CHAPTER 7

PHASE DIAGRAMS

9.1 INTRODUCTION

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.

Definitions and Basic Concepts

Components

Are pure metals and/or compounds of which an alloy is composed. For example, in a copper–zinc brass, the components are Cu and Zn. *Solute* and *solvent,* which are also common terms. *Solvent* represents the element or compound that is present in the greatest amount; on occasion, solvent atoms are also called *host atoms*. Solute is used to denote an element or compound present in a minor concentration.

System

Have two meanings. First, *system* may refer to a specific body of material under consideration (e.g., a ladle of molten steel). Or it may relate to the series of possible alloys consisting of the same components, but without regard to alloy composition (e.g., the iron–carbon system).

9.2 SOLUBILITY LIMIT

For many alloy systems and at some specific temperature, there is a maximum concentration of solute atoms that may dissolve in the solvent to form a solid solution; this is called a **solubility limit.**
The addition of solute in excess of this solubility limit results in the formation of another solid solution or compound that has a distinctly different composition.
This solubility limit depends on the temperature which increases with rising temperature (eg. Sugar & water), as shown in Figure 9.1.

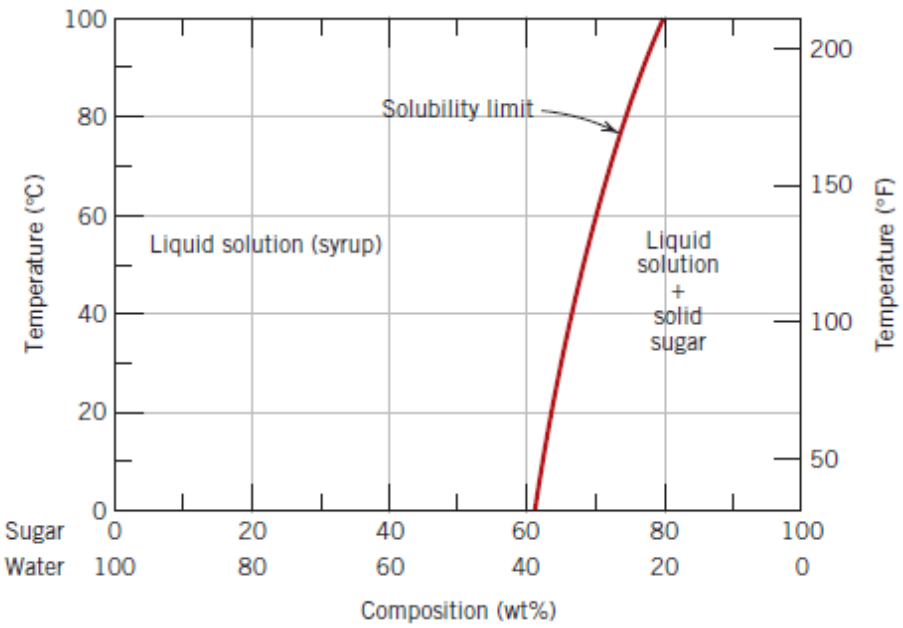


Figure 9.1 The solubility of sugar ($C_{12}H_{22}O_{11}$) in a sugar–water syrup.

9.3 PHASES

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. For example, the sugar–water syrup solution just discussed is one phase, and solid sugar is another as shown in Figure 9.1.

Each has different physical properties (one is a liquid, the other is a solid);

Each is different chemically (i.e., has a different chemical composition); one is virtually pure sugar; the other is a solution of H_2O and $C_{12}H_{22}O_{11}$.

If more than one phase is present in a given system, each will have its own distinct properties, and a boundary separating the phases will exist across which there will be a discontinuous and abrupt change in physical and/or chemical characteristics.

When two phases are present in a system, it is not necessary that there be a difference in both physical and chemical properties; When water and ice are present in a container, two separate phases exist; they are physically dissimilar (one is a solid, the other is a liquid) but identical in chemical makeup.

When a substance can exist in two or more polymorphic forms (e.g., having both FCC and BCC structures), each of these structures is a separate phase because their respective physical characteristics differ.

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.

9.5 PHASE EQUILIBRIA

Equilibrium is another essential concept that is best described in terms of a thermodynamic quantity called the **free energy.**

Free energy is a function of the internal energy of a system, and also the randomness or disorder of the atoms or molecules (or entropy).

A system is at equilibrium if its free energy is at a minimum under some specified combination of temperature, pressure, and composition.

A change in temperature, pressure, and/or composition for a system in equilibrium will result in an increase in the free energy and in a possible spontaneous change to another state whereby the free energy is lowered.

The term **phase equilibrium** is reflected by constancy with time in the phase characteristics of a system (eg. Liquid-solid system or just solid phases).

9.6 ONE-COMPONENT (OR UNARY) PHASE DIAGRAMS

Much of the information about the control of the phase structure of a particular system is conveniently and concisely displayed in what is called a **phase diagram,** also often termed an ***equilibrium diagram***.

Three externally controllable parameters that will affect phase structure—temperature, pressure, and composition— and phase diagrams are constructed when various combinations of these parameters are plotted against one another.

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*] is represented as a two-dimensional plot of pressure (ordinate, or vertical axis) versus temperature (abscissa, or horizontal axis). Most often, the pressure axis is scaled logarithmically as shown in Figure 9.2.

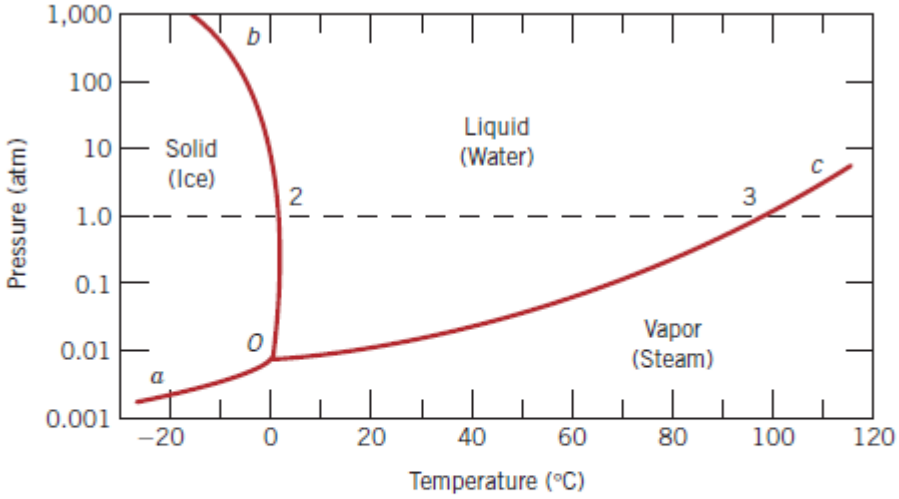


Figure 9.2 Pressure–temperature phase diagram for H_2O. Intersection of the dashed horizontal line at 1 atm pressure with the solid–liquid phase boundary (point 2) corresponds to the melting point at this pressure ($T = 0°C$). Similarly, point 3, the intersection with the liquid–vapor boundary, represents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

Regions for three different phases—solid, liquid, and vapor—are delineated on the plot.

Each of the phases will exist under equilibrium conditions over the temperature–pressure ranges of its corresponding area. Furthermore, the three curves shown on the plot (labeled *aO*, *bO*, and *cO*) are **phase boundaries**; at any point on one of these curves, the two phases on either side of the curve are in equilibrium (or coexist) with one another.

All three of the phase boundary curves intersect at a common point, which is labeled ***O*** (and for this H2O system, at a temperature of 273.16 K and a pressure of 6.04×10^{-3} atm). This means that at this point only, all of the solid, liquid, and vapor phases are simultaneously in equilibrium with one another. Appropriately, this, and any other point on a *P*–*T* phase diagram where three phases are in equilibrium, is called a ***triple point****;* sometimes it is also termed an ***invariant point*** inasmuch as its position is distinct, or fixed by definite values of pressure and temperature. Any deviation from this point by a change of temperature and/or pressure will cause at least one of the phases to disappear.

Binary Phase Diagrams

A common phase diagram is one in which temperature and composition is variable parameters, and pressure is held constant—normally 1 atm.

9.7 BINARY ISOMORPHOUS SYSTEMS

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*).

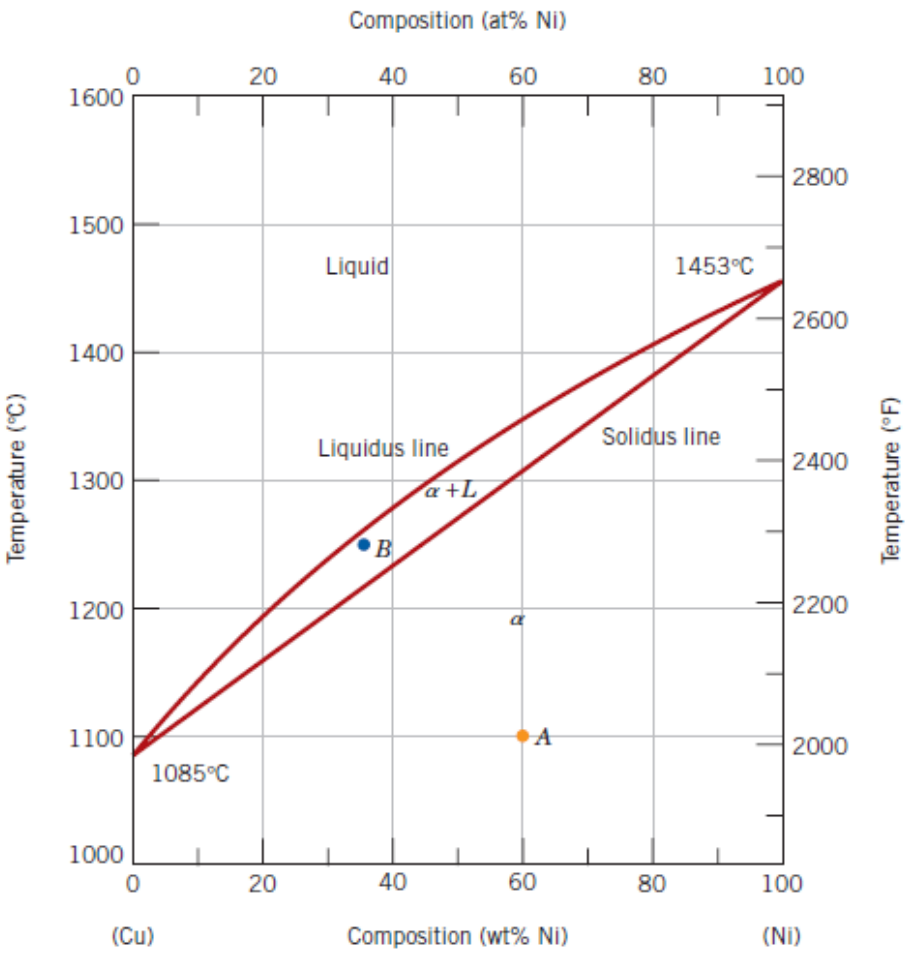
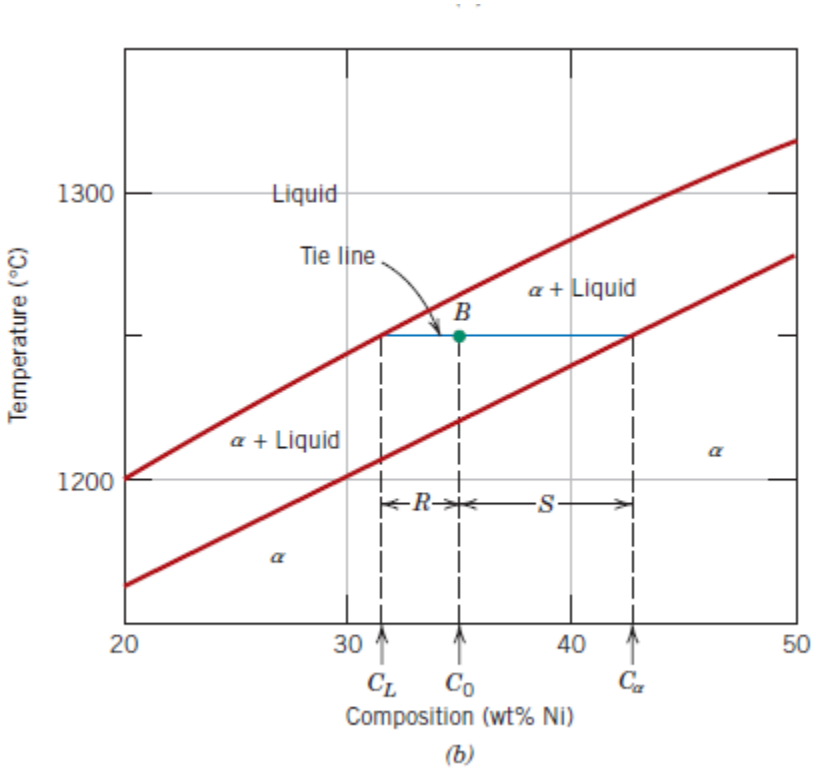


Figure 9.3 (*a*) The copper–nickel phase diagram. (*b*) A portion of the copper–nickel phase diagram for which compositions and phase amounts are determined at point *B*. (Adapted from *Phase Diagrams of Binary Nickel Alloys*, P. Nash, Editor, 1991. Reprinted by permission of ASM International, Materials Park, OH.)



Three different phase regions, or fields, appear on the diagram, an alpha (α) field, a liquid (L) field, and a two-phase ($\alpha+L$) field.

The liquid ***(L)*** is a homogeneous liquid solution composed of both copper and nickel.

The ***(α)*** phase is a substitutional solid solution consisting of both Cu and Ni atoms, and having an FCC crystal structure.

At temperatures below about 1080˚C, copper and nickel are mutually soluble in each other in the solid state for all compositions. The copper–nickel system is termed **isomorphous** because of this complete liquid and solid solubility of the two components.

For metallic alloys, solid solutions are commonly designated by lowercase Greek letters (α, β, γ, *etc.*).

The line separating the ***(L)*** *and* (α+*L)* phase fields is termed the ***liquidus line***, as indicated in Figure 9.3*a*; the liquid phase is present at all temperatures and compositions above this line.

The *solidus line* is located between the ***(α)*** and (α **+** ***L)*** regions, below which only the solid **α** phase exists.

For Figure 9.3*a*, the solidus and liquidus lines intersect at the two composition extremities; these correspond to the melting temperatures of the pure components. For example, the melting temperatures of pure copper and nickel are 1085˚C and 1453˚C, respectively

For any composition other than pure components, this melting phenomenon will occur over the range of temperatures between the solidus and liquidus lines; both solid ***α*** and liquid phases will be in equilibrium within this temperature range.

Example,
Upon heating an alloy of composition 50 wt% Ni–50 wt% Cu (Figure 9.3*a*), melting begins at approximately 1280˚C (2340˚F); the amount of liquid phase continuously increases with temperature until about 1320˚C (2410˚F), at which the alloy is completely liquid.

9.8 INTERPRETATION OF PHASE DIAGRAMS

For a binary system of known composition and temperature that is at equilibrium, at least three kinds of information are available:

Phases Present

The establishment of what phases are present is relatively simple. One just locates the temperature–composition point on the diagram and notes the phase(s) with which the corresponding phase field is labeled. For example, an alloy of composition 60 wt% Ni–40 wt% Cu at 1100°C would be located at point *A* in Figure 9.3*a*; because this is within the α region, only the single α phase will be present. On the other hand, a 35 wt% Ni–65 wt% Cu alloy at 1250°C (point *B*) will consist of both α and liquid phases at equilibrium.

Determination of Phase Compositions

The first step in the determination of phase compositions (in terms of the concentrations of the components) is to locate the temperature–composition point on the phase diagram. Different methods are used for single- and two-phase regions. If only one phase is present, the procedure is trivial: the composition of this phase is simply the same as the overall composition of the alloy. For example, consider the 60 wt% Ni–40 wt% Cu alloy at 1100°C (point *A*, Figure 9.3*a*). At this composition and temperature, only the α phase is present, having a composition of 60 wt% Ni–40 wt% Cu.

In all two-phase regions (and in two-phase regions only), one may imagine a series of horizontal lines, one at every temperature; each of these is known as a **tie line,** or sometimes as an isotherm. These tie lines extend across the two-phase region and terminate at the phase boundary lines on either side.

To compute the equilibrium concentrations of the two phases, the following procedure is used:

1. A tie line is constructed across the two-phase region at the temperature of the alloy.
2. The intersections of the tie line and the phase boundaries on either side are noted.
3. Perpendiculars are dropped from these intersections to the horizontal composition axis, from which the composition of each of the respective phases is read.

Example

consider again the 35 wt% Ni–65 wt% Cu alloy at 1250°C, lo-

cated at point B in Figure 9.3*b* and lying within the $\alpha + L$ region. Thus, the problem is to determine the composition (in wt% Ni and Cu) for both the α and liquid phases. The tie line has been constructed across the $\alpha + L$ phase region, as shown in Figure 9.3*b*. The perpendicular from the intersection of the tie line with the liquidus boundary meets the composition axis at 31.5 wt% Ni–68.5 wt% Cu, which is the composition of the liquid phase, C_L. Likewise, for the solidus–tie line intersection, we find a composition for the α solid-solution phase, C_α, of 42.5 wt% Ni–57.5 wt% Cu.

Determination of Phase Amounts

The relative amounts (as fraction or as percentage) of the phases present at equilibrium may also be computed with the aid of phase diagrams.

single-phase region: because only one phase is present, the alloy is composed entirely of that phase; that is, the phase fraction is 1.0 or, alternatively, the percentage is 100%. From the previous example for the 60 wt% Ni–40 wt% Cu alloy at 1100°C (point A in Figure 9.3*a*), only the α phase is present; hence, the alloy is completely or 100% α.

If the composition and temperature position is located within a two-phase region, things are more complex. The tie line must be utilized in conjunction with a procedure that is often called the **lever rule** (or the *inverse lever rule*), which is applied as follows:

1. The tie line is constructed across the two-phase region at the temperature of the alloy.
2. The overall alloy composition is located on the tie line.
3. The fraction of one phase is computed by taking the length of tie line from the overall alloy composition to the phase boundary for the *other* phase, and dividing by the total tie line length.
4. The fraction of the other phase is determined in the same manner.
5. If phase percentages are desired, each phase fraction is multiplied by 100. When the composition axis is scaled in weight percent, the phase fractions computed using the lever rule are mass fractions—the mass (or weight) of a specific phase divided by the total alloy mass (or weight). The mass of each phase is computed from the product of each phase fraction and the total alloy mass.

Example

Consider again the example shown in Figure 9.3*b*, in which at 1250°C both α and liquid phases are present for a 35 wt% Ni–65 wt% Cu alloy. The problem is to compute the fraction of each of the α and liquid phases. The tie line has been constructed that was used for the determination of α and L phase compositions. Let the overall alloy composition be located along the tie line and denoted as C_0, and mass fractions be represented by W_L and W_α for the respective phases. From the lever rule, W_L may be computed according to

$$W_L = \frac{S}{R + S} \tag{9.1a}$$

or, by subtracting compositions,

Lever rule expression for computation of liquid mass fraction (per Figure 9.3*b*)

$$W_L = \frac{C_\alpha - C_0}{C_\alpha - C_L} \tag{9.1b}$$

Composition need be specified in terms of only one of the constituents for a binary alloy; for the preceding computation, weight percent nickel will be used (i.e., C_0 = 35 wt% Ni, C_α = 42.5 wt% Ni, and C_L = 31.5 wt% Ni), and

$$W_L = \frac{42.5 - 35}{42.5 - 31.5} = 0.68$$

Similarly, for the α phase,

Lever rule expression for computation of α-phase mass fraction (per Figure 9.3*b*)

$$W_\alpha = \frac{R}{R + S} \tag{9.2a}$$

$$= \frac{C_0 - C_L}{C_\alpha - C_L} \tag{9.2b}$$

$$= \frac{35 - 31.5}{42.5 - 31.5} = 0.32$$

Of course, identical answers are obtained if compositions are expressed in weight percent copper instead of nickel.

Thus, the lever rule may be employed to determine the relative amounts or fractions of phases in any two-phase region for a binary alloy if the temperature and composition are known and if equilibrium has been established. Its derivation is presented as an example problem.

EXAMPLE PROBLEM 9.1

Lever Rule Derivation

Derive the lever rule.

Solution

Consider the phase diagram for copper and nickel (Figure 9.3*b*) and alloy of composition C_0 at 1250°C, and let C_α, C_L, W_α, and W_L represent the same parameters as given earlier. This derivation is accomplished through two conservation-of-mass expressions. With the first, because only two phases are present, the sum of their mass fractions must be equal to unity; that is,

$$W_\alpha + W_L = 1 \tag{9.3}$$

For the second, the mass of one of the components (either Cu or Ni) that is present in both of the phases must be equal to the mass of that component in the total alloy, or

$$W_\alpha C_\alpha + W_L C_L = C_0 \tag{9.4}$$

Simultaneous solution of these two equations leads to the lever rule expressions for this particular situation, Equations 9.1b and 9.2b:

$$W_L = \frac{C_\alpha - C_0}{C_\alpha - C_L} \tag{9.1b}$$

$$W_\alpha = \frac{C_0 - C_L}{C_\alpha - C_L} \tag{9.2b}$$

For multiphase alloys, it is often more convenient to specify relative phase amount in terms of volume fraction rather than mass fraction. Phase volume fractions are preferred because they (rather than mass fractions) may be determined from examination of the microstructure; furthermore, the properties of a multiphase alloy may be estimated on the basis of volume fractions.

For an alloy consisting of α and β phases, the volume fraction of the α phase, V_α, is defined as

α phase volume fraction—dependence on volumes of α and β phases

$$V_\alpha = \frac{v_\alpha}{v_\alpha + v_\beta} \tag{9.5}$$

where v_α and v_β denote the volumes of the respective phases in the alloy. Of course, an analogous expression exists for V_β, and, for an alloy consisting of just two phases, it is the case that $V_\alpha + V_\beta = 1$.

On occasion conversion from mass fraction to volume fraction (or vice versa) is desired. Equations that facilitate these conversions are as follows:

Conversion of mass fractions of α and β phases to volume fractions

$$V_\alpha = \frac{\dfrac{W_\alpha}{\rho_\alpha}}{\dfrac{W_\alpha}{\rho_\alpha} + \dfrac{W_\beta}{\rho_\beta}} \tag{9.6a}$$

$$V_\beta = \frac{\dfrac{W_\beta}{\rho_\beta}}{\dfrac{W_\alpha}{\rho_\alpha} + \dfrac{W_\beta}{\rho_\beta}} \tag{9.6b}$$

and

Conversion of volume fractions of α and β phases to mass fractions

$$W_\alpha = \frac{V_\alpha \rho_\alpha}{V_\alpha \rho_\alpha + V_\beta \rho_\beta} \tag{9.7a}$$

$$W_\beta = \frac{V_\beta \rho_\beta}{V_\alpha \rho_\alpha + V_\beta \rho_\beta} \tag{9.7b}$$

In these expressions, ρ_α and ρ_β are the densities of the respective phases; these may be determined approximately using Equations 4.10a and 4.10b.

$$\rho_{ave} = \frac{100}{\dfrac{C_1}{\rho_1} + \dfrac{C_2}{\rho_2}} \tag{4.10a}$$

$$C_1 = \frac{m_1}{m_1 + m_2} \times 100 \qquad \text{Composition in weight percent}$$

9.9 DEVELOPMENT OF MICROSTRUCTURE IN ISOMORPHOUS ALLOYS

Equilibrium Cooling

At this point it is instructive to examine the development of microstructure that occurs for isomorphous alloys during solidification. We first treat the situation in which the cooling occurs very slowly, in that phase equilibrium is continuously maintained.

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,

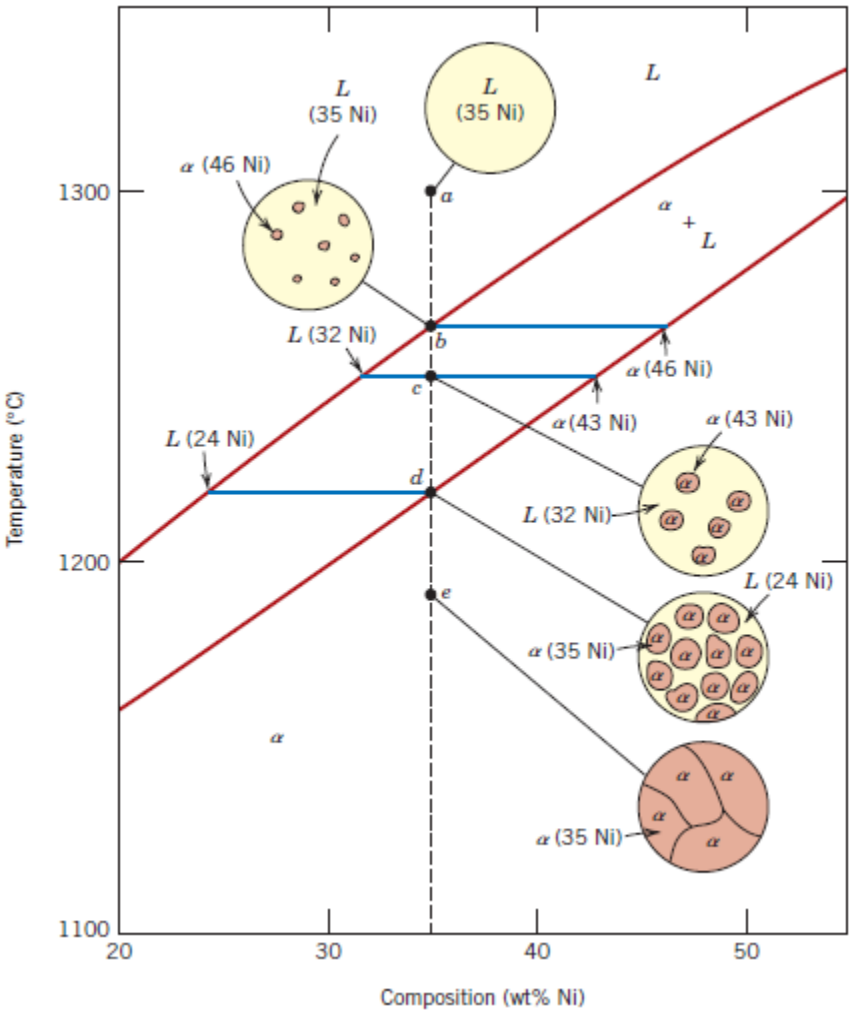


Figure 9.4 Schematic representation of the development of microstructure during the equilibrium solidification of a 35 wt% Ni–65 wt% Cu alloy.

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 α(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.

The solidification process is virtually complete at about 1220°C, point d; the composition of the solid α is approximately 35 wt% Ni–65 wt% Cu (the overall alloy composition), whereas that of the last remaining liquid is 24 wt% Ni–76 wt% Cu. Upon crossing the solidus line, this remaining liquid solidifies; the final product then is a polycrystalline α-phase solid solution that has a uniform 35 wt% Ni–65 wt% Cu composition (point e, Figure 9.4). Subsequent cooling will produce no microstructural or compositional alterations.

9.11 BINARY EUTECTIC SYSTEMS

Another type of common and relatively simple phase diagram found for binary alloys is shown in Figure 9.7 for the copper–silver system; this is known as a binary eutectic phase diagram. A number of features of this phase diagram are important and worth noting. First, three single-phase regions are found on the diagram: α, β, and liquid. The α phase is a solid solution rich in copper; it has silver as the solute

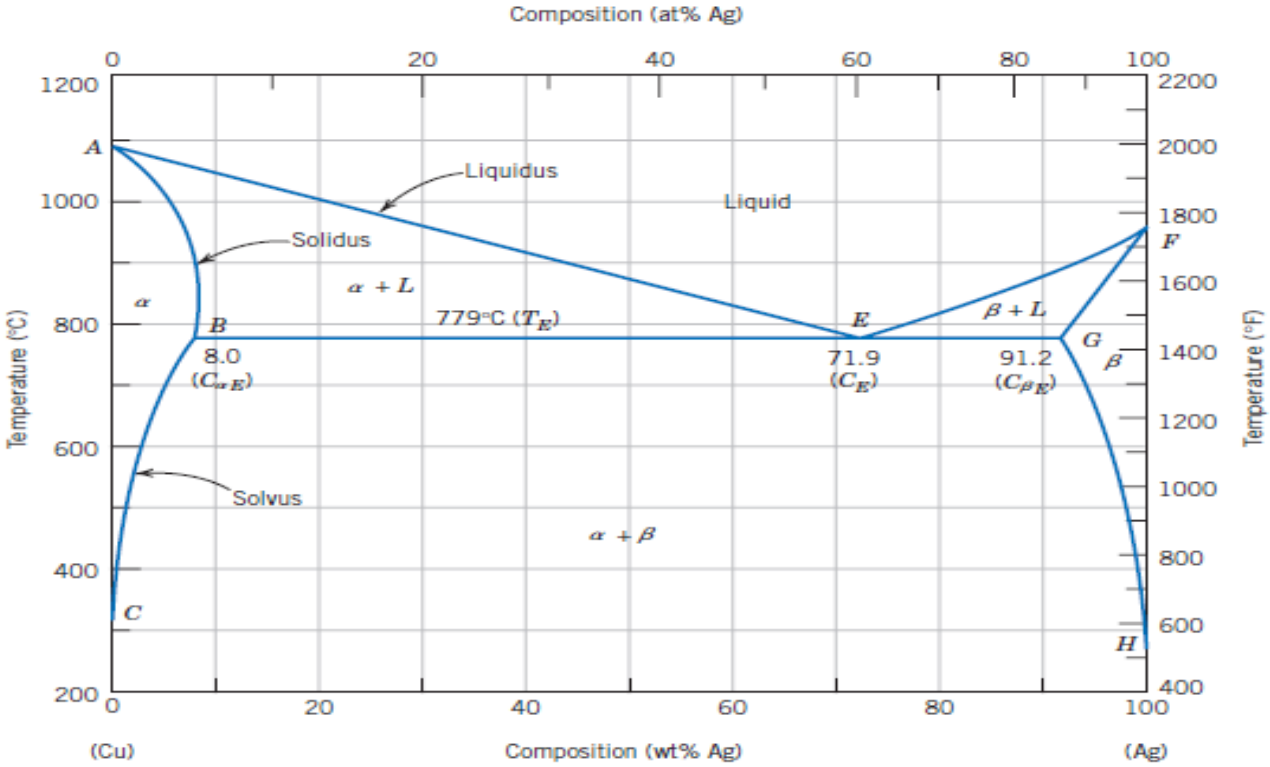


Figure 9.7 The copper–silver phase diagram. [Adapted from *Binary Alloy Phase Diagrams,* 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

component and an FCC crystal structure. The β-phase solid solution also has an FCC structure, but copper is the solute. Pure copper and pure silver are also considered to be α and β phases, respectively.

Thus, the solubility in each of these solid phases is limited, in that at any temperature below line BEG only a limited concentration of silver will dissolve in copper (for the α phase), and similarly for copper in silver (for the β phase). The solubility limit for the α phase corresponds to the boundary line, labeled CBA, between the $\alpha/(\alpha + \beta)$ and $\alpha/(\alpha + L)$ phase regions; it increases with temperature to a maximum [8.0 wt% Ag at 779°C (1434°F)] at point B, and decreases back to zero at the melting temperature of pure copper, point A [1085°C (1985°F)]. At temperatures below 779°C (1434°F), the solid solubility limit line separating the α and $\alpha + \beta$ phase regions is termed a **solvus line;** the boundary AB between the α and $\alpha + L$ fields is the **solidus line,** as indicated in Figure 9.7. For the β phase, both solvus and solidus lines also exist, HG and GF, respectively, as shown. The maximum solubility of copper in the β phase, point G (8.8 wt% Cu), also occurs at 779°C (1434°F). This horizontal line BEG, which is parallel to the composition axis and extends between these maximum solubility positions, may also be considered a solidus line; it represents the lowest temperature at which a liquid phase may exist for any copper–silver alloy that is at equilibrium.

solvus line

solidus line

There are also three two-phase regions found for the copper–silver system (Figure 9.7): $\alpha + L$, $\beta + L$, and $\alpha + \beta$. The α- and β-phase solid solutions coexist for all compositions and temperatures within the $\alpha + \beta$ phase field; the α + liquid and β + liquid phases also coexist in their respective phase regions. Furthermore, compositions and relative amounts for the phases may be determined using tie lines and the lever rule as outlined previously.

liquidus line

As silver is added to copper, the temperature at which the alloys become totally liquid decreases along the **liquidus line,** line AE; thus, the melting temperature of copper is lowered by silver additions. The same may be said for silver: the introduction of copper reduces the temperature of complete melting along the other liquidus line, FE. These liquidus lines meet at the point E on the phase diagram, through which also passes the horizontal isotherm line BEG. Point E is called an **invariant point,** which is designated by the composition C_E and temperature T_E; for the copper–silver system, the values of C_E and T_E are 71.9 wt% Ag and 779°C (1434°F), respectively.

invariant point

An important reaction occurs for an alloy of composition C_E as it changes temperature in passing through T_E; this reaction may be written as follows:

The eutectic reaction (per Figure 9.7)

$$L(C_E) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(C_{\alpha E}) + \beta(C_{\beta E}) \tag{9.8}$$

Or, upon cooling, a liquid phase is transformed into the two solid α and β phases at the temperature T_E; the opposite reaction occurs upon heating. This is called a **eutectic reaction** (*eutectic* means "easily melted"), and C_E and T_E represent the eutectic composition and temperature, respectively; $C_{\alpha E}$ and $C_{\beta E}$ are the respective compositions of the α and β phases at T_E. Thus, for the copper–silver system, the eutectic reaction, Equation 9.8, may be written as follows:

eutectic reaction

$$L(71.9\ \text{wt\%}\ \text{Ag}) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(8.0\ \text{wt\%}\ \text{Ag}) + \beta(91.2\ \text{wt\%}\ \text{Ag})$$

Often, the horizontal solidus line at T_E is called the *eutectic isotherm*.

Because of this eutectic reaction, phase diagrams similar to that in Figure 9.7 are termed ***eutectic phase diagrams*** (Figures 9.7, 9.8, 9.9, 9.10&9.20). Components exhibiting this behavior comprise a ***eutectic system***.

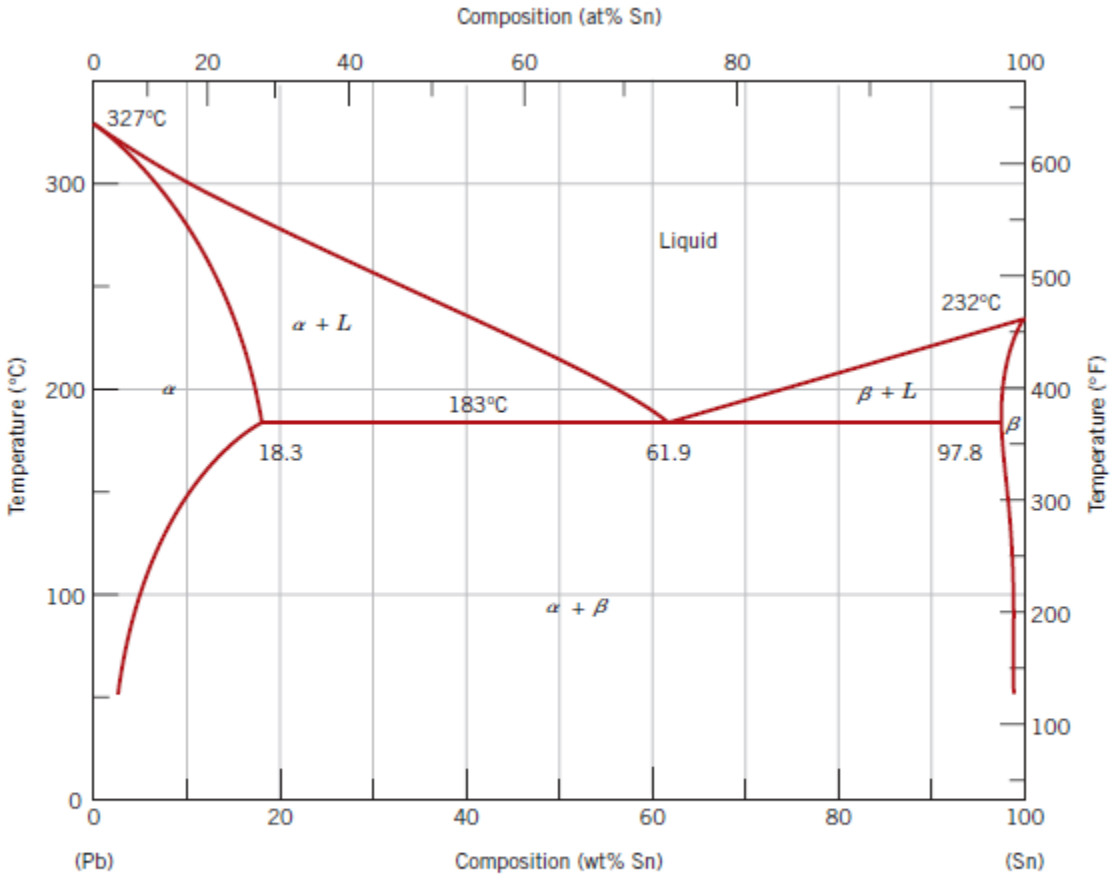


Figure 9.8 The lead–tin phase diagram. [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 3, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

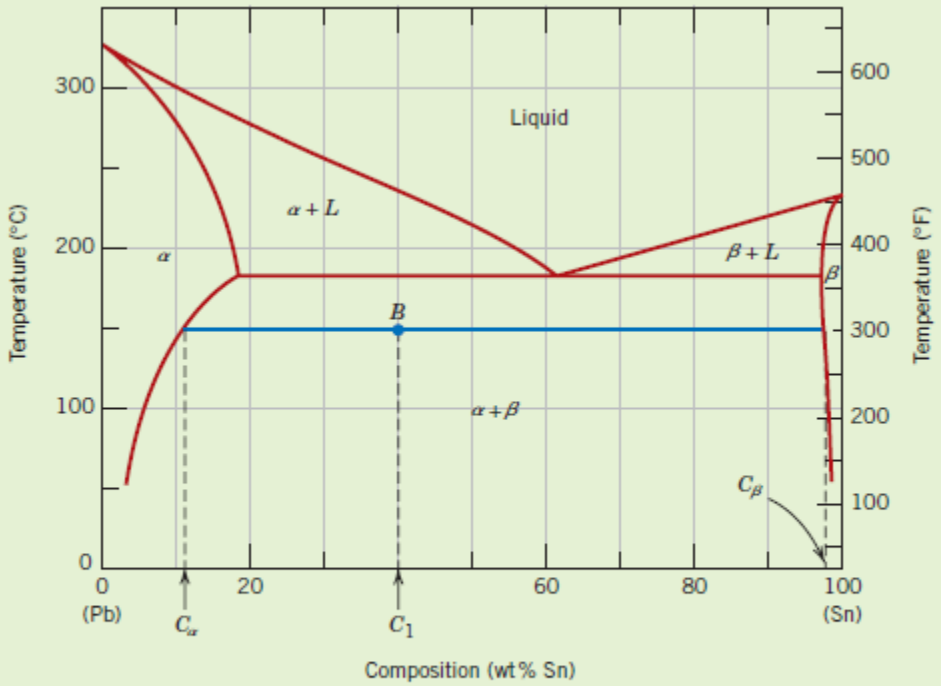


Figure 9.9 The lead–tin phase diagram. For a 40 wt% Sn–60 wt% Pb alloy at 150°C (point *B*), phase compositions and relative amounts are computed in Example Problems 9.2 and 9.3.

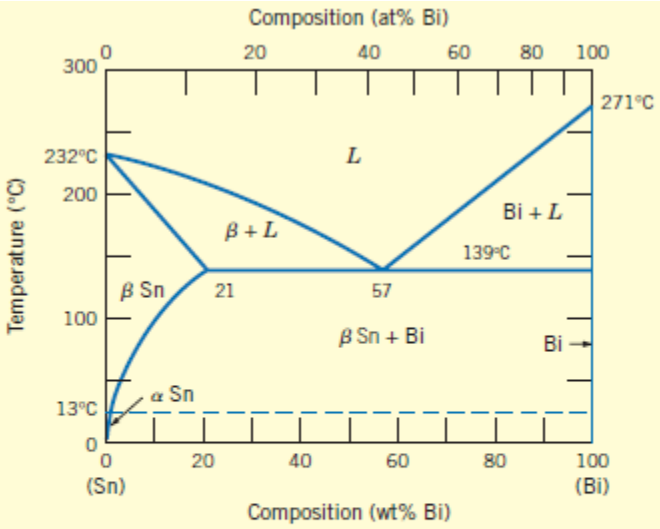


Figure 9.10 The tin–bismuth phase diagram. [Adapted from *ASM Handbook*, Vol. 3, *Alloy Phase Diagrams*, H. Baker (Editor), ASM International, 1992, p. 2.106. Reprinted by permission of ASM International, Materials Park, OH.]

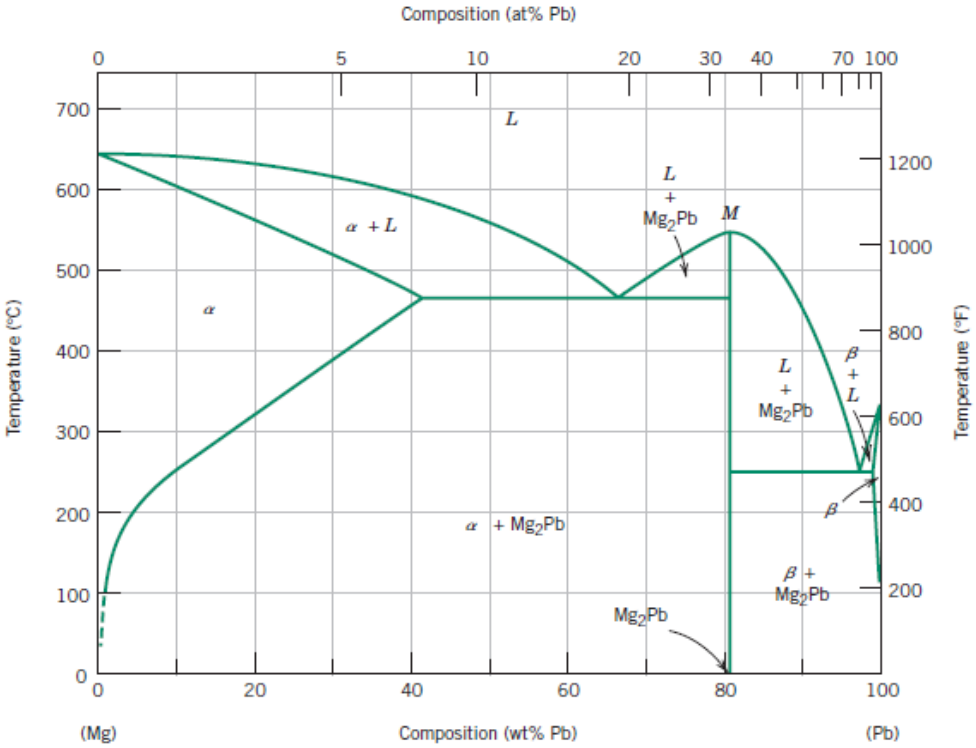


Figure 9.20 The magnesium–lead phase diagram. [Adapted from *Phase Diagrams of Binary Magnesium Alloys*, A. A. Nayeb-Hashemi and J. B. Clark (Editors), 1988. Reprinted by permission of ASM International, Materials Park, OH.]

The Iron–Carbon System

9.18 THE IRON–IRON CARBIDE ($Fe–Fe_3C$) PHASE DIAGRAM

ferrite

austenite

A portion of the iron–carbon phase diagram is presented in Figure 9.24. Pure iron, upon heating, experiences two changes in crystal structure before it melts. At room temperature the stable form, called **ferrite,** or α-iron, has a BCC crystal structure. Ferrite experiences a polymorphic transformation to FCC **austenite,** or γ-iron, at 912°C (1674°F). This austenite persists to 1394°C (2541°F), at which temperature the FCC austenite reverts back to a BCC phase known as δ-ferrite, which finally

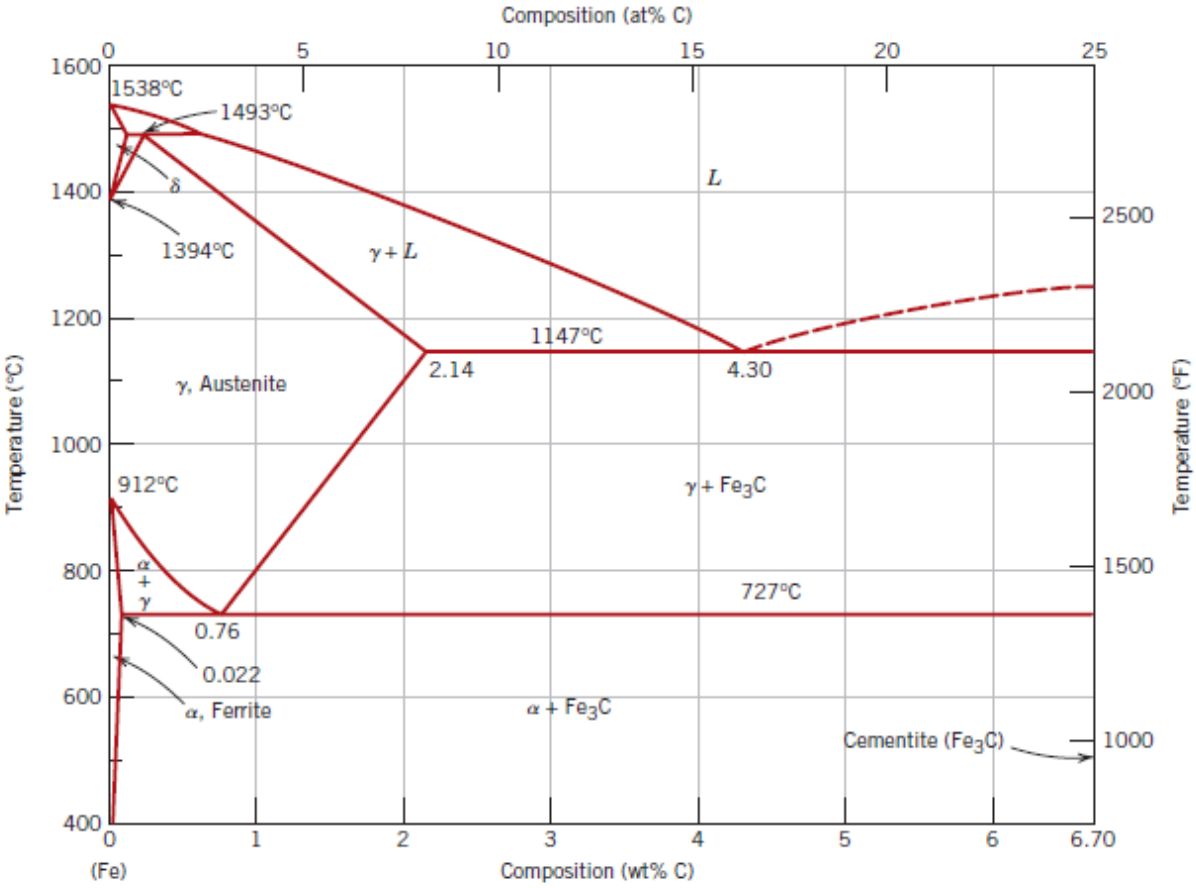


Figure 9.24 The iron–iron carbide phase diagram. [Adapted from *Binary Alloy Phase Diagrams,* 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

melts at 1538°C (2800°F). All these changes are apparent along the left vertical axis of the phase diagram.[1]

cementite

The composition axis in Figure 9.24 extends only to 6.70 wt% C; at this concentration the intermediate compound iron carbide, or **cementite** (Fe_3C), is formed, which is represented by a vertical line on the phase diagram. Thus, the iron–carbon system may be divided into two parts: an iron-rich portion, as in Figure 9.24, and the other (not shown) for compositions between 6.70 and 100 wt% C (pure graphite). In practice, all steels and cast irons have carbon contents less than 6.70 wt% C; therefore, we consider only the iron–iron carbide system. Figure 9.24 would be more appropriately labeled the Fe–Fe_3C phase diagram, because Fe_3C is now considered to be a component. Convention and convenience dictate that composition still be expressed in "wt% C" rather than "wt% Fe_3C"; 6.70 wt% C corresponds to 100 wt% Fe_3C.

Carbon is an interstitial impurity in iron and forms a solid solution with each of α- and δ-ferrites, and also with austenite, as indicated by the α, δ, and γ single-phase fields in Figure 9.24. In the BCC α-ferrite, only small concentrations of carbon are soluble; the maximum solubility is 0.022 wt% at 727°C (1341°F). The limited solubility is explained by the shape and size of the BCC interstitial positions, which make it difficult to accommodate the carbon atoms. Even though present in relatively low concentrations, carbon significantly influences the mechanical properties of ferrite. This particular iron–carbon phase is relatively soft, may be made magnetic at temperatures below 768°C (1414°F), and has a density of 7.88 g/cm^3. Figure 9.25*a* is a photomicrograph of α-ferrite.

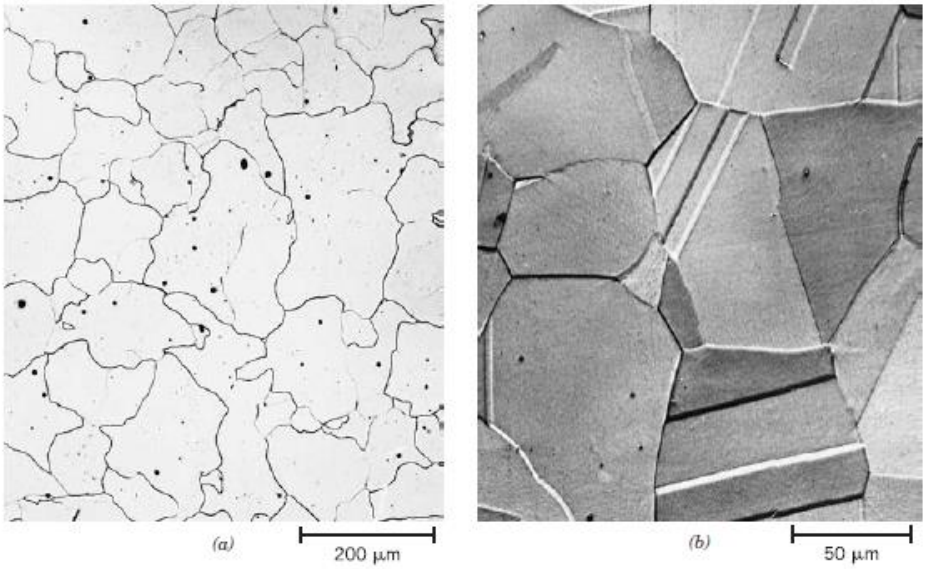


Figure 9.25 Photomicrographs of (*a*) α-ferrite (90×) and (*b*) austenite (325×). (Copyright 1971 by United States Steel Corporation.)

The austenite, or γ phase of iron, when alloyed with carbon alone, is not stable below 727°C (1341°F), as indicated in Figure 9.24. The maximum solubility of carbon in austenite, 2.14 wt%, occurs at 1147°C (2097°F). This solubility is approximately 100 times greater than the maximum for BCC ferrite, because the FCC interstitial positions are larger and, therefore, the strains imposed on the surrounding iron atoms are much lower.

The δ-ferrite is virtually the same as α-ferrite, except for the range of temperatures over which each exists. Because the δ-ferrite is stable only at relatively high temperatures, it is of no technological importance and is not discussed further.

Cementite (Fe_3C) forms when the solubility limit of carbon in α-ferrite is exceeded below 727°C (1341°F) (for compositions within the $\alpha + Fe_3C$ phase region). As indicated in Figure 9.24, Fe_3C will also coexist with the γ phase between 727 and 1147°C (1341 and 2097°F). Mechanically, cementite is very hard and brittle; the strength of some steels is greatly enhanced by its presence.

Strictly speaking, cementite is only metastable; that is, it will remain as a compound indefinitely at room temperature. However, if heated to between 650 and 700°C (1200 and 1300°F) for several years, it will gradually change or transform into α-iron and carbon, in the form of graphite, which will remain upon subsequent cooling to room temperature. Thus, the phase diagram in Figure 9.24 is not a true equilibrium one because cementite is not an equilibrium compound. However, inasmuch as the

The two-phase regions are labeled in Figure 9.24. It may be noted that one eutectic exists for the iron–iron carbide system, at 4.30 wt% C and 1147°C (2097°F); for this eutectic reaction,

Eutectic reaction for the iron–iron carbide system

$$L \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \gamma + Fe_3C \qquad (9.18)$$

the liquid solidifies to form austenite and cementite phases. Of course, subsequent cooling to room temperature will promote additional phase changes.

It may be noted that a eutectoid invariant point exists at a composition of 0.76 wt% C and a temperature of 727°C (1341°F). This eutectoid reaction may be represented by

Eutectoid reaction for the iron–iron carbide system

$$\gamma(0.76\ \text{wt\%}\ C) \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \alpha(0.022\ \text{wt\%}\ C) + Fe_3C(6.7\ \text{wt\%}\ C) \qquad (9.19)$$

or, upon cooling, the solid γ phase is transformed into α-iron and cementite.

Ferrous alloys are those in which iron is the prime component, but carbon as well as other alloying elements may be present. In the classification scheme of ferrous alloys based on carbon content, there are three types: iron, steel, and cast iron. Commercially pure iron contains less than 0.008 wt% C and, from the phase diagram, is composed almost exclusively of the ferrite phase at room temperature. The

iron–carbon alloys that contain between 0.008 and 2.14 wt% C are classified as steels. In most steels the microstructure consists of both α and Fe_3C phases. Upon

Cast irons are classified as ferrous alloys that contain between 2.14 and 6.70 wt% C. However, commercial cast irons normally contain less than 4.5 wt% C.

CHAPTER 7

QUESTIONS and ANSWERS

EXAMPLE PROBLEM 9.2

Determination of Phases Present and Computation of Phase Compositions

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)?

Solution

(a) Locate this temperature–composition point on the phase diagram (point B in Figure 9.9). Inasmuch as it is within the $\alpha + \beta$ region, both α and β phases will coexist.

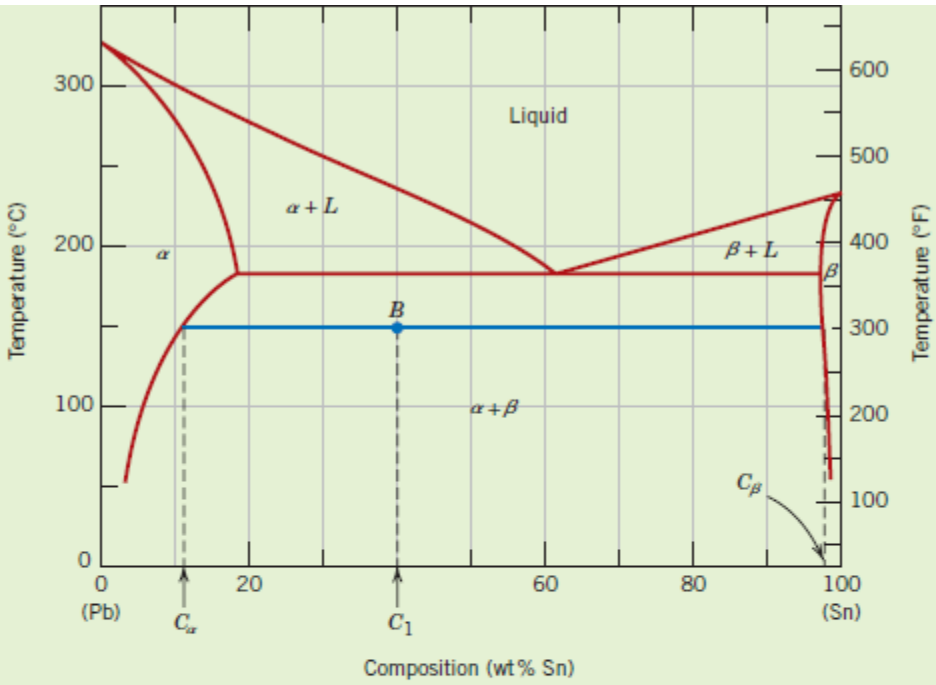


Figure 9.9 The lead–tin phase diagram. For a 40 wt% Sn–60 wt% Pb alloy at 150°C (point B), phase compositions and relative amounts are computed in Example Problems 9.2 and 9.3.

(b) Because two phases are present, it becomes necessary to construct a tie line across the $\alpha + \beta$ phase field at 150°C, as indicated in Figure 9.9. The composition of the α phase corresponds to the tie line intersection with the $\alpha/(\alpha + \beta)$ solvus phase boundary—about 11 wt% Sn–89 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).

EXAMPLE PROBLEM 9.3

Relative Phase Amount Determinations—Mass and Volume Fractions

For the lead–tin alloy in Example Problem 9.2, calculate the relative amount of each phase present in terms of **(a)** mass fraction and **(b)** volume fraction. At 150°C take the densities of Pb and Sn to be 11.23 and 7.24 g/cm^3, respectively.

Solution

(a) Because the alloy consists of two phases, it is necessary to employ the lever rule. If C_1 denotes the overall alloy composition, mass fractions may be computed by subtracting compositions, in terms of weight percent tin, as follows:

$$W_\alpha = \frac{C_\beta - C_1}{C_\beta - C_\alpha} = \frac{98 - 40}{98 - 11} = 0.67$$

$$W_\beta = \frac{C_1 - C_\alpha}{C_\beta - C_\alpha} = \frac{40 - 11}{98 - 11} = 0.33$$

(b) To compute volume fractions it is first necessary to determine the density of each phase using Equation 4.10a. Thus

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

where $C_{\mathrm{Sn}(\alpha)}$ and $C_{\mathrm{Pb}(\alpha)}$ denote the concentrations in weight percent of tin and lead, respectively, in the α phase. From Example Problem 9.2, these values are 11 wt% and 89 wt%. Incorporation of these values along with the densities of the two components leads to

$$\rho_\alpha = \frac{100}{\dfrac{11}{7.24\ \mathrm{g/cm^3}} + \dfrac{89}{11.23\ \mathrm{g/cm^3}}} = 10.59\ \mathrm{g/cm^3}$$

Similarly for the β phase:

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

$$= \frac{100}{\dfrac{98}{7.24\ \mathrm{g/cm^3}} + \dfrac{2}{11.23\ \mathrm{g/cm^3}}} = 7.29\ \mathrm{g/cm^3}$$

Now it becomes necessary to employ Equations 9.6a and 9.6b to determine V_α and V_β as

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

$$= \frac{\dfrac{0.67}{10.59\ \text{g/cm}^3}}{\dfrac{0.67}{10.59\ \text{g/cm}^3} + \dfrac{0.33}{7.29\ \text{g/cm}^3}} = 0.58$$

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

$$= \frac{\dfrac{0.33}{7.29\ \text{g/cm}^3}}{\dfrac{0.67}{10.59\ \text{g/cm}^3} + \dfrac{0.33}{7.29\ \text{g/cm}^3}} = 0.42$$

Example problem 9.19

9.19 For alloys of two hypothetical metals A and B, there exist an α, A-rich phase and a β, B-rich phase. From the mass fractions of both phases for two different alloys provided in the following table (which are at the same temperature), determine the composition of the phase boundary (or solubility limit) for both α and β phases at this temperature.

Alloy Composition	*Fraction α Phase*	*Fraction β Phase*
60 wt% A–40 wt% B	0.57	0.43
30 wt% A–70 wt% B	0.14	0.86

Solution

The problem is to solve for compositions at the phase boundaries for both α and β phases (i.e., C_α and C_β). We may set up two independent lever rule expressions, one for each composition, in terms of C_α and C_β as follows:

$$W_{\alpha 1} = 0.57 = \frac{C_\beta - C_{01}}{C_\beta - C_\alpha} = \frac{C_\beta - 60}{C_\beta - C_\alpha}$$

$$W_{\alpha 2} = 0.14 = \frac{C_\beta - C_{02}}{C_\beta - C_\alpha} = \frac{C_\beta - 30}{C_\beta - C_\alpha}$$

In these expressions, compositions are given in wt% of A. Solving for C_α and C_β from these equations, yield

$$C_\alpha = 90 \text{ (or 90 wt\% A-10 wt\% B)}$$

$$C_\beta = 20.2 \text{ (or 20.2 wt\% A-79.8 wt\% B)}$$

9.4 – *Consider the sugar–water phase diagram of Figure 9.1.*

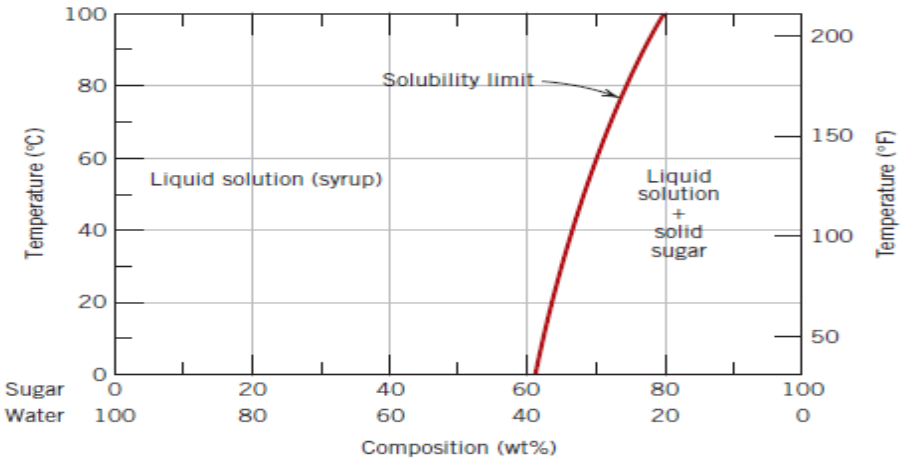


Figure 9.1 The solubility of sugar ($C_{12}H_{22}O_{11}$) in a sugar–water syrup.

(a) How much sugar will dissolve in 1500 g water at 90 °C (194 °F)?

(b) If the saturated liquid solution in part (a) is cooled to 20 °C (68 °F), some of the sugar will precipitate out as a solid. What will be the composition of the saturated liquid solution (in wt% sugar) at 20 °C?

(c) How much of the solid sugar will come out of solution upon cooling to 20 °C?

Solution

(a) We are asked to determine how much sugar will dissolve in 1000 g of water at 90°C. From the solubility limit curve in Figure 9.1, at 90°C the maximum concentration of sugar in the syrup is about 77 wt%. It is now possible to calculate the mass of sugar using Equation 4.3 as

$$C_{\text{sugar}}(\text{wt\%}) = \frac{m_{\text{sugar}}}{m_{\text{sugar}} + m_{\text{water}}} \times 100$$

$$77\ \text{wt\%} = \frac{m_{\text{sugar}}}{m_{\text{sugar}} + 1500\ \text{g}} \times 100$$

Solving for m_{sugar} yields $m_{\text{sugar}} = 5022$ g

(b) Again using this same plot, at 20°C the solubility limit (or the concentration of the saturated solution) is about 64 wt% sugar.

(c) The mass of sugar in this saturated solution at 20°C (m'_{sugar}) may also be calculated using Equation 4.3 as follows:

$$64\ \text{wt\%} = \frac{m'_{\text{sugar}}}{m'_{\text{sugar}} + 1500\ \text{g}} \times 100$$

which yields a value for m'_{sugar} of 2667 g. Subtracting the latter from the former of these sugar concentrations yields the amount of sugar that precipitated out of the solution upon cooling m''_{sugar}; that is

$$m''_{\text{sugar}} = m_{\text{sugar}} - m\tilde{Q}_{\text{sugar}} = 5022\ \text{g} - 2667\ \text{g} = 2355\ \text{g}$$

9.5-

At 500 °C (930 °F), what is the maximum solubility (a) of Cu in Ag? (b) Of Ag in Cu?

Solution

(a) From Figure 9.7, the maximum solubility of Cu in Ag at 500°C corresponds to the position of the β–(α + β) phase boundary at this temperature, or to about 2 wt% Cu.

(b) From this same figure, the maximum solubility of Ag in Cu corresponds to the position of the α–(α + β) phase boundary at this temperature, or about 1.5 wt% Ag.

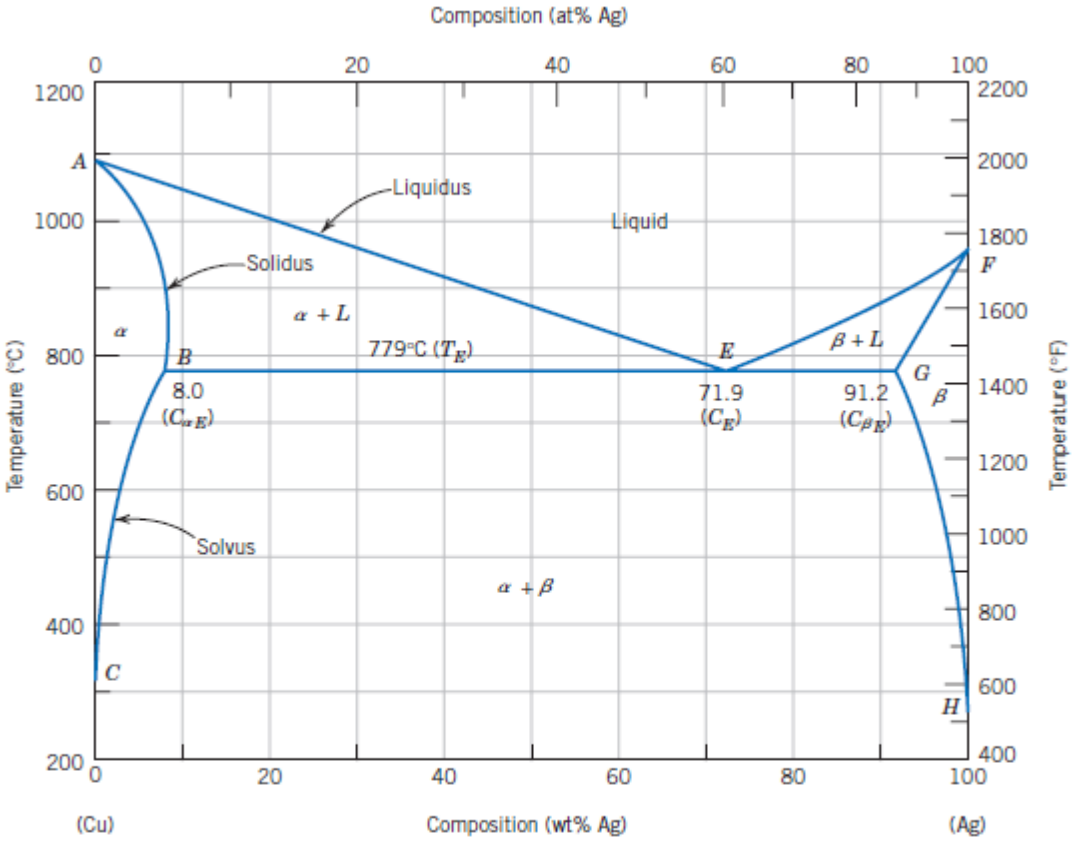


Figure 9.7 The copper–silver phase diagram. [Adapted from *Binary Alloy Phase Diagrams,* 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

9.6-

Consider a specimen of ice that is at −10°C and 1 atm pressure. Using Figure 9.2, the pressure–

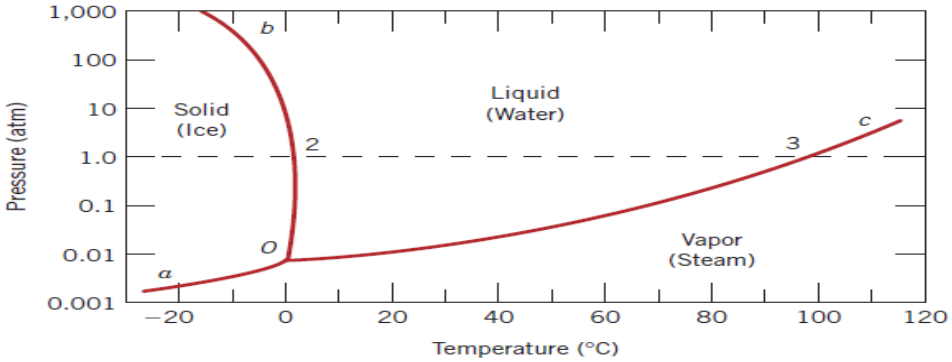
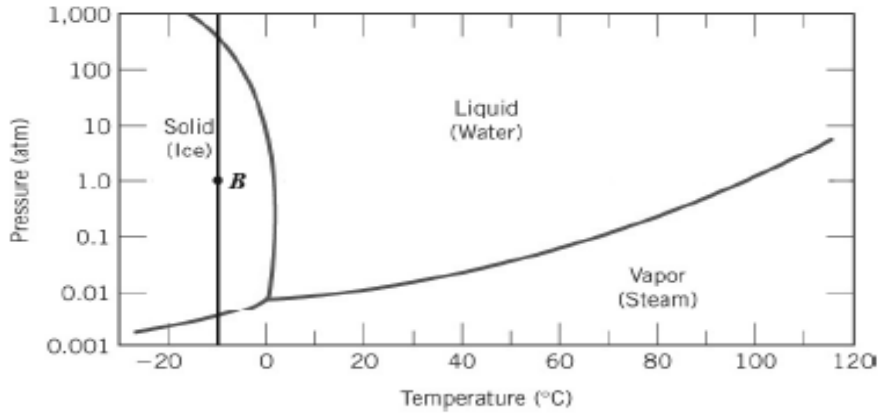


Figure 9.2 Pressure–temperature phase diagram for H_2O.

temperature phase diagram for H_2O, determine the pressure to which the specimen must be raised or lowered to cause it (a) to melt, and (b) to sublime.

Solution

The figure below shows the pressure-temperature phase diagram for H_2O, Figure 10.2; a vertical line has been constructed at -10°C, and the location on this line at 1 atm pressure (point *B*) is also noted.



(a) Melting occurs, (by changing pressure) as, moving vertically (upward) at this temperature, we cross the Ice-Liquid phase boundary. This occurs at approximately 570 atm; thus, the pressure of the specimen must be raised from 1 to 570 atm.

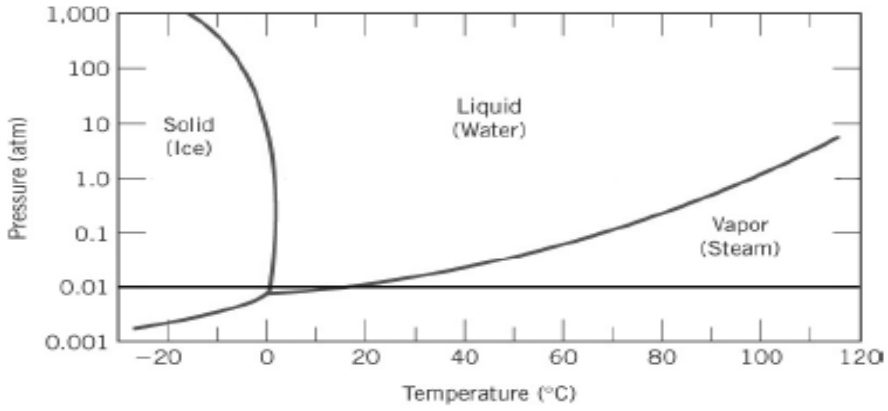
(b) In order to determine the pressure at which sublimation occurs at this temperature, we move vertically downward from 1 atm until we cross the Ice-Vapor phase boundary. This intersection occurs at approximately 0.0023 atm.

9.7-

At a pressure of 0.01 atm, determine (a) the melting temperature for ice, and (b) the boiling temperature for water.

Solution

The melting temperature for ice and the boiling temperature for water at a pressure of 0.01 atm may be determined from the pressure-temperature diagram for this system, Figure 10.2, which is shown below; a horizontal line has been constructed across this diagram at a pressure of 0.01 atm.



The melting and boiling temperatures for ice at a pressure of 0.01 atm may be determined by moving horizontally across the pressure-temperature diagram at this pressure. The temperature corresponding to the intersection of the Ice-Liquid phase boundary is the melting temperature, which is approximately 1°C. On the other hand, the boiling temperature is at the intersection of the horizontal line with the Liquid-Vapor phase boundary--approximately 16°C.

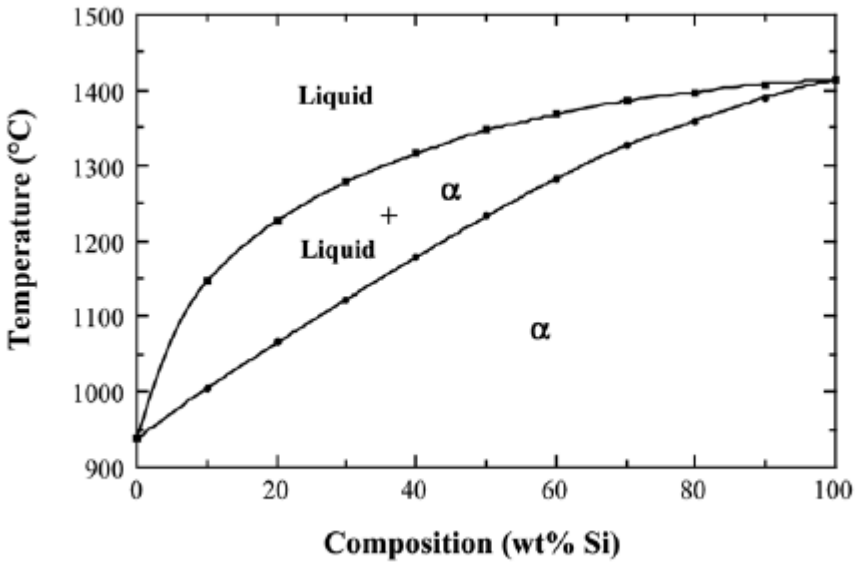
9.8-

Given here are the solidus and liquidus temperatures for the germanium-silicon 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*

Solution

The germanium-silicon phase diagram is constructed below.



9.9-

Cite the phases that are present and the phase compositions for the following alloys:

(a) 75 wt% Sn-25 wt% Pb at 175°C (345°F)

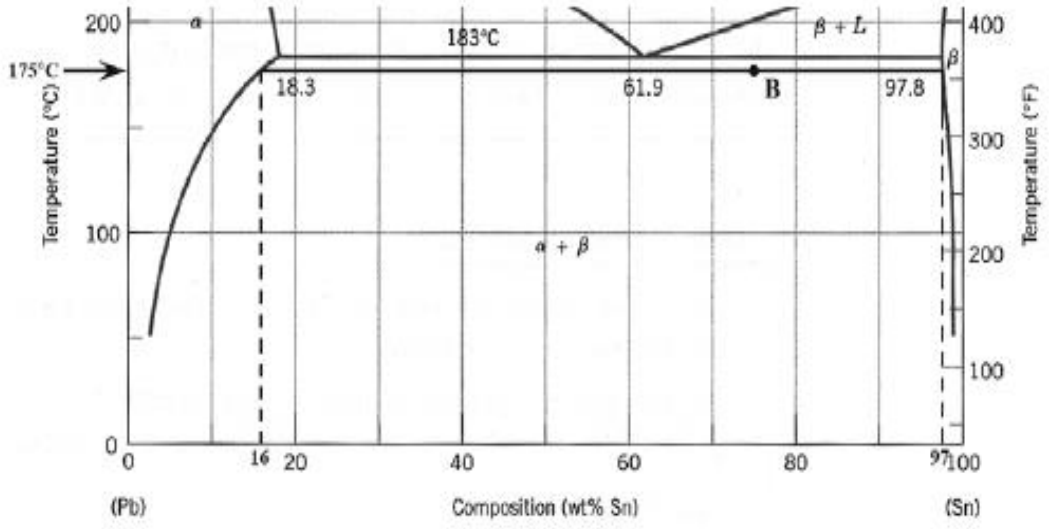
(b) 55 wt% Ag-45 wt% Cu at 900°C (1650°F)

(c) 8.2 mol Ni and 4.3 mol Cu at 1250°C (2280°F)

Solution

This problem asks that we cite the phase or phases present for several alloys at specified temperatures.

(a) That portion of the Pb-Sn phase diagram (Figure 9.8) that pertains to this problem is shown below; the point labeled "B" represents the 75 wt% Sn-25 wt% Pb composition at 175°C.

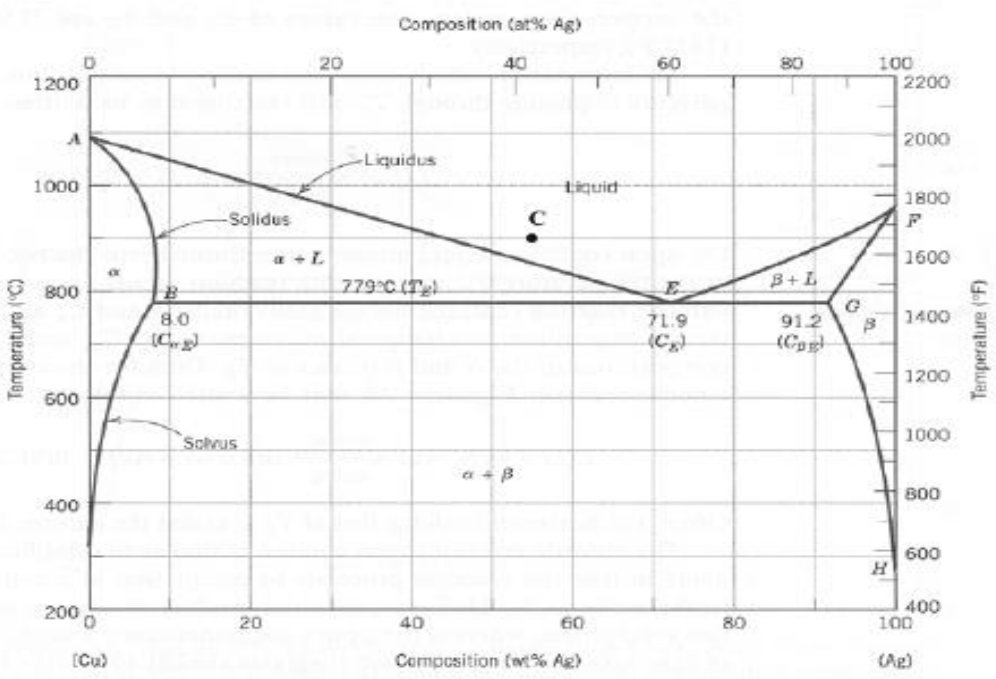


As may be noted, point B lies within the α + β phase field. A tie line has been constructed at 175°C; its intersection with the α–α + β phase boundary is at 16 wt% Sn, which corresponds to the composition of the α phase. Similarly, the tie-line intersection with the α + β–β phase boundary occurs at 97 wt% Sn, which is the composition of the β phase. Thus, the phase compositions are as follows:

$$C_\alpha = 16 \text{ wt\% Sn-84 wt\% Pb}$$

$$C_\beta = 97 \text{ wt\% Sn-3 wt\% Pb}$$

(b) The Ag-Cu phase diagram (Figure 9.7) is shown below; the point labeled "C" represents the 55 wt% Ag-45 wt% Cu composition at 900°C.



As may be noted, point C lies within the Liquid phase field. Therefore, only the liquid phase is present; its composition is 55 wt% Ag-45 wt% Cu.

(c) For an alloy composed of 8.2 mol Ni and 4.3 mol Cu and at 1250°C, it is first necessary to determine the Ni and Cu concentrations, which we will do in wt% as follows:

$$n'_{Ni} = n_{m_{Ni}} A_{Ni} = (8.2 \text{ mol})(58.69 \text{ g/mol}) = 481.3 \text{ g}$$

$$n'_{Cu} = n_{m_{Cu}} A_{Cu} = (4.3 \text{ mol})(63.55 \text{ g/mol}) = 273.3 \text{ g}$$

$$C_{Ni} = \frac{481.3 \text{ g}}{481.3 \text{ g} + 273.3 \text{ g}} \times 100 = 63.8 \text{ wt\%}$$

$$C_{Cu} = \frac{273.3 \text{ g}}{481.3 \text{ g} + 273.3 \text{ g}} \times 100 = 36.2 \text{ wt\%}$$

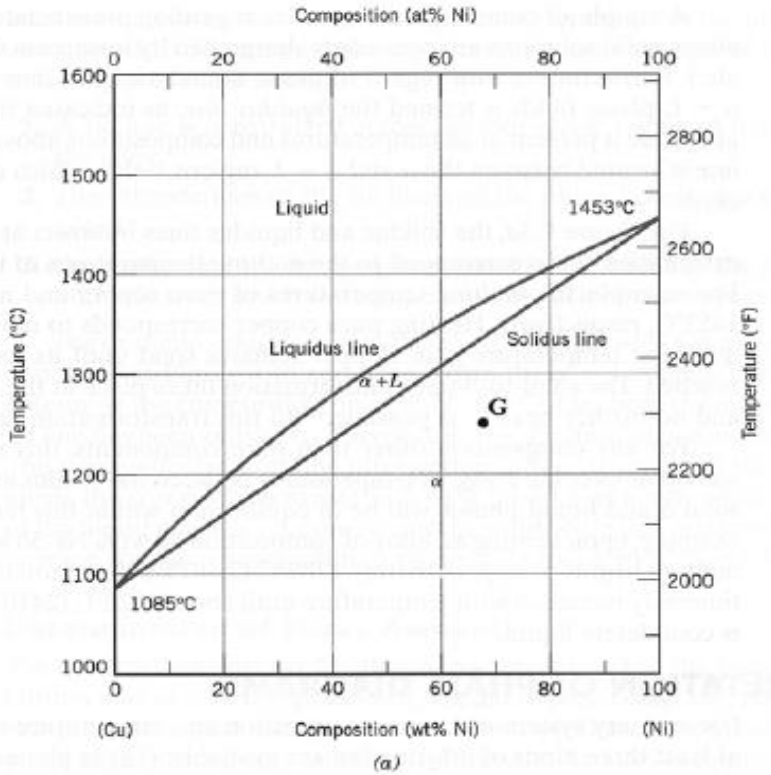
The Cu-Ni phase diagram (Figure 9.3*a*) is shown below; the point labeled "G" represents the 63.8 wt% Ni-36.2 wt% Cu composition at 1250°C.

9.10-

Is it possible to have a copper–nickel alloy that, at equilibrium, consists of a liquid phase of composition 20 wt% Ni–80 wt% Cu and also an α phase of composition 37 wt% Ni–63 wt% Cu? If so, what will be the approximate temperature of the alloy? If this is not possible, explain why.

Solution

It is *not possible* to have a Cu-Ni alloy, which at equilibrium, consists of a liquid phase of composition 20 wt% Ni-80 wt% Cu and an α phase of composition 37 wt% Ni-63 wt% Cu. From Figure 9.3*a*, a single tie line does not exist within the $\alpha + L$ region that intersects the phase boundaries at the given compositions. At 20 wt% Ni, the L-$(\alpha + L)$ phase boundary is at about 1200°C, whereas at 37 wt% Ni the $(L + \alpha)$-α phase boundary is at about 1230°C.



(a)

As may be noted, point G lies within the α phase field. Therefore, only the α phase is present; its composition is 63.8 wt% Ni-36.2 wt% Cu.

9.11 *A copper-nickel alloy of composition 70 wt% Ni-30 wt% Cu is slowly heated from a temperature of 1300°C (2370°F).*

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

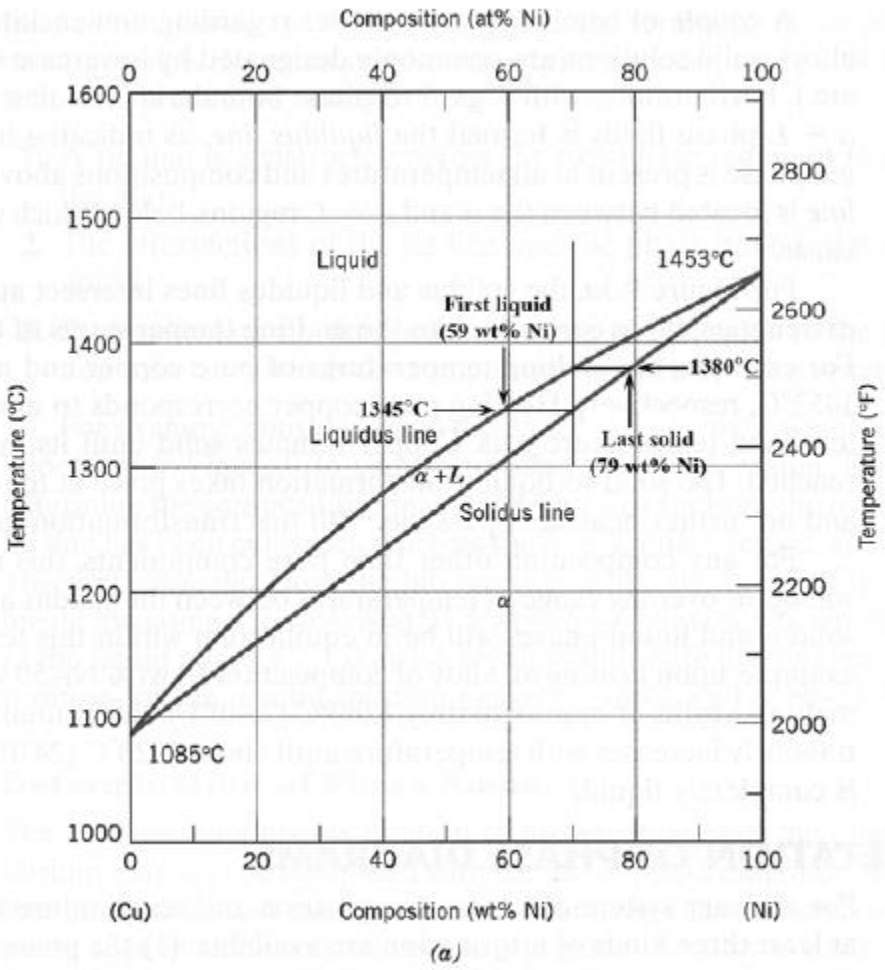
(b) What is the composition of this liquid phase?

(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?

Solution

Shown below is the Cu-Ni phase diagram (Figure 9.3*a*) and a vertical line constructed at a composition of 70 wt% Ni-30 wt% Cu.



(a) Upon heating from 1300°C, the first liquid phase forms at the temperature at which this vertical line intersects the α-(α + *L*) phase boundary--i.e., about 1345°C.

(b) The composition of this liquid phase corresponds to the intersection with the (α + *L*)-*L* phase boundary, of a tie line constructed across the α + *L* phase region at 1345°C--i.e., 59 wt% Ni;

(c) Complete melting of the alloy occurs at the intersection of this same vertical line at 70 wt% Ni with the (α + *L*)-*L* phase boundary--i.e., about 1380°C;

9.12-

Is it possible to have a copper-silver alloy of composition 50 wt% Ag-50 wt% Cu, which, at

equilibrium, consists of α and β phases having mass fractions $W_\alpha = 0.60$ and $W_\beta = 0.40$? If so, what will be the approximate temperature of the alloy? If such an alloy is not possible, explain why.

Solution

It is *not possible* to have a Cu-Ag alloy of composition 50 wt% Ag-50 wt% Cu which consists of mass fractions $W_\alpha = 0.60$ and $W_\beta = 0.40$. Using the appropriate phase diagram, Figure 9.7, and, using Equations 9.1 and 9.2 let us determine W_α and W_β at just below the eutectic temperature and also at room temperature. At just below the eutectic, $C_\alpha = 8.0$ wt% Ag and $C_\beta = 91.2$ wt% Ag; thus,

$$W_\alpha = \frac{C_\beta - C_0}{C_\beta - C_\alpha} = \frac{91.2 - 50}{91.2 - 8} = 0.50$$

$$W_\beta = 1.00 - W_\alpha = 1.00 - 0.50 = 0.50$$

Furthermore, at room temperature, $C_\alpha = 0$ wt% Ag and $C_\beta = 100$ wt% Ag; employment of Equations 9.1 and 9.2 yields

$$W_\alpha = \frac{C_\beta - C_0}{C_\beta - C_\alpha} = \frac{100 - 50}{100 - 0} = 0.50$$

And, $W_\beta = 0.50$. Thus, the mass fractions of the α and β phases, upon cooling through the α + β phase region will remain approximately constant at about 0.5, and will never have values of $W_\alpha = 0.60$ and $W_\beta = 0.40$ as called for in the problem.

9.13-

For 11.20 kg of a magnesium-lead alloy of composition 30 wt% Pb-70 wt% Mg, is it possible, at equilibrium, to have α and Mg_2Pb phases having respective masses of 7.39 kg and 3.81 kg? If so, what will be the approximate temperature of the alloy? If such an alloy is not possible, explain why.

Solution

Yes, it *is possible* to have a 30 wt% Pb-70 wt% Mg alloy which has masses of 7.39 kg and 3.81 kg for the α and Mg_2Pb phases, respectively. In order to demonstrate this, it is first necessary to determine the mass fraction of each phase as follows:

$$W_\alpha = \frac{m_\alpha}{m_\alpha + m_{Mg_2Pb}} = \frac{7.39\ \text{kg}}{7.39\ \text{kg} + 3.81\ \text{kg}} = 0.66$$

$$W_{Mg_2Pb} = 1.00 - 0.66 = 0.34$$

Now, if we apply the lever rule expression for W_α

$$W_\alpha = \frac{C_{Mg_2Pb} - C_0}{C_{Mg_2Pb} - C_\alpha}$$

Since the Mg_2Pb phase exists only at 81 wt% Pb, and $C_0 = 30$ wt% Pb

$$W_\alpha = 0.66 = \frac{81 - 30}{81 - C_\alpha}$$

9.14-

A 45 wt% Pb–55 wt% Mg alloy is rapidly quenched to room temperature from an elevated temperature in such a way that the high-temperature microstructure is preserved. This microstructure is found to consist of the α phase and Mg_2Pb, having respective mass fractions of 0.65 and 0.35. Determine the approximate temperature from which the alloy was quenched.

Solution

We are asked to determine the approximate temperature from which a 45 wt% Pb-55 wt% Mg alloy was quenched, given the mass fractions of α and Mg_2Pb phases. We can write a lever-rule expression for the mass fraction of the α phase as

$$W_\alpha = 0.65 = \frac{C_{Mg_2Pb} - C_0}{C_{Mg_2Pb} - C_\alpha}$$

The value of C_0 is stated as 45 wt% Pb-55 wt% Mg, and C_{Mg_2Pb} is 81 wt% Pb-19 wt% Mg, which is independent of temperature (Figure 9.20); thus,

$$0.65 = \frac{81 - 45}{81 - C_\alpha}$$

which yields

$$C_\alpha = 25.6 \text{ wt\% Pb}$$

The temperature at which the α–(α + Mg_2Pb) phase boundary (Figure 9.20) has a value of 25.6 wt% Pb is about 360°C (680°F).

9.15-

Consider the hypothetical eutectic phase diagram for metals A and B, which is similar to that for the lead-tin system, Figure 9.8. Assume that (1) α and β phases exist at the A and B extremities of the phase diagram, respectively; (2) the eutectic composition is 47 wt% B-53 wt% A; and (3) the composition of the β phase at the eutectic temperature is 92.6 wt% B-7.4 wt% A. Determine the composition of an alloy that will yield primary α and total α mass fractions of 0.356 and 0.693, respectively.

Solution

We are given a hypothetical eutectic phase diagram for which $C_{eutectic}$ = 47 wt% B, C_β = 92.6 wt% B at the eutectic temperature, and also that $W_{\alpha'}$ = 0.356 and W_α = 0.693; from this we are asked to determine the composition of the alloy. Let us write lever rule expressions for $W_{\alpha'}$ and W_α

$$W_\alpha = \frac{C_\beta - C_0}{C_\beta - C_\alpha} = \frac{92.6 - C_0}{92.6 - C_\alpha} = 0.693$$

$$W_{\alpha'} = \frac{C_{eutectic} - C_0}{C_{eutectic} - C_\alpha} = \frac{47 - C_0}{47 - C_\alpha} = 0.356$$

Thus, we have two simultaneous equations with C_0 and C_α as unknowns. Solving them for C_0 gives C_0 = 32.6 wt% B.

9.16-

Compute the mass fractions of α ferrite and cementite in pearlite.

Solution

This problem asks that we compute the mass fractions of α ferrite and cementite in pearlite. The lever-rule expression for ferrite is

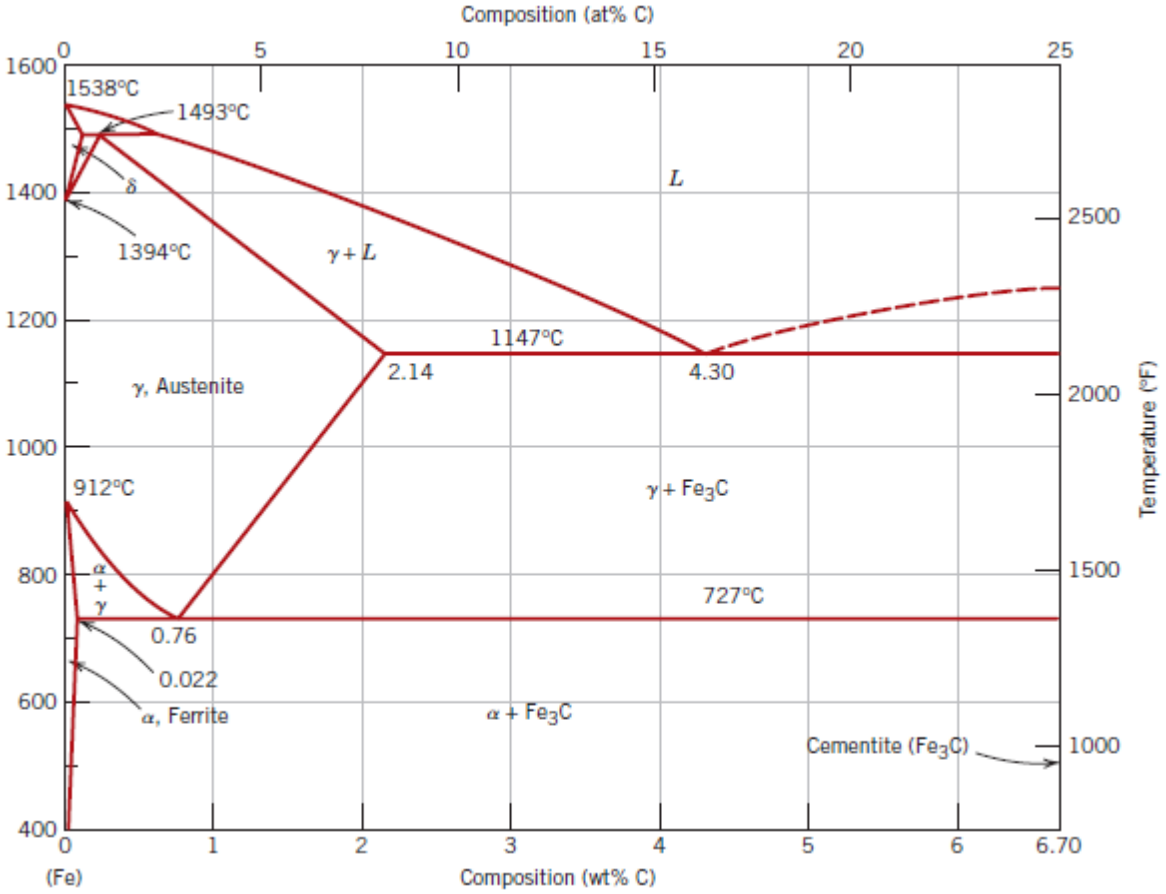
$$W_\alpha = \frac{C_{Fe_3C} - C_0}{C_{Fe_3C} - C_\alpha}$$

and, since $C_{Fe_3C} = 6.70$ wt% C, $C_0 = 0.76$ wt% C, and $C_\alpha = 0.022$ wt% C

$$W_\alpha = \frac{6.70 - 0.76}{6.70 - 0.022} = 0.89$$

Similarly, for cementite

$$W_{Fe_3C} = \frac{C_0 - C_\alpha}{C_{Fe_3C} - C_\alpha} = \frac{0.76 - 0.022}{6.70 - 0.022} = 0.11$$



9.17-

What is the carbon concentration of an iron–carbon alloy for which the fraction of total ferrite is 0.94?

Solution

This problem asks that we compute the carbon concentration of an iron-carbon alloy for which the fraction of total ferrite is 0.94. Application of the lever rule (of the form of Equation 9.12) yields

$$W_\alpha = 0.94 = \frac{C_{Fe_3C} - C_0'}{C_{Fe_3C} - C_\alpha} = \frac{6.70 - C_0'}{6.70 - 0.022}$$

and solving for C_0'

$$C_0' = 0.42 \text{ wt\% C}$$

9.18-

What is the proeutectoid phase for an iron–carbon alloy in which the mass fractions of total ferrite and total cementite are 0.92 and 0.08, respectively? Why?

Solution

In this problem we are given values of W_α and W_{Fe_3C} (0.92 and 0.08, respectively) for an iron-carbon alloy and then are asked to specify the proeutectoid phase. Employment of the lever rule for total α leads to

$$W_\alpha = 0.92 = \frac{C_{Fe_3C} - C_0}{C_{Fe_3C} - C_\alpha} = \frac{6.70 - C_0}{6.70 - 0.022}$$

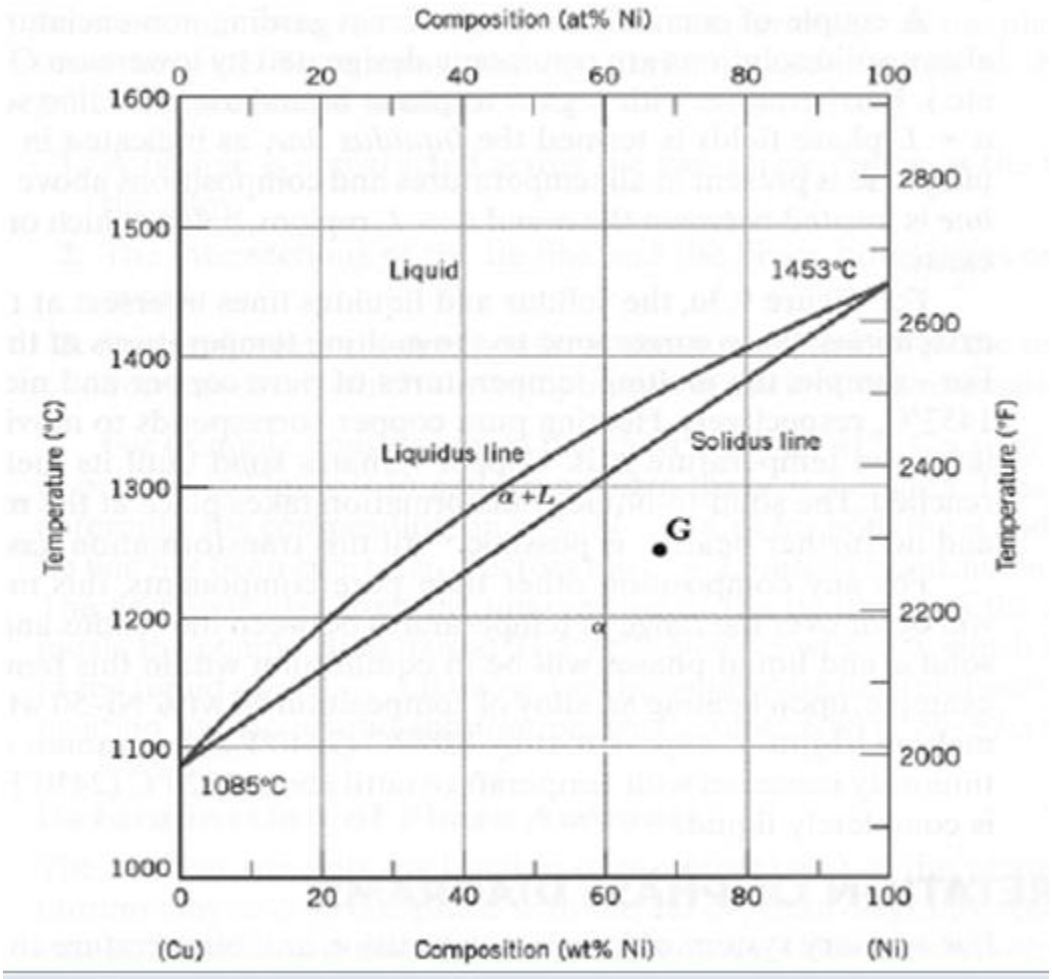
Now, solving for C_0, the alloy composition, leads to $C_0 = 0.56$ wt% C. Therefore, the proeutectoid phase is α-ferrite since C_0 is less than 0.76 wt% C.

9.10-

Is it possible to have a copper–nickel alloy that, at equilibrium, consists of a liquid phase of composition 20 wt% Ni–80 wt% Cu and also an α phase of composition 37 wt% Ni–63 wt% Cu? If so, what will be the approximate temperature of the alloy? If this is not possible, explain why.

Solution

It is *not possible* to have a Cu-Ni alloy, which at equilibrium, consists of a liquid phase of composition 20 wt% Ni-80 wt% Cu and an α phase of composition 37 wt% Ni-63 wt% Cu. From Figure 9.3*a*, a single tie line does not exist within the α + *L* region that intersects the phase boundaries at the given compositions. At 20 wt% Ni, the *L*-(α + *L*) phase boundary is at about 1200°C, whereas at 37 wt% Ni the (*L* + α)-α phase boundary is at about 1230°C.


Composition (at% Ni)
0
20
40
60
80
100
1600
1500
1400
1300
1200
1100
1000
2800
2600
2400
2200
2000
Liquid
1453°C
Liquidus line
Solidus line
α + L
G
α
1085°C
Temperature (°C)
Temperature (°F)
(Cu)
Composition (wt% Ni)
(Ni)