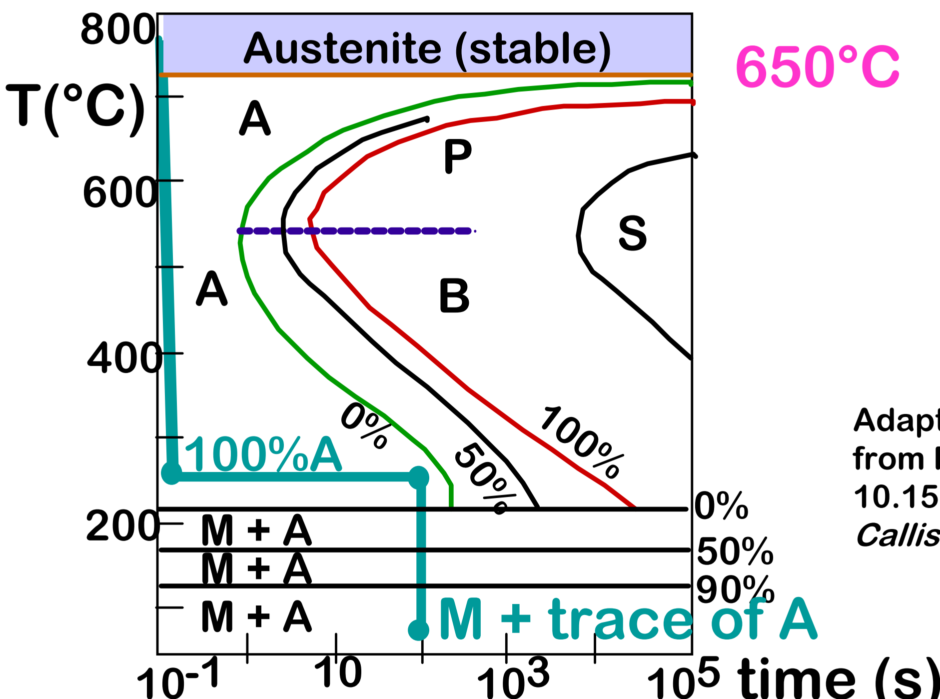
Adapted from Fig. 10.15, *Callister 6e*.

COOLING EX: Fe-C SYSTEM (2)

- $C_o = C_{eutectoid}$
- Three histories...

Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
350°C	10^4s	T_{room}		
250°C	10^2s	T_{room}		
650°C	20s	400°C	10^3s	T_{room}

Case II



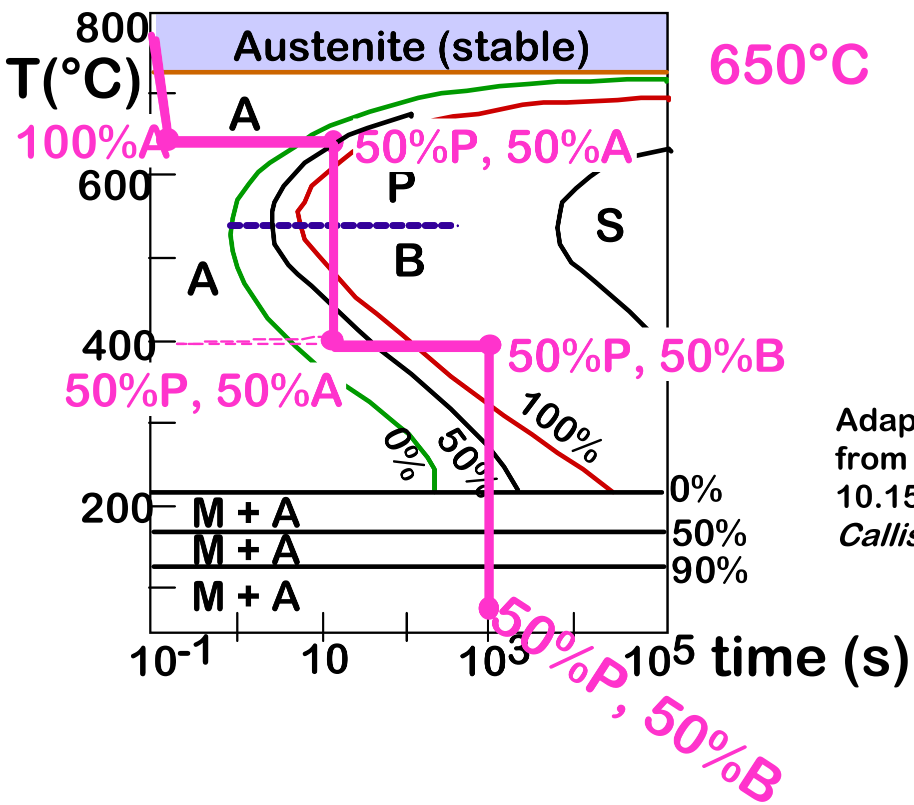
Adapted from Fig. 10.15, *Callister 6e.*

COOLING EX: Fe-C SYSTEM (3)

- $C_o = C_{eutectoid}$
- Three histories...

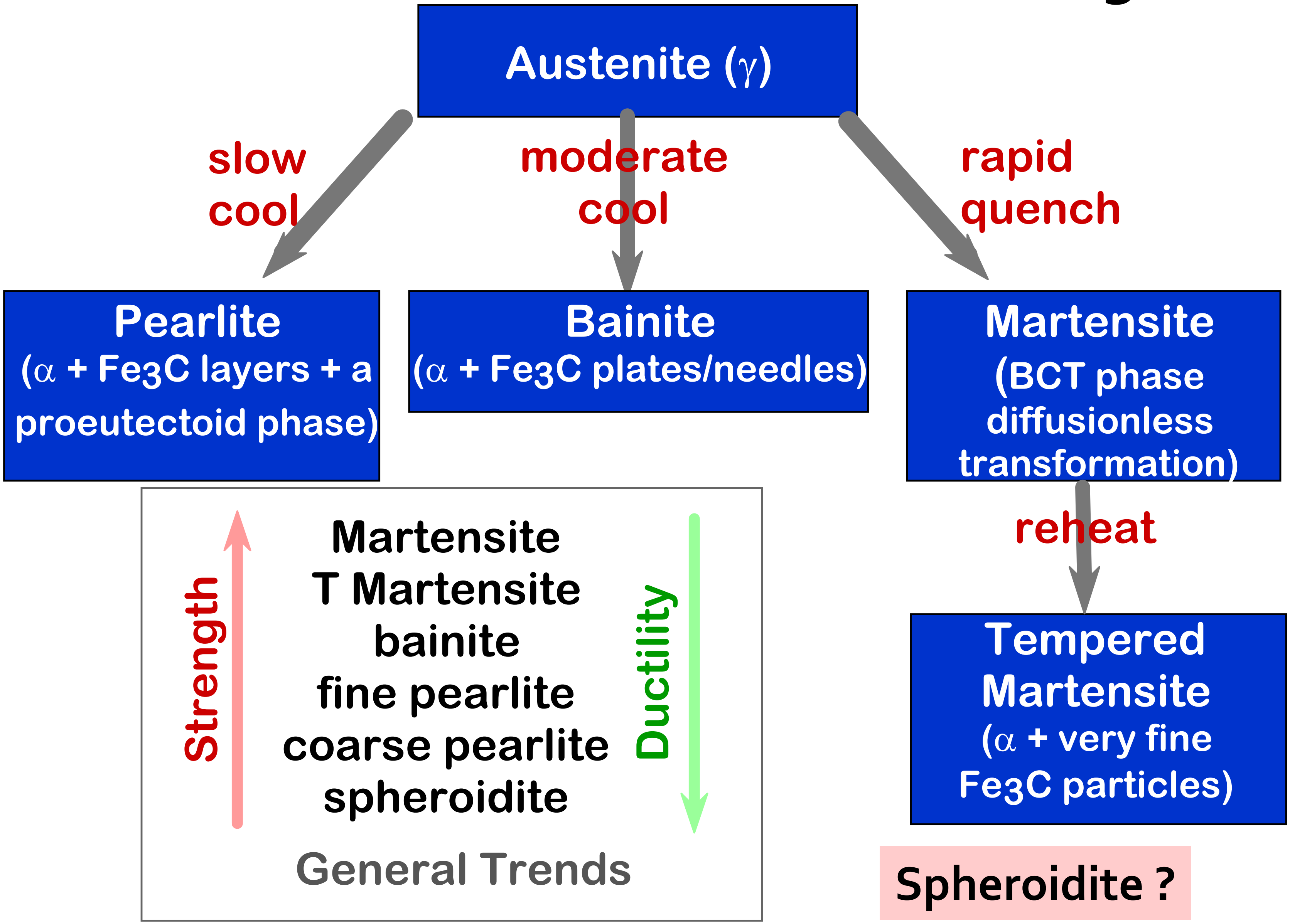
Rapid cool to:	Hold for:	Rapid cool to:	Hold for:	Rapid cool to:
350°C	10^4s	T_{room}		
250°C	10^2s	T_{room}		
650°C	20s	400°C	10^3s	T_{room}

Case III

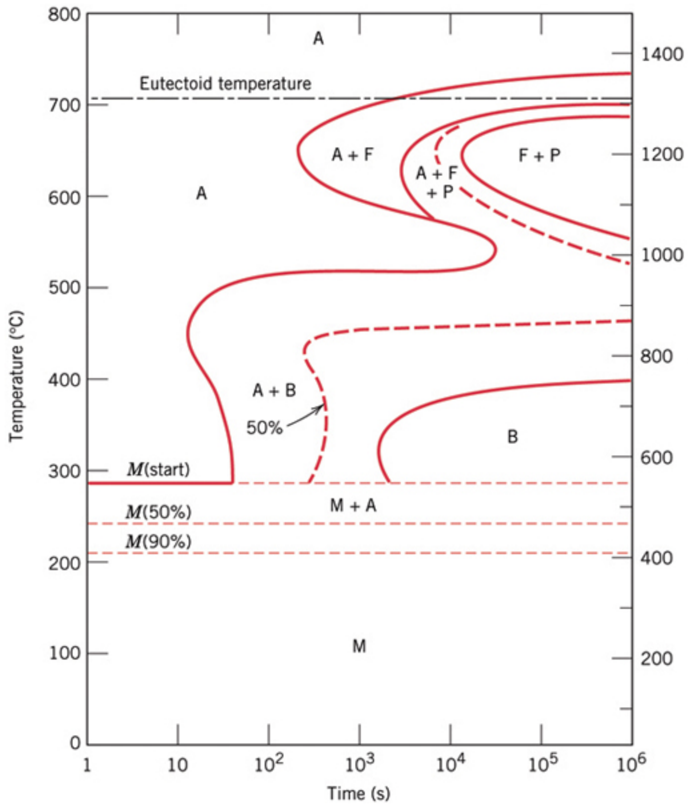


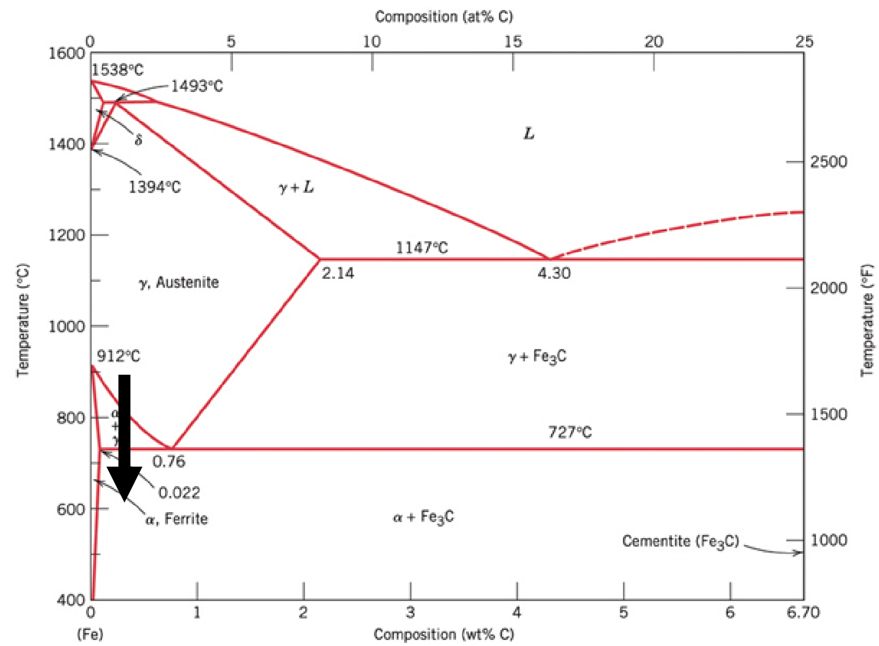
Adapted from Fig. 10.15, *Callister 6e.*

SUMMARY: Fe-C Processing

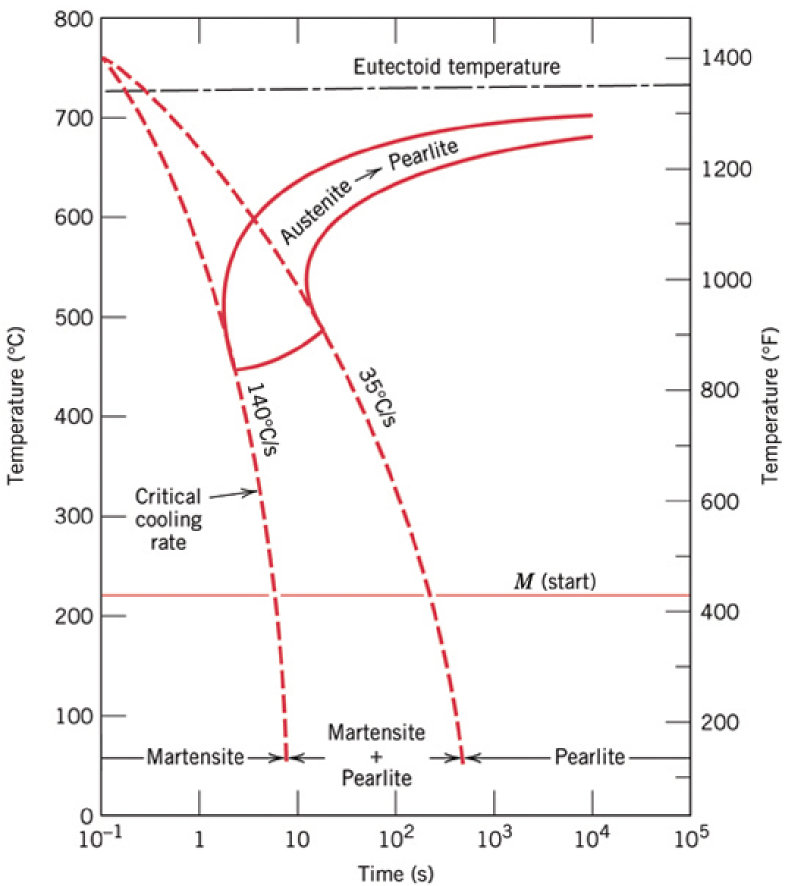


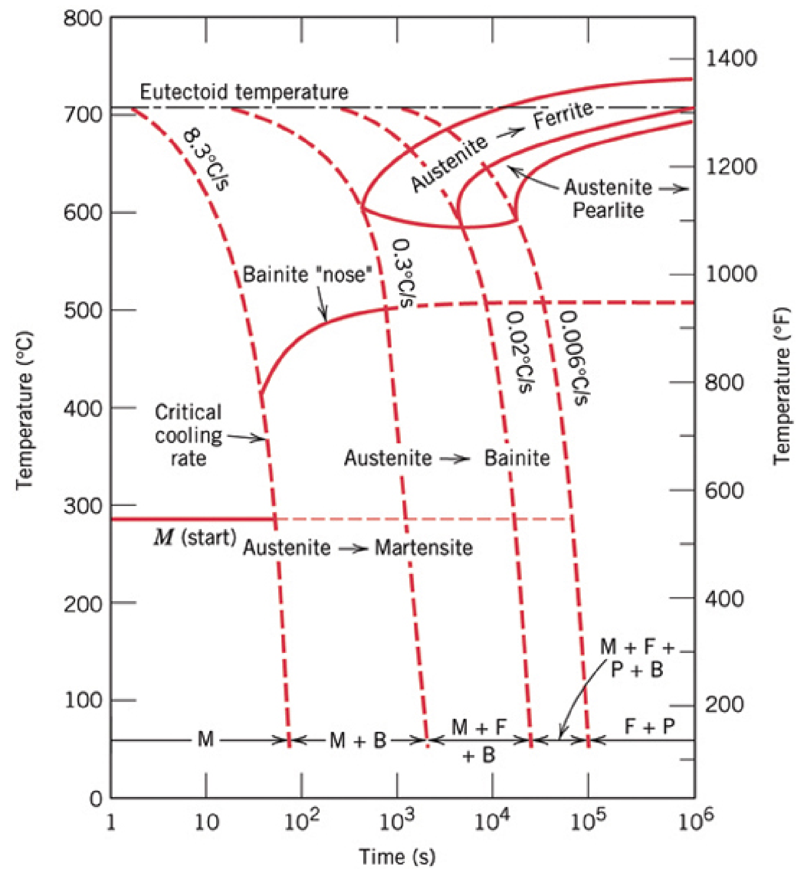
TTT for Hypo-eutectoid composition





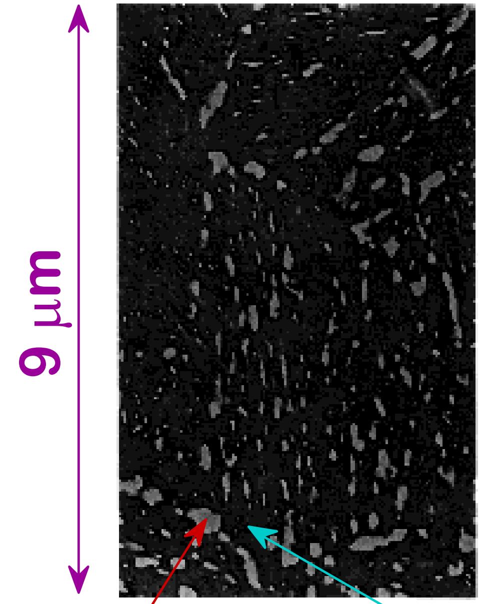
Fe-C: Continuous Cooling Transformations





TEMPERING MARTENSITE

- **reduces brittleness of martensite,**
- **reduces internal stress caused by quenching.**

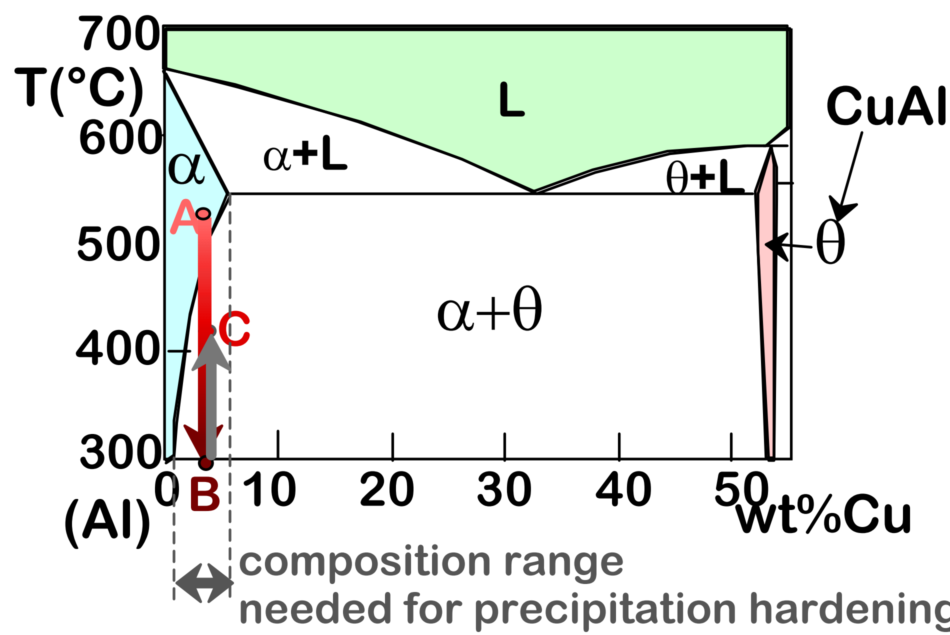


Adapted from Fig. 10.24, *Callister 6e*. (Fig. 10.24 copyright by United States Steel Corporation, 1971.)

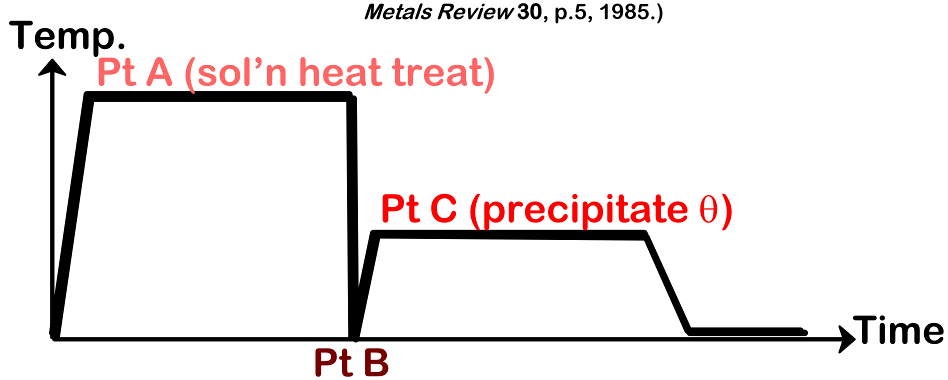
- **produces extremely small Fe_3C particles surrounded by α.**

PRECIPITATION HARDENING

- Particles impede dislocations.
- Ex: Al-Cu system
- Procedure:
  --Pt A: solution heat treat
  (get α solid solution)
  --Pt B: quench to room temp.
  --Pt C: reheat to nucleate
  small θ crystals within
  α crystals.
- Other precipitation
  systems:
  - Cu-Be
  - Cu-Sn
  - Mg-Al

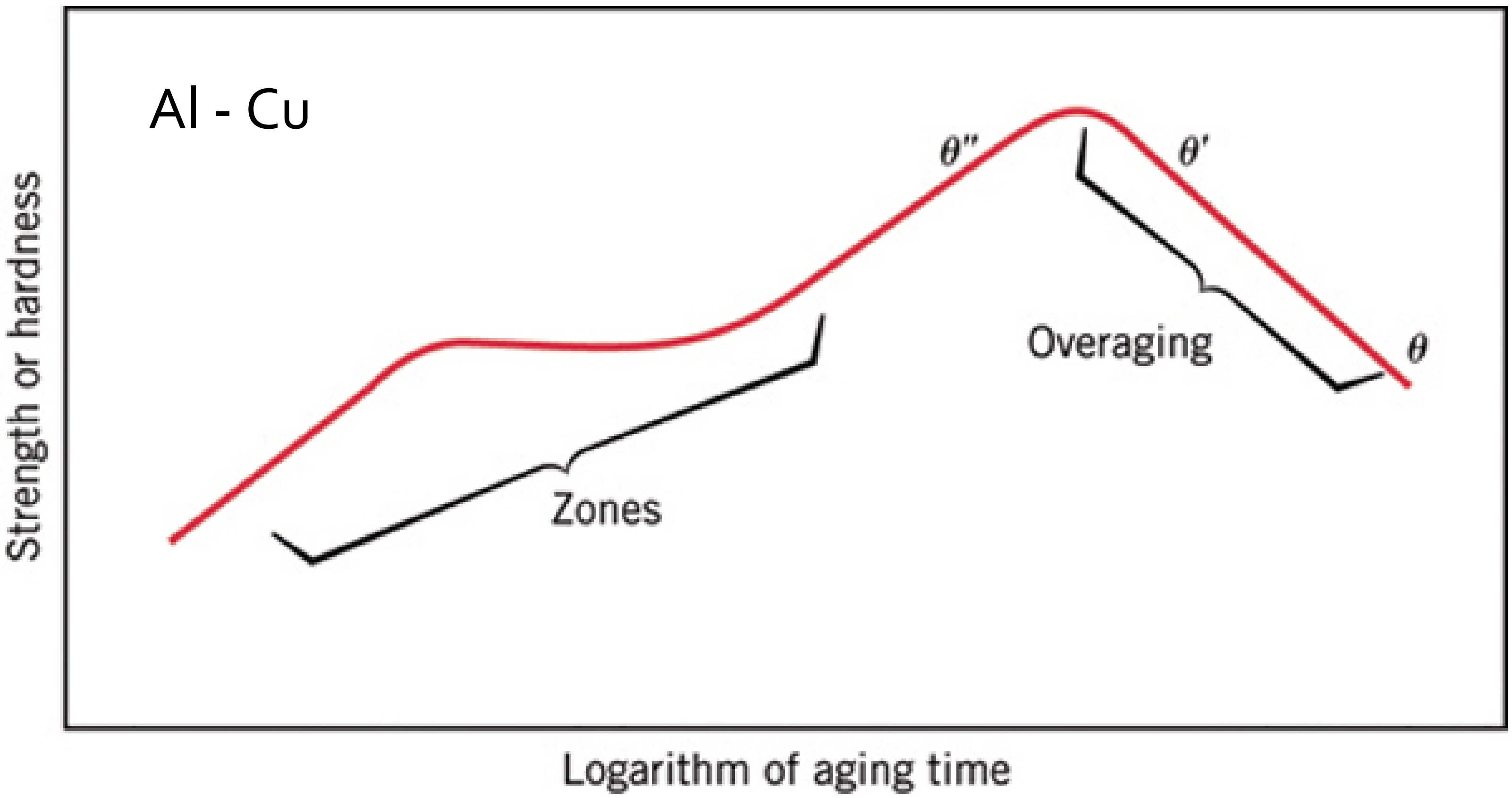


Adapted from Fig. 11.22, *Callister 6e*. (Fig. 11.22 adapted from J.L. Murray, *International Metals Review* **30**, p.5, 1985.)



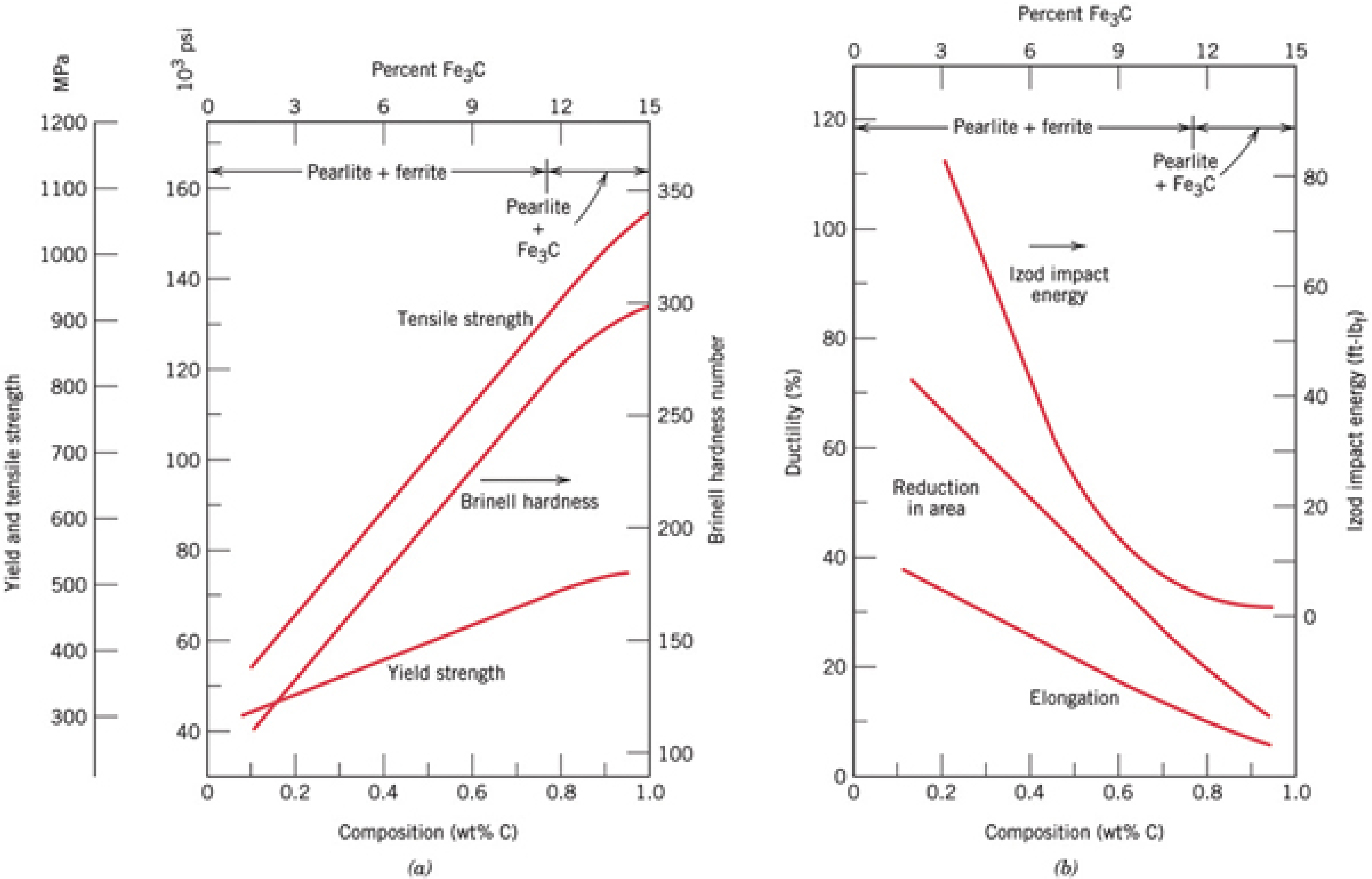
Adapted from Fig. 11.20, *Callister 6e*.

Preview of Mechanical Properties



Precipitation hardening for temp, T
- Longer time, larger ppts
- Different curve for each T

Preview of Mechanical Properties



All pearlite is in the form of fine pearlite.

Preview of Mechanical Properties