MATERIAL SCIENCE

Chapter 9:

Phase Diagram

Introduction and Basic Concepts

- The understanding of phase diagrams for alloy systems is extremely important because there is a strong correlation between microstructure and mechanical properties, and the development of microstructure of an alloy is related to the characteristics of its phase diagram. In addition, phase diagrams provide valuable information about melting, casting, crystallization, and other phenomena.
- **Alloy** is a metallic substance that is composed of two or more elements.

- **Components** are pure metals and/or compounds of which an alloy is composed.

- A **phase** may be defined as a homogeneous portion of a system that has uniform physical and chemical characteristics. Every pure material is considered to be a phase; so also is every solid, liquid, and gaseous solution.

- Many times, the physical properties and, in particular, the mechanical behavior of a material depend on the microstructure. Microstructure is subject to direct microscopic observation, using optical or electron microscopes

- Sometimes, a single-phase system is termed *homogeneous*. Systems composed of two or more phases are termed *mixtures* or *heterogeneous systems*. Most metallic alloys and, for that matter, ceramic, polymeric, and composite systems are heterogeneous.

Phase Equilibria: Solubility Limit

- Solution – solid, liquid, or gas solutions, single phase
- Mixture – more than one phase

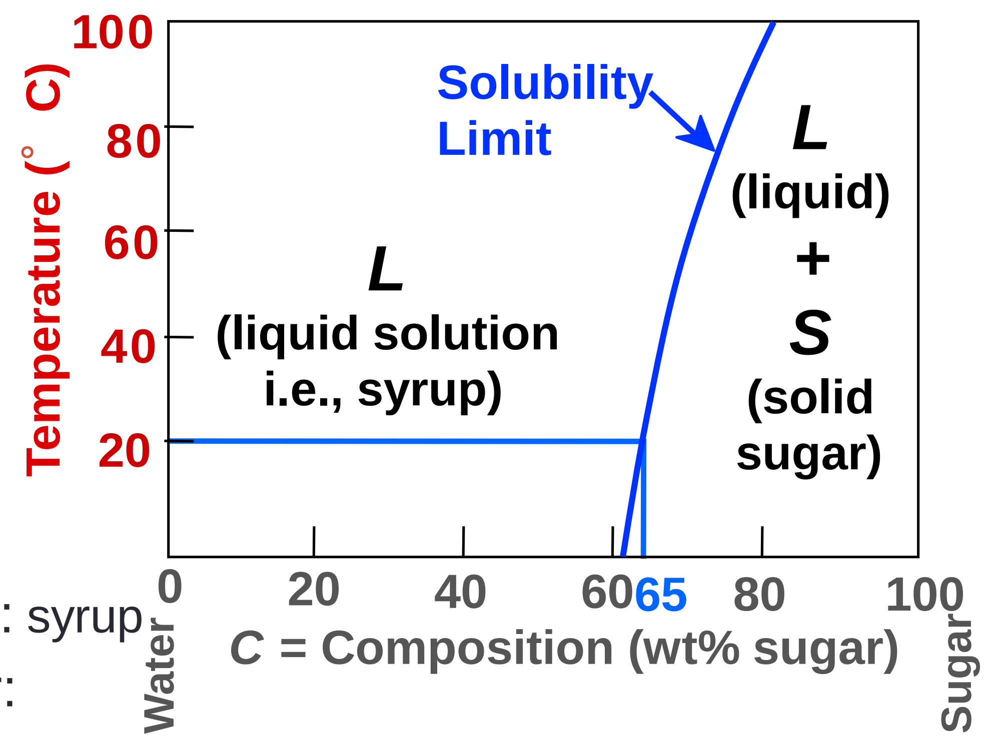
Adapted from Fig. 9.1, *Callister & Rethwisch 9e.*

- Solubility Limit:
  Maximum concentration for which only a single phase solution exists.

Question: What is the solubility limit for sugar in water at 20° C?

Answer: 65 wt% sugar.
At 20° C, if C < 65 wt% sugar: syrup
At 20° C, if C > 65 wt% sugar: syrup + sugar

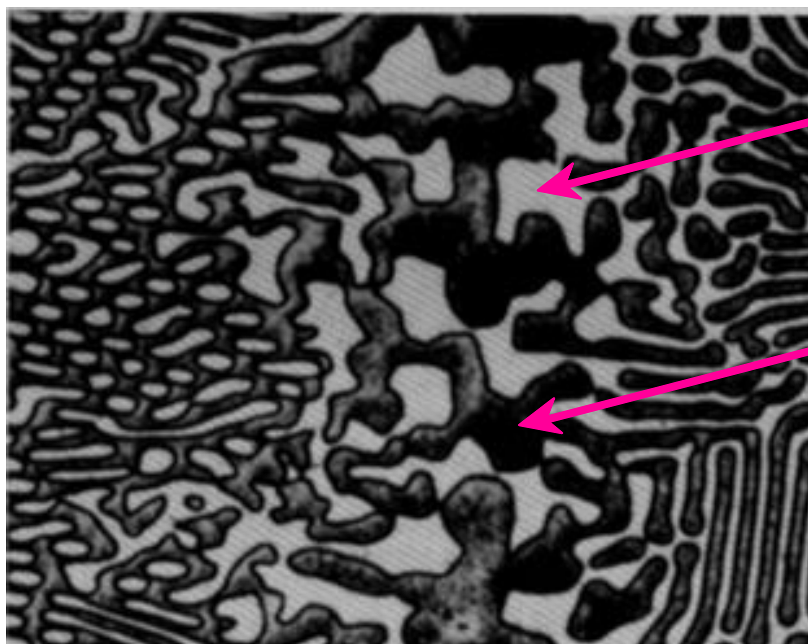
Sugar/Water Phase Diagram



Components and Phases

- Components:
  The elements or compounds which are present in the alloy (e.g., Al and Cu)
- Phases:
  The physically and chemically distinct material regions that form (e.g., α and β).

Aluminum-Copper Alloy



β (lighter phase)

α (darker phase)

Adapted from chapter-opening photograph, Chapter 9, *Callister, Materials Science & Engineering: An Introduction, 3e.*

One-Component (or Unary) Phase Diagrams

- There are three externally controllable parameters that will affect phase structure:
- temperature, pressure, and composition.
- Phase diagrams are constructed when various combinations of these parameters are plotted against one another.
- Perhaps the simplest and easiest type of phase diagram to understand is that for a one-component system, in which composition is held constant (i.e., the phase diagram is for a pure substance); this means that pressure and temperature are the variables. This one-component phase diagram (or *unary phase diagram*) [sometimes also called a *pressure–temperature* (or *P–T*) *diagram*]

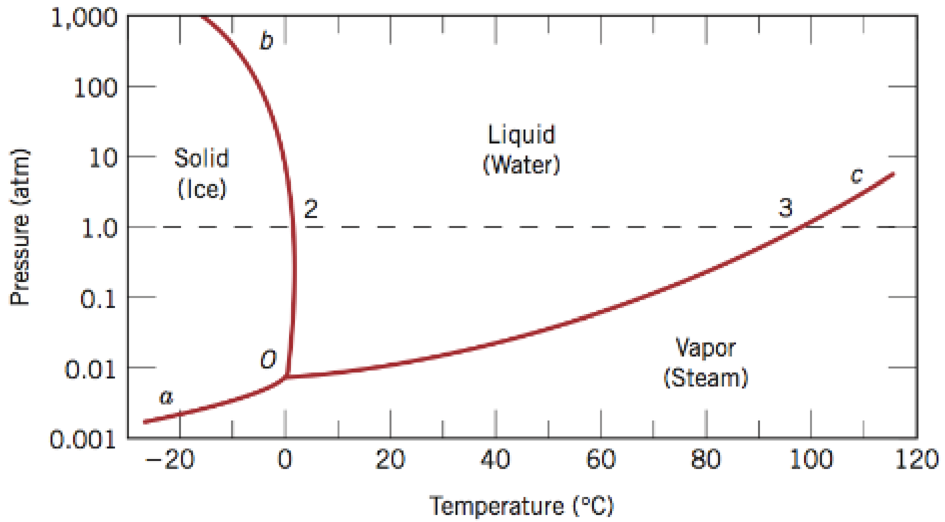


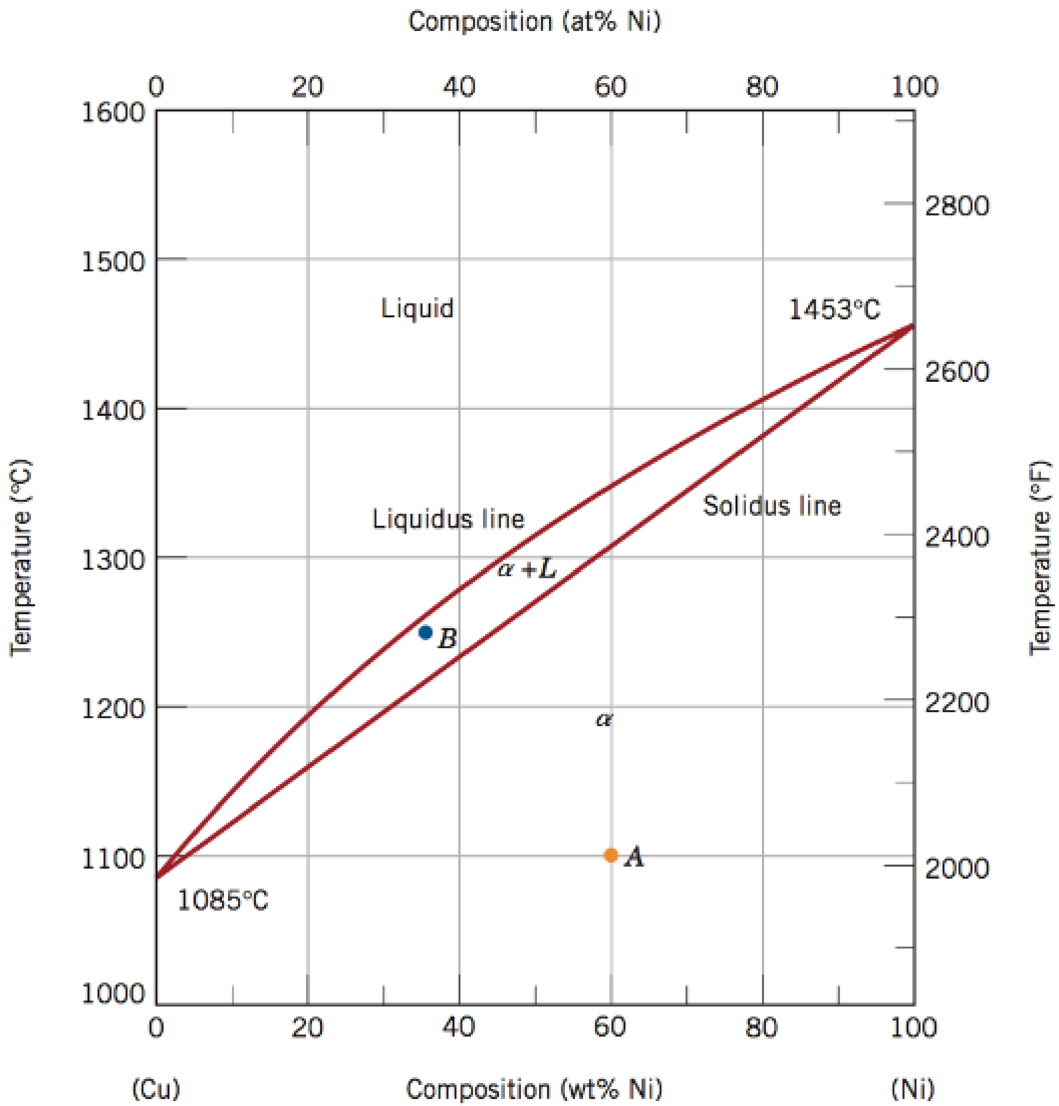
Figure 9.2 Pressure–temperature phase diagram for H_2O. Intersection of the dashed horizontal line at 1 atm pressure with the solid–liquid phase boundary (point 2) corresponds to the melting point at this pressure (T = 0°C). Similarly, point 3, the intersection with the liquid–vapor boundary, represents the boiling point (T = 100°C).

Binary Phase Diagrams

- Another type of extremely common phase diagram is one in which temperature and composition are variable parameters, and pressure is held constant—normally 1 atm.

- Possibly the easiest type of binary phase diagram to understand and interpret is the type that is characterized by the copper–nickel system (Figure 9.3*a*). Temperature is plotted along the Y-axis, and the X-axis represents the composition of the alloy, in weight percent (bottom) and atom percent (top) of nickel. The composition

- 2 phases:
  - *L* (liquid)
  - *α* (FCC solid solution)



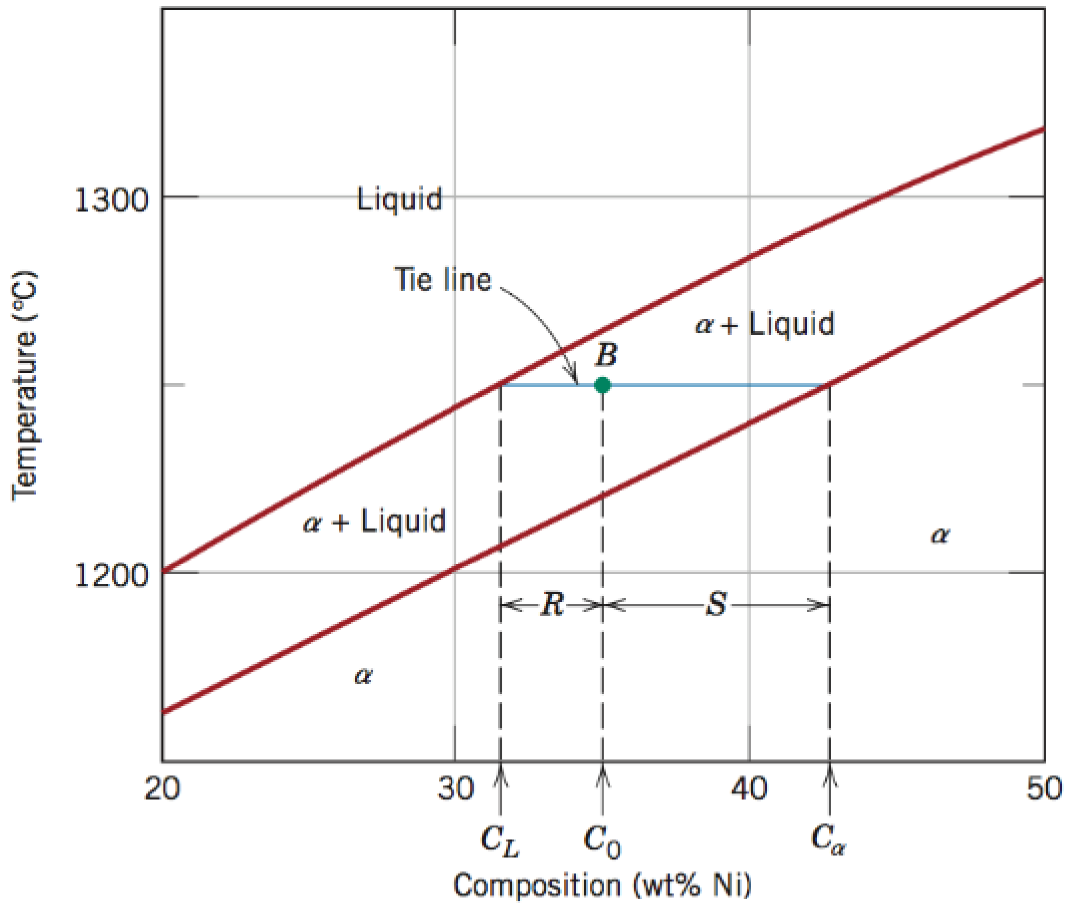
(a)

Ni and Cu are totally soluble in one another for all proportions.

Isomorphous *i.e.*, complete solubility of one component in another; *α* phase field extends from 0 to 100 wt% Ni.

Binary Phase Diagrams

For a binary system of known composition and temperature that is at equilibrium, at least three kinds of information are available: (1) the phases that are present, (2) the compositions of these phases, and (3) the percentages or fractions of the phases.



(b)

Phase Diagrams:

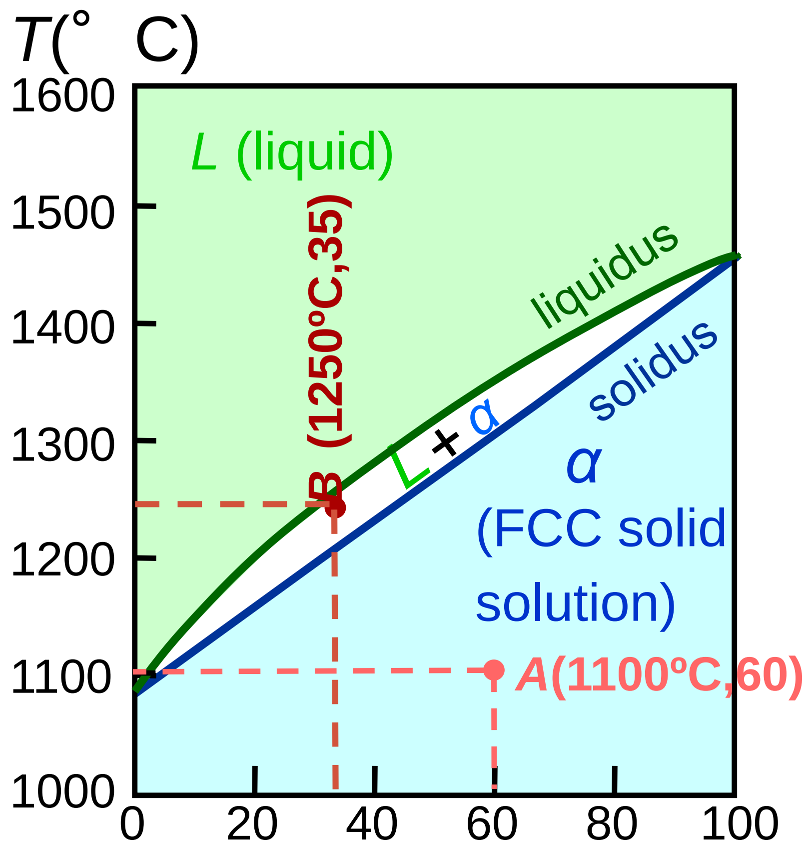
Determination of phase(s) present

- Rule 1: If we know T and C_o, then we know:
  -- which phase(s) is (are) present.

- Examples:

  A(1100° C, 60 wt% Ni):
  1 phase: *α*

  B(1250° C, 35 wt% Ni):
  2 phases: *L* + *α*



Cu-Ni phase diagram

Fig. 9.3(a), *Callister & Rethwisch 9e.*
(Adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

Phase Diagrams:

Determination of phase compositions

- Rule 2: If we know T and C_0, then we can determine:
  -- the composition of each phase.

- Examples:

Consider C_0 = 35 wt% Ni

At T_A = 1320° C:

Only Liquid (L) present

$C_L = C_0$ (= 35 wt% Ni)

At T_D = 1190° C:

Only Solid (α) present

$C_\alpha = C_0$ (= 35 wt% Ni)

At T_B = 1250° C:

Both α and L present

$C_L = C_{liquidus}$ (= 32 wt% Ni)

$C_\alpha = C_{solidus}$ (= 43 wt% Ni)

Cu-Ni system

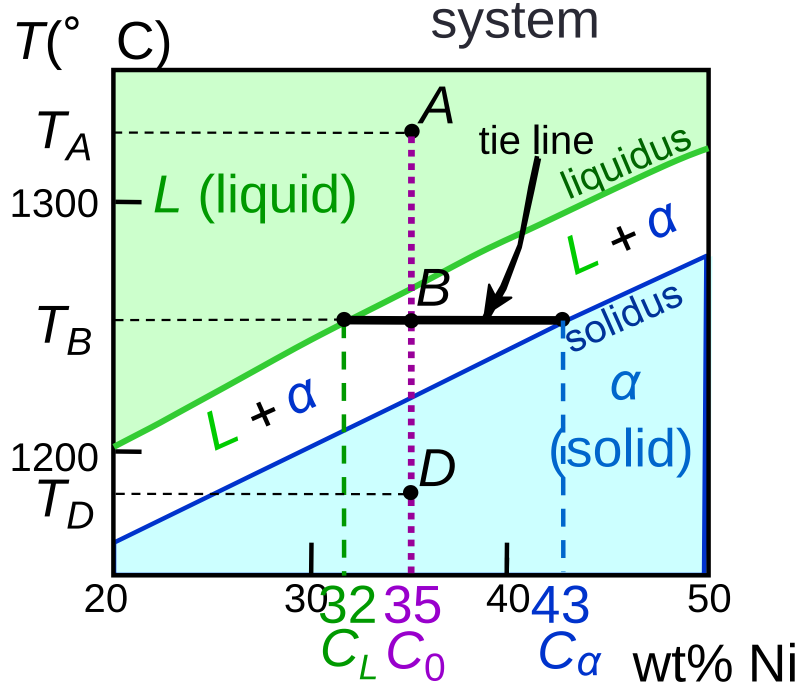


Fig. 9.3(b), *Callister & Rethwisch 9e.* (Adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

Phase Diagrams:
Determination of phase weight fractions

- Rule 3: If we know T and C_0, then can determine:
  - -- the weight fraction of each phase.
- Examples:

Consider C_0 = 35 wt% Ni

At T_A : Only Liquid (L) present

W_L = 1.00, W_α = 0

At T_D : Only Solid (α) present

W_L = 0, W_α = 1.00

At T_B : Both α and L present

$$W_L = \frac{S}{R+S} = \frac{43 - 35}{43 - 32} = 0.73$$

$$W_\alpha = \frac{R}{R+S} = 0.27$$

Cu-Ni system

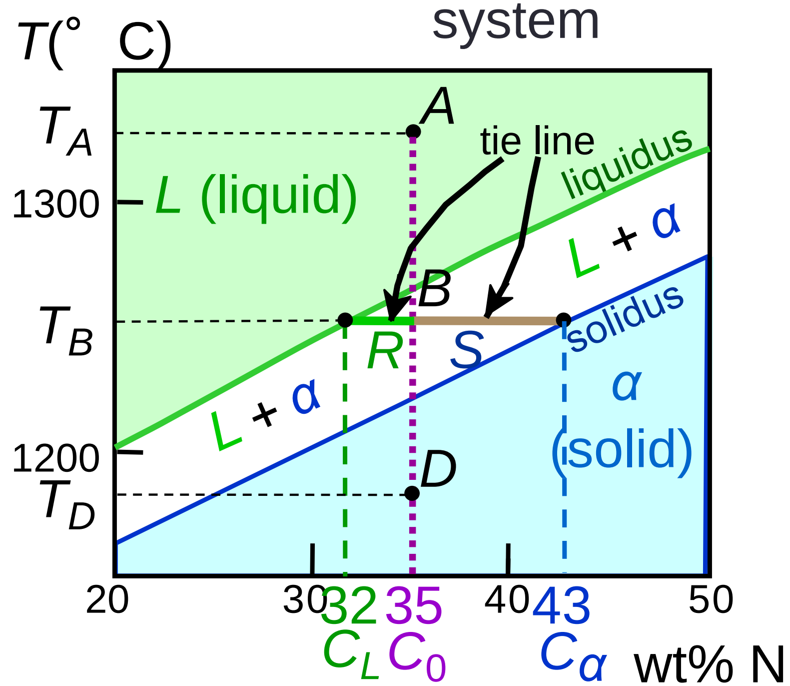
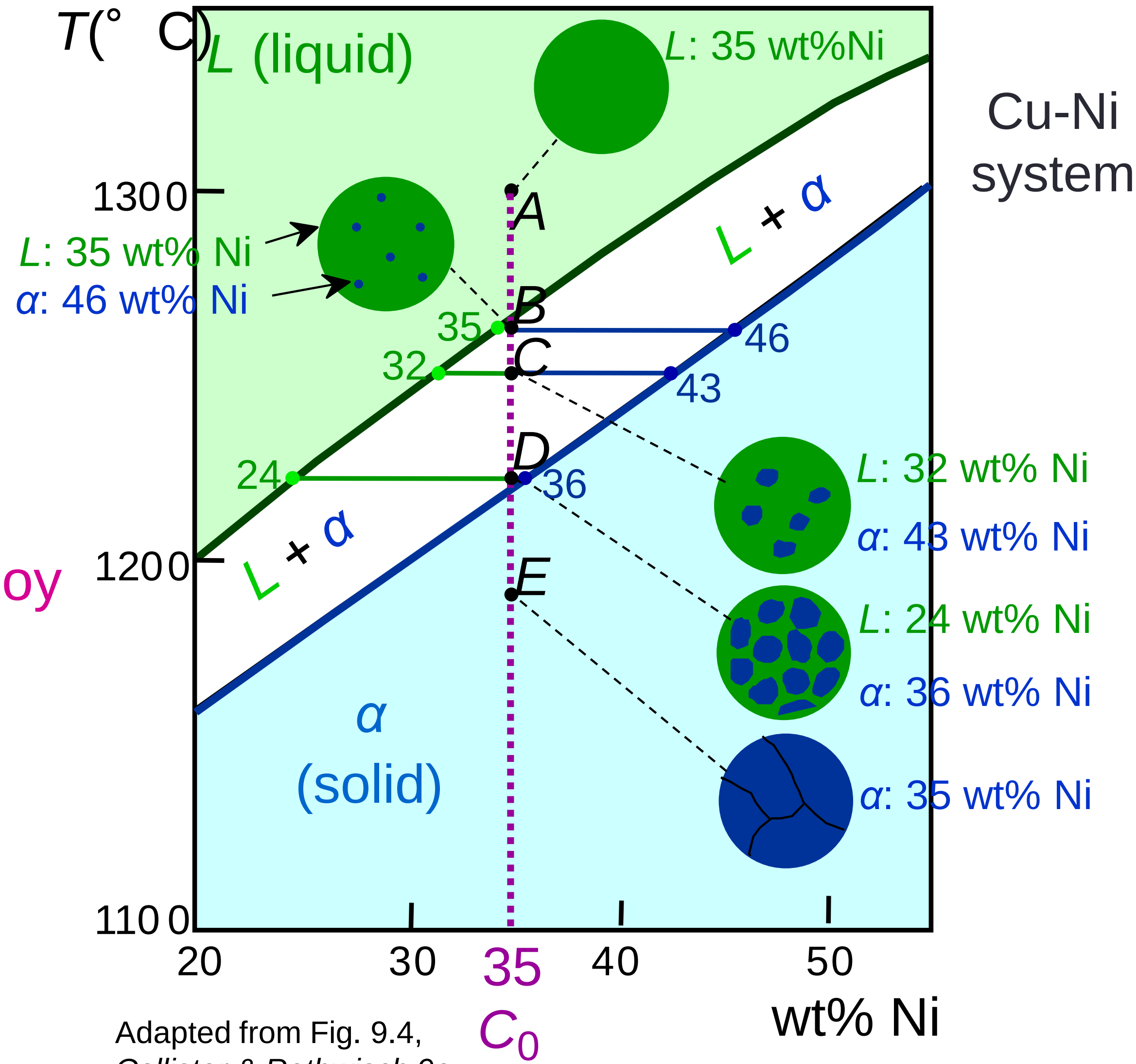


Fig. 9.3(b), *Callister & Rethwisch 9e.* (Adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)

Ex: Cooling of a Cu-Ni Alloy

- Phase diagram:
  Cu-Ni system.
- Consider microstuctural changes that accompany the cooling of a C_0 = 35 wt% Ni alloy



Adapted from Fig. 9.4, *Callister & Rethwisch 9e.*

Binary Phase Diagrams

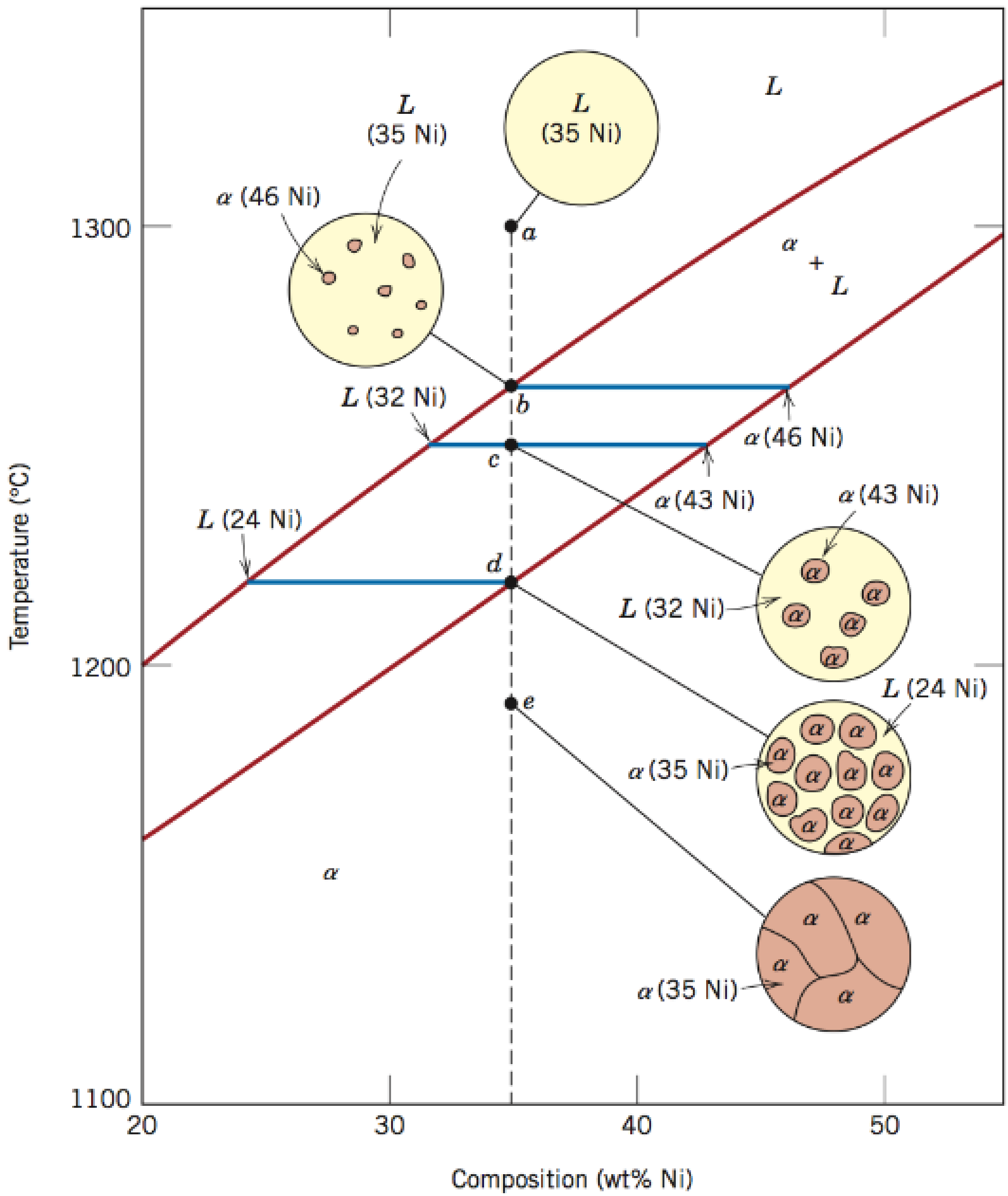
A copper–nickel alloy of composition 65 wt% Ni–35 wt% Cu is slowly cooled from a temperature of 1300ºC (2370ºF).

(a) At what temperature does the first solid phase form?

(b) What is the composition of this solid phase?

(c) At what temperature does complete solidification of the alloy occur?

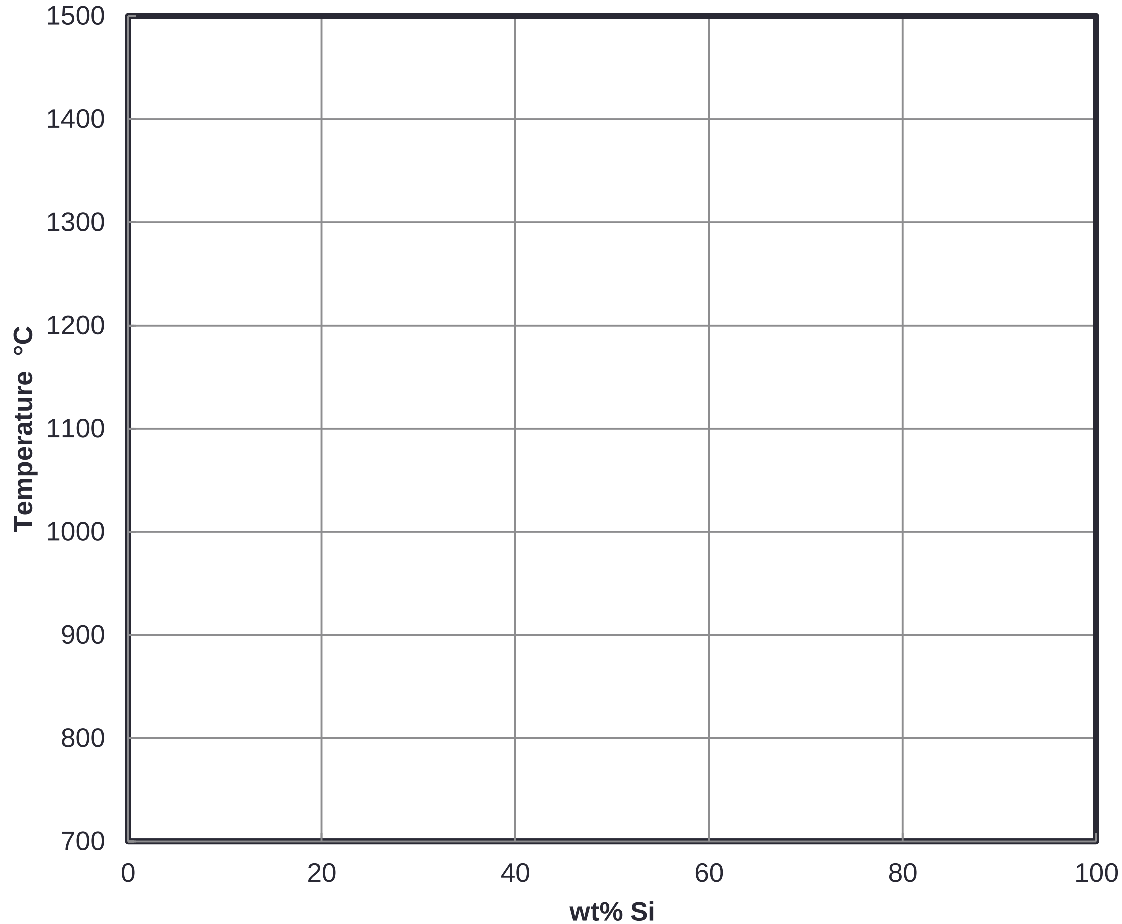
(d) What is the composition of the last solid remaining prior to complete solidification?



- Let us consider the copper–nickel system (Figure 9.3*a*), specifically an alloy of composition 35 wt% Ni–65 wt% Cu as it is cooled from 1300°C. The region of the Cu–Ni phase diagram in the vicinity of this composition is shown in Figure 9.4. Cooling of an alloy of this composition corresponds to moving down the vertical dashed line. At 1300°C, point *a*, the alloy is completely liquid (of composition 35 wt% Ni–65 wt% Cu) and has the microstructure represented by the circle inset in the figure. As cooling begins, no microstructural or compositional changes will be realized until we reach the liquidus line (point *b*, ~1260°C). At this point, the first solid α begins to form, which has a composition dictated by the tie line drawn at this temperature [i.e., 46 wt% Ni–54 wt% Cu, noted as (46 Ni)]; the composition of liquid is still approximately 35 wt% Ni–65 wt% Cu [*L*(35 Ni)], which is different from that of the solid α . With continued cooling, both compositions and relative amounts of each of the phases will change. The compositions of the liquid and α phases will follow the liquidus and solidus lines, respectively. Furthermore, the fraction of the α phase will increase with continued cooling. Note that the overall alloy composition (35 wt% Ni–65 wt% Cu) remains unchanged during cooling even though there is a redistribution of copper and nickel between the phases.
- At 1250 C, point *c* in Figure 9.4, the compositions of the liquid and α phases are 32 wt% Ni–68 wt% Cu [*L*(32 Ni)] and 43 wt% Ni–57 wt% Cu [α (43 Ni)], respectively.

Given here are the solidus and liquidus temperatures for the germanium (Ge) – silicon (Si) system. Construct the phase diagram for this system and label each region,

Composition (wt% Si)	**Solidus** Temperature (°C)	**Liquidus** Temperature (°C)
0	938	938
10	1005	1147
20	1065	1226
30	1123	1278
40	1178	1315
50	1232	1346
60	1282	1367
70	1326	1385
80	1359	1397
90	1390	1408
100	1414	1414



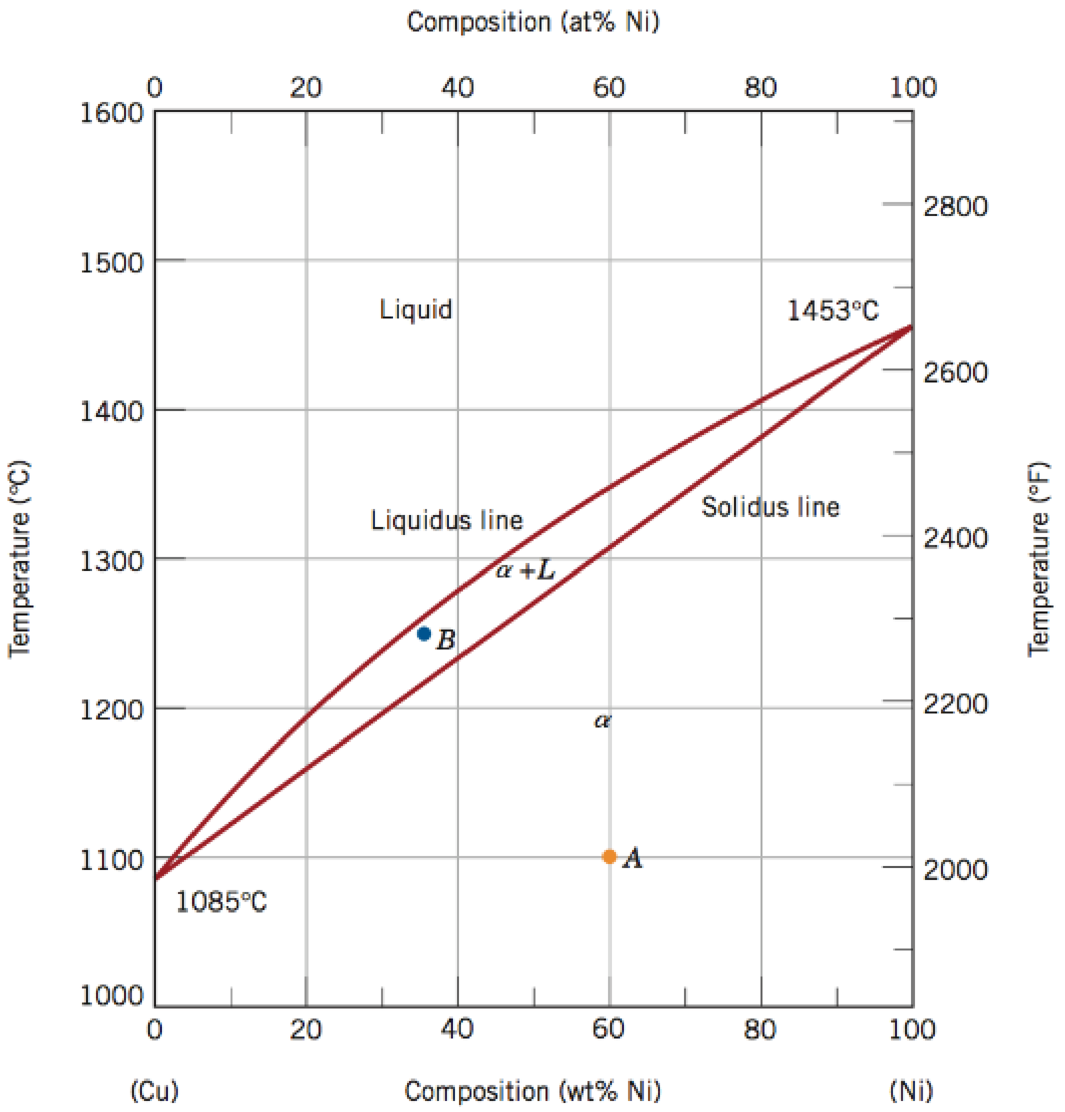
A copper–nickel alloy of composition 70 wt% Ni–30 wt% Cu is slowly heated to a temperature of 1300C (2370F).

(a) At what temperature does the first liquid phase form?

(b) What is the composition of this liquid phase?

(c) At what temperature does complete melting of the alloy occur?

(d) What is the composition of the last solid remaining prior to complete melting?



(a)