Engineering materials

Lecture 6

Metal and Alloys
Phase Diagrams
Metals and alloys

• Some metals may have more than one crystal structure, a phenomenon known as polymorphism (同質異性), when found in elemental solids, the condition is termed allotropy (同素異性).

• For example, pure iron has a bcc crystal structure (\( \alpha \) phase), at room temperature, which changes to fcc iron (\( \gamma \) phase) at 912 °C but goes back to bcc crystal structure (\( \delta \) phase) at 1391 °C.
Metals and alloys, cont’d

• Temperature and cooling rate are important in controlling the microstructure. If molten metals are cooled very fast, there is no time for the randomly arranged atoms in the liquid to switch into the orderly arrangement of a solid crystal. The metal becomes a glassy or amorphous solid.

• Metals always have other elements added to them which turn them into alloys and give them better mechanical properties. The allowing elements always dissolve in the basic metal to form solid solution.
Metals and alloys, cont’d

• Many alloys contain more of the alloying elements than the host metal can dissolve. The surplus atoms of the alloying element separate out as chemical compounds.

• The microstructure of a metal is defined by the constitution (the overall composition, the number of phases and their weight fractions, and the composition of each phase) and the shape and size of each phase.

• The constitution of an alloy is summarized by its phase diagram.

• A binary alloy has two components, and a ternary alloy has three components.

• A phase is a region of material that has uniform physical and chemical properties.
Alloy composition

• The composition of an alloy is usually measured in weight% (wt% or w%); in A-B alloy system,

• \( W_A = \frac{\text{Wt. of A}}{\text{Wt. of A + Wt. of B}} \times 100\% \)

• \( W_B = \frac{\text{Wt. of B}}{\text{Wt. of A + Wt. of B}} \times 100\% \)

• Equilibrium constitution: no further tendency for the constitution to change with time
Introduction

• **Phase**: A region in a material that differs in structure and function from other regions.

• **Phase diagrams**:
  • Represents phases present in metal at different conditions (Temperature, pressure and composition).
  • Indicates equilibrium solid solubility of one element in another.
  • Indicates temperature range under which solidification occurs.
  • Indicates temperature at which different phases start to melt.
Phase Diagram of Pure Substances

- Pure substance exist as solid, liquid and vapor.
- Phases are separated by phase boundaries.
- Example: Water, Pure Iron.
- Different phases coexist at triple point.

Figure 8.2
Gibbs Phase Rule

- \( P + F = C + 2 \)
  
  - \( P \) = number of phases that coexist in a system
  - \( C \) = Number of components
  - \( F \) = Degrees of freedom

- Degrees of freedom indicate number of variables that can be changed without changing number of phases.

Ex(1): For pure water, at triple point, 3 phases coexist. There is one component (water) in the system. Therefore \( 3 + F = 1 + 2 \) \( F = 0 \).

Ex(2): For pure water, when 2 phases coexist. \( 2 + F = 1 + 2 \) \( F = 1 \). (T or P can change)

Ex(3): For pure water, when only 1 phases exist. \( 1 + F = 1 + 2 \) \( F = 2 \). (T and P can both change)
Binary Isomorphous Alloy Systems

- Binary alloy → Mixture of two systems → Two component system

- Isomorphous system: Two elements completely soluble in each other in liquid and solid state.

- Example: Cu-Ni solution.

Composition at liquid and solid phases at any temperature can be determined by drawing a tie line.
The Lever Rule

- The Lever rule gives the weight % of phases in any two phase regions.

Wt fraction of solid phase
\[ X_s = \frac{w_0 - w_1}{w_s - w_1} \]

Wt fraction of liquid phase
\[ X_1 = \frac{w_s - w_0}{w_s - w_1} \]
Weight fraction

Wt fraction of solid phase in A-B system = $X_s$
Wt fraction of liquid phase in A-B system = $X_1$

$X_s + X_1 = 1$

Wt fraction of B in solid phase = $W_S$
Wt fraction of B in liquid phase = $W_L$

Balance of mass of B

Weight of B in two-phase mixture = Weight of B in phase L + Weight of B in phase S

$(1g)xW_o = (1g)xX_LxW_L + (1g)xX_SxW_S$

$W_o = X_LW_L + X_SW_S$

The Lever Rule
Example

At 1300 °C, the Cu-Ni alloy with $W_o=53 \% \text{ Ni}$ consists of two phases, Liquid and solid. Liquid with composition $W_L=45\%\text{ Ni}$, and solid with composition $W_S=58\%\text{ Ni}$.

The weight fraction

\[
X_S = \frac{W_o - W_L}{W_S - W_L} = \frac{0.53 - 0.45}{0.58 - 0.45} = \frac{0.58 - 0.53}{0.58 - 0.45}
\]
Binary Eutectic Alloy System

Proeutectic $\alpha = 24\%$

Liquid = 76%

Proeutectic $\alpha = 51\%$

Liquid = 49%

Proeutectic $\alpha$

Eutectic $\beta$

Eutectic $\alpha$

100% Liquid

Solidus

Liquidus

Alloy 2

Alloy 1

Solidus

Liquidus

Liquid

$\beta +$ liquid

$\alpha +$ liquid

$\alpha$

$\alpha$

$\alpha + \beta$

Eutectic point

183

19.2

40.0

61.9

97.5

0

10

20

30

40

50

60

70

80

90

100%

Pb

Weight percent tin

Sn
Eutectics and Eutectoids

A eutectic reaction is a three-phase reaction, i.e., on cooling, a liquid transforms simultaneously into a two solid phases.

\[
L \rightarrow \alpha + \beta
\]

At a eutectic point, the three phases \((L, \alpha, \beta)\) are in equilibrium.

A eutectoid reaction is a three-phase reaction, i.e., on cooling, a solid transforms simultaneously into a two solid phases.

\[
\beta \rightarrow \alpha + \gamma
\]

At a eutectoid point, the three phases \((\gamma, \alpha, \beta)\) are in equilibrium.
# Phase reactions

<table>
<thead>
<tr>
<th>Name of reaction</th>
<th>Equation</th>
<th>Phase-diagram characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eutectic</td>
<td>$L \xrightarrow{\text{cooling}} \alpha + \beta$</td>
<td>$\alpha \xrightarrow{L} \beta$</td>
</tr>
<tr>
<td>Eutectoid</td>
<td>$\alpha \xrightarrow{\text{cooling}} \beta + \gamma$</td>
<td>$\beta \xrightarrow{\alpha} \gamma$</td>
</tr>
<tr>
<td>Peritectic</td>
<td>$\alpha + L \xrightarrow{\text{cooling}} \beta$</td>
<td>$\alpha \xrightarrow{\beta} L$</td>
</tr>
<tr>
<td>Peritectoid</td>
<td>$\alpha + \beta \xrightarrow{\text{cooling}} \gamma$</td>
<td>$\alpha \xrightarrow{\gamma} \beta$</td>
</tr>
<tr>
<td>Monotectic</td>
<td>$L_1 \xrightarrow{\text{cooling}} \alpha + L_2$</td>
<td>$\alpha \xrightarrow{L_1} L_2$</td>
</tr>
</tbody>
</table>

*Table 8.1 Types of three-phase invariant reactions occurring in binary phase diagrams*
Phase analysis

The phase analyses of lead-tin alloys

a. at the eutectic composition just below 183°C
b. the point c at 40% Sn and 230°C
c. the point d at 40% Sn and 183°C+ $\Delta T$
d. the point e at 40% Sn and 183°C- $\Delta T$

What are the phases?
Compositions of phases?
Weight fraction of each phase?