Metals

Engineering Materials, MECH 390

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Metals

Objectives :

Upon studying this part of the chapter student should be able to:

1. Introduce some examples of Phase Diagrams
2. Understand different factors that account for wide spread application of ferrous alloy.
3. Describe a classification scheme for the various ferrous alloys (steels and cast irons).
4. List different applications for different types of ferrous alloys.
5. To be aware of the AISI/SAE designation system of plain carbon steel.
6. Understand the limitations of ferrous alloys and the characteristic of nonferrous alloys.
7. Introduce supperalloys and list their groups and applications.

Four Types of Engineering Materials

1. Metals
2. Ceramics
3. Polymers
4. Composites

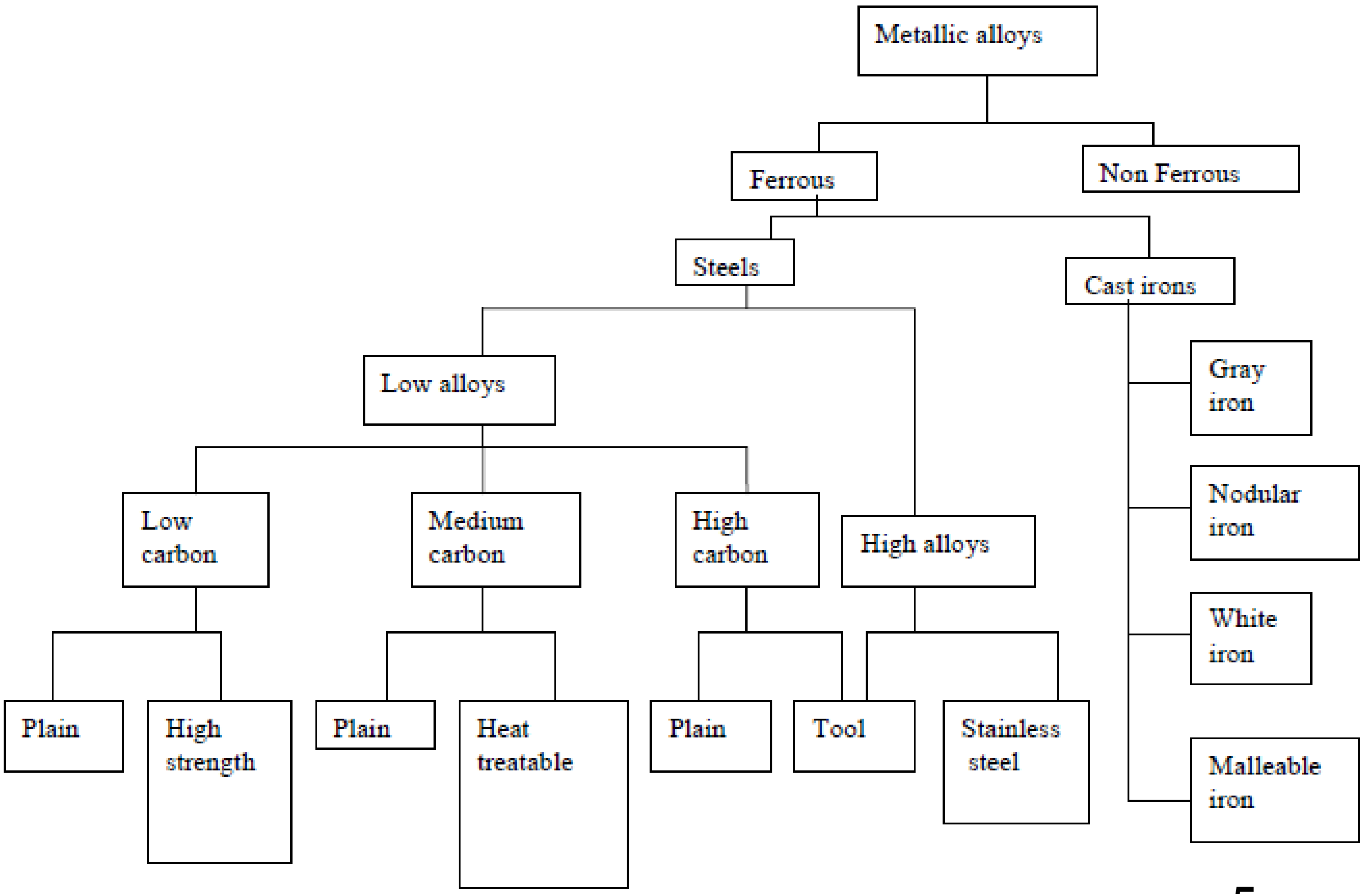
METALS

1. Alloys and Phase Diagrams
2. Ferrous Metals
3. Nonferrous Metals
4. Superalloys

Why Metals Are Important

- High stiffness and strength - can be alloyed for high rigidity, strength, and hardness
- Toughness - capacity to absorb energy better than other classes of materials
- Good electrical conductivity - Metals are conductors
- Good thermal conductivity - conduct heat better than ceramics or polymers
- Cost – the price of steel is very competitive with other engineering materials

Classification of Metals



Classification of Metals

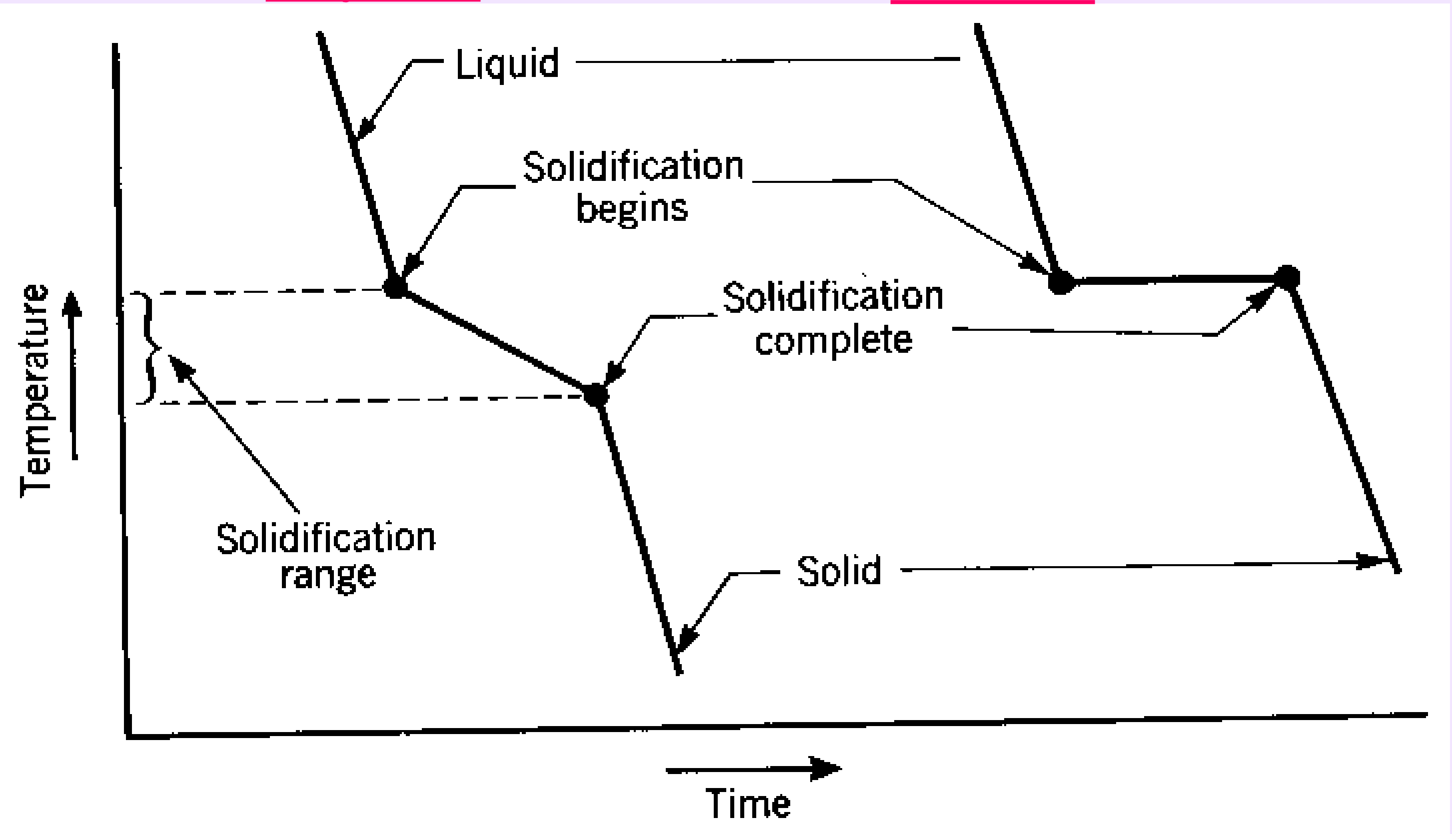
- *Ferrous* - those based on iron
  - Steels
  - Cast irons
- *Nonferrous* - all other metals
  - Aluminum, magnesium, copper, nickel, titanium, zinc, lead, tin, molybdenum, tungsten, gold, silver, platinum, and others
- *Superalloys*

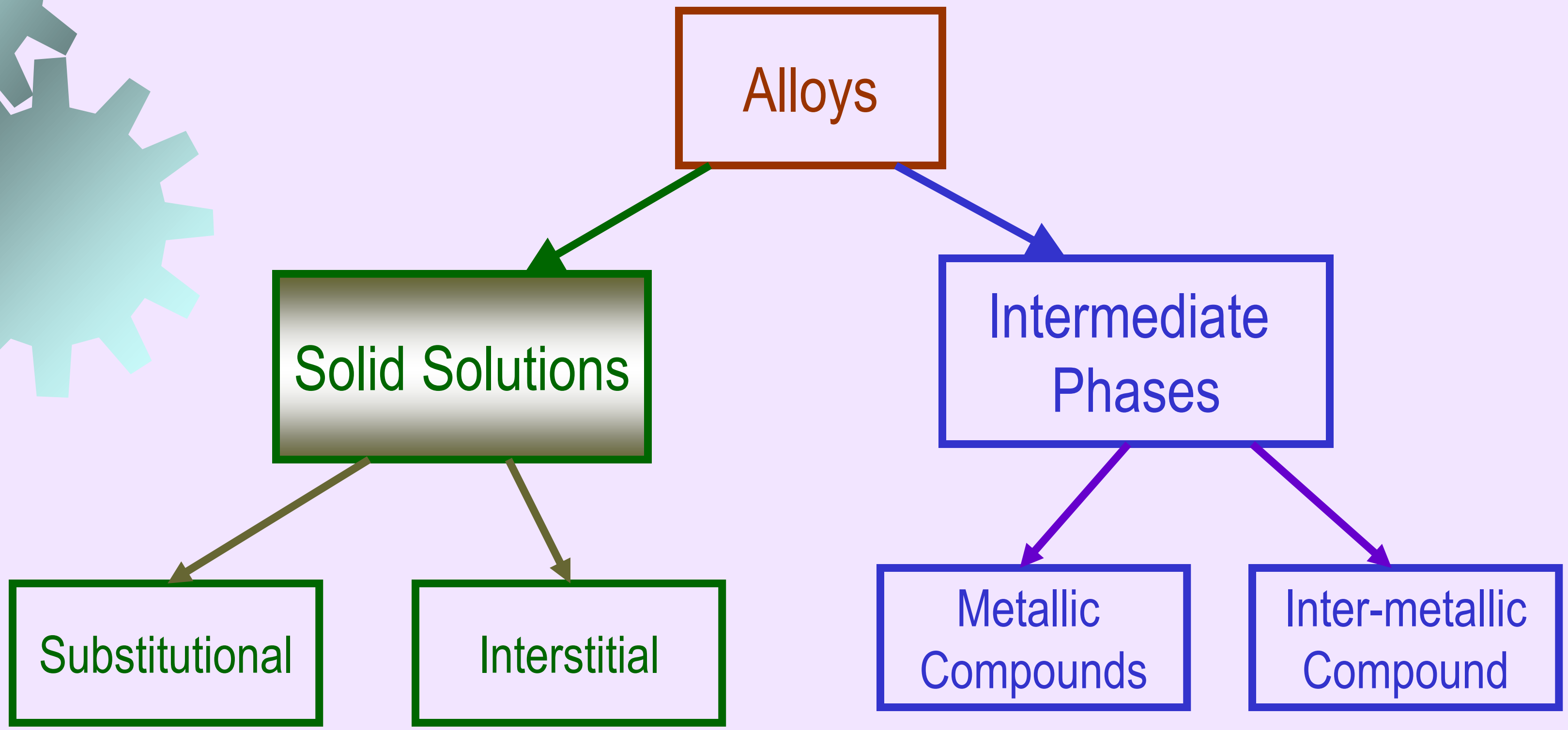
Metals and Alloys

- An Alloy = A metal composed of two or more elements
  - **At least one element is metallic**
- Enhanced properties versus pure metals
  - Strength
  - Hardness
  - Corrosion resistance
- Two main categories of Alloys
  - Solid Solutions
  - Intermediate Phases

Difference between solidification of an alloy and a pure metal

Alloy Metal **Pure Metal**




Alloys
Solid Solutions
Intermediate Phases
Substitutional
Interstitial
Metallic Compounds
Inter-metallic Compound

Solid Solutions

An alloy in which one element is dissolved in another to form a single-phase structure

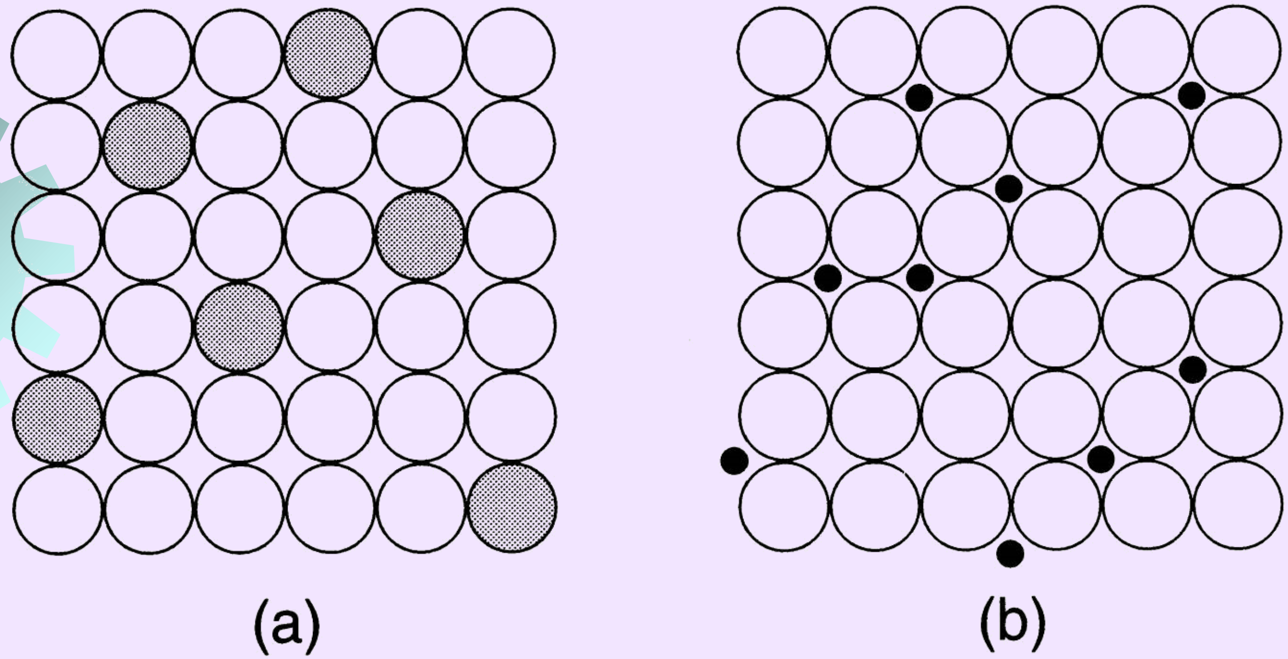
- Base element is metallic (Solvent)
- Dissolved element, metallic or non-metal

What is a phase (in a material structure)?

A *phase* = any homogeneous mass of material, such as a metal, in which the grains all have the same crystal lattice structure!

Two Forms of Solid Solutions

Atomic radii must be similar



Must be small atoms: Hydrogen, Carbon, Nitrogen, Boron

Figure 6.1

Substitutional solid solution - atoms of solvent element are replaced in its unit cell by dissolved element

Interstitial solid solution - atoms of dissolving element fit into vacant spaces between base metal atoms in the lattice structure

In both forms, the alloy structure is generally stronger and harder than either of the component elements

Two Forms of Solid Solutions

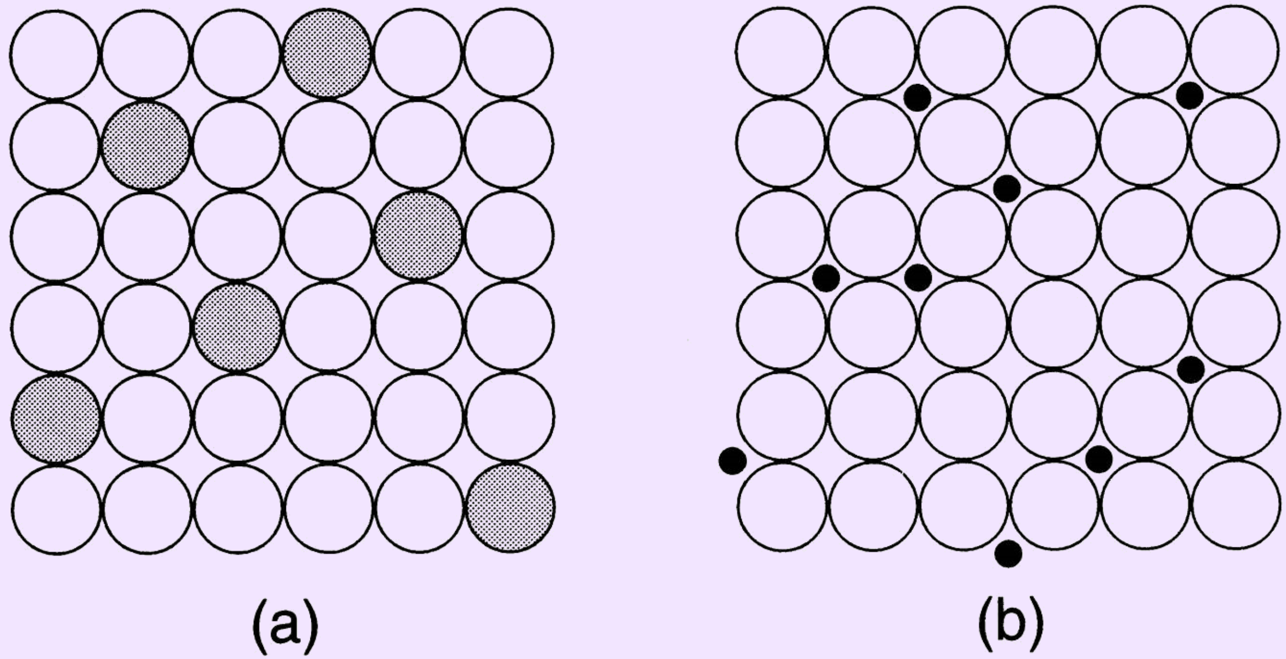


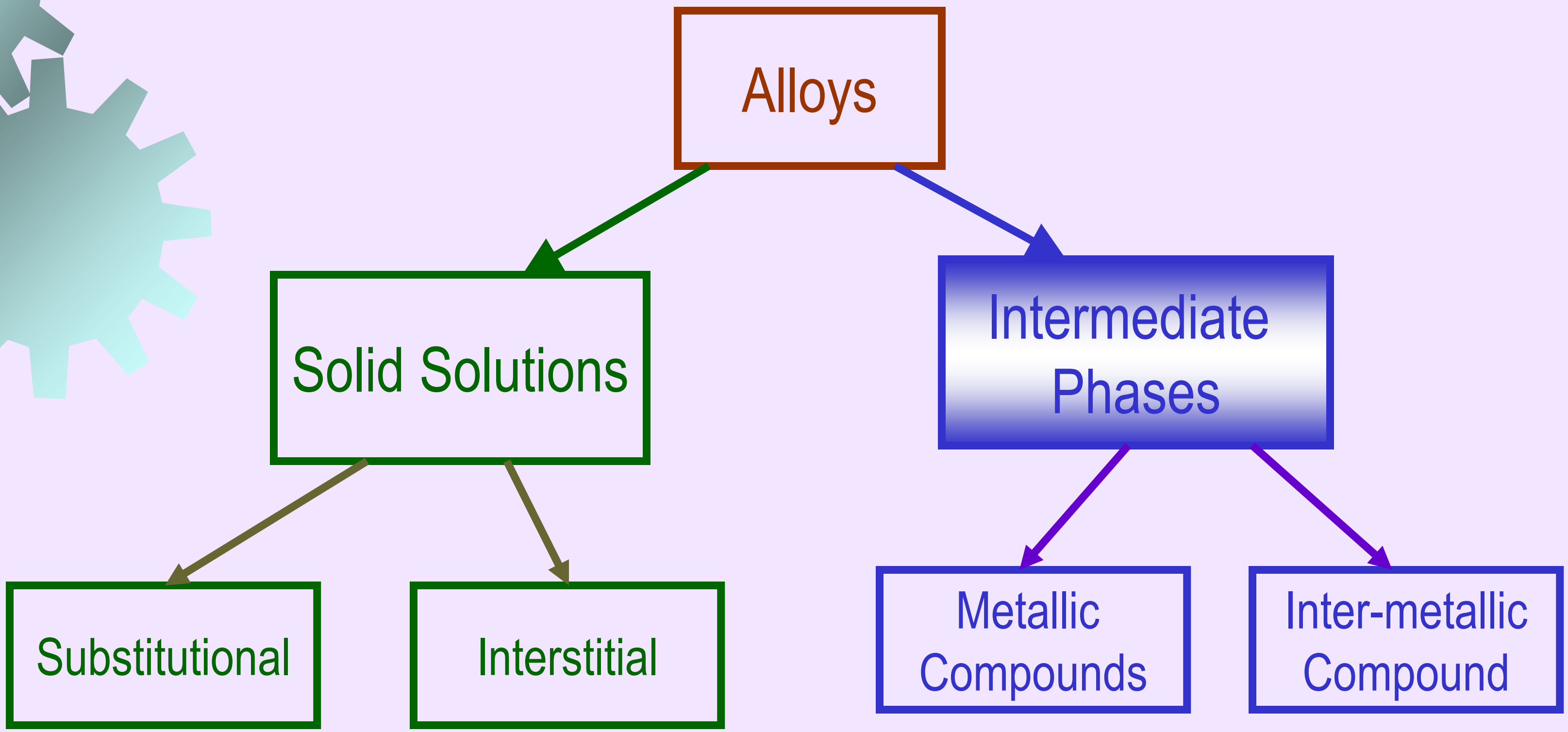
Figure 6.1

Substitutional solid solution

Zinc dissolved in Copper = **Brass**

Interstitial solid solution

Carbon dissolved in Iron = **Steel**


Alloys
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Intermediate Phases

- There are usually <u>limits to the solubility</u> of one element in another
- When the amount of the dissolving element in the alloy <u>exceeds the solid solubility limit</u> of the base metal, a second phase forms in the alloy
- The term *intermediate phase* is used to describe it because its chemical composition is intermediate between the two pure elements
- Its crystalline structure is also different from those of the pure metals

Types of Intermediate Phases

1. Metallic compounds – consist of a metal and nonmetal, such as Fe_3C
2. Intermetallic compounds - two metals that form a compound, such as Mg_2Pb

- In some alloy compositions, the intermediate phase is mixed with the primary solid solution to form a two-phase structure
- Some two-phase alloys are important because they can be heat treated for much higher strength than solid solutions

Phase Diagrams

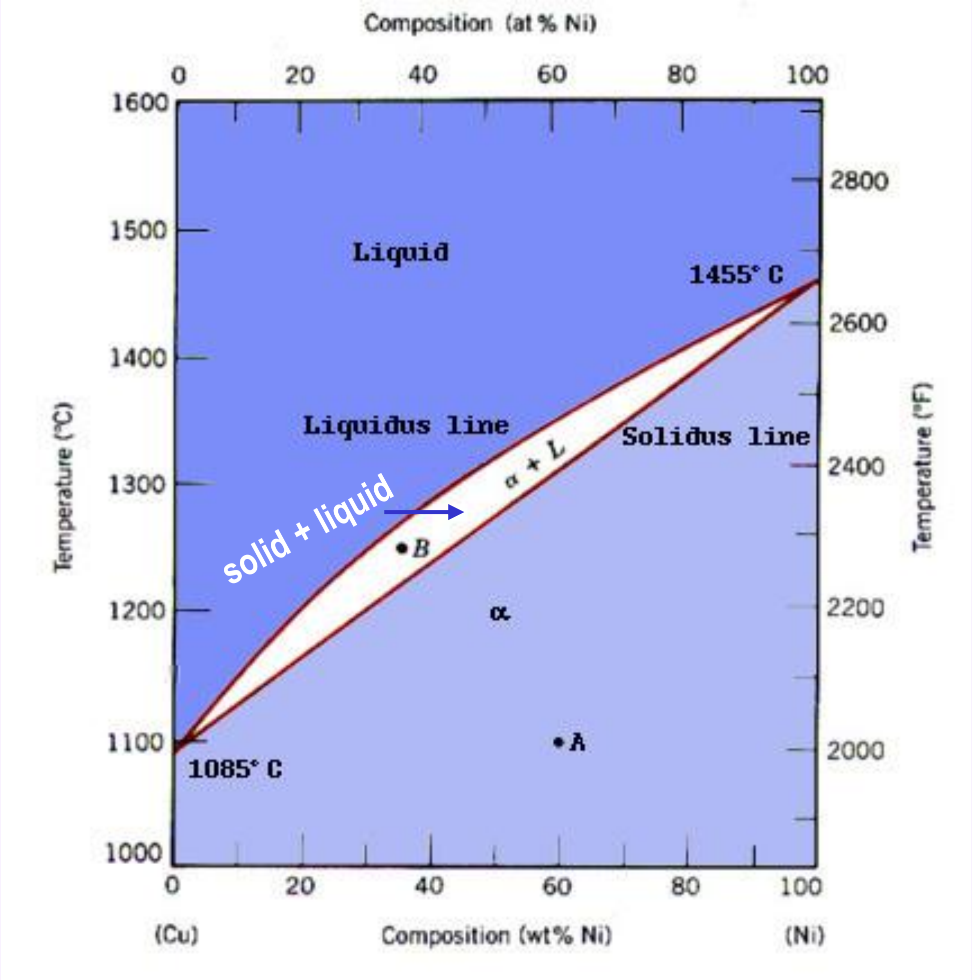
Phase Diagrams

A graphical picture showing the <u>phases of a metal alloy</u> system as a function of <u>composition</u> and <u>temperature</u>

- <u>Composition</u> is plotted on the <u>horizontal axis</u> and <u>temperature</u> on the <u>vertical axis</u>
- Any point in the diagram indicates the overall composition and the phase or phases present at the given temperature under equilibrium conditions
- A phase diagram for an alloy system consisting of two elements at atmospheric pressure is called a *binary phase diagram*

Binary Phase Diagrams
Copper-Nickel (Cu- Ni) Phase Diagram

The overall composition of the alloy is given by its position along the horizontal axis



Consider point A:
Composition: 60% Ni, 40% Cu
At 1100^0 C (or 2000^o F) the alloy is still at solid stage.

Consider point B:
About 35% Ni and 65% Cu,
At 1250^{o}C, it is a mixture of liquid and solid.

Figure 6.2 Phase diagram for the copper-nickel alloy system.

Chemical Compositions of Phases

- The overall composition of the alloy is given by its position along the horizontal axis
- However, the <u>compositions of liquid and solid phases are not the same</u>
  - These compositions can be found by drawing a horizontal line at the temperature of interest
  - Where the line intersects the solidus and liquidus indicates the compositions of solid and liquid phases, respectively. We use the Inverse Lever Rule to find the compositions:

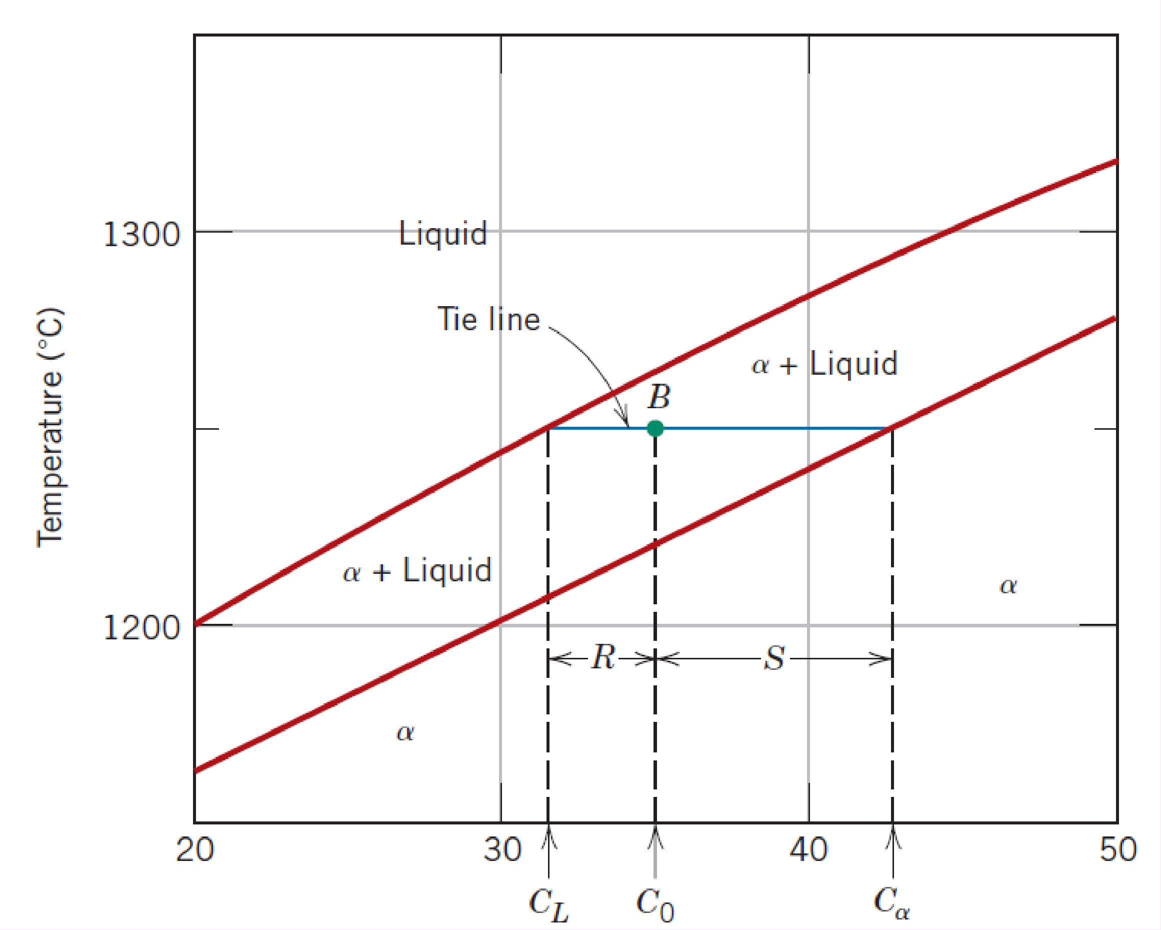
Chemical Compositions of Phases

$$W_L = \frac{S}{R + S}$$

$$W_L = \frac{C_\alpha - C_0}{C_\alpha - C_L}$$

$$W_\alpha = \frac{R}{R + S}$$

$$= \frac{C_0 - C_L}{C_\alpha - C_L}$$



W_L and W_α are mass fractions

Example

Determine compositions of liquid and solid phases in the Cu-Ni system at an aggregate composition of 50% nickel and a temperature of 1260ºC (2300ºF)

- The proportion of solid phase present is given by

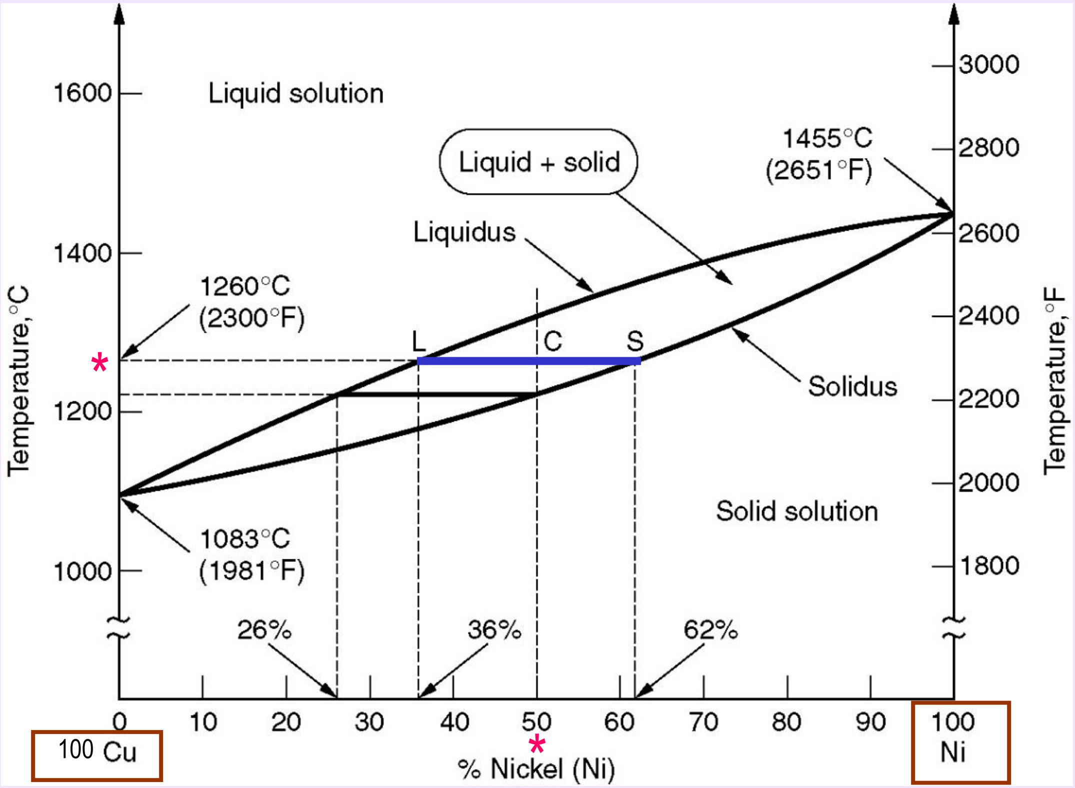
S phase proportion $= \dfrac{CL}{CS + CL}$

$= (50-36)/(14+12)=54\%$

- And the proportion of liquid phase present is given by

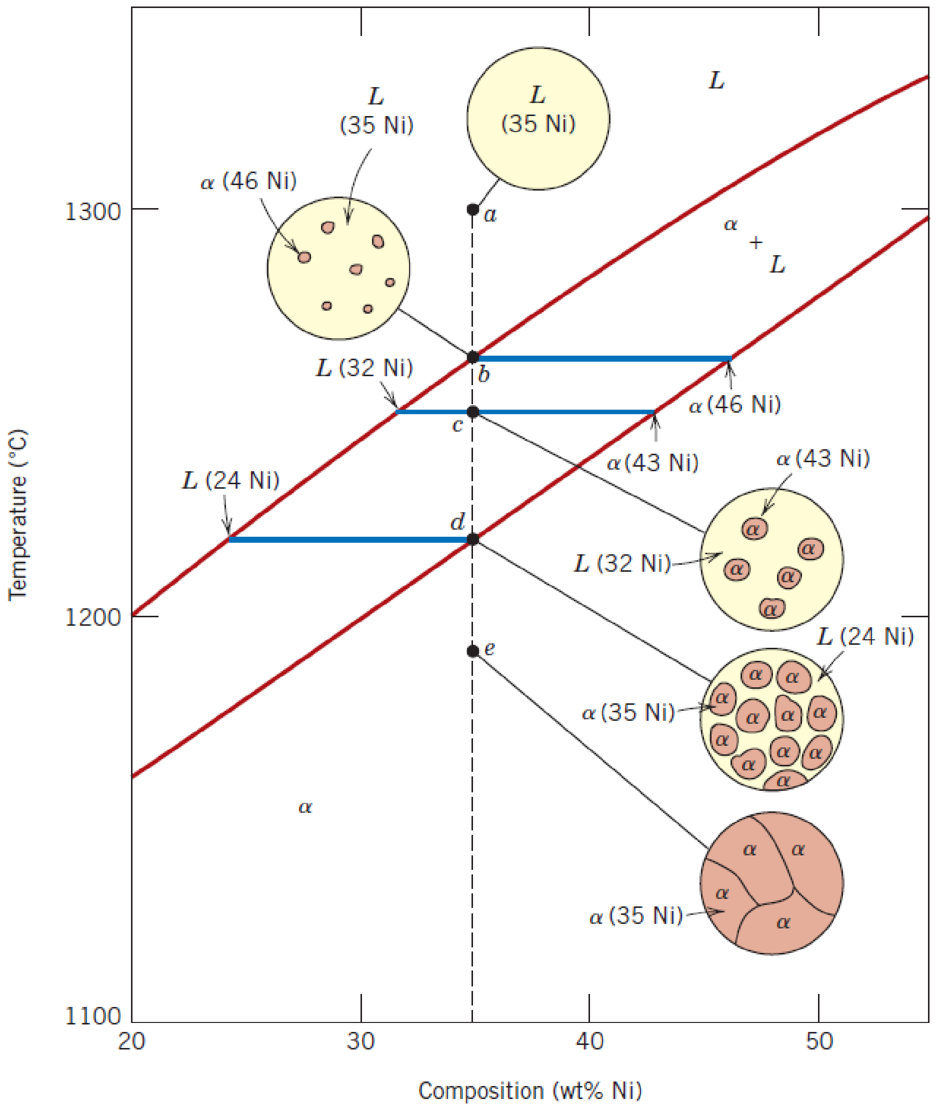
L phase proportion $= \dfrac{CS}{(CS + CL)}$

$= 100\% - 54\% = 46\%$



Example

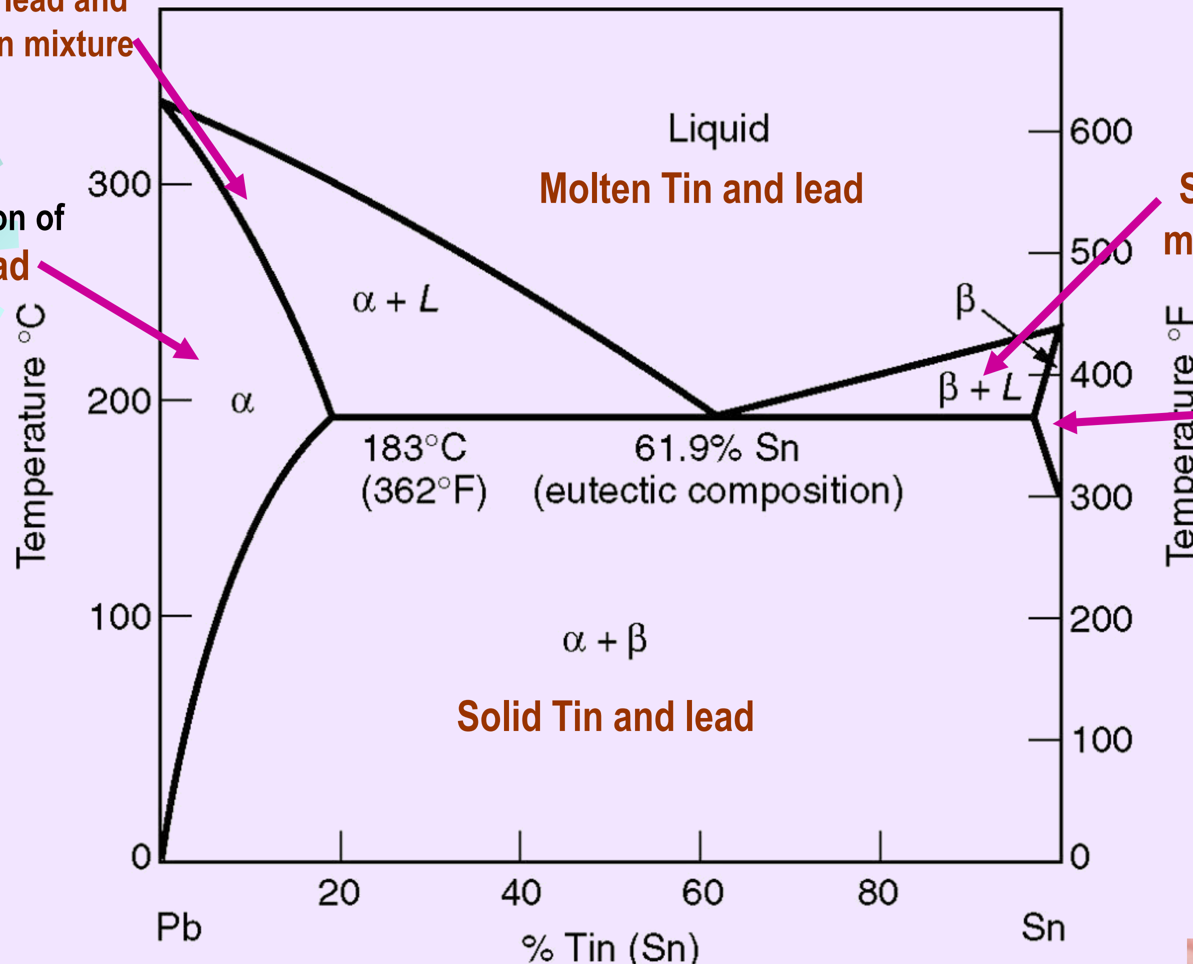
Figure 9.4 Schematic representation of the development of microstructure during the equilibrium solidification of a 35 wt% Ni–65 wt% Cu alloy.



Lead-Tin (Pb-Sn) Phase Diagram

Solid lead and molten mixture

Solid solution of Tin in Lead



Solid Tin and molten mixture

Solid solution of Lead in Tin

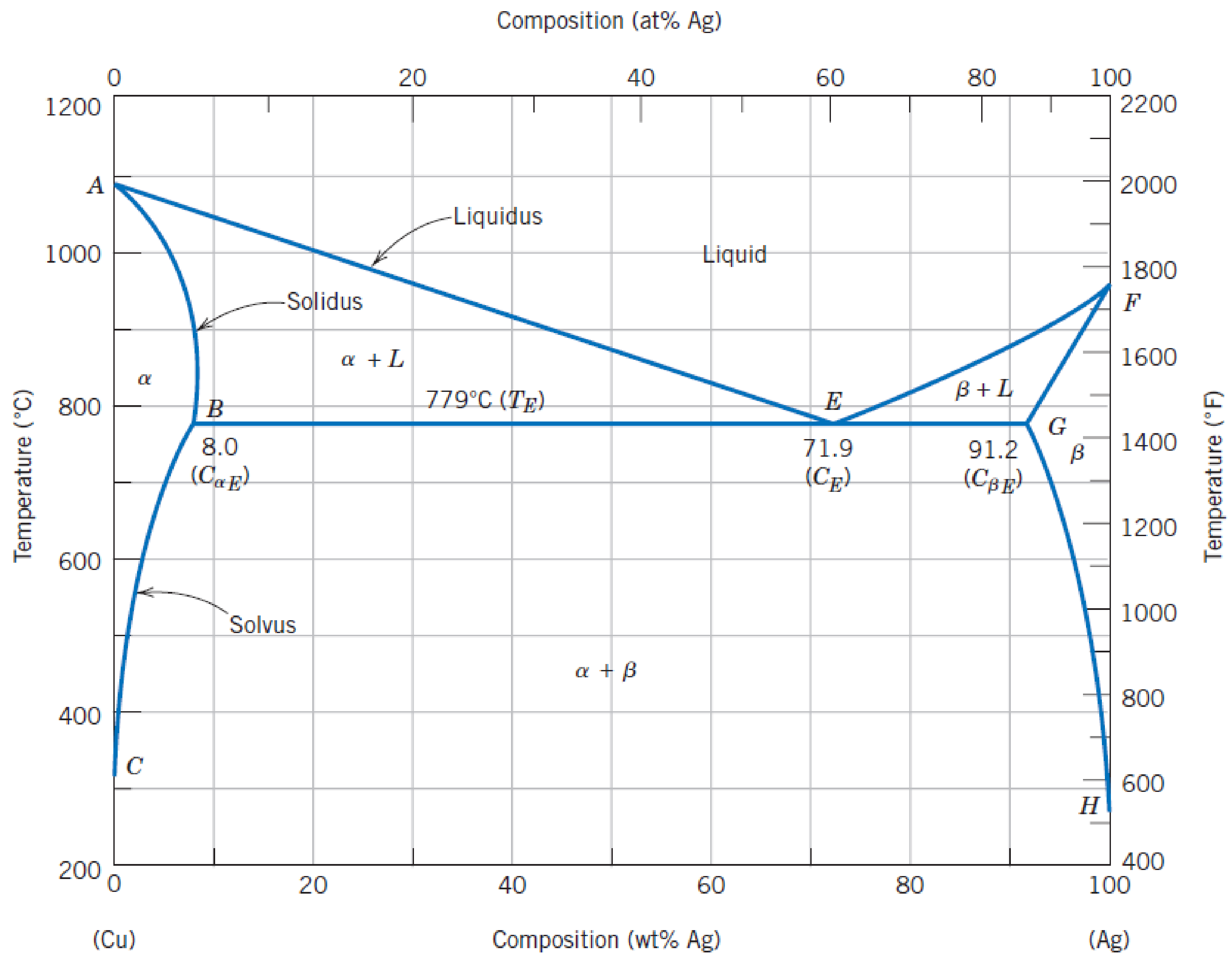
Widely used in soldering for making electrical connections

Figure 6.3 Phase diagram for the tin-lead alloy system.

Pure tin melts at 232°C (449°F)

Pure lead melts at 327°C (621°F)

The copper–silver phase diagram.



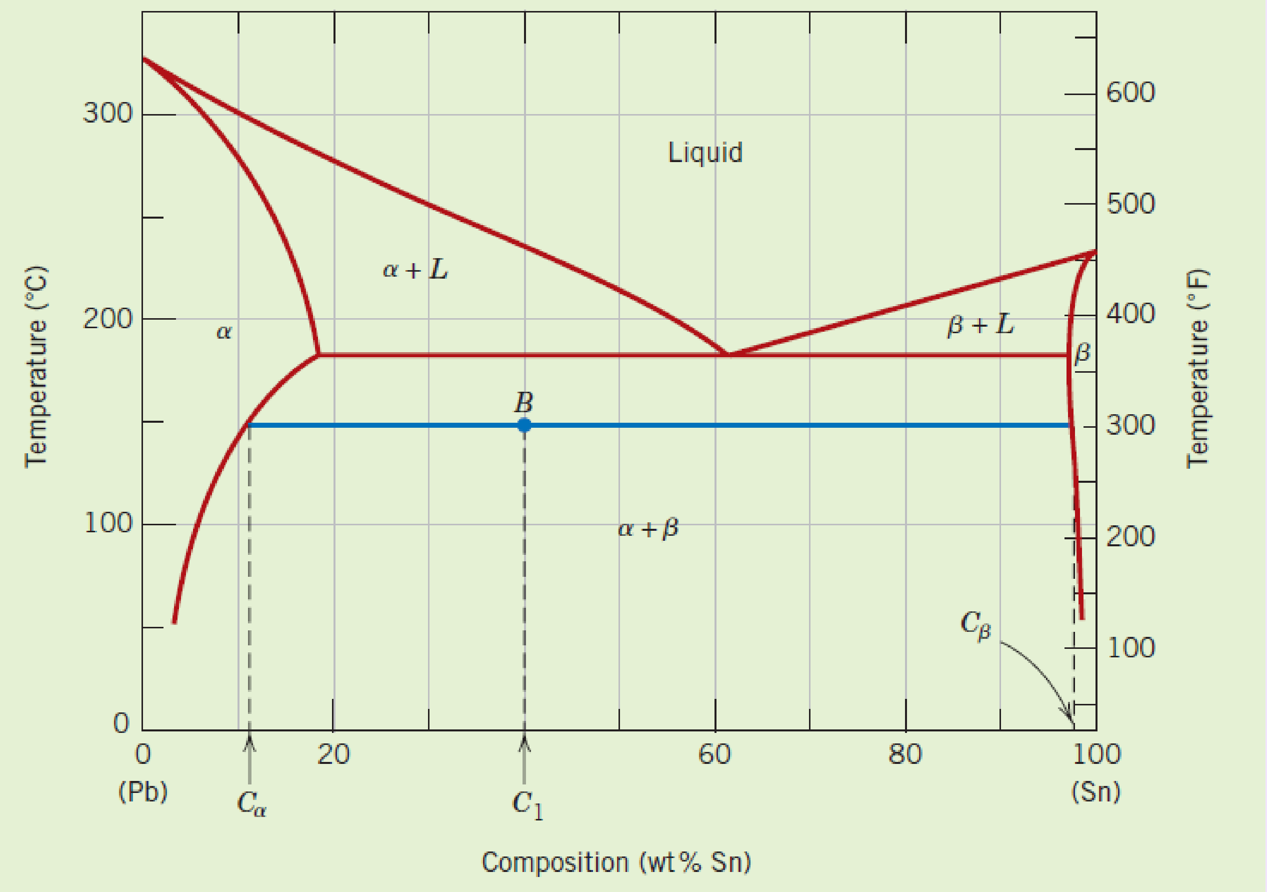
Example

For a 40 wt% Sn–60 wt% Pb alloy at 150°C (300°F),

(a) What phase(s) is (are) present?
(b) What is (are) the composition(s) of the phase(s)?
(c) Calculate the relative amount of each phase present in terms of mass fraction
(d) Calculate the relative amount of each phase present in terms of volume fraction.

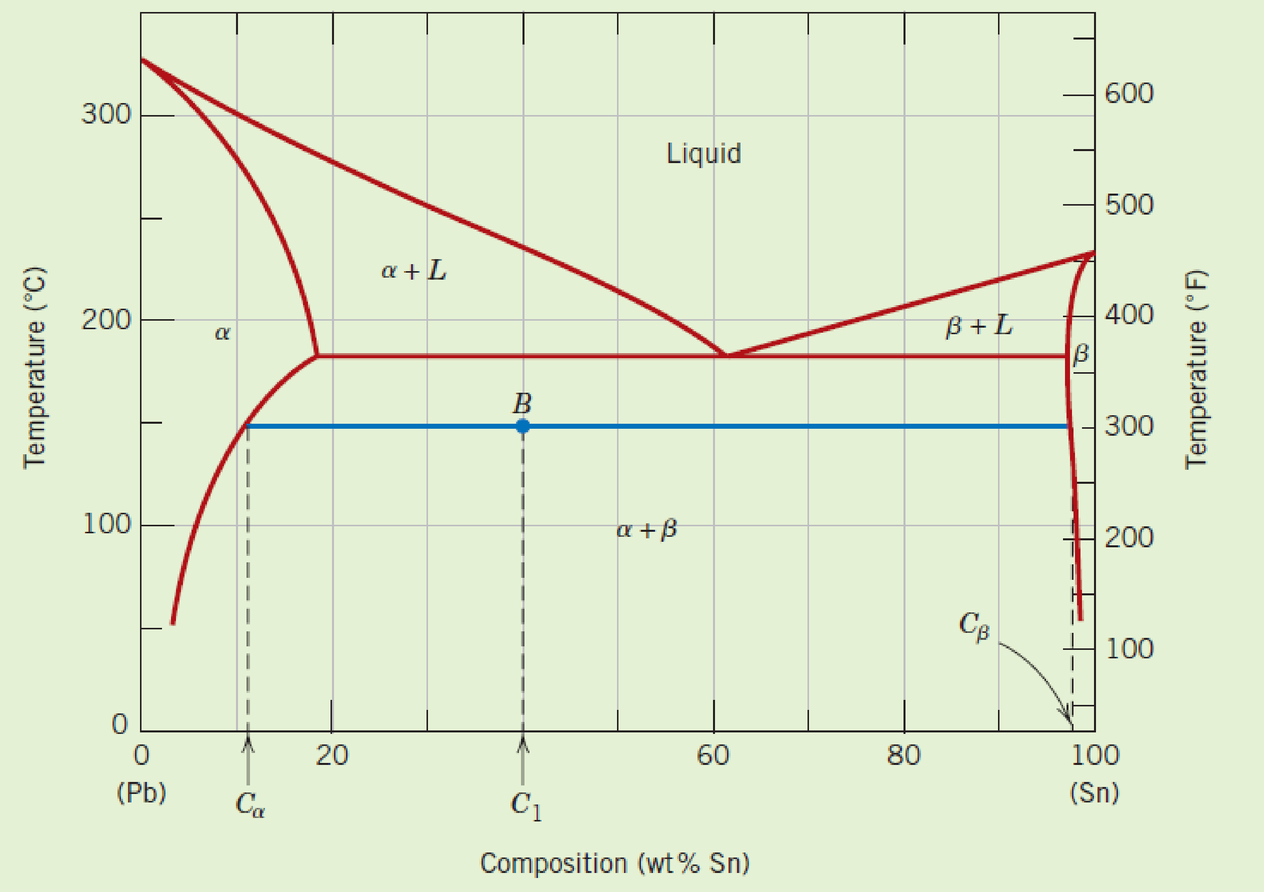
At 150 ^{o}C take the densities of Pb and Sn to be 11.23 and 7.24 g/cm3, respectively.

Solution



(a) Locate this temperature–composition point on the phase diagram (point *B* in Figure). It is within the α+β region, both α and β phases will coexist.

Solution



(b) Since two phases are present, it becomes necessary to construct a tie line across α+β the phase field at 150 ºC as indicated in Figure. The composition of the phase corresponds to the tie line intersection with the α & α+β solvus phase boundary—about 10 wt% Sn–90 wt% Pb, denoted as C_α. Similarly for the β phase, which will have a composition of approximately 98 wt% Sn–2 wt% Pb (C_β).

Solution

(c) mass fractions may be computed by subtracting compositions, in terms of weight percent tin, as follows

$$W_\alpha = \frac{C_\beta - C_1}{C_\beta - C_\alpha} = \frac{98 - 40}{98 - 10} = 0.66$$

$$W_\beta = \frac{C_1 - C_\alpha}{C_\beta - C_\alpha} = \frac{40 - 10}{98 - 10} = 0.34$$

(d) To compute volume fractions it is first necessary to determine the density of each phase

$$\rho_\alpha = \frac{100}{\dfrac{C_{\mathrm{Sn}(\alpha)}}{\rho_{\mathrm{Sn}}} + \dfrac{C_{\mathrm{Pb}(\alpha)}}{\rho_{\mathrm{Pb}}}}$$

$$\rho_\alpha = \frac{100}{\dfrac{10}{7.24\ \mathrm{g/cm^3}} + \dfrac{90}{11.23\ \mathrm{g/cm^3}}} = 10.64\ \mathrm{g/cm^3}$$

$$\rho_\beta = \frac{100}{\dfrac{C_{\mathrm{Sn}(\beta)}}{\rho_{\mathrm{Sn}}} + \dfrac{C_{\mathrm{Pb}(\beta)}}{\rho_{\mathrm{Pb}}}} = \frac{100}{\dfrac{98}{7.24\ \mathrm{g/cm^3}} + \dfrac{2}{11.23\ \mathrm{g/cm^3}}} = 7.29\ \mathrm{g/cm^3}$$

Where $C_{sn(\alpha)}$ and $C_{Pb(\alpha)}$ denote the concentrations in weight percent of tin and lead, respectively, in the phase α

Solution

volume fractions V_α and V_β is

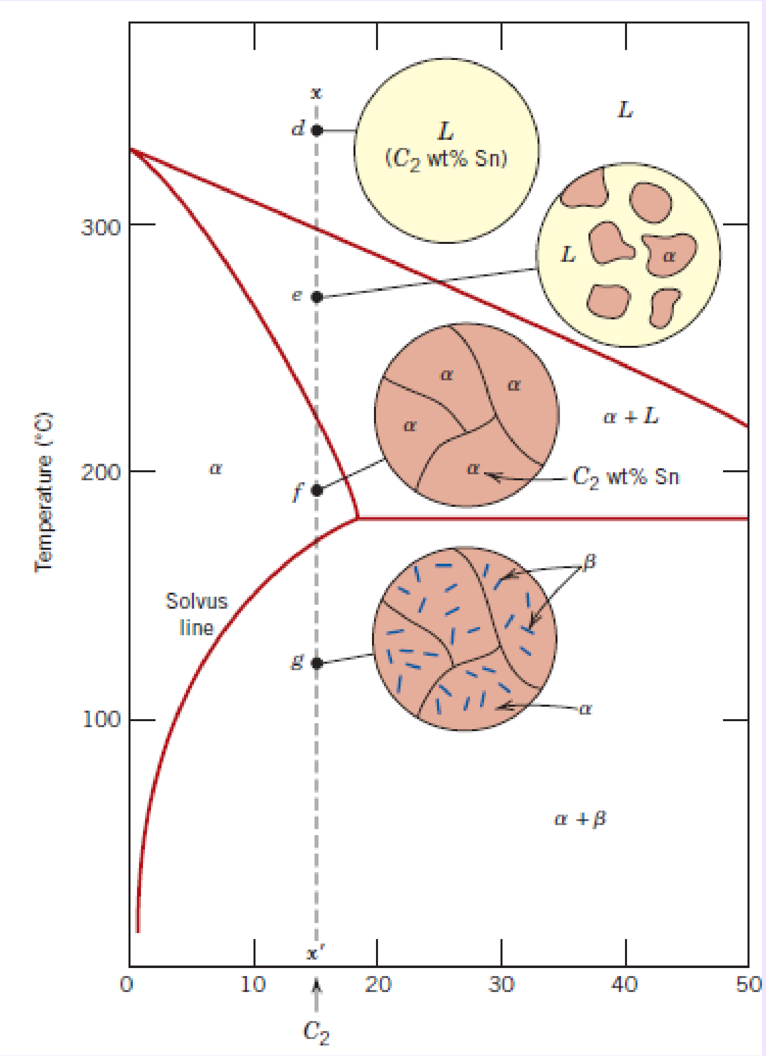
$$V_\alpha = \frac{\dfrac{W_\alpha}{\rho_\alpha}}{\dfrac{W_\alpha}{\rho_\alpha} + \dfrac{W_\beta}{\rho_\beta}}$$

$$= \frac{\dfrac{0.66}{10.64\ \text{g/cm}^3}}{\dfrac{0.66}{10.64\ \text{g/cm}^3} + \dfrac{0.34}{7.29\ \text{g/cm}^3}} = 0.57$$

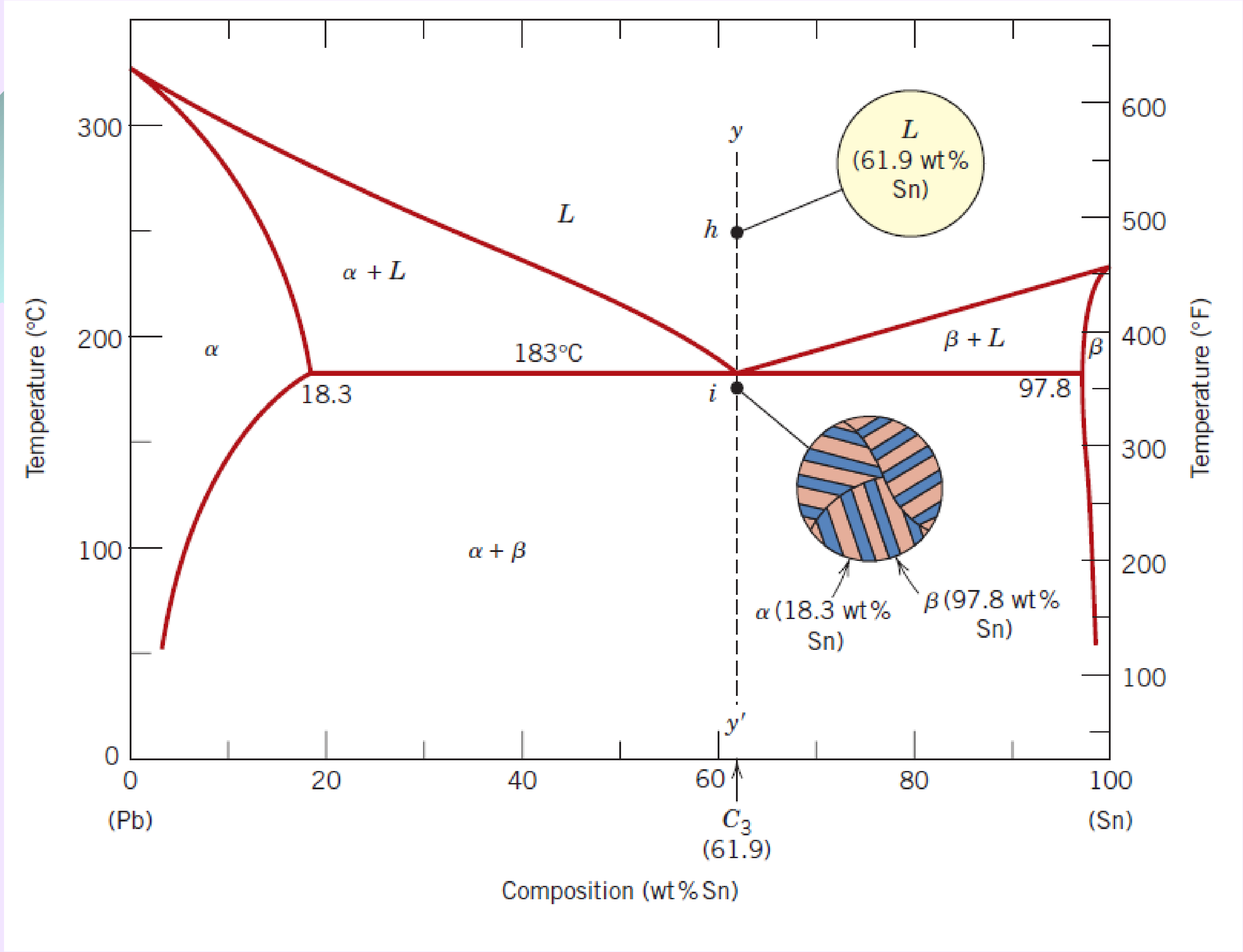
$$V_\beta = \frac{\dfrac{W_\beta}{\rho_\beta}}{\dfrac{W_\alpha}{\rho_\alpha} + \dfrac{W_\beta}{\rho_\beta}}$$

$$= \frac{\dfrac{0.34}{7.29\ \text{g/cm}^3}}{\dfrac{0.66}{10.64\ \text{g/cm}^3} + \dfrac{0.34}{7.29\ \text{g/cm}^3}} = 0.43$$

Schematic representations of the equilibrium microstructures for a lead–tin alloy



Schematic representations of the equilibrium microstructures for a lead–tin alloy



Ferrous Metals

Ferrous Metals

Based on iron, one of the oldest metals known to man

- Ferrous metals of engineering importance are alloys of iron and carbon

- These alloys divide into <u>two major groups</u>:
  - Steel
  - Cast iron

- Together, they constitute approximately 85% of the metal tonnage in the United States

Steel and Cast Iron

What is the difference between steel and cast iron?!

Steel and Cast Iron Defined

Steel = an iron-carbon alloy containing from 0.02% to 2.1% carbon.

Cast iron = an iron-carbon alloy containing from 2.1% to about 4% or 5% carbon.

- Steels and cast irons can also contain other alloying elements besides carbon.

Iron-Carbon Phase Diagram

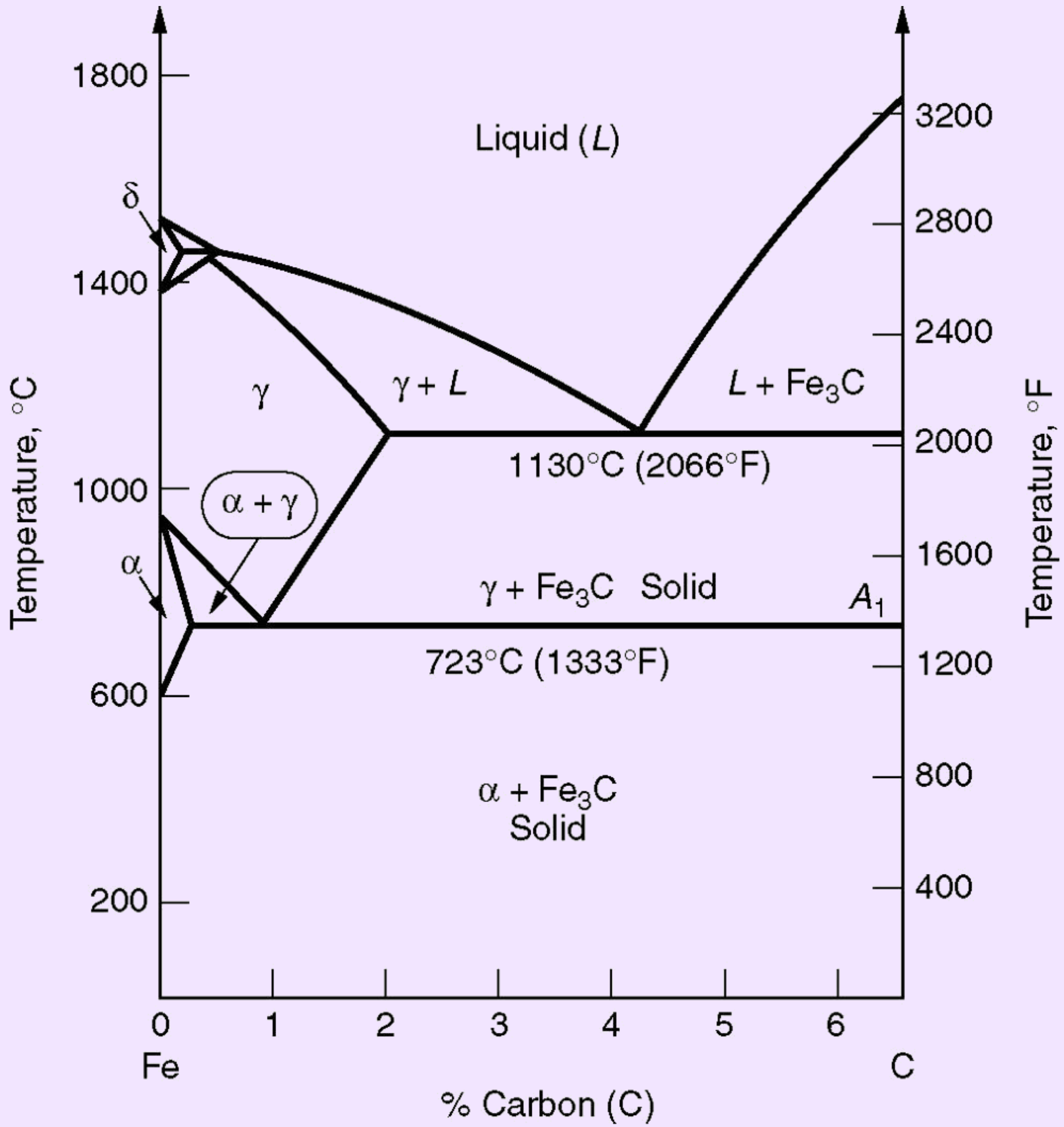
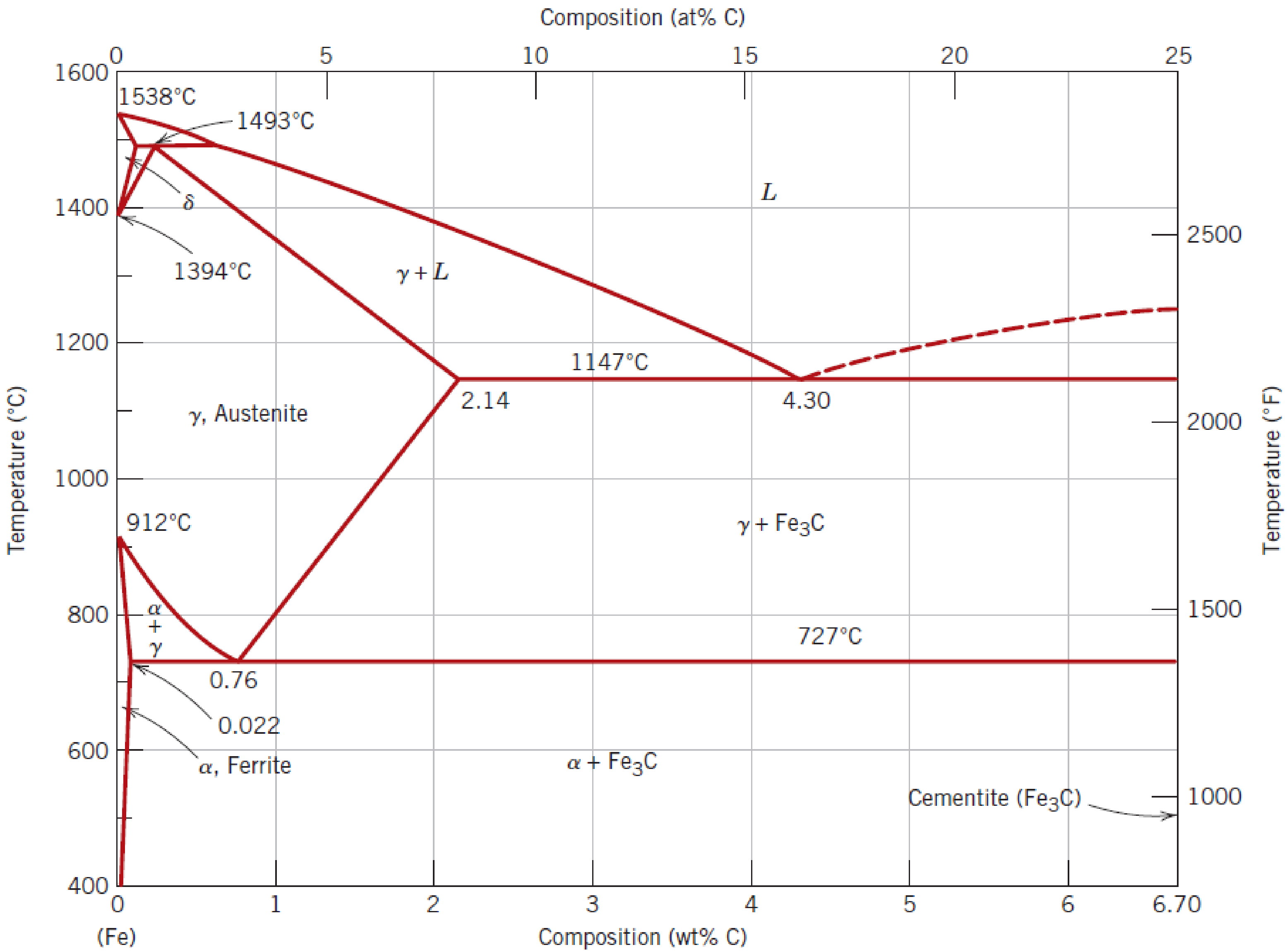


Figure 6.4 Phase diagram for iron-carbon system, up to about 6% carbon.

Iron-Carbon Phase Diagram



Steel

Steel

An alloy of iron containing from 0.02% and 2.11% carbon by weight.

- Often includes other alloying elements: nickel, manganese, chromium, and molybdenum.

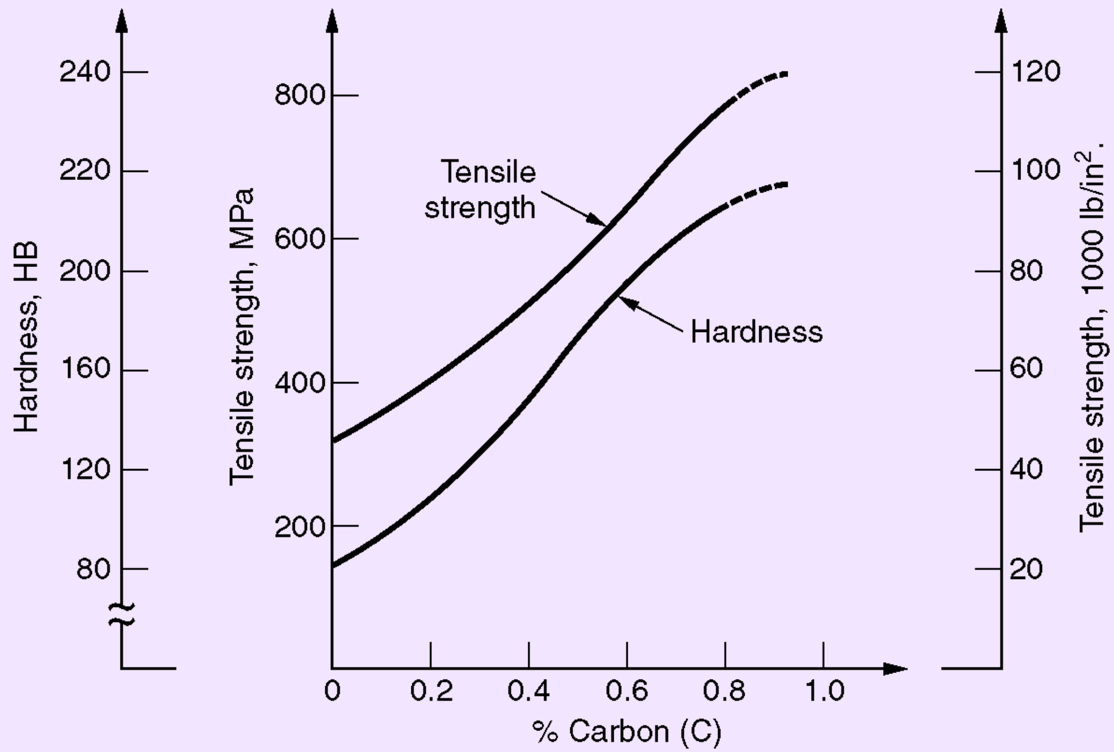
- Steel alloys can be grouped into four categories:
  1. **Plain carbon steels**
  2. **Low alloy steels**
  3. **Stainless steels**
  4. **Tool steels**

Plain Carbon Steels

- <u>Carbon is the principal alloying element</u>, with only small amounts of other elements (about 0.5% manganese is normal)
- Strength of plain carbon steels increases with carbon content, but ductility is reduced

Carbon ↗ Strength ↗ Carbon ↗ Ductility ↘

Tensile strength and hardness as a function of carbon content in plain carbon steel.

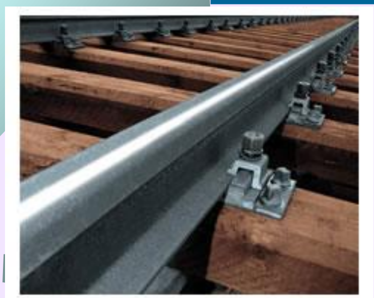


AISI-SAE Designation Scheme

Specified by a 4-digit number system: 10XX, where 10 indicates plain carbon steel, and XX indicates carbon % in hundredths of percentage points

- For example, 1020 steel contains 0.20% C
- Developed by American Iron and Steel Institute (AISI) and Society of Automotive Engineers (SAE), so designation often expressed as AISI 1020 or SAE 1020

Plain Carbon Steels



1. Low carbon steels - contain less than 0.20% C
   - Applications: automobile sheet metal parts, plate steel for fabrication, railroad rails

2. Medium carbon steels - range between 0.20% and 0.50% C
   - Applications: machinery components and engine parts such as crankshafts and connecting rods

3. High carbon steels - contain carbon in amounts greater than 0.50%
   - Applications: cutting tools and blades, wear-resistant parts

Low Alloy Steels

Iron-carbon alloys that contain additional alloying elements in amounts totaling less than ~ 5% by weight

Large diameter pipeline

- Mechanical properties superior to plain carbon steels for given applications
- Higher strength, hardness, wear resistance, toughness, and more desirable combinations of these properties
- Heat treatment is often required to achieve these improved properties

AISI-SAE Designation Scheme

AISI-SAE designation uses a 4-digit number system: YYXX, where YY indicates alloying elements, and XX indicates carbon % in hundredths of % points

- Examples:
  - 13XX - Manganese steel
  - 20XX - Nickel steel
  - 31XX - Nickel-chrome steel
  - 40XX - Molybdenum steel
  - 41XX - Chrome-molybdenum steel

High Alloy Steels: Stainless Steel (SS)

Highly alloyed steels designed for corrosion resistance

- Principal alloying element is Chromium, usually <u>greater than 15%</u>
  - Cr forms a thin <u>oxide film</u> that protects surface from corrosion

- Carbon is used to strengthen and harden SS, but high C content reduces corrosion protection since <u>chromium carbide</u> forms to reduce available free Cr

Carbon ↗ Strength ↗   Carbon ↗ Corrosion protection ↘

- Nickel (Ni) is another alloying ingredient in certain SS to increase <u>corrosion protection</u>

Properties of Stainless Steels

- In addition to corrosion resistance, stainless steels are noted for their combination of strength and ductility
  - While desirable in many applications, these properties generally make stainless steel difficult to work in manufacturing
- Significantly more expensive than plain C or low alloy steels

Tool Steels

A class of (usually) highly alloyed steels designed for use as industrial cutting tools, dies, and molds.

- To perform in these applications, they must possess high strength, hardness, wear resistance, and toughness <u>under impact.</u>
- Tool steels are <u>heat treated</u>.

AISI Classification of Tools Steels

T, M	*High-speed tool steels* - cutting tools in machining
H	*Hot-working tool steels* - hot-working dies for forging, extrusion, and die-casting
D	*Cold-work tool steels* - cold working dies for sheetmetal pressworking, cold extrusion, and forging
W	*Water-hardening tool steels* - high carbon but little else
S	*Shock-resistant tool steels* - tools needing high toughness, as in sheetmetal punching and bending
P	*Mold steels* - molds for molding plastics and rubber

AISI Classification of Tools Steels

TABLE 6.5 Tool steels by AISI prefix identification, with examples of composition and typical hardness values.

AISI	Example	Chemical Analysis, %[a]							Hardness, HRC
		C	Cr	Mn	Mo	Ni	V	W	
T	T1	0.7	4.0				1.0	18.0	65
M	M2	0.8	4.0		5.0		2.0	6.0	65
H	H11	0.4	5.0		1.5		0.4		55
D	D1	1.0	12.0		1.0				60
A	A2	1.0	5.0		1.0				60
O	O1	0.9	0.5	1.0				0.5	61
W	W1	1.0							63
S	S1	0.5	1.5					2.5	50
P	P20	0.4	1.7		0.4				40[b]
L	L6	0.7	0.8		0.2	1.5			45[b]