Engineering materials

Lecture 7

Carbon Steel
Strengthening mechanisms

- Crystals contain dislocations
- A shear stress $\tau$, applied to the slip plane of a dislocation, exerts a force $\tau b$ to push it forward.
- When the force $\tau b$ exceeds $R$, the resistance force opposing the motion of a dislocation, crystals deform plastically, i.e., it yields.
- How to increase yield strength of metals: introduce obstacles into the path of the dislocations
Strengthening Mechanisms

• Solid solution strengthening

• Precipitate strengthening

• Dispersion strengthening

• Strain hardening
  – Example: 冷軋鋼筋
Solid Solution Strengthening

- Addition of one or more metals can increase the strength of metals.
- Solute atoms, on case of substitutional solid solution, create stress fields around themselves and hinder the dislocation movement.
- Distortion of lattice and clustering of like atoms also impede dislocation movement.
- **Example:** Solid solution of 70 wt % Cu & 30 wt % Zn (cartridge brass) has tensile strength of 500 MPa. Tensile strength of unalloyed copper is 330 MPa.
Solid solution strengthening

- Obstacles are formed via solid solution

- Example: Brass: Zn and Cu

- Example: Bronze: Sn and Cu

- Example: Stainless steel: Cr, Ni and Fe
Precipitate strengthening

• Some impurities introduced into a metal at high temperature precipitate as compounds when cooled to room temperature.
• If we have more alloying element than that can be dissolved in the lattice, then it forms a precipitate.
• Example: CuAl$_2$ precipitate in Al lattice
• Example: Fe$_3$C precipitate in Fe lattice
Dispersion strengthening

- Introduce a dispersion of intrinsically hard covalently bonded ceramic into the metal lattice

- Example: Al\textsubscript{2}O\textsubscript{3} in Al
Strain strengthening

• Dislocations gliding on intersecting planes can interact, and then obstruct each other. Hence, higher stress is required to continue deformation. This process is called strain strengthening.

• Example: 冷軋鋼筋
Phase Diagram of the Iron-Carbon System
Iron Carbide Phase Diagram

• **Plain carbon steel** → 0.03% to 1.2% C, 0.25 to 1% Mn and other impurities.

• $\alpha$ **Ferrite**: Very low solubility of carbon.
  Max 0.02 % at 723°C and 0.005% at 0°C.

• **Austenite**: Interstitial solid solution of carbon in $\gamma$ iron.
  Solubility of C is 2.08% at 1148°C and 0.8% at 0°C.

• **Cementite**: Intermetallic compound.
  6.67% C and 93.3% Fe.
Invariant reactions

- **Peritectic reaction:**
  
  Liquid (0.53% C) + $\delta$ (0.09% C) $\rightarrow_{1495^\circ\text{C}}$ $\gamma$ (0.17% C)

- **Eutectic reaction:**
  
  Liquid (4.3% C) $\rightarrow_{1148^\circ\text{C}}$ $\gamma$ austenite (2.08% C) + Fe$_3$C (6.67% C)

- **Eutectoid reaction:**
  
  $\gamma$ Austenite (0.8% C) $\rightarrow_{723^\circ\text{C}}$ $\alpha$ Ferrite (0.02% C) + Fe$_3$C (6.67% C)

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Hypoeutectoid Steel: Less than 0.8% C  
Eutectoid Steel: 0.8% C  
Hypereutectoid Steel: More than 0.8% C
**Eutectoid plain carbon steel**: If a sample is heated up to 750°C and held for sufficient time, structure will become **homogeneous austenite**.

- Below eutectoid temperature, **layers** of ferrite and cementite are formed. **Pearlite**.
Slow Cooling of Plain Carbon Steel

- **Hypoeutectoid plain carbon steel**: If a sample of 0.4% C is heated up to 900°C, it gets **austenitized**.
- Further cooling gives rise to $\alpha$ and pearlite.

![Iron-carbon phase diagram](image)

- **0.35%C hypoeutectoid steel**
Slow Cooling of Plain Carbon Steel

- Hypereutectoid plain carbon steel: If a 1.2% C sample is heated up to 950°C and held for sufficient time, it entirely gets austenitized.
- Further cooling results in eutectoid cementite and pearlite.
Example 1

A 0.8% C eutectoid plain-carbon steel is slowly cooled from 750°C to a temperature just slightly below 723°C. Assuming that the austenite is completely transformed to $\alpha$ ferrite and cementite.

a. Calculate the weight percent eutectoid ferrite formed
b. Calculate the weight percent eutectoid cementite formed

a. Wt% of ferrite = \( \frac{6.67-0.80}{6.67-0.02} \) = 88.3%

b. Wt% of cementite = \( \frac{0.80-0.02}{6.67-0.02} \) = 11.7%
Example 2

A 0.4 % C hypoeutectoid plain-carbon steel is slowly cooled from 940°C to a temperature just slightly above 723 °C.

a. Calculate the weight percent austenite present in the steel.
b. Calculate the weight percent proeutectoid ferrite present in the steel.

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a. \text{Wt\% of austenite} = \frac{0.4-0.02}{0.8-0.02} = 50\%
b. \text{Wt\% of proeutectoid ferrite} = \frac{0.8-0.4}{0.8-0.02} = 50\% 
\]
Microstructure of steel

- Eutectoid steel (0.8 wt% C): pearlite

- Hypoeutectoid steel (< 0.8 wt% C), Figure 13.1 (b), p.285.

- Hypereutectoid steel (> 0.8 wt% C): pearlite + cementite (Fe₃C)

- Pearlite: the composite eutectoid structure of alternating plate of alpha and Fe₃C produced when gamma phase containing 0.8 wt% C is cooled below 723°C
Steel

- High C content gives rise to high hardness, UTS and yield strength
- High C content reduces ductility, toughness and elongation
Steel, cont’d

- The yield strength and tensile strength of carbon steels increase linearly with carbon content because Fe₃C acts as a strengthening phase.

- The ductility of carbon steels decrease with carbon content because the α-Fe₃C interface are good at nucleating cracks, causing brittleness.

- Quenched and tempered carbon steels may give rise to even higher strength due to dislocation mechanisms.

- Rapid cooling also gives rise to high strength.
Steel, cont’d

- Hypoeutectoid and hypereutectoid steels can be quenched to give martensite
- Pure iron at room temperature would be BCC structure, but super saturated carbon distorts the lattice making

![Diagram of FCC γ, BCC α, BCT structures]

- The hardness and strength of martensite increase rapidly with carbon content. However, ductility and toughness decrease with increasing carbon content, i.e. martensites are brittle
Steel, cont’d

- Tempering (i.e., reheat it to 300 ~ 600 °C, below 723 °C) martensite gives the carbon atoms enough thermal energy that can diffuse out of supersaturated solution and react with iron to form small closely packed precipitates of Fe$_3$C.

- If the steel is over-tempered, the Fe$_3$C particles coarsen and the hardness falls.

- Large improvement in yield and tensile strength that can be obtained by quenching and tempering steels.