Chapter 10
Phase Transformations in Metals
The Kinetics of Solid-State Reactions

- Obstacles in solid-state transformation
  - Diffusion
  - Energy increase
- Phase transformation stages
  - Nucleation: at grain boundaries
  - Growth
- Kinetics (time-dependent)
  \[ y = 1 - \exp(-kt^n) \]
  \[ T = \text{constant} \]
- Rate of transformation
- Characterization of transformation

S-Curve
Temperature Dependence

\[ r = Ae^{-Q/RT} \]

Percent recrystallization for pure copper
Iron-Carbon Isothermal Transformation

- Pearlite

\[ \gamma(0.76\text{wt}\%C) \Leftrightarrow \alpha(0.022\text{wt}\%C) + Fe_3C(6.7\text{wt}\%C) \]
Iron-Carbon Isothermal Transformation

- T-T-T diagram (isothermal transformation diagram)
  - Eutectoid temperature
  - Supercooling
  - Phase regions
- Transformation rate
  - Pearlite nucleation
- This curve only valid for eutectoid composition
Iron-Carbon Isothermal Transformation

- Thermal treatment curve
Iron-Carbon Isothermal Transformation

- Coarse pearlite
- Fine pearlite
Iron-Carbon Isothermal Transformation
Iron-Carbon Isothermal Transformation

- Coarse pearlite
- Fine pearlite
Iron-Carbon Isothermal Transformation

- Bainite

Pearlite vs. Bainite

- Competitive
Iron-Carbon Isothermal Transformation

- **Spheroidite**
  - From pearlite or bainite
  - Heated about 700 °C for 18 ~24 hours
  - Driving force
    - Reduction of $\alpha$ - Fe$_3$C phase boundary area
Iron-Carbon Isothermal Transformation

- **Martensite**
  - Nonequilibrium single-phase
  - From diffusionless transformation of austenite
  - Rapid quenching
  - Occurs instantaneously
  - Time-independent
  - Competitive with pearlite and bainite
  - Body-centered tetragonal (BCT)
  - Supersaturated solid solution

Lenticular (more than 0.6 wt% C)

Lath (less than 0.6 wt% C)
Iron-Carbon Isothermal Transformation
Iron-Carbon Isothermal Transformation

1. Rapidly cool to 350 °C, hold for $10^4$ s, and quench to room temperature.

2. Rapidly cool to 250 °C, hold for 100 s, and quench to room temperature.

3. Rapidly cool to 650 °C, hold for 20 s, rapidly cool to 400 °C, hold for $10^3$ s, and quench to room temperature.
Iron-Carbon Isothermal Transformation
Continuous Cooling Transformation Diagram

Shift to longer time and lower temperature
Continuous Cooling Transformation Diagram
Critical Quenching Rate

- The minimum rate of quenching to generate 100% martensite.
Mechanical Behavior of Pearlite

- Cementite is very hard and brittle.

- Fine pearlite is harder and stronger than coarse pearlite.
Mechanical Behavior of Spheroidite

- Less boundary area per unit volume in spheroidite
- Spheroidized steels are extremely ductile.
Mechanical Behavior of Bainite

- Bainite is stronger and harder than pearlite.

Pearlite vs. Bainite

- Competitive

![Graph showing Brinell hardness number vs. transformation temperature](image)

- Upper bainite (300 ~ 540 °C)
- Lower bainite (200 ~ 300 °C)
Mechanical Behavior of Martensite

- Martensite is the hardest and strongest and most brittle (negligible ductility).
- Related to interstitial carbon atoms.
- Volume increase during phase transformation.
Tempered Martensite

- Heat treatment martensite between 250 ~ 650 °C.
- Internal stress is relieved.
- Ductility and toughness are enhanced.

martensite (BCT, single phase) → tempered martensite (ferrite + cementite)

9300 X
Temperature and Time Influence on Tempering

![Graph showing the influence of temperature and time on tensile strength and yield strength during tempering.](image)

![Graph showing the reduction in area and Rockwell hardness over time for different tempering temperatures.](image)
Iron-Carbon Transformation
Iron-Carbon Transformation

- Austenite
  - Slow cooling:
    - Pearlite \((\alpha + Fe_2C)\) + a proeutectoid phase
  - Moderate cooling:
    - Bainite \((\alpha + Fe_3C\) phases)
  - Rapid quench:
    - Martensite \((BCT\) phase)

- Reheat:
  - Tempered martensite \((\alpha + Fe_3C\) phases)
Mechanical Behavior

(a) Tensile strength, Brinell hardness, and yield strength vs. composition (wt% C)
(b) Izod impact energy, ductility, and reduction in area vs. composition (wt% C)
Mechanical Behavior
Mechanical Behavior

![Graph showing the mechanical behavior of materials with transformation temperature, Brinell hardness number, and tensile strength in MPa. The graph indicates a decrease in Brinell hardness number and an increase in tensile strength with increasing transformation temperature. The phase changes from Bainite to Pearlite are marked.]
Mechanical Behavior