Chapter 10: Phase Transformations

The diagram shows the phase transformations of iron-carbon alloy as a function of temperature (T) and carbon content (C₀). The different phases are labeled as follows:

- \( \gamma \) (austenite)
- \( \gamma + L \)
- \( \gamma + Fe_3C \)
- \( \alpha + Fe_3C \)
- \( L + Fe_3C \)

Key temperatures and compositions mentioned in the diagram include:

- 1148°C
- Various compositions ranging from 0 to 6.7 wt% C

The diagram also indicates the transformation paths and stability regions for each phase.
Chapter 10: Phase Transformations

• Transforming one phase into another takes time.

• How does the rate of transformation depend on time and $T$?
• How can we slow down the transformation so that we can engineer non-equilibrium structures?
• Are the mechanical properties of non-equilibrium structures better?
t=time!
T=temperature!
$\Delta T =$ temperature difference from phase transition temperature
Phase Transformations

Nucleation
   – nuclei (seeds) act as template to grow crystals

Driving force to nucleate increases as we increase $\Delta T$
In $\Delta T$ range close to $T_m$, rate of nucleation higher with higher $\Delta T$
   – supercooling (eutectic, eutectoid)

Growth
  Growth rate increases with T (thermally activated)
  \[ \frac{dG}{dt} = C \exp\left(-\frac{Q}{kT}\right) \]

Small supercooling $\rightarrow$ few nuclei - large crystals
Large supercooling $\rightarrow$ rapid nucleation - many nuclei, small crystals
Rate of Phase Transformations

Kinetics - measure approach to equilibrium vs. time

• Hold temperature constant & measure conversion vs. time

  – How is conversion measured?
    • X-ray diffraction – have to do many samples
    • electrical conductivity – follow one sample
    • sound waves – one sample
Rate of Phase Transformation

Avrami rate equation: $y = 1 - \exp(-kt^n)$

- $k$ and $n$ fit for specific sample

By convention: $r = 1 / t_{0.5}$

- $t_{0.5}$ is the time at which half of the material has transformed.

- Maximum rate reached – now amount unconverted decreases so rate slows.

- Rate increases as surface area increases & nuclei grow.

- All out of material - done.

Adapted from Fig. 10.10, Callister 7e.
Eutectoid Transformation Rate

• Growth of pearlite from austenite:

  Course pearlite \( \rightarrow \) formed at higher \( T \) - softer
  Fine pearlite \( \rightarrow \) formed at low \( T \) - harder

- Recrystallization rate increases with \( \Delta T \).

Adapted from Fig. 9.15, Callister 7e.

Adapted from Fig. 10.12, Callister 7e.
Chapter 10

Fe₃C (cementite)

1600
1400
1200
1000
800
600
400
0
1
2
3
4
5
6
6.7

T(°C)

γ
(austenite)

γ + L

L + Fe₃C

γ + Fe₃C

α + Fe₃C

Co, wt% C

(Fe)
Nucleation and Growth

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

- Examples:

  - $T$ just below $T_E$:
    - Nucleation rate low
    - Growth rate high

  - $T$ moderately below $T_E$:
    - Nucleation rate med.
    - Growth rate med.

  - $T$ way below $T_E$:
    - Nucleation rate high
    - Growth rate low

Adapted from Fig. 10.10, *Callister 7e*. 
Isothermal Transformation Diagrams

- Fe-C system, $C_o = 0.76$ wt% C
- Transformation at $T = 675 \degree C$. 

![Diagram showing isothermal transformation at 675°C](image)
Effect of Cooling History in Fe-C System

- Eutectoid composition, $C_o = 0.76$ wt% C
- Begin at $T > 727^\circ$C
- Rapidly cool to 625°C and hold isothermally.

Adapted from Fig. 10.14, Callister 7e.
(Fig. 10.14 adapted from H. Boyer (Ed.) Atlas of Isothermal Transformation and Cooling Transformation Diagrams, American Society for Metals, 1997, p. 28.)
Non-Equilibrium Transformation Products: Fe-C

- Bainite:
  - \( \alpha \) lathes (strips) with long rods of \( \text{Fe}_3\text{C} \)
  - diffusion controlled.

- Isothermal Transf. Diagram

(Adapted from Fig. 10.18, Callister, 7e. (Fig. 10.18 adapted from H. Boyer (Ed.) Atlas of Isothermal Transformation and Cooling Transformation Diagrams, American Society for Metals, 1997, p. 28.))
Martensite: Fe-C System

- **Martensite:**
  -- $\gamma$ (FCC) to Martensite (BCT)
  (involves single atom jumps)

- **Isothermal Transf. Diagram**

  Adapted from Fig. 10.22, *Callister 7e*.

- $\gamma$ to M transformation..
  -- is rapid!
  -- % transf. depends on T only.
Martensite Formation

\[
\gamma \rightarrow \alpha + \text{Fe}_3\text{C}
\]

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

quench \(\rightarrow\)

M (BCT) \(\rightarrow\) tempering

\(M = \text{martensite}\) is body centered tetragonal (BCT)

Diffusionless transformation \(\rightarrow\) BCT if \(C > 0.15\) wt%

BCT \(\rightarrow\) few slip planes \(\rightarrow\) hard, brittle
Spheroidite: Fe-C System

- **Spheroidite:**
  - $\alpha$ grains with spherical Fe$_3$C
  - diffusion dependent.
  - heat bainite or pearlite for long times
  - reduces interfacial area (driving force)

(Adapted from Fig. 10.19, *Callister, 7e*. (Fig. 10.19 copyright United States Steel Corporation, 1971.)
Mechanical Prop: Fe-C System (1)

- Effect of wt% C
  - More wt% C: TS and YS increase, %EL decreases.

Adapted from Fig. 9.30, Callister 7e. (Fig. 9.30 courtesy Republic Steel Corporation.)

Adapted from Fig. 9.33, Callister 7e. (Fig. 9.33 copyright 1971 by United States Steel Corporation.)

Adapted from Fig. 10.29, Callister 7e. (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 Prop: Fe-C System (2)

- Fine vs coarse pearlite vs spheroidite

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

Adapted from Fig. 10.30, Callister 7e.
(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 Prop: Fe-C System (3)

• Fine Pearlite vs Martensite:

- Hardness: fine pearlite << martensite.

Adapted from Fig. 10.32, Callister 7e. (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.)
Tempering Martensite

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

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

Adapted from Fig. 10.33, Callister 7e. (Fig. 10.33 copyright by United States Steel Corporation, 1971.) Adapted from Fig. 10.34, Callister 7e. (Fig. 10.34 adapted from Fig. furnished courtesy of Republic Steel Corporation.)
Summary: Processing Options

Austenite (γ)
- slow cool
  - Pearlite
    - (α + Fe₃C layers + a proeutectoid phase)
- moderate cool
  - Bainite
    - (α + Fe₃C plates/needles)
- rapid quench
  - Martensite
    - (BCT phase diffusionless transformation)

Martensite
- reheating
  - Tempered Martensite
    - (α + very fine Fe₃C particles)

General Trends:
- Martensite
- T Martensite
- bainite
- fine pearlite
- coarse pearlite
- spheroidite

Strength
Ductility

Adapted from Fig. 10.36, Callister 7e.