ISSUES TO ADDRESS...

- Transforming one phase into another takes time.
- How does the rate of transformation depend on time and temperature?
- Is it possible to slow down transformations so that non-equilibrium structures are formed?
- Are the mechanical properties of non-equilibrium structures more desirable than equilibrium ones?
Phase Transformations

Nucleation

- nuclei (seeds) act as templates on which crystals grow
- for nucleus to form rate of addition of atoms to nucleus must be faster than rate of loss
- once nucleated, growth proceeds until equilibrium is attained

Driving force to nucleate increases as we increase $\Delta T$

- supercooling (eutectic, eutectoid)
- superheating (peritectic)

Small supercooling $\rightarrow$ slow nucleation rate - few nuclei - large crystals

Large supercooling $\rightarrow$ rapid nucleation rate - many nuclei - small crystals

Kinetics - study of reaction rates of phase transformations

- To determine reaction rate – measure degree of transformation as function of time (while holding temp constant)
Chapter 10 - Rate of Phase Transformation

Avrami equation => \( y = 1 - \exp(-kt^n) \)

- \( k \) & \( n \) are transformation specific parameters

By convention \( rate = 1 / t_{0.5} \)

Adapted from Fig. 10.10, *Callister & Rethwisch 8e.*
Temperature Dependence of Transformation Rate

For the recrystallization of Cu, since

\[ \text{rate} = \frac{1}{t_{0.5}} \]

rate increases with increasing temperature

Rate often so slow that attainment of equilibrium state not possible!
Transformations & Undercooling

- **Eutectoid transf.** (Fe-Fe$_3$C system):

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

\[
\gamma \Rightarrow \alpha + Fe_3C
\]

- 0.76 wt% C
- 6.7 wt% C
- 0.022 wt% C

Adapted from Fig. 9.24, *Callister & Rethwisch* 8e. (Fig. 9.24 adapted from *Binary Alloy Phase Diagrams*, 2nd ed., Vol. 1, T.B. Massalski (Ed.-in-Chief), ASM International, Materials Park, OH, 1990.)
The Fe-Fe₃C Eutectoid Transformation

- Transformation of austenite to pearlite:
  - Austenite (γ)
  - Ferrite (α)
  - Cementite (Fe₃C)

  ![Diagram](image)

  Adapted from Fig. 9.15, Callister & Rethwisch 8e.

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

  ![Graph](image)

  Adapted from Fig. 10.12, Callister & Rethwisch 8e.

Coarse pearlite $\rightarrow$ formed at higher temperatures – relatively soft
Fine pearlite $\rightarrow$ formed at lower temperatures – relatively hard
Consider:

- The Fe-Fe₃C system, for C₀ = 0.76 wt% C
- A transformation temperature of 675°C.

Adapted from Fig. 10.13, *Callister & Rethwisch 8e.* (Fig. 10.13 adapted from H. Boyer (Ed.) *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1977, p. 369.)
Austenite-to-Pearlite Isothermal Transformation

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

Adapted from Fig. 10.14, Callister & Rethwisch 8e. (Fig. 10.14 adapted from H. Boyer (Ed.) Atlas of Isothermal Transformation and Cooling Transformation Diagrams, American Society for Metals, 1997, p. 28.)
Bainite: Another Fe-Fe$_3$C Transformation Product

- Bainite:
  - elongated Fe$_3$C particles in $\alpha$-ferrite matrix
  - diffusion controlled
- Isothermal Transf. Diagram, $C_0 = 0.76$ wt% C

Adapted from Fig. 10.18, Callister & Rethwisch 8e.

Adapted from Fig. 10.17, Callister & Rethwisch 8e. (Fig. 10.17 from Metals Handbook, 8th ed., Vol. 8, Metallography, Structures, and Phase Diagrams, American Society for Metals, Materials Park, OH, 1973.)
**Spheroidite: Another Microstructure for the Fe-Fe₃C System**

- **Spheroidite:**
  - Fe₃C particles within an α-ferrite matrix
  - formation requires diffusion
  - heat bainite or pearlite at temperature just below eutectoid for long times
  - driving force – reduction of α-ferrite/Fe₃C interfacial area

Adapted from Fig. 10.19, *Callister & Rethwisch 8e.* (Fig. 10.19 copyright United States Steel Corporation, 1971.)
Martensite: A Nonequilibrium Transformation Product

- **Martensite:**
  - $\gamma$(FCC) to Martensite (BCT)

- **Isothermal Transf. Diagram**

  - $\gamma$ to martensite (M) transformation...
  - is rapid! (diffusionless)
  - % transf. depends only on $T$ to which rapidly cooled

-- Adapted from Fig. 10.20, *Callister & Rethwisch 8e.*
-- Fig. 10.21 courtesy United States Steel Corporation.

-- Adapted from Fig. 10.22, *Callister & Rethwisch 8e.*

-- Adapted from Fig. 10.21, *Callister & Rethwisch 8e.* (Fig. 10.21 courtesy United States Steel Corporation.)
Martensite Formation

\[ \gamma \text{ (FCC)} \xrightarrow{\text{slow cooling}} \alpha \text{ (BCC)} + \text{Fe}_3\text{C} \]

\[ \gamma \text{ (FCC)} \xrightarrow{\text{quench}} \text{M (BCT)} \xrightarrow{\text{tempering}} \alpha \text{ (BCC)} + \text{Fe}_3\text{C} \]

Martensite (M) – single phase

– has body centered tetragonal (BCT) crystal structure

Diffusionless transformation

BCT if \( C_0 > 0.15 \) wt% C

BCT \( \rightarrow \) few slip planes \( \rightarrow \) hard, brittle
Heat flow vs. Temp

Y > X

or

X > Y

euthermic melt

Y °C/min

X °C/min
Continuous Cooling Transformation Diagrams

Conversion of isothermal transformation diagram to continuous cooling transformation diagram

Adapted from Fig. 10.25, *Callister & Rethwisch 8e.*
Mechanical Props: Influence of C Content

- Increase C content: $TS$ and $YS$ increase, $\%EL$ decreases

Adapted from Fig. 9.30, Callister & Rethwisch 8e.

C$_0$ < 0.76 wt% C

Hypoeutectoid

Pearlite (med)
ferrite (soft)

Adapted from Fig. 9.33, Callister & Rethwisch 8e.

C$_0$ > 0.76 wt% C

Hyper eutectoid

Cementite (hard)

Adapted from Fig. 10.29, Callister & Rethwisch 8e. (Fig. 10.29 based on data from Metals Handbook: Heat Treating, Vol. 4, 9th ed., V. Masseria (Managing Ed.), American Society for Metals, 1981, p. 9.)
Mechanical Props: Fine Pearlite vs. Coarse Pearlite vs. Spheroidite

- Hardness: fine > coarse > spheroidite
- %RA: fine < coarse < spheroidite

Adapted from Fig. 10.30, *Callister & Rethwisch 8e*. (Fig. 10.30 based on data from *Metals Handbook: Heat Treating*, Vol. 4, 9th ed., V. Masseria (Managing Ed.), American Society for Metals, 1981, pp. 9 and 17.)
Mechanical Props: Fine Pearlite vs. Martensite

- Hardness: fine pearlite << martensite.

Adapted from Fig. 10.32, *Callister & Rethwisch 8e*. (Fig. 10.32 adapted from Edgar C. Bain, *Functions of the Alloying Elements in Steel*, American Society for Metals, 1939, p. 36; and R.A. Grange, C.R. Hribal, and L.F. Porter, *Metall. Trans. A*, Vol. 8A, p. 1776.)
Tempered Martensite

Heat treat martensite to form tempered martensite
• tempered martensite less brittle than martensite
• tempering reduces internal stresses caused by quenching

- tempering decreases $TS$, $YS$ but increases $\%RA$
- tempering produces extremely small $\text{Fe}_3\text{C}$ particles surrounded by $\alpha$. 

Adapted from Fig. 10.33, Callister & Rethwisch 8e. (Fig. 10.33 copyright by United States Steel Corporation, 1971.)
Summary of Possible Transformations

Austenite (γ)

- **Pearlite** (α + Fe₃C layers + a proeutectoid phase)
  - slow cool

- **Bainite** (α + elong. Fe₃C particles)
  - moderate cool

- **Martensite** (BCT phase diffusionless transformation)
  - rapid quench

- **Tempered Martensite** (α + very fine Fe₃C particles)
  - reheat

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Martensite

- T Martensite
- bainite
- fine pearlite
- coarse pearlite
- spheroidite

General Trends

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Adapted from Fig. 10.36, Callister & Rethwisch 8e.

Chapter 10 - 19
Prob 10.15

Prob. 10.18

(+1) extra-credit  (+1) extra-credit
Prob. 10.15 \( C_f = 0.76 \)

a) 2.5 sec for 80%  
6 sec for 100%

b) Fig 10.30a

Hardness is H  
265 HB  
27 HRC
a) 50% coarse pearlite
   50% martensite

b) will transform to spheroidite

c) 50% to pearlite (medium)
   50% of remaining austenite will be bainite (25% of original)
   The remaining 25% becomes martensite.

d) 100% martensite

e) 40% bainite
   60% martensite

f) 100% bainite

gh) 100% five pearlite

h) 100% tempered martensite