Phase Transformation

ISSUES TO ADDRESS...

• 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 engineering non-equilibrium structures?

• Are the mechanical properties of non-equilibrium structures better?
Fraction of Transformation

- Fraction transformed depends on time.

\[ y = 1 - e^{-kt^n} \]  

Avrami Eqn.

- Transformation rate depends on T.

\[ r = \frac{1}{t^{0.5}} = Ae^{-Q/RT} \]

- \( r \) often small: equilibrium is not possible!

Ex: recrystallization of Cu

\[ y (\%) \]

\[ \log (t) \text{ min} \]
Transformation & Undercooling

- **Eutectoid** transf. (Fe-C System):
- Can make it occur at:
  - ...727°C (cool it slowly)
  - ...below 727°C (“undercool” it!)

### Eutectoid:

<table>
<thead>
<tr>
<th>C₀, wt% C</th>
<th>α + Fe₃C</th>
<th>L + Fe₃C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6.7</td>
<td>0.77</td>
<td>0.022</td>
</tr>
</tbody>
</table>

\[ γ \rightarrow α + Fe₃C \]

Eutectoid:

- Equil. cooling: \( T_{\text{transf.}} = 727°C \)
- Undercooling by \( \Delta T: T_{\text{transf.}} < 727°C \)

\[ \Delta T: 0.022 \text{wt}\% C \]

\[ 0.77 \text{wt}\% C \]

\[ 6.7 \text{wt}\% C \]
Eutectoid Transformation Rate $\sim \Delta T$

- Growth of pearlite from austenite:

  - Austenite ($\gamma$)
  - Cementite ($\text{Fe}_3\text{C}$)
  - Ferrite ($\alpha$)

  - Diffusive flow of C needed
  - Pearlite growth direction

- Reaction rate increases with $\Delta T$.

![Graph showing the transformation rate](image)
Isothermal Transformation Diagram

- Fe-C system, C₀ = 0.77wt%C  Transformation at T = 675°C.
Ex: Cooling in Fe-C System

- Eutectoid composition, $C_0 = 0.77\text{wt}\%\text{C}$
- Begin at $T > 727^\circ\text{C}$
- Rapidly cool to $625^\circ\text{C}$ and hold isothermally.
Pearlite Morphology

Two cases:

- \( T_{\text{transf}} \) just below \( T_E \)
  - Larger \( T \): diffusion is faster
  - Pearlite is coarser.

- \( T_{\text{transf}} \) well below \( T_E \)
  - Smaller \( T \): diffusion is slower
  - Pearlite is finer.

- Smaller \( \Delta T \):
  - Colonies are larger

- Larger \( \Delta T \):
  - Colonies are smaller
**Non-Equil. Transformation Products: Fe-C**

- **Bainite:**
  - $\alpha$ lathes (strips) with long rods of Fe$_3$C
  - diffusion controlled.

`Fe_3C (cementite)`

`5 \mu m`

**Bainite reaction rate:**

$$r_{\text{bainite}} = e^{-\frac{Q}{RT}}$$
Other Products: Fe-C System (I)

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

![Diagram showing phase transformation with spheroidite formation](image)
Other Products: Fe-C System (II)

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

- **Fe atom sites**

- **Potential C atom sites**

- **Martensite needles**

- **Austenite**

- **$\gamma$ to M transformation..**
  - is rapid!
  - % transf. depends on T only.
# Quenching Medium & Geometry

- **Effect of quenching medium:**

<table>
<thead>
<tr>
<th>Medium</th>
<th>Severity of Quench</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>oil</td>
<td>moderate</td>
<td>moderate</td>
</tr>
<tr>
<td>water</td>
<td>large</td>
<td>large</td>
</tr>
</tbody>
</table>

- **Effect of geometry:**

  When surface-to-volume ratio increases:
  - cooling rate increases
  - hardness increases

<table>
<thead>
<tr>
<th>Position</th>
<th>Cooling rate</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>center</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>surface</td>
<td>large</td>
<td>large</td>
</tr>
</tbody>
</table>
Cooling Ex.

(a) Rapidly cool to 350°C, hold for 10^4s, quench to \( T_{\text{room}} \)
(b) Rapidly cool to 250°C, hold for 100s, quench to \( T_{\text{room}} \)
(c) Rapidly cool to 650°C, hold for 20s, rapidly cool to 400°C, hold for 10^3s, quench to \( T_{\text{room}} \)
Mechanical Prop: Fe-C System (I)

- Hypoeutectoid:
  - Pearlite (med)
  - Ferrite (soft)

- Hypereutectoid:
  - Cementite (hard)
  - Pearlite (med)
Mechanical Prop: Fe-C System (II)
Mechanical Prop: Fe-C System (III)

- **Brinell hardness number**
  - Martensite
  - Tempered martensite (tempered at 371°C)
  - Fine pearlite

- **Rockwell hardness, HRC**

- **Tensile and yield strength**

- **Tempering temperature (°F)**
  - Tensile strength
  - Yield strength
  - Reduction in area

- **Reduction in area (%)**
Summary: Processing Options

- **Austenite (γ)**
  - slow cool → **Pearlite**
    - (α + Fe 3C layers + a proeutectoid phase)
  - moderate cool → **Bainite**
    - (α + Fe 3C plates/needles)
  - rapid quench → **Martensite**
    - (BCT phase diffusionless transformation)

- **Tempered Martensite**
  - reheat → **Tempered Martensite**
    - (α + very fine Fe 3C particles)

- **General Trends**
  - **Strength**: Martensite, T martensite bainite, fine pearlite, coarse pearlite, spheroidite
  - **Ductility**: Tempered martensite

- **Processing Options**
  - Slow cool
  - Moderate cool
  - Rapid quench

- **Properties**
  - **Martensite**: T martensite bainite, fine pearlite, coarse pearlite, spheroidite
  - **Tempered Martensite**: Fe 3C particles

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Problem 10.16

Figure 10.28
Isothermal transformation diagram for a 1.13 wt% C iron–carbon alloy: A, austenite; B, bainite; C, proeutectoid cementite; M, martensite; P, pearlite. [Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1977, p. 33.]