ASE324: Aerospace Materials Laboratory

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Last lecture:

- Introduction of dislocations;
- Motion of dislocations accounts for the discrepancy between theoretical and measured strengths;
- Strengthening mechanisms;
- Plastic deformation in polycrystals.
Alloys

- Few metals are used in their pure state.
- Other elements are added to form alloys.
- Alloying provides a wide range of properties that can be manipulated by composition and heat treatment.

- Examples: steels, brass (Cu+Zn), and aluminum alloys.
Structure of an alloy

• Constitution
  – Overall composition
  – Phases and their weight fractions
  – Composition of each phase

• Shape and size of the present phases

• Mechanical properties of an alloy depends on both, and both depend on how the alloy was made (casting, heat treatments, etc.)
Phase diagram

• A phase is a region of material that has uniform physical and chemical properties.
• A phase diagram summarizes the equilibrium constitution of an alloy system.
• However, the real alloy may not have the equilibrium constitution.

• “Teaching Yourself Phase Diagrams”
Cu/Ni Alloys

- Two single-phase fields:
  - Below solidus line: solid solution (complete solubility)
  - Above liquidus line: liquid solution

- One two-phase field in between
Reading Cu/Ni phase diagram

• A: single phase solid solution with 60wt% Ni.

• B: two phases
  – Overall composition: 36wt% Ni
  – Composition of each phase: 30wt% Ni in the liquid phase and 42wt% Ni in the solid phase
  – Proportion of each phase (lever rule): 50wt% liquid and 50wt% solid.
Pb/Sn phase diagram

- 3 single-phase fields
- 3 two-phase fields
- limited solubility
- Eutectic point (lowest melting point)
Example (Figure 3.2a)

- A 50-50 Pd-Sn alloy at 170°C:
  - Two phases: (Sn) and (Pb)
  - Composition of (Sn): 2% Pb
  - Composition of (Pb): 85% Pb
  - Phase proportion: 42% (Sn) and 58% (Pb).
Soft solders

- **Eutectic solder**: 38% Pb, “easy to melt”, for electronic circuit boards.
- **Plumber’s solder**: 65% Pb, pasty and easy to shape, for joining lead pipes.
- **High-melting solder**: nearly pure Pb, for high temperature applications.
Carbon steels

- Three solid phases for pure iron;
- One intermetallic compound phase to the right.
Phases of pure iron

- Ferrite (\(\alpha\)): below 914°C, bcc crystal
- Austenite (\(\gamma\)): between 914°C and 1391°C, fcc crystal
- \(\delta\)-iron (\(\delta\)): between 1391°C and 1536°C, bcc crystal
- Melted iron: above 1536°C, liquid.

- Polymorphism: multiple crystal structures at different temperatures.
Phase transformations in pure iron

• $\alpha$ (bcc) $\leftrightarrow \gamma$ (fcc) $\leftrightarrow \delta$ (bcc) $\leftrightarrow$ Liquid

• Diffusive transformation
  – Atoms diffuse through the material
  – Depends on temperature and time

• Displacive transformation
  – Minor atomic changes occur locally at the speed of sound
  – Depends on temperature only
Diffusive $\gamma \rightarrow \alpha$ transformation

- **Speed of $\gamma/\alpha$ interface ($v$)**
  - Close to 914°C, driving force is small
  - Far below 914°C, atomic mobility is small
  - Maximum speed at about 700°C

- **Number of $\alpha$-nuclei ($N$)**
  - Depends on temperature in a similar way

- **Rate of transformation (volume per second)**: proportional to the product of $v$ and $N$. 

![Diagram showing transformation between $\gamma$ and $\alpha$ phases with temperature range from 700°C to 914°C]
TTT diagram

• Time-Temperature-Transformation (C-curves)
• Maximum transformation rate at 700°C (the “nose”).
• Slow cooling: complete transformation
• Fast cooling (quenching): unstable fcc iron?
Displacive $\gamma \rightarrow \alpha$ transformation

- FCC iron at room temperature is unstable.

- There exists a large driving force for fcc to bcc transformation.

- However, diffusive transformation is very slow and could take many years.

- Displacive transformation takes place almost instantaneously to form “martensite”.
Martensite formation

- Small lens-shaped grains of bcc nucleate at fcc grain boundaries and move across the grains
- “switch zone”: atomic bonds are broken and remade to switch fcc to bcc.
Martensite in iron

- Start at $\sim550 \, ^{\circ}C$.
- Strain energy due to local distortion stabilizes the transformation.
- More martensite at a lower temperature.
- Martensite finish (100%) at $\sim350^\circ C$.

Martensite iron is about twice as hard as ordinary bcc iron, because of smaller grain sizes.
Carbon steels

- 4 solid phases:
  - ferrite (α)
  - austenite (γ)
  - δ-iron (δ)
  - cementite (Fe₃C, an intermetallic compound with 6.7% C).

- **Eutectic reaction**: liquid (~4.3%C) → austenite + cementite

- **Eutectoid reaction**: austenite (~0.8%C) → ferrite + cementite
Eutectoid structure: pearlite

- A mixture of two phases (ferrite + cementite) with a structure of alternating plates produced by eutectoid reaction.

Pearlite in a eutectoid carbon steel.
Microstructures of a eutectoid steel

- Pearlite is not a phase (88.5% \( \alpha \) + 11.5% \( \text{Fe}_3\text{C} \)).
- Nodules, not grains.
Eutectic structure: ledeburite

- Slow cooling from liquid phase at eutectic composition (4.3%C) produces alternating layers of austenite and cementite.
- Similar structure to pearlite.
- Occur during solidification of cast irons.
- Transform to ferrite + cementite at 723°C.
Hypoeutectoid steel

- Slow cooling of low or medium carbon steels (< 0.8% C).
- Resulting structure: primary ferrite (α) grains and pearlite nodules.
Hypereutectoid steel

- Slow cooling of high-carbon steels (>0.8%C).
- Resulting structure: primary Fe₃C and pearlite.
Normalized carbon steels

- Microstructures produced by slow cooling.
- Fe₃C acts as a strengthening phase.
- α- Fe₃C interfaces in pearlite, however, is prone to crack nucleation.

- As a result, the strength increases and the ductility decreases with increasing carbon content.
TTT diagram for an eutectoid steel

- Eutectoid reaction starts at 723°C.
- Slow cooling produces pearlit by diffusive transformation.
- The nose of the C-curve is at \(~525°C\) (vs 700°C for iron)
- A cooling rate of \(~200~°C/s\) (vs \(10^5~°C/s\) for iron) misses the nose and produces martensite.
Martensite in steels

- Quenched steels form martensite.
- The martensite is oversaturated with carbon.
- Carbon atoms stretch the iron lattice to form a body centered tetragonal unit cell.
- The distortion of the lattice impedes dislocation motion (i.e., interstitial solution strengthening).
- As a result, the martensite is much harder than pearlite.
Tempered martensite

- Reheat to an intermediate temperature (300-600°C).
- Carbon atoms diffuse out to form Fe₃C precipitates.
- Distorted lattice relaxes back to bcc, and ductility goes up.
- Fe₃C precipitates keep the hardness up (precipitation strengthening).

- Big improvements in yield and tensile strength of steels can be obtained by quenching and tempering.
Lab 2

- **Videos**
  - Bubble model of dislocations
  - Deformation of crystalline materials 1 & 2

- Use the microscope to examine the metallurgical samples

- Measure Rockwell hardness of martensitic steels

- Assignments: answer all questions of Lab 2 and Lab 4 in the Manual.
Metallographic samples

• Cut specimens along sections of interest.
• Polish the section.
• Etch to expose the crystal structure.
• View the etched surfaces under the microscope.
Summary

- Phase diagrams of binary alloys.
- Phase transformation in pure iron, diffusive and displacive (martensite).
- Microstructures of normalized carbon steels.
- Control the mechanical properties (strength and ductility) of steels by heat treatments: quenching and tempering.