Ahsanullah University of Science and Technology (AUST)
Department of Mechanical and Production Engineering

LABORATORY MANUAL
For the students of
Department of Mechanical and Production Engineering
1st Year, 2nd Semester
Course Title: Engineering Materials Sessional
Course Code: IPE 1212
Credit Hours: 0.75

Student Name :

Student ID :

Department of Mechanical and Production Engineering
Ahsanullah University of Science and Technology (AUST)

IPE 1212: Engineering Materials Sessional
Credit Hour: 0.75

General Instructions:

1. Attend the lab 5 minutes prior to the scheduled time and be prepared for the experiment.
2. Students must be prepared for the experiment prior to the class.
3. A report on an experiment must be submitted in the next class.
4. The report should be submitted the following week during the session.
5. Write a report on one side of an 80-gram A4 paper and follow the following format
    - a) Top sheet
    - b) Objective
    - c) Apparatus
    - d) Figure
    - e) Data Sheets
    - f) Sample calculation
    - g) Result
    - h) Graph
    - i) Discussion
        - i) Discuss the graphs and results
        - ii) Discuss the experimental setup if it could be improved
        - iii) Discuss the different parameters that could affect the result
        - iv) Discuss any assumption made
        - v) Discuss any discrepancies in the experimental procedure and result
    - j) Finally, add the data sheet with the report.

Marks Distribution:

Total Marks		
Report	Attendance and Viva	Quiz
40	20	40

Ahsanullah University of Science and Technology

Course Code: IPE 1212

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Relevant Theory

Alloy: An alloy is a mixture of two or more elements, where at least one of the elements is metal. Alloys are created to improve the properties of the base metal, such as strength, hardness, corrosion resistance, or workability.

Examples:

- **Steel** = Iron (Fe) + Carbon (C)
- **Brass** = Copper (Cu) + Zinc (Zn)
- **Bronze** = Copper (Cu) + Tin (Sn)
- **Stainless Steel** = Iron (Fe) + Chromium (Cr) + Nickel (Ni)

Ferrous Alloy

Ferrous alloys—those of which iron is the prime constituent—are produced in larger quantities than any other metal type. They are especially important as engineering construction materials. Their widespread use is accounted for by three factors:

(1) iron-containing compounds exist in abundant quantities within the earth's crust

(2) metallic iron and steel alloys may be produced using relatively economical ex traction, refining, alloying, and fabrication techniques

(3) ferrous alloys are extremely versatile; in that they may be tailored to have a wide range of mechanical and physical properties. The principal disadvantage of many ferrous alloys is their susceptibility to corrosion**.**

A taxonomic classification scheme for the various ferrous alloys is presented in Figure 1**.**

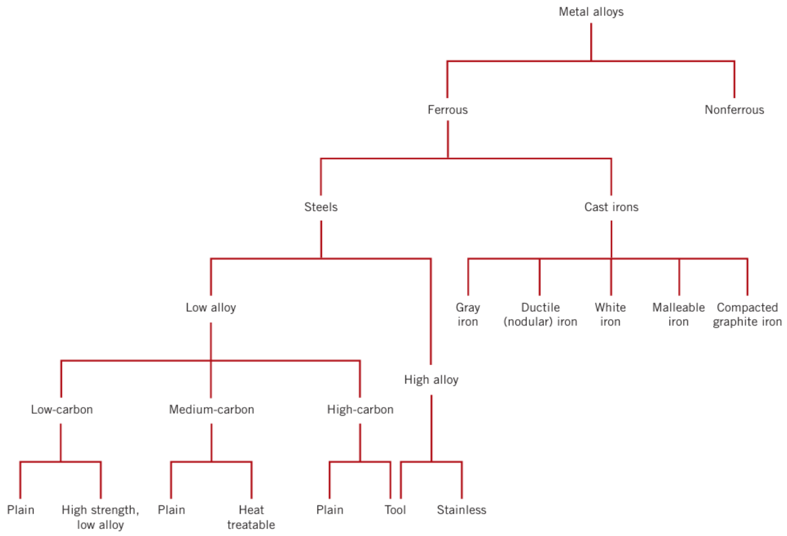


Figure 1: Classification scheme for the various ferrous alloys

Cast Iron

Generically, cast irons are a class of ferrous alloys with carbon contents above 2.14 wt%; in practice, however, most cast irons contain between 3.0 and 4.5 wt% C and, in addition, other alloying elements. The description of different types of cast iron are given below:

Gray Cast Iron

The carbon and silicon contents of gray cast irons vary between 2.5 and 4.0 wt% and 1.0 and 3.0 wt%, respectively. For most of these cast irons, the graphite exists in the form of flakes (similar to corn flakes), which are normally surrounded by an-ferrite or pearlite matrix; the microstructure of a typical gray iron is shown in Figure 2. Because of these graphite flakes, a fractured surface takes on a gray appearance, hence its name.

Figure 2: Optical photomicrographs of Gray Cast iron: the dark graphite flakes are embedded in a ferrite matrix. 500X.

Mechanically, gray iron is comparatively weak and brittle in tension as a con sequence of its microstructure; the tips of the graphite flakes are sharp and pointed and may serve as points of stress concentration when an external tensile stress is applied. Strength and ductility are much higher under compressive loads. Gray irons do have some desirable characteristics and are utilized extensively. They are very effective in damping vibrational energy. Base structures for machines and heavy equipment that are exposed to vibrations are frequently constructed of this material. In addition, gray irons exhibit a high resistance to wear. Furthermore, in the molten state they have a high fluidity at casting temperature, which permits casting pieces that have intricate shapes; also, casting shrinkage is low. Finally, and perhaps most important, gray cast irons are among the least expensive of all metallic materials.

Ductile (or Nodular Cast Iron)

Adding a small amount of magnesium and/or cerium to the gray iron before casting produces a distinctly different microstructure and set of mechanical properties. Graphite still forms, but as nodules or spherelike particles instead of flakes. The resulting alloy is called ductile or nodular iron, and a typical microstructure is shown in Figure 3.

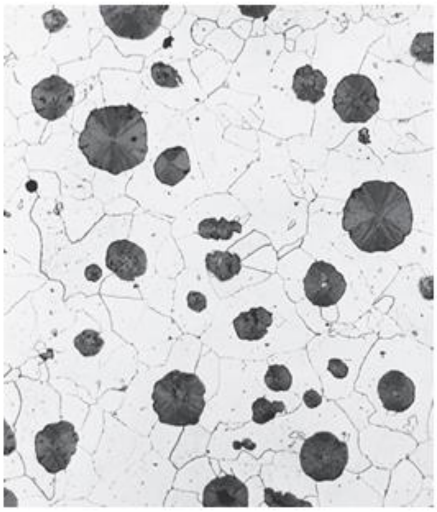


Figure 3: Optical photomicrographs of nodular Cast iron: Nodular (ductile) iron: the dark graphite nodules are surrounded by a ferrite matrix. 200X.

In fact, ductile iron has mechanical characteristics approaching those of steel. For example, ferritic ductile irons have tensile strengths ranging between 380 and 480 MPa (55,000 and 70,000 psi), and ductility (as percent elongation) from 10% to 20%. Typical applications for this material include valves, pump bodies, crankshafts, gears, and other automotive and machine components.

White Iron and Malleable Iron

For low silicon cast irons (containing less than 1.0 wt% Si) and rapid cooling rates, most of the carbon exists as cementite instead of graphite. The fracture surface of this alloy has a white appearance, and thus it is termed white cast iron. An optical photomicrograph showing the microstructure of white iron is presented in Figure 4(a). Thick sections may have only a surface layer of white iron that was “chilled” during the casting process; gray iron forms at interior regions, which cool more slowly. As a consequence of large amounts of the cementite phase, white iron is extremely hard but also very brittle, to the point of being virtually unmachinable. Its use is limited to applications that necessitate a very hard and wear-resistant surface, without a high degree of ductility—for example, as rollers in rolling mills.

Generally, white iron is used as an intermediary in the production of yet another cast iron, **malleable iron**. Heating white iron at temperatures between 800 and 900C (1470 and 1650F) for a prolonged time period and in a neutral atmosphere (to prevent oxidation) causes a decomposition of the cementite, forming graphite, which exists in the form of clusters or rosettes surrounded by a ferrite or pearlite matrix, depending on cooling rate, as indicated in Figure 5. A photomicrograph of a ferritic malleable iron is presented in Figure 4(b). The microstructure is similar to that of nodular iron, which accounts for relatively high strength and appreciable ductility or malleability. Representative applications include connecting rods, transmission gears, and differential cases for the automotive industry, and also flanges, pipe fittings, and valve parts for railroad, marine, and other heavy-duty services.

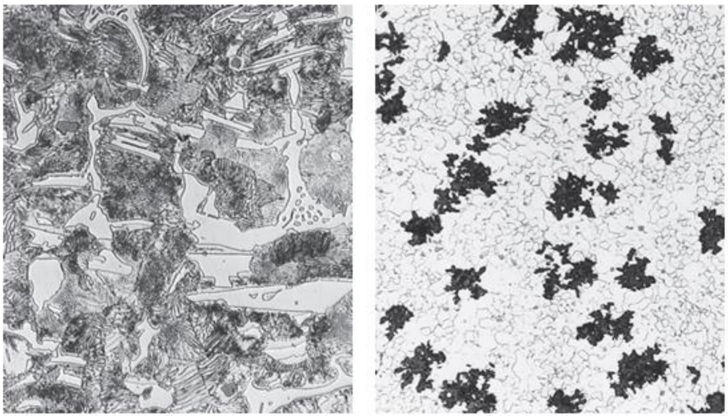


Figure 4: (a) (to the left) White iron: the light cementite regions are surrounded by pearlite, which has the ferrite–cementite layered structure. 400X. (b) (to the right) Malleable iron: dark graphite rosettes (temper carbon) in a -ferrite matrix. 150X.

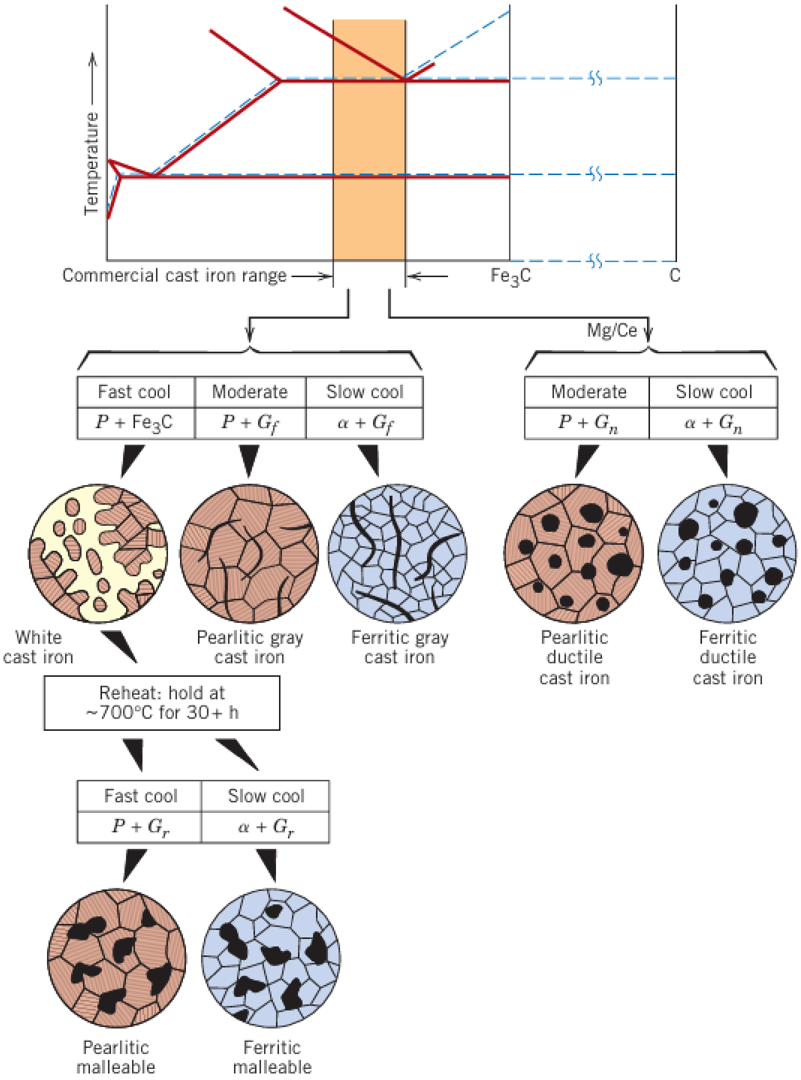


Figure 5: From the iron–carbon phase diagram, composition ranges for commercial cast irons. Also shown are schematic microstructures that result from a variety of heat treatments. G_f, flake graphite; G_r, graphite rosettes; G_n, graphite nodules; P, pearlite; α, ferrite

Component: 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: Solvent represents the element that is present in a solution in the greatest amount and solute is the element that is present in a solution in the minor concentration.

System: 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).

Solid Solution: A solid solution consists of atoms of at least two different types; the solute atoms occupy either substitutional or interstitial positions in the solvent lattice, and the crystal structure of the solvent is maintained.

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 more than this solubility limit results in the formation of another solid solution or compound that has a distinctly different composition. To illustrate this concept, consider the sugar–water system, Initially, as sugar is added to water, a sugar–water solution or syrup forms. As more sugar is introduced, the solution becomes more concentrated, until the solubility limit is reached, or the solution becomes saturated with sugar and further additions simply settle to the bottom of the container. Thus, the system now consists of two separate substances: a sugar–water syrup liquid solution and solid crystals of undissolved sugar.

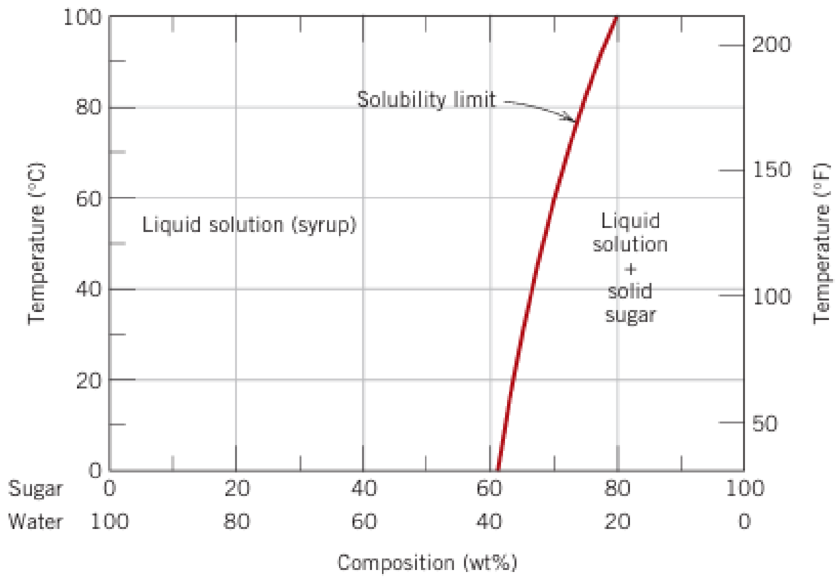


Figure 9.1 The solubility of sugar ($C_{12}H_{22}O_{11}$) in a sugar–water syrup.

This solubility limit of sugar in water depends on the temperature of the water and may be represented in graphical form on a plot of temperature along the ordinate and composition (in weight percent sugar) along the abscissa. For example, at 20C the maximum solubility of sugar in water is 65 wt%. The sum of the concentrations at any composition will equal 100 wt% as two components are involved.

Phases: A phase may be defined as a homogeneous portion of a system that has uniform physical and chemical characteristics. For example, the sugar–water syrup solution just discussed is one phase, and solid sugar is another. Each has different physical properties (one is a liquid; the other is a solid). Furthermore, each is different chemically (i.e., has a different chemical composition); one is virtually pure sugar, the other is a solution of water and sugar.

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.

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.

Microstructure: Microstructure is subject to direct microscopic observation, using optical or electron microscopes.

In metal alloys, microstructure is characterized by the number of phases present, their proportions, and the way they are distributed or arranged. The microstructure of an alloy depends on such variables as the alloying elements present, their concentrations, and the heat treatment of the alloy (i.e., the temperature, the heating time at temperature, and the rate of cooling to room temperature).

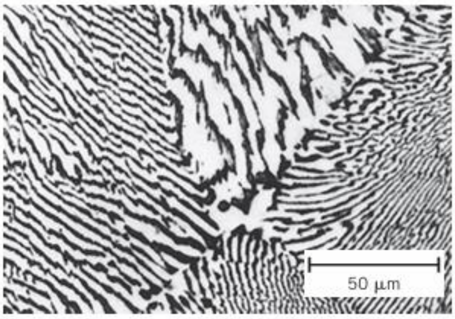


Figure 9.14 Photomicrograph showing the microstructure of a lead–tin alloy of eutectic composition. This microstructure consists of alternating layers of a lead-rich α-phase solid solution (dark layers), and a tin-rich β-phase solid solution (ligh layers). 375 ×. (Reproduced with permission from *Metals Handbook,* 9th edition, Vol. 9, *Metallography and Microstructures,* American Society for Metals, Materials Park, OH, 1985.)

Equilibrium: Equilibrium is another essential concept that is best described in terms of a thermodynamic quantity called free energy. In brief, free energy is a function of the internal energy of a system, and 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.

Phase Equilibrium: The term phase equilibrium, often used in the context of this discussion, refers to equilibrium as it applies to systems in which more than one phase may exist.

One Component (or Unary) Phase Diagram:

Phase Diagram: 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.

Now, there are 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.

Perhaps the simplest and easiest type of phase diagram to understand is 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).

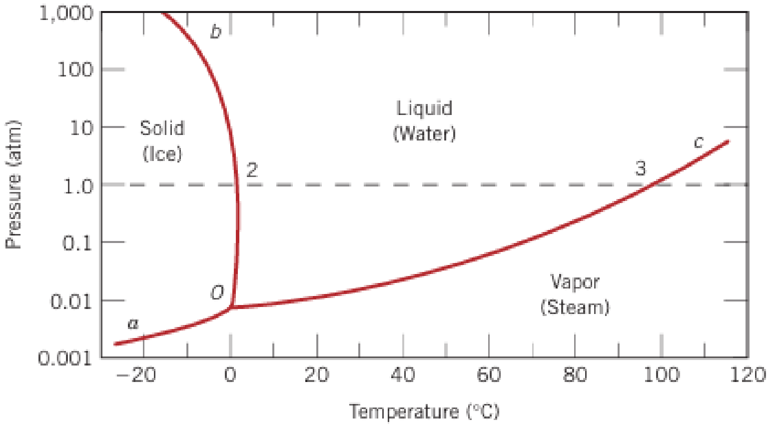


Figure 9.2 Pressure–temperature phase diagram for H_2O. Intersection of the dashed horizontal line at 1 atm pressure with the solid–liquid phase boundary (point 2) corresponds to the melting point at this pressure ($T = 0$°C). Similarly, point 3, the intersection with the liquid–vapor boundary, represents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

Here it may be noted that regions for three different phases—solid, liquid, and vapor—are delineated on the plot. 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. Also, upon crossing a boundary (as temperature and/or pressure is altered), one phase transforms to another. For example, at 1 atm pressure, during heating the solid phase transforms to the liquid phase (i.e., melting occurs) at the point labeled 2.

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 6.04X10^-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. Any deviation from this point by a change of temperature and/or pressure will cause at least one of the phases to disappear.

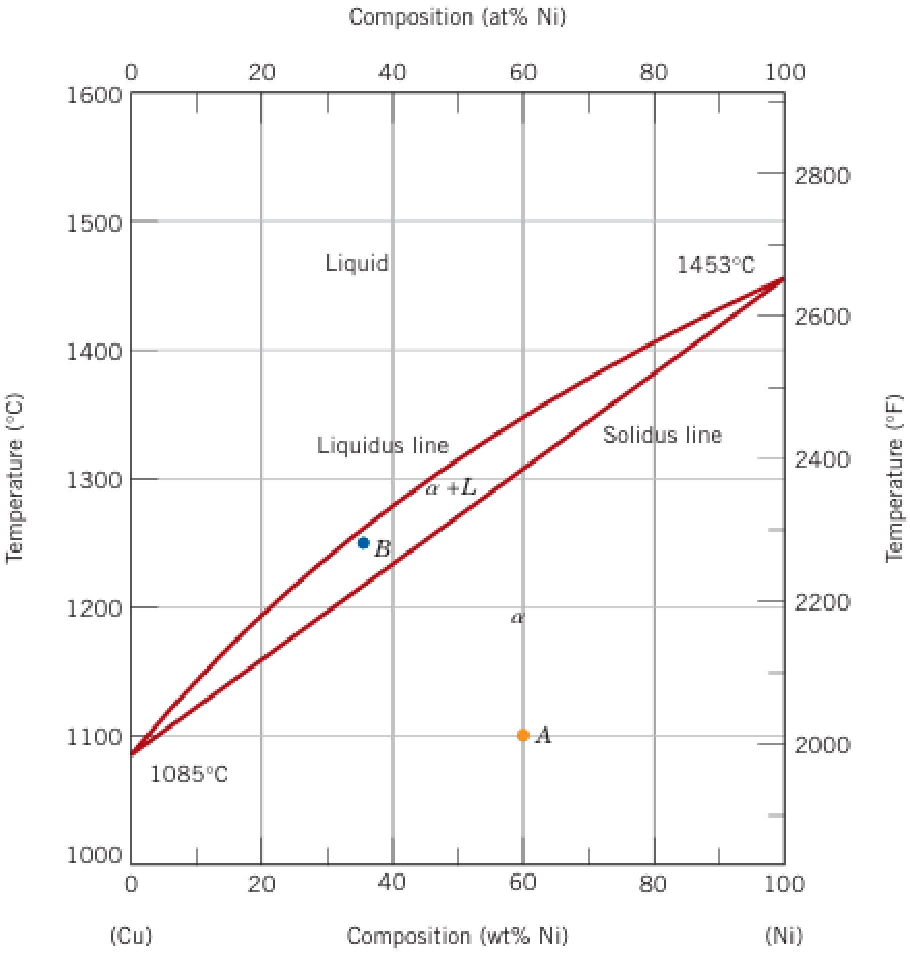
Binary Phase Diagrams: Another type of extremely common phase diagram is one in which temperature and composition are variable parameters, and pressure is held constant—normally 1 atm. Binary phase diagrams are maps that represent the relationship between temperature and the compositions and quantities of phases at equilibrium, which influence the microstructure of an alloy.

Binary Isomorphous Systems:

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

Three different phase regions, or fields, appear on the diagram, an alpha (α) field, a liquid (α+L) field, and a two-phase L field. Each region is defined by the phase or phases that exist over the range of temperatures and compositions delineated by the phase boundary lines.

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.)



Liquid L is a homogeneous liquid solution composed of both copper and nickel. The phase is a substitute solid solution consisting of both Cu and Ni atoms and having an FCC crystal structure. The copper–nickel system is termed isomorphous because of this complete liquid and solid solubility of the two components. Furthermore, regarding phase boundaries, the line separating the L and α+L phase fields is termed the liquidus line, The solidus line is located between the α and α+L regions, below which only the solid phase exists.

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: (1) the phases that are present, (2) the compositions of these phases, and (3) the percentages or fractions of the phases.

Phases Present: an alloy of composition 60 wt% Ni–40 wt% Cu at 1100C would be located at point A in Figure 9.3a; because this is within the region, only the single phase will be present. On the other hand, a 35 wt% Ni–65 wt% Cu alloy at 1250C (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. 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

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.

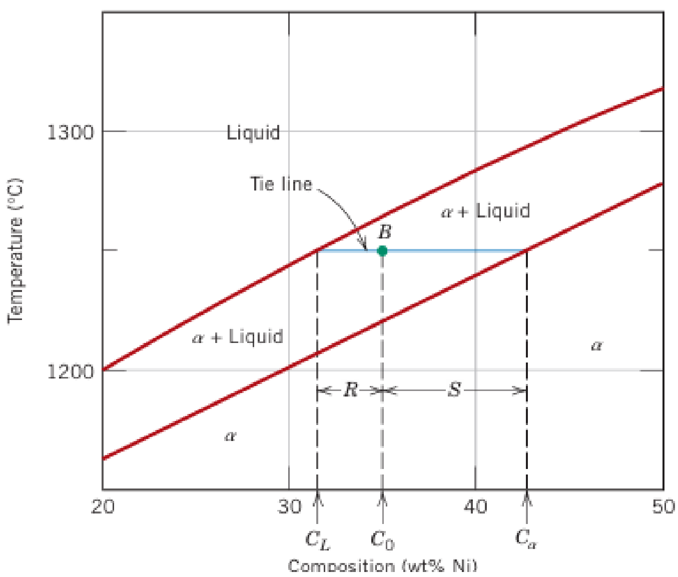


Figure 9.3 (b): A portion of the copper–nickel phase diagram for which compositions and phase amounts are determined at point B.

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 42.5 %Ni–57.5 wt% Cu

Determination of Phase Amount:

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

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 ap plied 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.

the composition axis.

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,

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

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, $C_\alpha =$ 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,

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

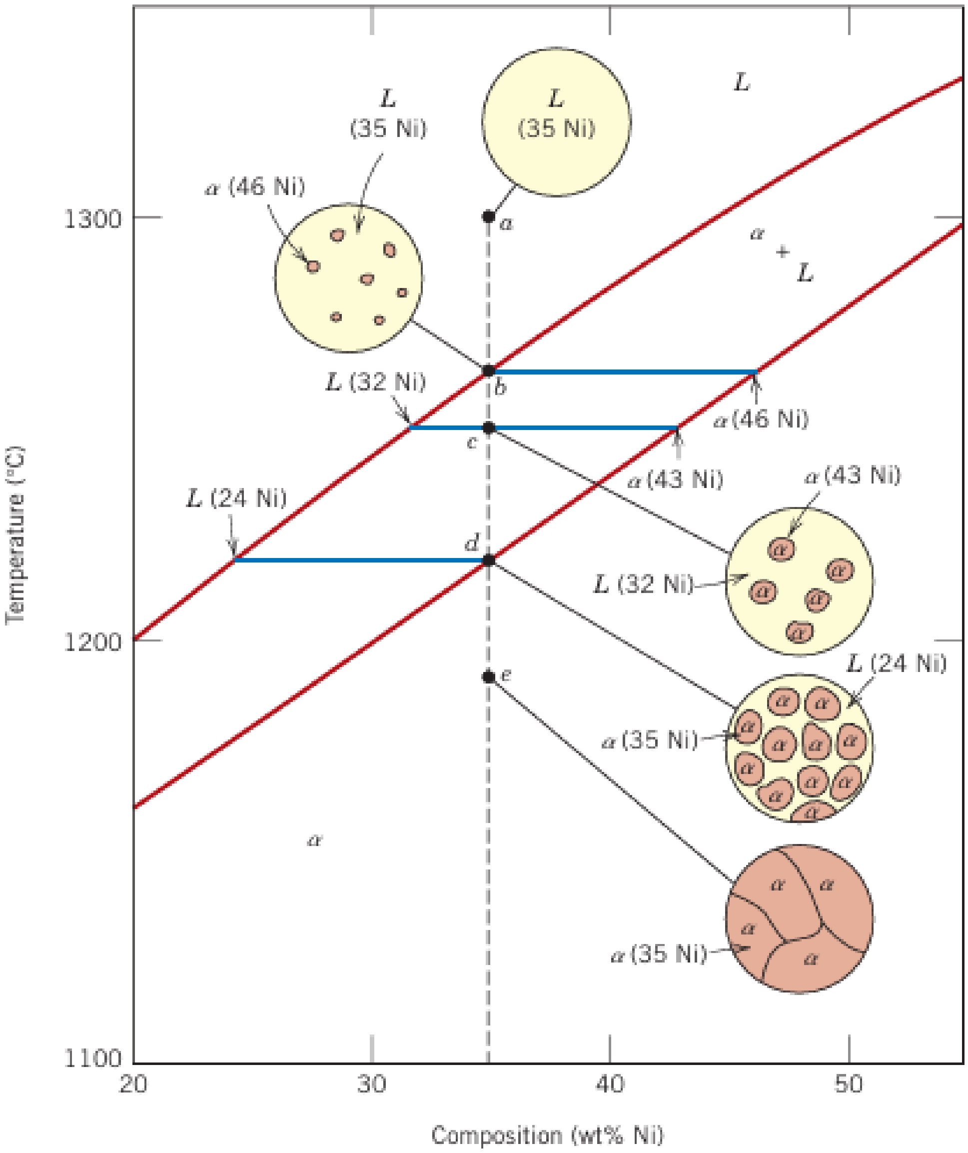
$$= \frac{C_0 - C_L}{C_\alpha - C_L} \tag{9.2b}$$

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

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

Development of Microstructure in Isomorphous Alloys: 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.

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



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. 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. The -phase solid solution also has an FCC structure, but copper is the solute.

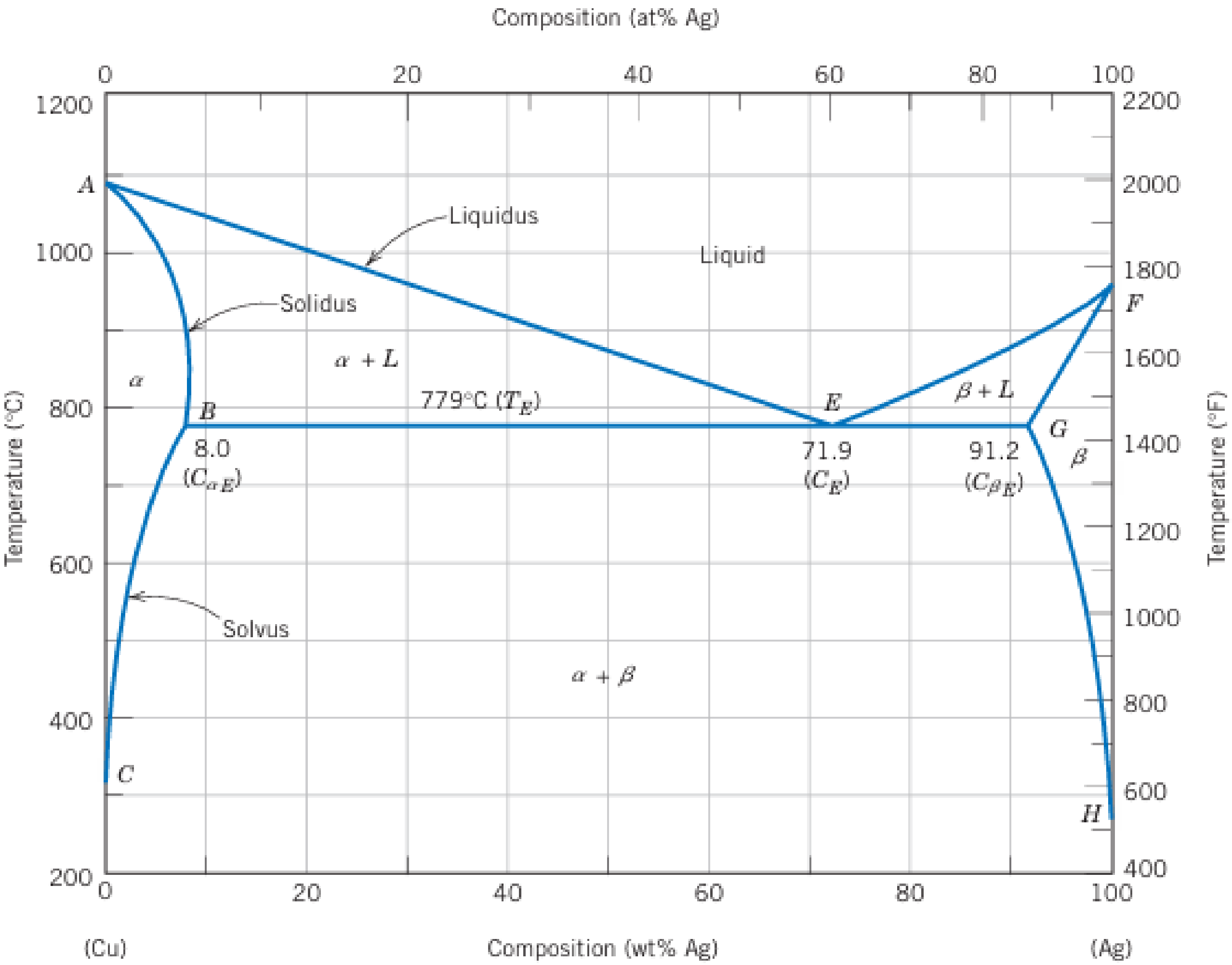


Figure 9.7 The copper–silver phase diagram. [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

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.

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:

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

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:

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

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

Another common eutectic system is that for lead and tin; the phase diagram (Figure 9.8) has a general shape similar to that for copper–silver. For the lead–tin system the solid-solution phases are also designated by α and β; in this case, α represents a solid solution of tin in lead and, for β, tin is the solvent and lead is the solute. The eutectic invariant point is located at 61.9 wt% Sn and 183°C (361°F). Of course, maximum solid solubility compositions as well as component melting temperatures will be different for the copper–silver and lead–tin systems, as may be observed by comparing their phase diagrams.

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.

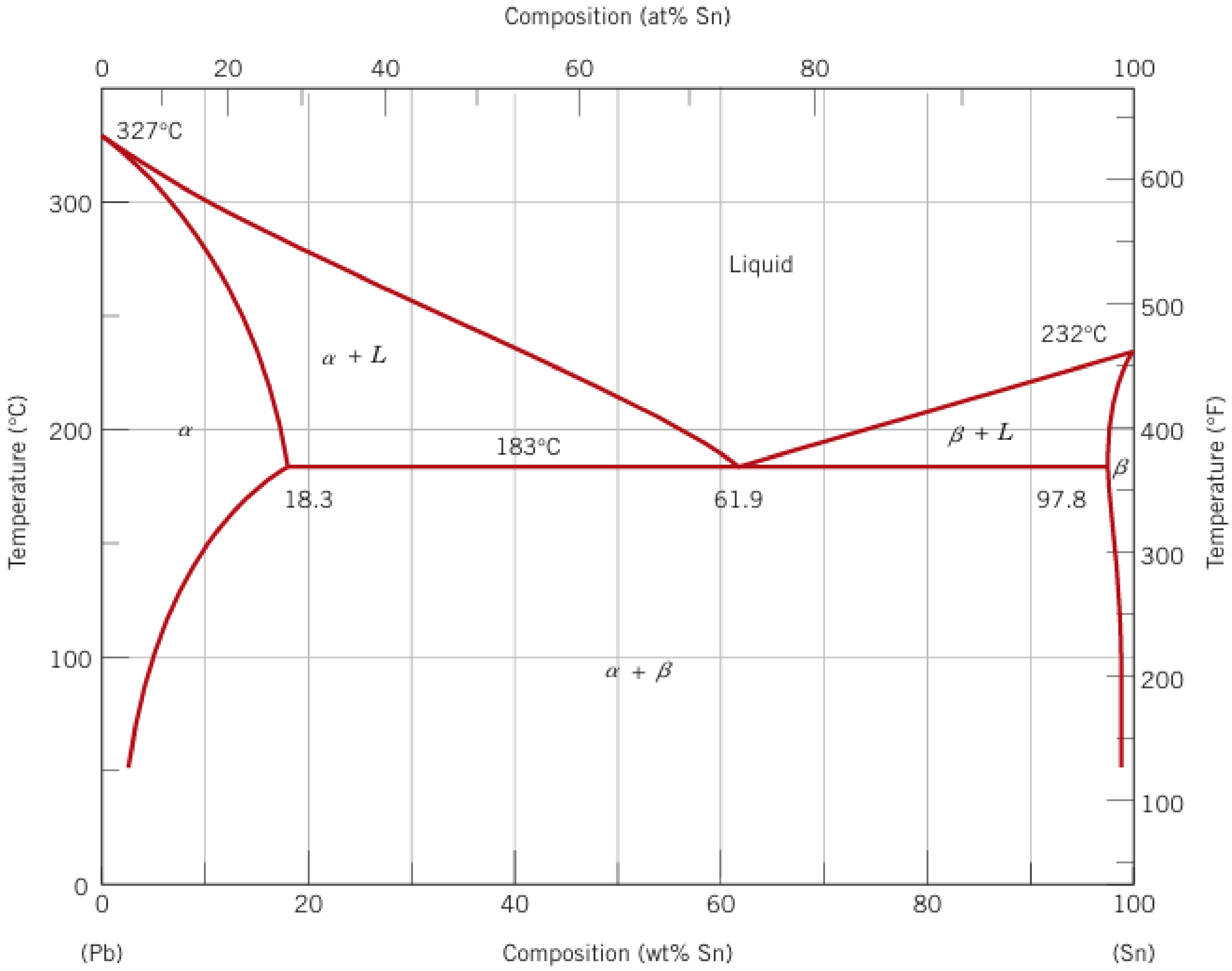


Figure 9.8 The lead–tin phase diagram. [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 3, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

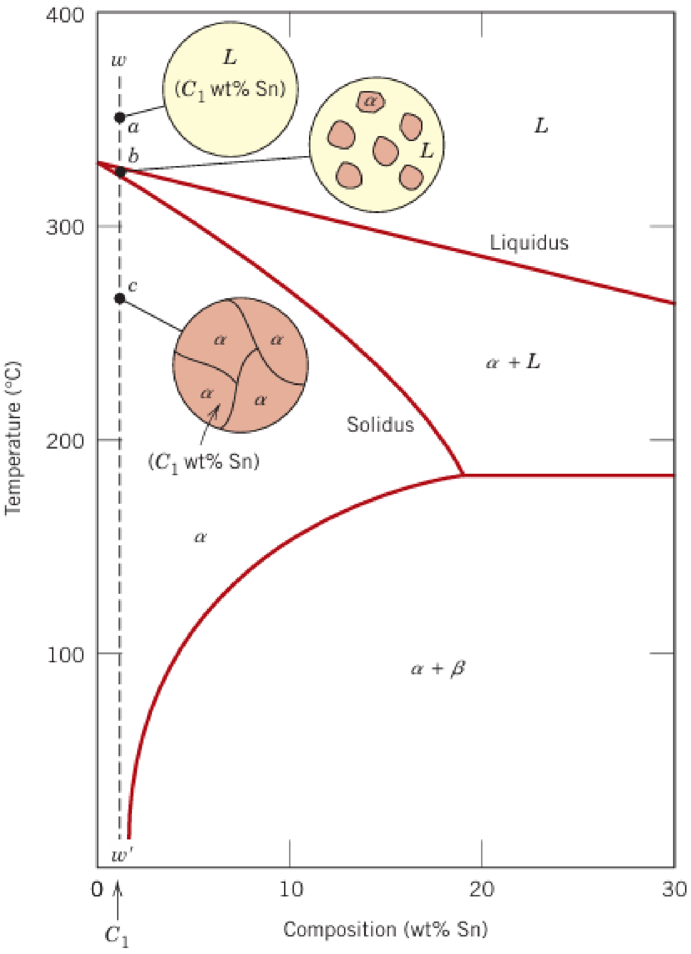


Figure 9.11 Schematic representations of the equilibrium microstructures for a lead–tin alloy of composition C_1 as it is cooled from the liquid-phase region.

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:

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

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

Development of Microstructure in Eutectics Alloys

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.

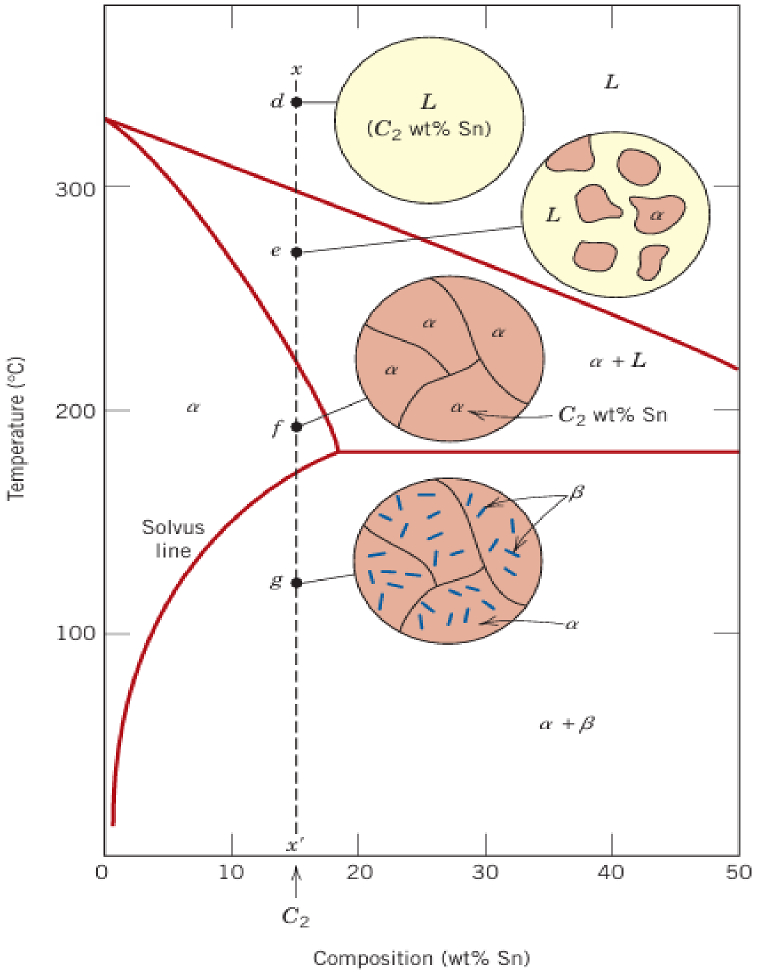


Figure 9.12 Schematic representations of the equilibrium microstructures for a lead–tin alloy of composition C_2 as it is cooled from the liquid-phase region.

It is possible to compute the relative amounts of both eutectic and primary α microconstituents. Because the eutectic microconstituent always forms from the liquid having the eutectic composition, this microconstituent may be assumed to have a composition of 61.9 wt% Sn. Hence,the lever rule is applied using a tie line between the α – (α+β) phase boundary (18.3 wt% Sn) and the eutectic composition. For example, consider the alloy of composition C4in

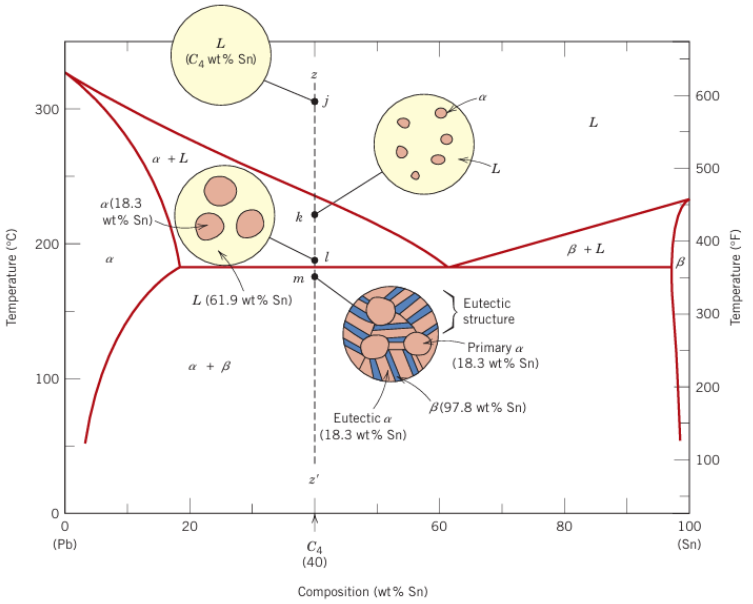


Figure 9.16 Schematic representations of the equilibrium microstructures for a lead–tin alloy of composition C_4 as it is cooled from the liquid-phase region.

9.12 Development of Microstructure in Eutectic Alloys

Figure 9.13 Schematic representations of the equilibrium microstructures for a lead–tin alloy of eutectic composition C_3 above and below the eutectic temperature.

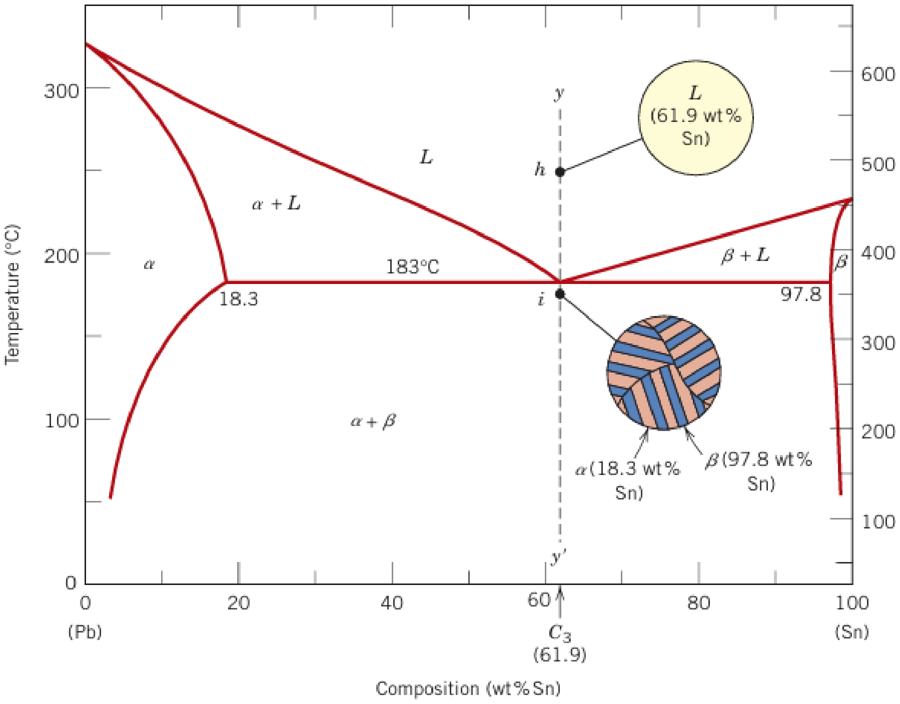


Figure 9.18. The fraction of the eutectic microconstituent is just the same as the fraction of liquid WL from which it transforms, or

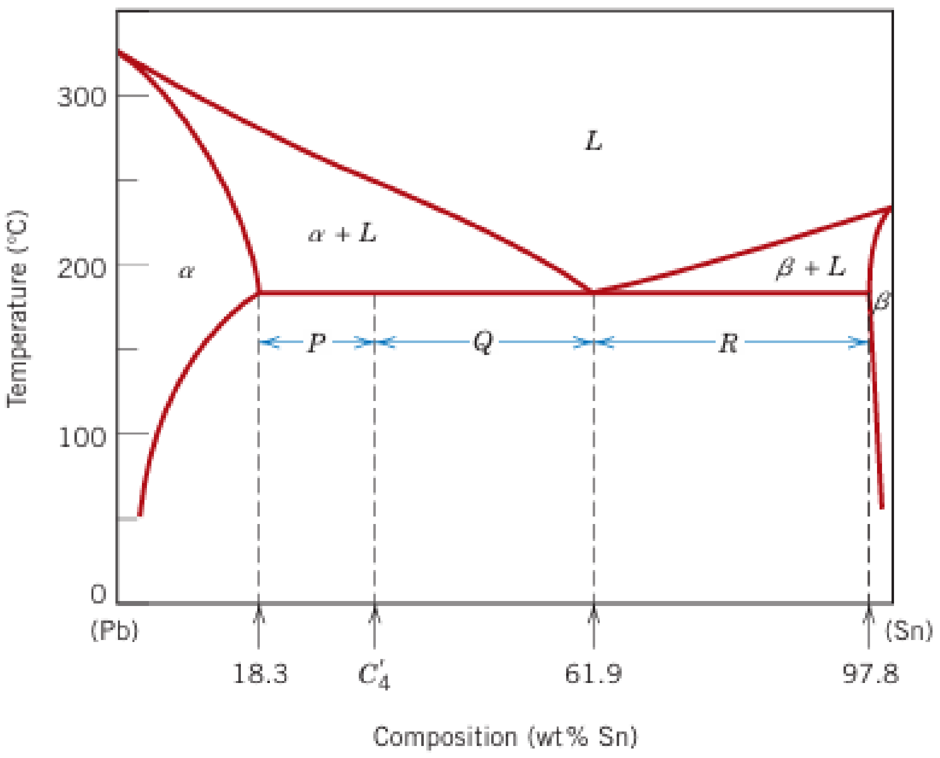
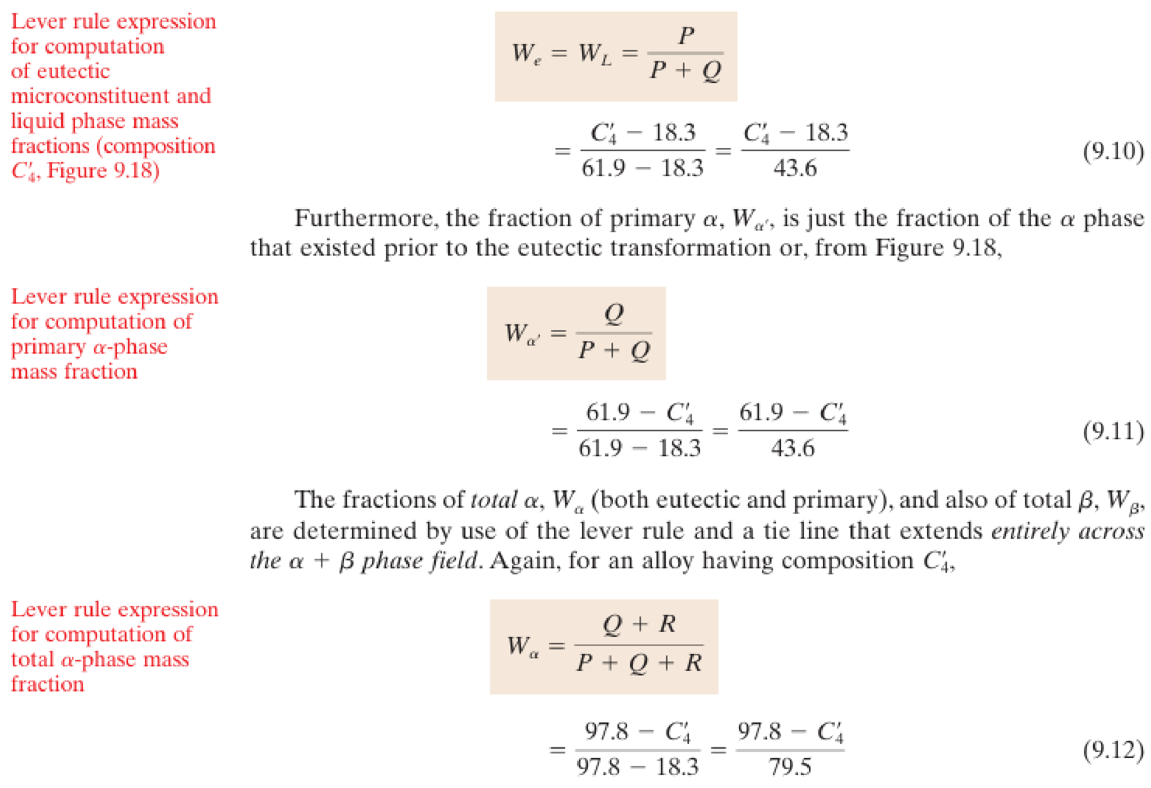


Figure 9.18 The lead–tin phase diagram used in computations for relative amounts of primary α and eutectic microconstituents for an alloy of composition C'_4.



Lever rule expression for computation of eutectic microconstituent and liquid phase mass fractions (composition C'_4, Figure 9.18)

$$W_e = W_L = \frac{P}{P+Q}$$

$$= \frac{C'_4 - 18.3}{61.9 - 18.3} = \frac{C'_4 - 18.3}{43.6} \qquad (9.10)$$

Furthermore, the fraction of primary α, $W_{\alpha'}$, is just the fraction of the α phase that existed prior to the eutectic transformation or, from Figure 9.18,

Lever rule expression for computation of primary α-phase mass fraction

$$W_{\alpha'} = \frac{Q}{P+Q}$$

$$= \frac{61.9 - C'_4}{61.9 - 18.3} = \frac{61.9 - C'_4}{43.6} \qquad (9.11)$$

The fractions of *total* α, W_α (both eutectic and primary), and also of total β, W_β, are determined by use of the lever rule and a tie line that extends *entirely across the α + β phase field*. Again, for an alloy having composition C'_4,

Lever rule expression for computation of total α-phase mass fraction

$$W_\alpha = \frac{Q+R}{P+Q+R}$$

$$= \frac{97.8 - C'_4}{97.8 - 18.3} = \frac{97.8 - C'_4}{79.5} \qquad (9.12)$$

and

$$W_\beta = \frac{P}{P + Q + R}$$

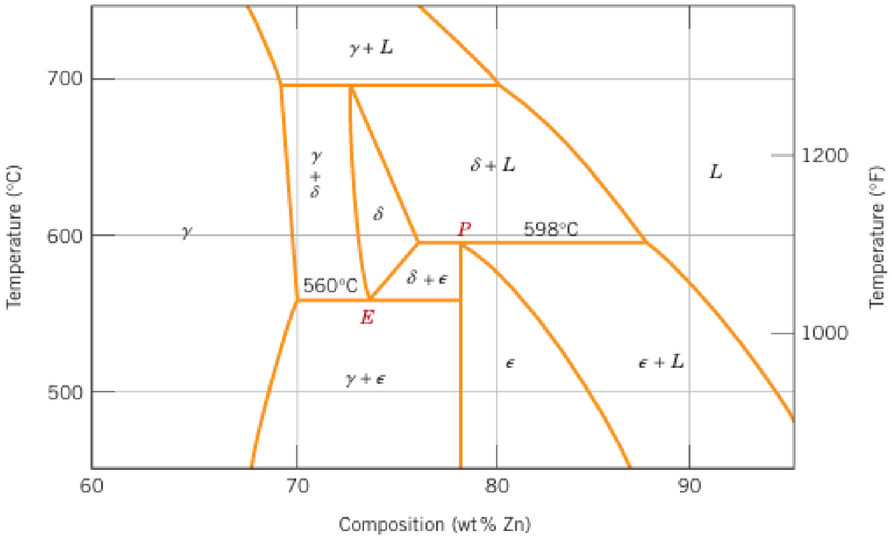
$$= \frac{C_4' - 18.3}{97.8 - 18.3} = \frac{C_4' - 18.3}{79.5} \qquad (9.13)$$

Analogous transformations and microstructures result for alloys having compositions to the right of the eutectic (i.e., between 61.9 and 97.8 wt% Sn). However, below the eutectic temperature, the microstructure will consist of the eutectic and primary β microconstituents because, upon cooling from the liquid, we pass through the β + liquid phase field.

EUTECTOID and PERITECTIC Reactions

In addition to the eutectic, other invariant points involving three different phases are found for some alloy systems. One of these occurs for the copper–zinc system (Figure 9.19) at 560°C (1040°F) and 74 wt% Zn–26 wt% Cu. A portion of

Figure 9.21 A region of the copper–zinc phase diagram that has been enlarged to show eutectoid and peritectic invariant points, labeled *E* (560°C, 74 wt% Zn) and *P* (598°C, 78.6 wt% Zn), respectively. [Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 2, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]



Composition (wt% Zn)

the phase diagram in this vicinity appears enlarged in Figure 9.21. Upon cooling, a solid δ phase transforms into two other solid phases (γ and ϵ) according to the reaction

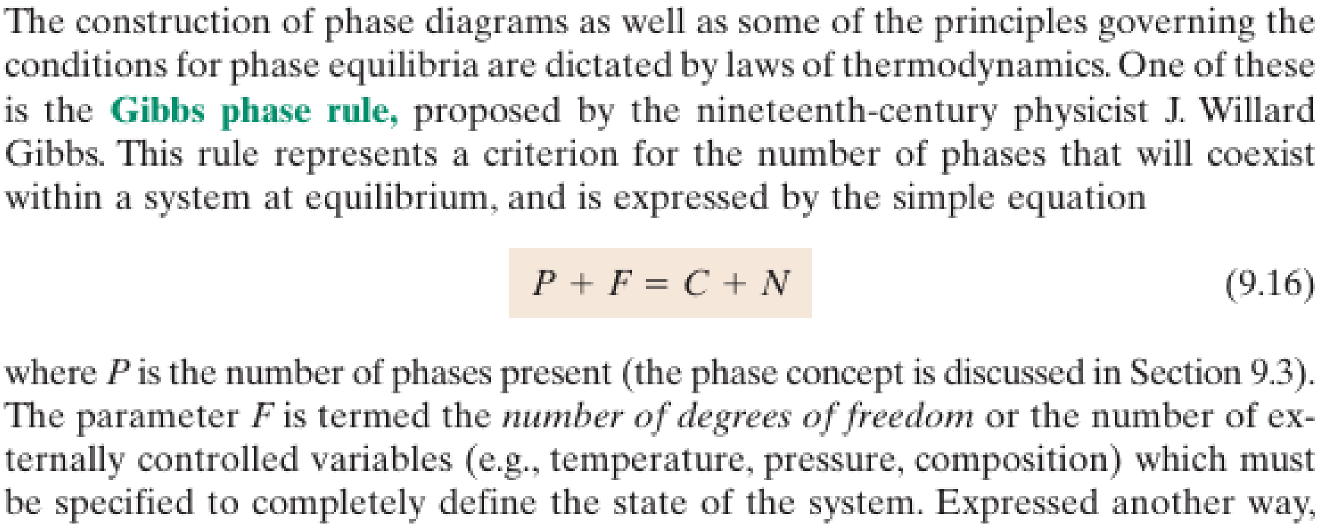
$$\delta \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \gamma + \epsilon \qquad (9.14)$$

The reverse reaction occurs upon heating. It is called a **eutectoid** (or eutectic-like) **reaction,** and the invariant point (point *E*, Figure 9.21) and the horizontal tie line at 560°C are termed the *eutectoid* and *eutectoid isotherm,* respectively. The feature distinguishing "eutectoid" from "eutectic" is that one solid phase instead of a liquid transforms into two other solid phases at a single temperature. A eutectoid reaction is found in the iron–carbon system (Section 9.18) that is very important in the heat treating of steels.

The **peritectic reaction** is yet another invariant reaction involving three phases at equilibrium. With this reaction, upon heating, one solid phase transforms into a liquid phase and another solid phase. A peritectic exists for the copper–zinc system (Figure 9.21, point *P*) at 598°C (1108°F) and 78.6 wt% Zn–21.4 wt% Cu; this reaction is as follows:

$$\delta + L \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \epsilon \qquad (9.15)$$

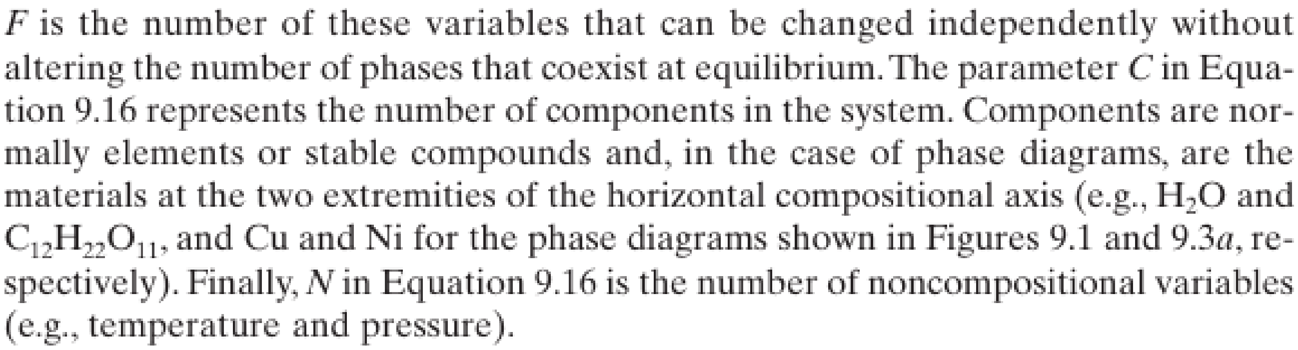
The GIBBS Phase Rule



The construction of phase diagrams as well as some of the principles governing the conditions for phase equilibria are dictated by laws of thermodynamics. One of these is the **Gibbs phase rule,** proposed by the nineteenth-century physicist J. Willard Gibbs. This rule represents a criterion for the number of phases that will coexist within a system at equilibrium, and is expressed by the simple equation

$$P + F = C + N \tag{9.16}$$

where P is the number of phases present (the phase concept is discussed in Section 9.3). The parameter F is termed the *number of degrees of freedom* or the number of externally controlled variables (e.g., temperature, pressure, composition) which must be specified to completely define the state of the system. Expressed another way,



F is the number of these variables that can be changed independently without altering the number of phases that coexist at equilibrium. The parameter C in Equation 9.16 represents the number of components in the system. Components are normally elements or stable compounds and, in the case of phase diagrams, are the materials at the two extremities of the horizontal compositional axis (e.g., H_2O and $C_{12}H_{22}O_{11}$, and Cu and Ni for the phase diagrams shown in Figures 9.1 and 9.3*a*, respectively). Finally, N in Equation 9.16 is the number of noncompositional variables (e.g., temperature and pressure).

Let us demonstrate the phase rule by applying it to binary temperature–composition phase diagrams, specifically the copper–silver system, Figure 9.7. Because pressure is constant (1 atm), the parameter N is 1—temperature is the only noncompositional variable. Equation 9.16 now takes the form

$$P + F = C + 1 \tag{9.17}$$

Furthermore, the number of components C is 2 (Cu and Ag), and

$$P + F = 2 + 1 = 3$$

or

$$F = 3 - P$$

Consider the case of single-phase fields on the phase diagram (e.g., α, β, and liquid regions). Because only one phase is present, $P = 1$ and

$$\begin{aligned} F &= 3 - P \\ &= 3 - 1 = 2 \end{aligned}$$

This means that to completely describe the characteristics of any alloy that exists within one of these phase fields, we must specify two parameters; these are composition and temperature, which locate, respectively, the horizontal and vertical positions of the alloy on the phase diagram.

For the situation wherein two phases coexist, for example, $\alpha + L$, $\beta + L$, and $\alpha + \beta$ phase regions, Figure 9.7, the phase rule stipulates that we have but one degree of freedom because

$$\begin{aligned} F &= 3 - P \\ &= 3 - 2 = 1 \end{aligned}$$

For binary systems, when three phases are present, there are no degrees of freedom, because

$$F = 3 - P$$
$$= 3 - 3 = 0$$

This means that the compositions of all three phases as well as the temperature are fixed. This condition is met for a eutectic system by the eutectic isotherm; for the Cu–Ag system (Figure 9.7), it is the horizontal line that extends between points B and G. At this temperature, 779°C, the points at which each of the α, L, and β phase fields touch the isotherm line correspond to the respective phase compositions; namely, the composition of the α phase is fixed at 8.0 wt% Ag, that of the liquid at 71.9 wt% Ag, and that of the β phase at 91.2 wt% Ag. Thus, three-phase equilibrium will not be represented by a phase field, but rather by the unique horizontal isotherm line. Furthermore, all three phases will be in equilibrium for any alloy composition that lies along the length of the eutectic isotherm (e.g., for the Cu–Ag system at 779°C and compositions between 8.0 and 91.2 wt% Ag).

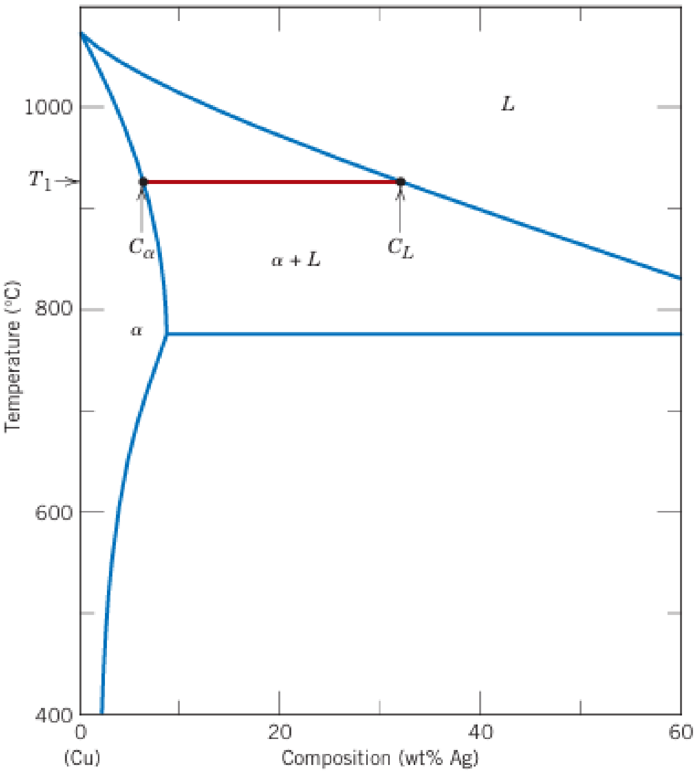


Figure 9.23 Enlarged copper-rich section of the Cu–Ag phase diagram in which the Gibbs phase rule for the coexistence of two phases (α and L) is demonstrated. Once the composition of either phase (C_α or C_L) or the temperature (T_1) is specified, values for the two remaining parameters are established by construction of the appropriate tie line.

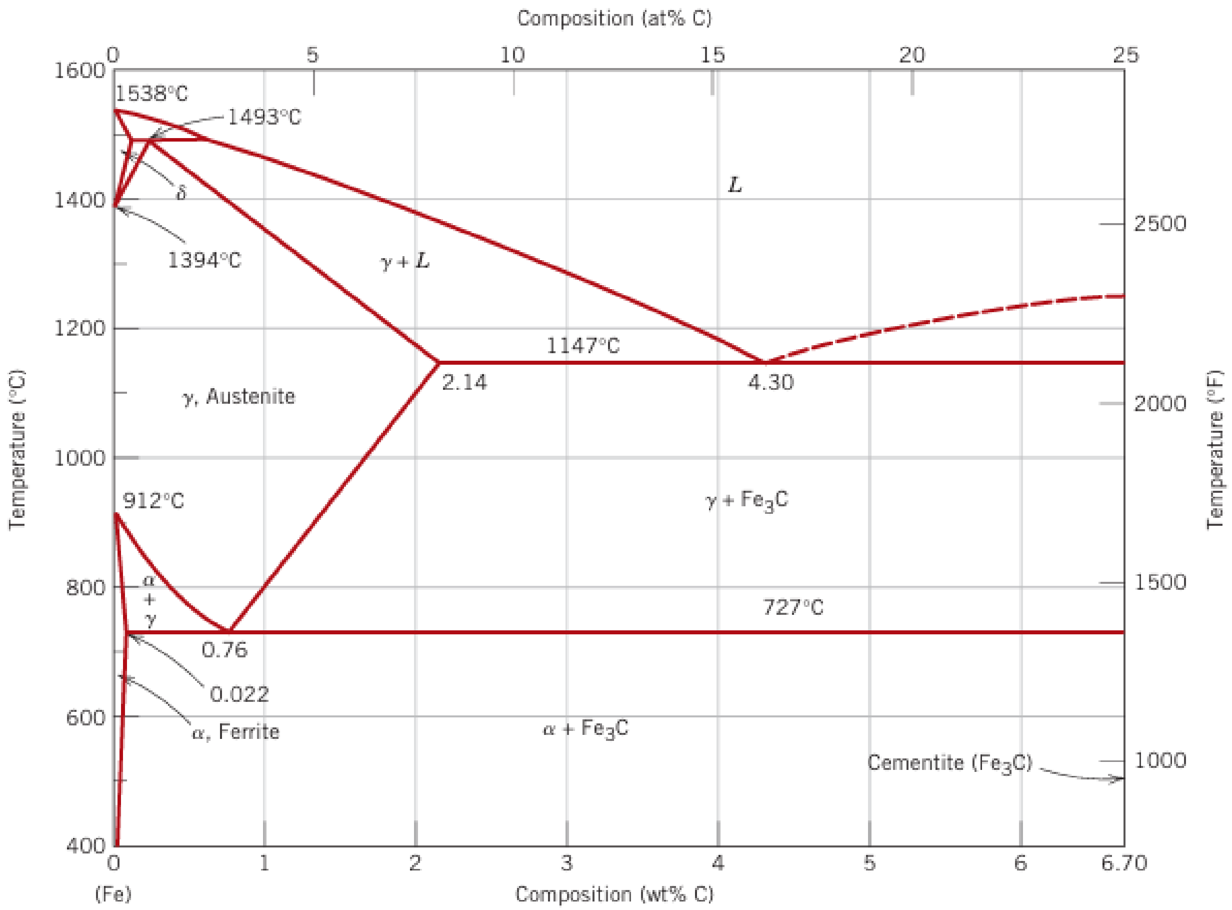


Figure 9.24 The iron–iron carbide phase diagram. [Adapted from *Binary Alloy Phase Diagrams,* 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

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

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,

$$L \underset{\text{heating}}{\overset{\text{cooling}}{\rightleftharpoons}} \gamma + Fe_3C \tag{9.18}$$

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

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

or, upon cooling, the solid γ phase is transformed into α-iron and cementite. (Eutectoid phase transformations were addressed in Section 9.14.) The eutectoid phase changes described by Equation 9.19 are very important, being fundamental to the heat treatment of steels, as explained in subsequent discussions.

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

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.

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 (see the results of Problem 4.5), and, therefore, the strains imposed on the surrounding iron atoms are much lower. As the discussions that follow demonstrate, phase transformations involving austenite are very important in the heat treating of steels. In passing, it should be mentioned that austenite is nonmagnetic. Figure 9.25*b* shows a photomicrograph of this austenite phase.^{2}

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.

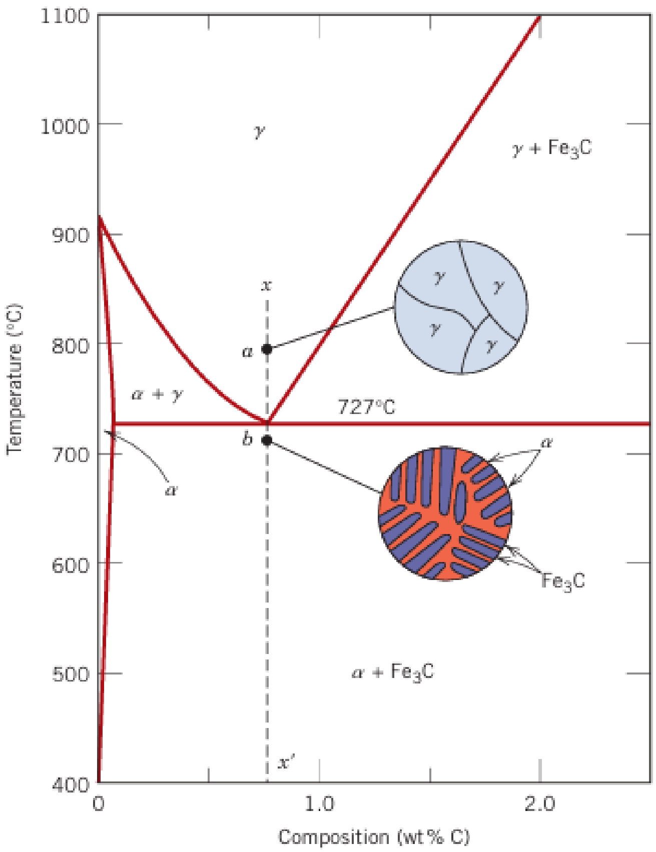


Figure 9.26 Schematic representations of the microstructures for an iron–carbon alloy of eutectoid composition (0.76 wt% C) above and below the eutectoid temperature.

$\alpha + \gamma$ phase region. The ferrite that is present in the pearlite is called *eutectoid ferrite,* whereas the other, that formed above T_e, is termed **proeutectoid** (meaning "pre- or before eutectoid") **ferrite,** as labeled in Figure 9.29. Figure 9.30 is a photomicrograph of a 0.38 wt% C steel; large, white regions correspond to the proeutectoid ferrite. For pearlite, the spacing between the α and Fe_3C layers varies

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 cooling to room temperature, an alloy within this composition range must pass through at least a portion of the γ-phase field; distinctive microstructures are subsequently produced, as discussed shortly. Although a steel alloy may contain as much as 2.14 wt% C, in practice, carbon concentrations rarely exceed 1.0 wt%. The properties and various classifications of steels are treated in Section 11.2. 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. These alloys are discussed further also in Section 11.2.

The microstructure for this eutectoid steel that is slowly cooled through the eutectoid temperature consists of alternating layers or lamellae of the two phases (α and Fe_3C) that form simultaneously during the transformation. In this case, the relative layer thickness is approximately 8 to 1. This microstructure, represented schematically in Figure 9.26, point *b*, is called **pearlite** because it has the appearance of mother-of-pearl when viewed under the microscope at low magnifications. Figure 9.27 is a photomicrograph of a eutectoid steel showing the pearlite. The

Hypoeutectoid Alloys

Microstructures for iron–iron carbide alloys having other than the eutectoid composition are now explored; these are analogous to the fourth case described in Section 9.12 and illustrated in Figure 9.16 for the eutectic system. Consider a composition C_0 to the left of the eutectoid, between 0.022 and 0.76 wt% C; this is termed a **hypoeutectoid** (less than eutectoid) **alloy.** Cooling an alloy of this composition is

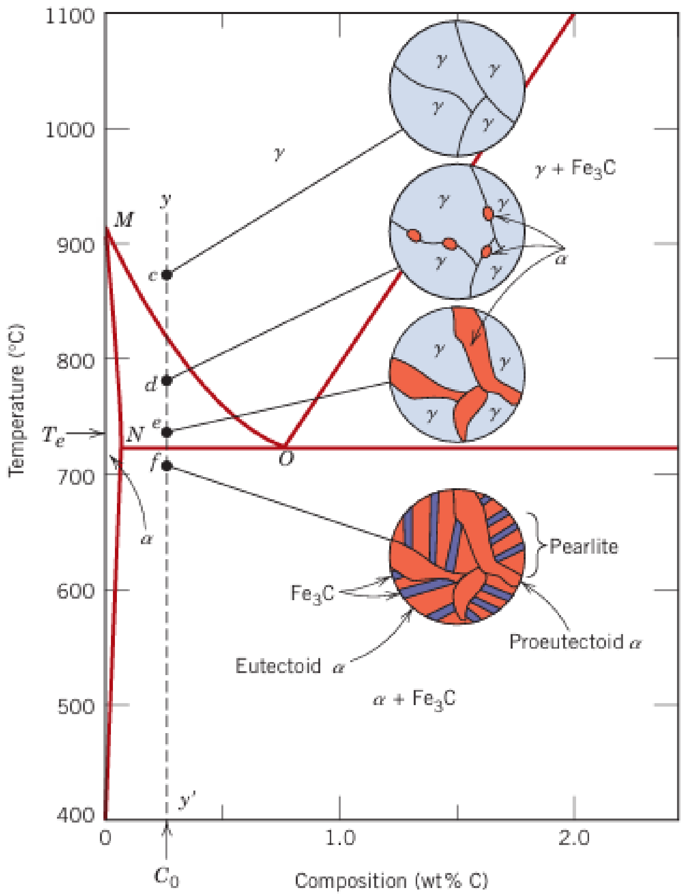


Figure 9.29 Schematic representations of the microstructures for an iron–carbon alloy of hypoeutectoid composition C_0 (containing less than 0.76 wt% C) as it is cooled from within the austenite phase region to below the eutectoid temperature.

The relative amounts of the proeutectoid α and pearlite may be determined in a manner similar to that described in Section 9.12 for primary and eutectic microconstituents. We use the lever rule in conjunction with a tie line that extends from the $\alpha - (\alpha + Fe_3C)$ phase boundary (0.022 wt% C) to the eutectoid composition (0.76 wt% C), inasmuch as pearlite is the transformation product of austenite having this composition. For example, let us consider an alloy of composition C_0' in Figure 9.31. Thus, the fraction of pearlite, W_p, may be determined according to

$$W_p = \frac{T}{T + U}$$

$$= \frac{C_0' - 0.022}{0.76 - 0.022} = \frac{C_0' - 0.022}{0.74} \tag{9.20}$$

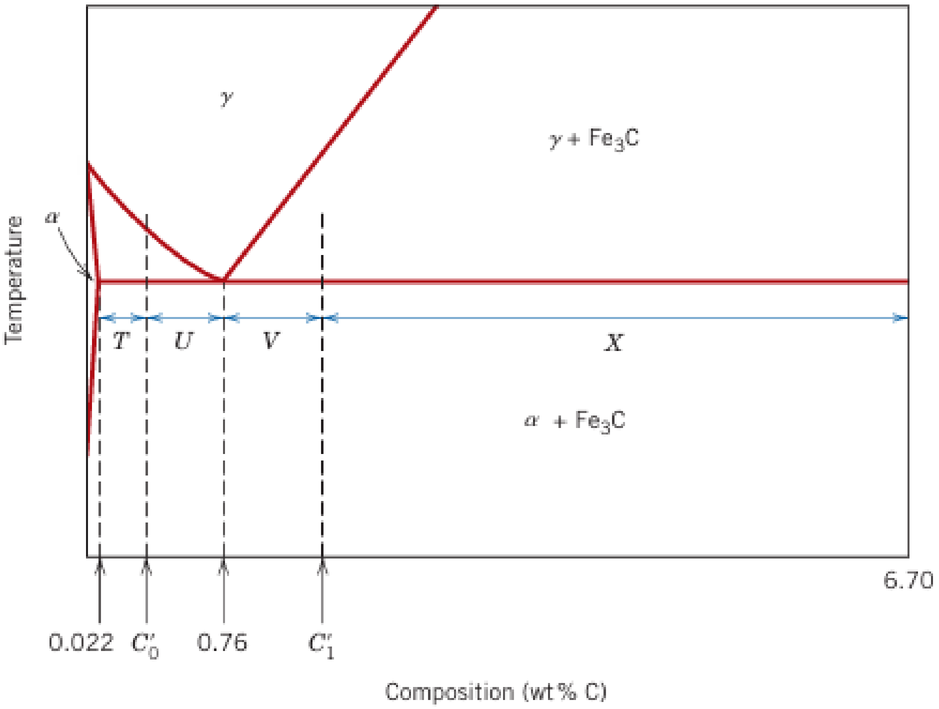
Furthermore, the fraction of proeutectoid α, $W_{\alpha'}$, is computed as follows:

$$W_{\alpha'} = \frac{U}{T + U}$$

$$= \frac{0.76 - C_0'}{0.76 - 0.022} = \frac{0.76 - C_0'}{0.74} \tag{9.21}$$

Of course, fractions of both total α (eutectoid and proeutectoid) and cementite are determined using the lever rule and a tie line that extends across the entirety of the $\alpha + Fe_3C$ phase region, from 0.022 to 6.70 wt% C.

Figure 9.31 A portion of the Fe–Fe_3C phase diagram used in computations for relative amounts of proeutectoid and pearlite microconstituents for hypoeutectoid C_0' and hypereutectoid C_1' compositions.



Hypereutectoid Alloys

Analogous transformations and microstructures result for **hypereutectoid alloys,** those containing between 0.76 and 2.14 wt% C, which are cooled from temperatures within the γ phase field. Consider an alloy of composition C_1 in Figure 9.32 that, upon cooling, moves down the line zz'. At point g only the γ phase will be present with a composition of C_1; the microstructure will appear as shown, having only γ grains. Upon cooling into the $\gamma + Fe_3C$ phase field—say, to point h—the cementite phase will begin to form along the initial γ grain boundaries, similar to the α phase in Figure 9.29, point d. This cementite is called **proeutectoid cementite**—that which forms before the eutectoid reaction. Of course, the cementite composition remains constant (6.70 wt% C) as the temperature changes. However, the com-

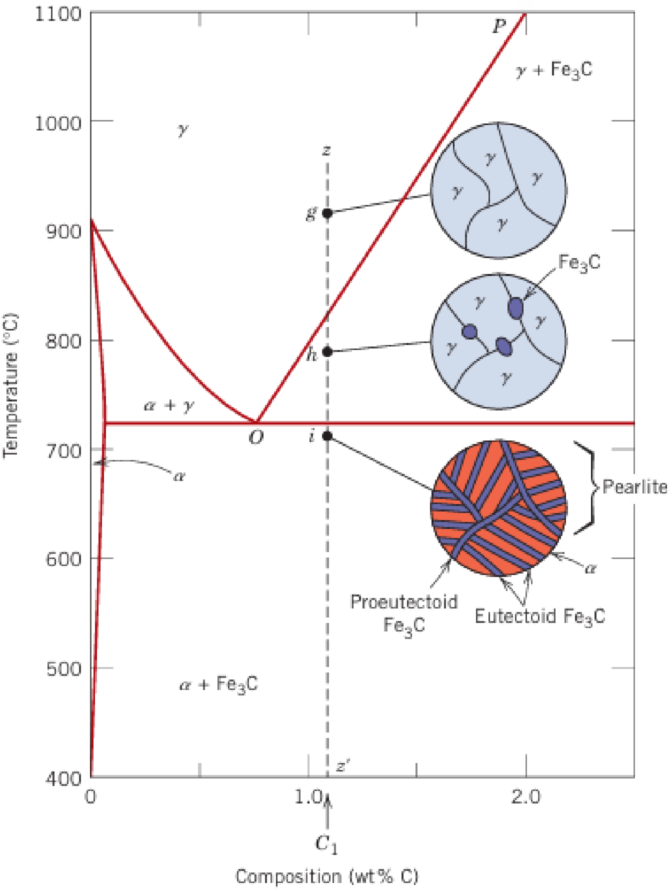


Figure 9.32 Schematic representations of the microstructures for an iron–carbon alloy of hypereutectoid composition C_1 (containing between 0.76 and 2.14 wt% C), as it is cooled from within the austenite phase region to below the eutectoid temperature.

Relative amounts of both pearlite and proeutectoid Fe_3C microconstituents may be computed for hypereutectoid steel alloys in a manner analogous to that for hypoeutectoid materials; the appropriate tie line extends between 0.76 and 6.70

wt% C. Thus, for an alloy having composition C_1' in Figure 9.31, fractions of pearlite W_p and proeutectoid cementite $W_{\mathrm{Fe_3C'}}$ are determined from the following lever rule expressions:

$$W_p = \frac{X}{V + X} = \frac{6.70 - C_1'}{6.70 - 0.76} = \frac{6.70 - C_1'}{5.94} \tag{9.22}$$

and

$$W_{\mathrm{Fe_3C'}} = \frac{V}{V + X} = \frac{C_1' - 0.76}{6.70 - 0.76} = \frac{C_1' - 0.76}{5.94} \tag{9.23}$$

EXAMPLE PROBLEM 9.4

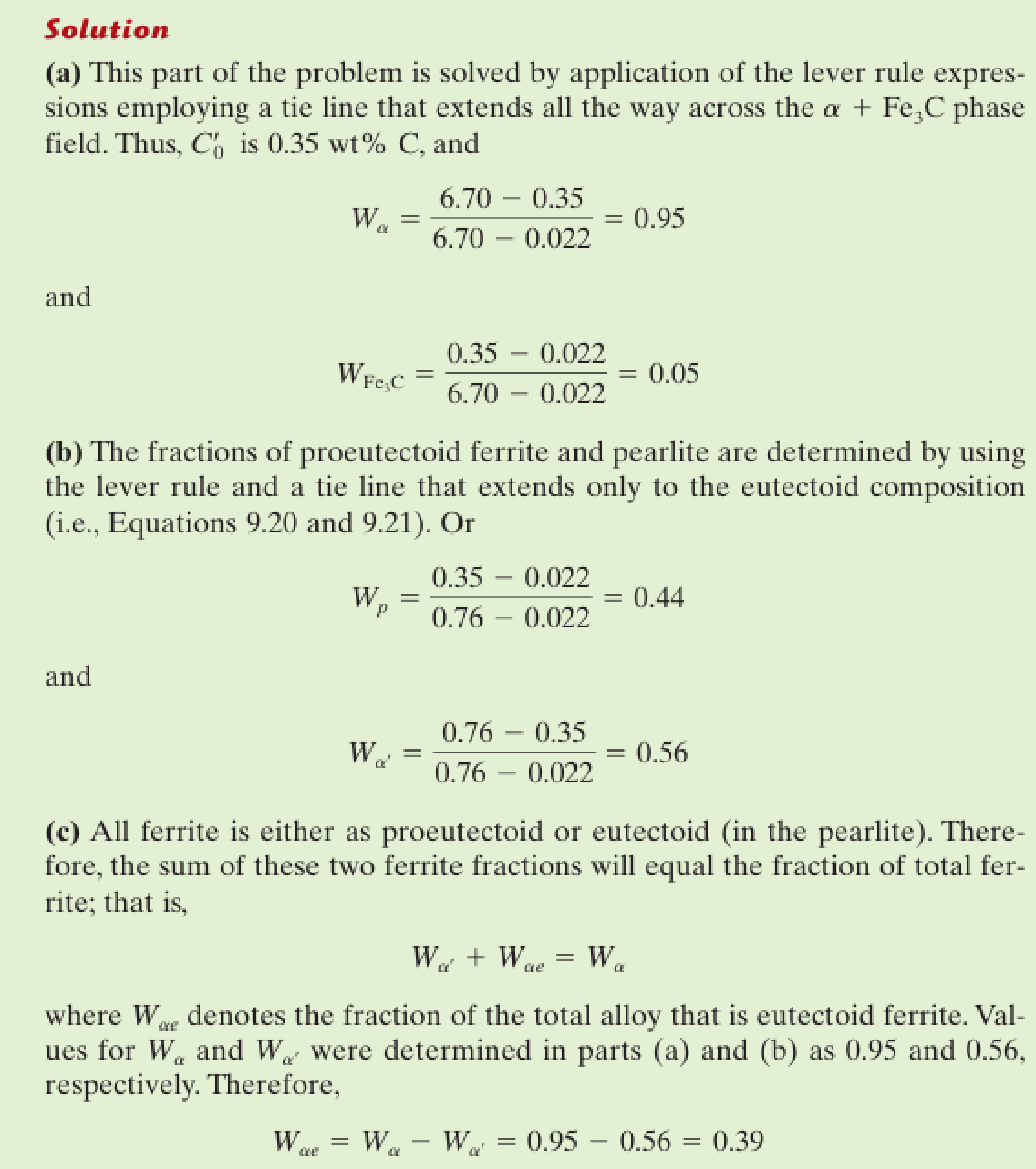
Determination of Relative Amounts of Ferrite, Cementite, and Pearlite Microconstituents

For a 99.65 wt% Fe–0.35 wt% C alloy at a temperature just below the eutectoid, determine the following:

(a) The fractions of total ferrite and cementite phases

(b) The fractions of the proeutectoid ferrite and pearlite

(c) The fraction of eutectoid ferrite



Solution

(a) This part of the problem is solved by application of the lever rule expressions employing a tie line that extends all the way across the $\alpha + Fe_3C$ phase field. Thus, C_0' is 0.35 wt% C, and

$$W_\alpha = \frac{6.70 - 0.35}{6.70 - 0.022} = 0.95$$

and

$$W_{Fe_3C} = \frac{0.35 - 0.022}{6.70 - 0.022} = 0.05$$

(b) The fractions of proeutectoid ferrite and pearlite are determined by using the lever rule and a tie line that extends only to the eutectoid composition (i.e., Equations 9.20 and 9.21). Or

$$W_p = \frac{0.35 - 0.022}{0.76 - 0.022} = 0.44$$

and

$$W_{\alpha'} = \frac{0.76 - 0.35}{0.76 - 0.022} = 0.56$$

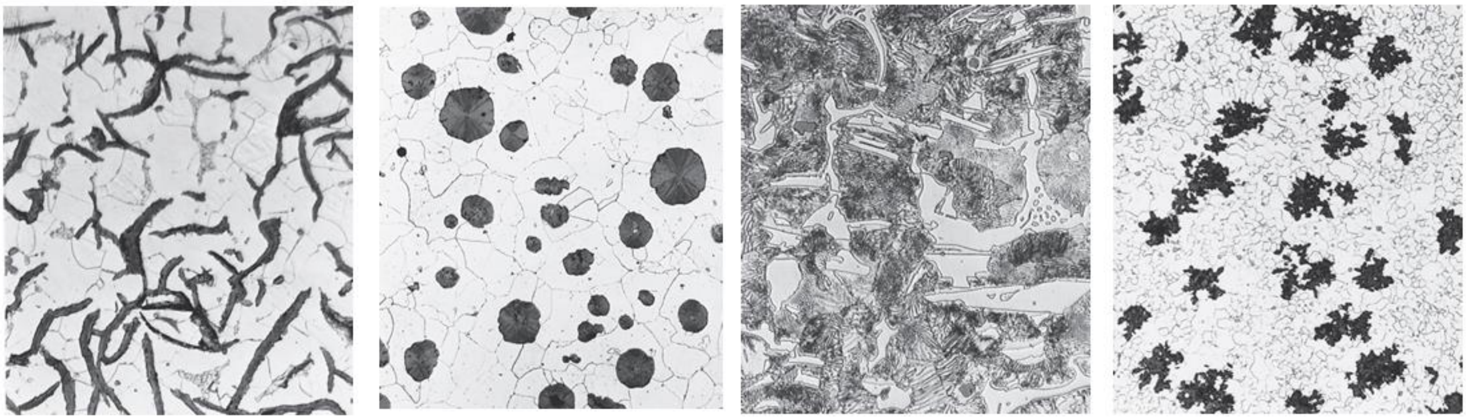
(c) All ferrite is either as proeutectoid or eutectoid (in the pearlite). Therefore, the sum of these two ferrite fractions will equal the fraction of total ferrite; that is,

$$W_{\alpha'} + W_{\alpha e} = W_\alpha$$

where $W_{\alpha e}$ denotes the fraction of the total alloy that is eutectoid ferrite. Values for W_α and $W_{\alpha'}$ were determined in parts (a) and (b) as 0.95 and 0.56, respectively. Therefore,

$$W_{\alpha e} = W_\alpha - W_{\alpha'} = 0.95 - 0.56 = 0.39$$

Experiment 1: Examination of various forms of cast iron and their characteristics

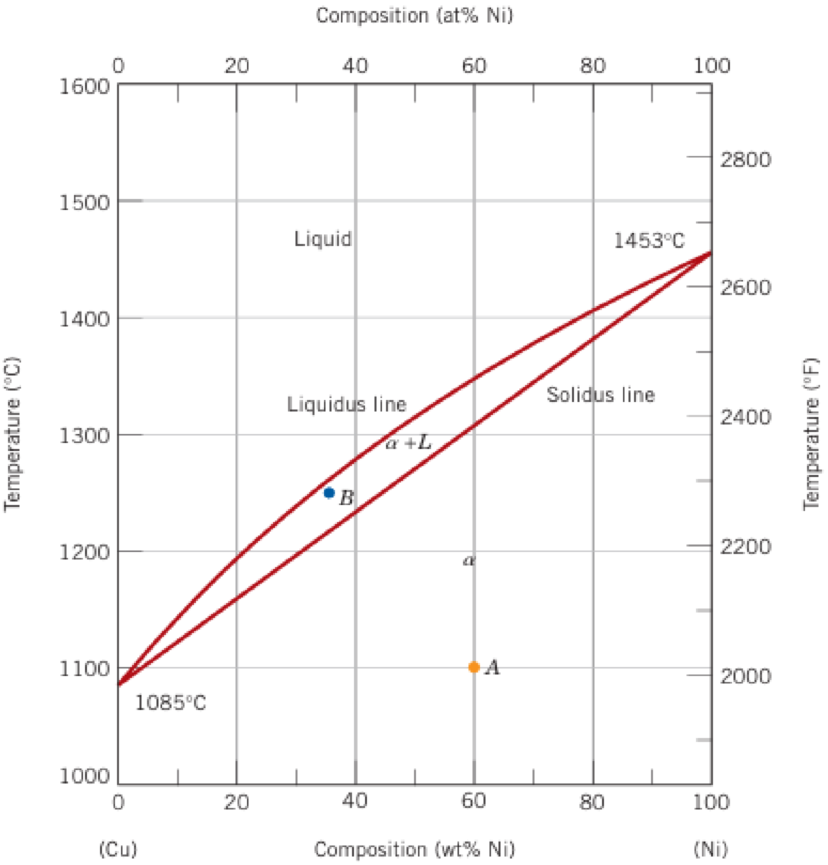


Question:

1. On the basis of microstructure, briefly explain why gray iron is brittle and weak in tension.
2. Compare gray and malleable cast irons with respect to (a) composition and heat treatment, (b) microstructure, and (c) mechanical characteristics.
3. Compare white and nodular cast irons with respect to (a) composition and heat treatment, (b) microstructure, and (c) mechanical characteristics.
4. Is it possible to produce malleable cast iron in pieces having large cross-sectional dimensions? Why or why not?

Experiment 2: Analysis of Various Categories of Phase Diagram

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.)



Question

1. A copper–nickel alloy of composition 70 wt% Ni–30 wt% Cu is slowly heated from 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 the complete melting of the alloy occur? (d) What is the composition of the last solid remaining prior to complete melting?
2. 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 a 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.
3. A copper–nickel alloy of composition 70 wt% Ni–30 wt% Cu is slowly heated from 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 the complete melting of the alloy occur? (d) What is the composition of the last solid remaining prior to complete melting?

Experiment 3: Analysis of Fe-Fe$_3$C Phase Diagram

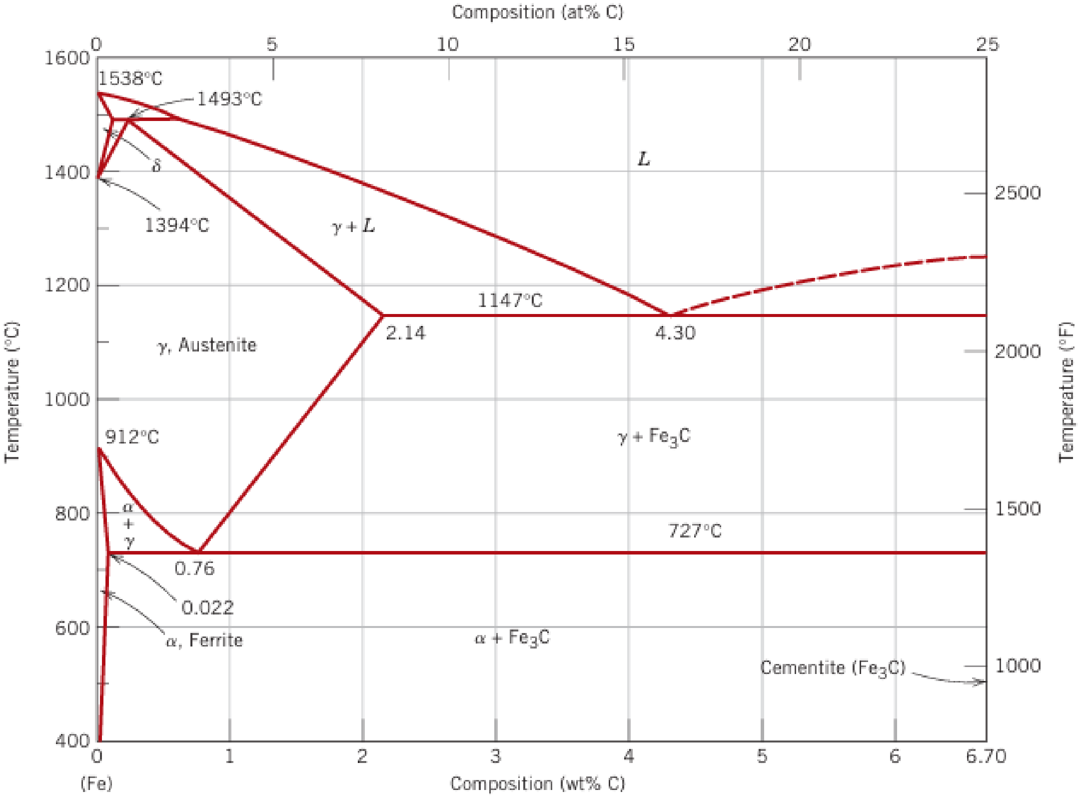


Figure 9.24 The iron–iron carbide phase diagram. [Adapted from *Binary Alloy Phase Diagrams,* 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

Questions:

1. What is the distinction between hypoeutectoid and hypereutectoid steels?
2. What is the carbon concentration of an iron–carbon alloy for which the fraction of total ferrite is 0.94?
3. Consider 1.0 kg of austenite containing 1.15 wt% C, cooled to below 727C (1341F). (a) What is the proeutectoid phase? (b) How many kilograms each of total ferrite and cementite form? (c) How many kilograms each of pearlite and the proeutectoid phase form? (d) Schematically sketch and label the resulting microstructure.
4. The microstructure of an iron–carbon alloy consists of proeutectoid ferrite and pearlite; the mass fractions of these microconstituents are 0.20 and 0.80, respectively. Determine the concentration of carbon in this alloy.
5. Consider 2.0 kg of a 99.6 wt% Fe–0.4 wt% C alloy that is cooled to a temperature just below the eutectoid. (a) How many kilograms of proeutectoid ferrite form? (b) How many kilograms of eutectoid ferrite form? (c) How many kilograms of cementite form?
6. Is it possible to have an iron–carbon alloy for which the mass fractions of total cementite and pearlite are 0.039 and 0.417, respectively? Why or why not?

Experiment No: 04

Experiment Name: Construction and identification of different types of crystallographic planes and directions in crystal structure models

Learning Outcomes:

1. Introduction to Crystallography
2. Crystallographic Directions ([uvw])
4. Common Planes and Directions in Different Crystal Systems
5. Applications in Materials Science and Engineering

Theory:

A crystal structure is the basic arrangement or base orientation of a solid material. Any structure held together by atoms, ions, or molecules arranged in a highly ordered 3-dimensional arrangement is a crystal structure.

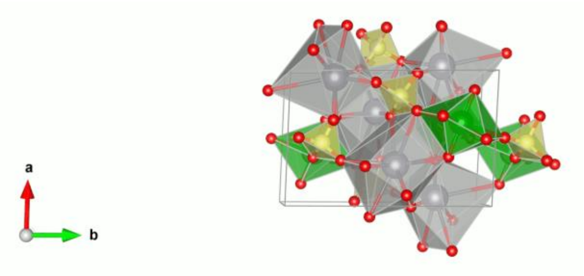


Figure: Crystal Structure example

- A crystal structure consists of atoms arranged in a repeating pattern.
- Defined by lattice points and unit cells.
- Important for understanding material properties.

Crystallographic planes and directions are fundamental to understanding the mechanical, electronic, and optical properties of crystalline materials. They are typically described using Miller indices (hkl) for planes and [uvw] notation for directions.

Miller Indices:

Miller indices are a shorthand notation used to describe the orientation of crystallographic planes and directions in a material. They are a set of three integers (h, k, and ℓ) that are used to represent the orientation of a plane or set of parallel planes.

Why are Miller indices useful?

Miller indices are useful in many areas of materials science, including Explaining the shapes of single crystals, Understanding the form of some materials' microstructure, Interpreting X-ray diffraction patterns, and Understanding the movement of a dislocation.

How are Miller indices calculated?

Determine the intercepts of the plane with the crystallographic axes

Take the reciprocals of the intercepts

Clear any fractions to get the three Miller indices

FCC (Face-Centered Cubic), BCC (Body-Centered Cubic), and HCP (Hexagonal Close-Packed) Crystal Structures

The FCC, BCC, and HCP are the three common crystal structures found in metals, each with distinct properties and characteristics. Understanding their structure is important for determining material properties like strength, ductility, and thermal conductivity.

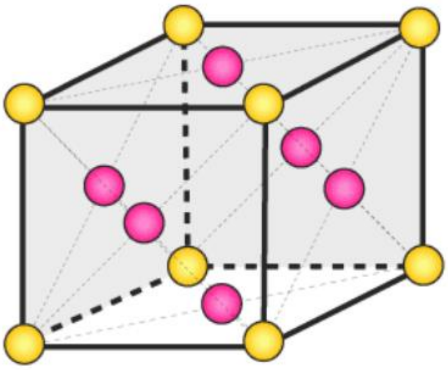
FCC (Face-Centered Cubic):

Structure: In FCC, atoms are located at each corner and the centers of all the faces of the unit cell.

Packing efficiency: 74%, which is the highest packing efficiency of the common crystal structures.

Examples: Aluminum, copper, gold, and silver.

Properties: FCC crystals have high ductility and excellent formability, as their slip systems (mechanisms of dislocation movement) are more numerous, allowing easier deformation.



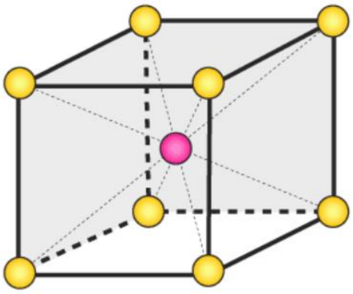
BCC (Body-Centered Cubic):

Structure: In BCC, atoms are positioned at the corners of the unit cell with one atom at the center.

Packing efficiency: 68%.

Examples: Iron (at room temperature), chromium, tungsten.

Properties: BCC crystals tend to be less ductile than FCC structures but are stronger at higher temperatures. They have fewer slip systems, leading to more brittle behavior at lower temperatures.



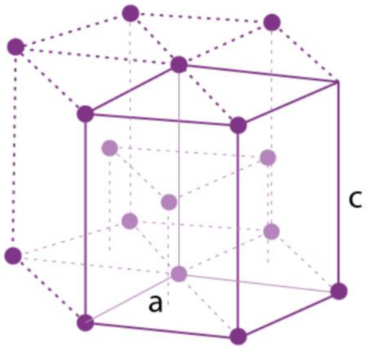
HCP (Hexagonal Close-Packed):

Structure: HCP consists of two hexagonal layers, with atoms at each corner of the hexagon and one in the center of each hexagonal face.

Packing efficiency: 74%, similar to FCC, but the atomic arrangement is different.

Examples: Titanium, magnesium, and zinc.

Properties: HCP structures are typically less ductile than FCC crystals due to fewer slip systems. They exhibit anisotropy, meaning their properties can vary depending on the direction in which the material is stressed.

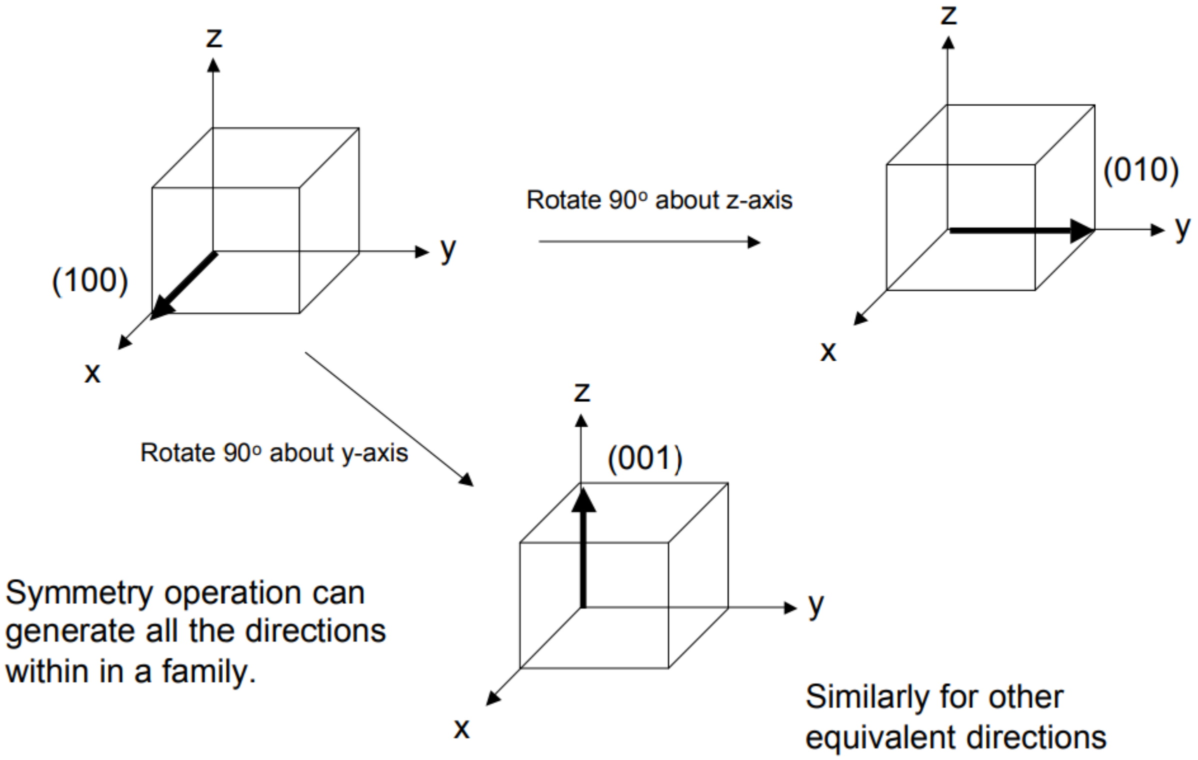


Applications of Crystallographic Planes and Directions

Crystallographic planes and directions are essential in understanding the behavior and properties of materials. These orientations influence a material’s mechanical, electrical, and thermal properties.

1. **Mechanical Properties**: Crystallographic planes define how materials deform. Slip systems, which control plastic deformation, depend on specific directions and planes. This is critical in metal forming and welding processes.
2. **X-ray Diffraction (XRD)**: The arrangement of crystallographic planes in a material affects how X-rays are diffracted. This principle is used to determine crystal structures and interatomic spacings in materials.
3. **Electron Microscopy**: In techniques like SEM and TEM, crystallographic orientation affects how materials interact with electrons, helping to reveal grain boundaries and phase distributions.
4. **Materials Processing**: The crystallographic orientation in polycrystalline materials can significantly affect their strength and ductility, guiding their use in industries like aerospace and automotive.

Crystallographic Directions ([uvw])



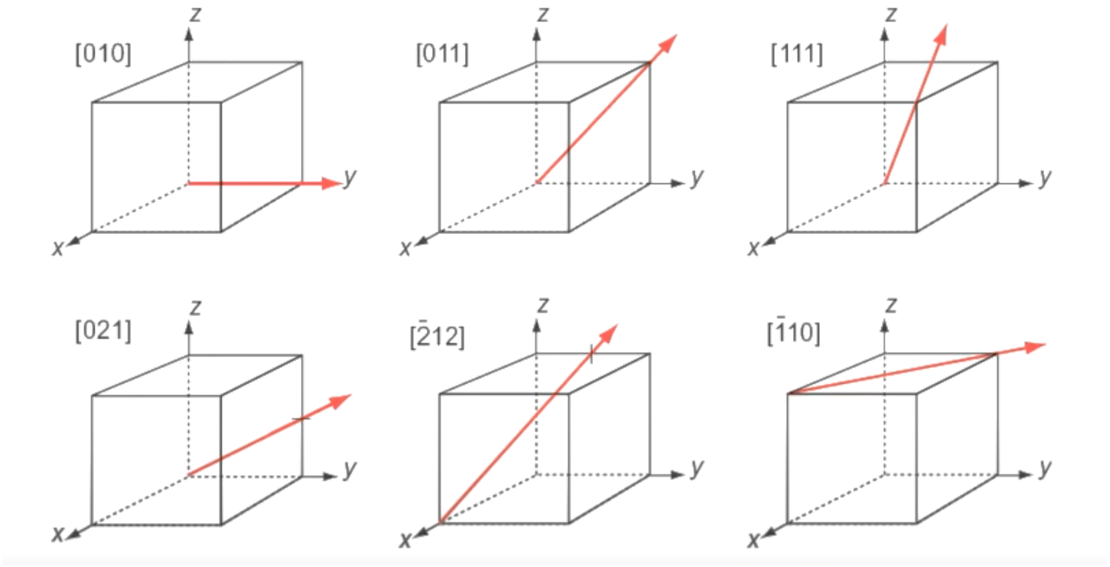


Figure: Crystallographic Directions

Plane direction drawing procedure:

1. Draw axes (X, Y, and Z)

2. Determine the origin as the tail of your direction vector. (Note: In case there is a negative number/value in the vector directions, move the origin in the positive direction for that axis before moving forward)

3. Determine the vector endpoint (Note: Common factors should be removed if any of the indices are larger than 1).

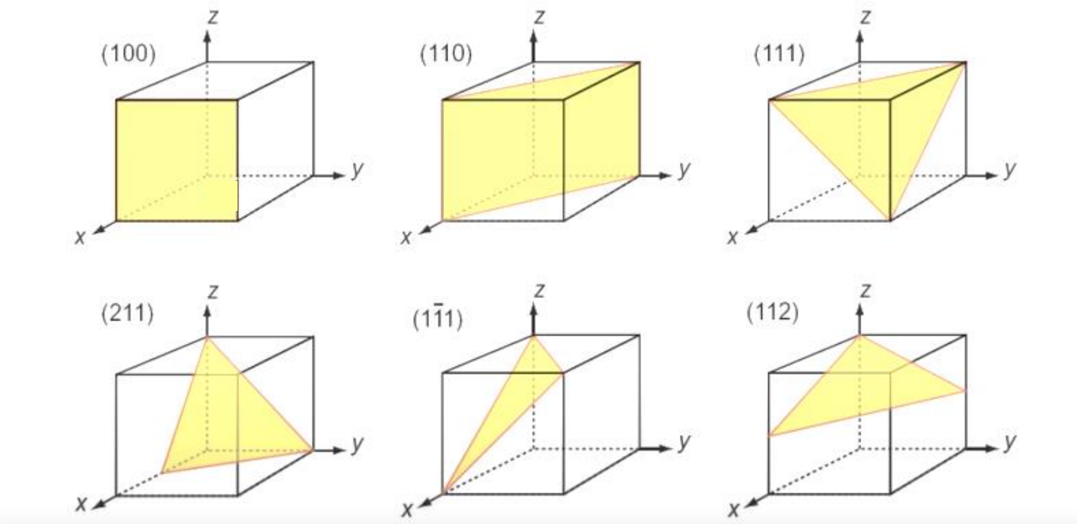


Figure: Crystallographic Planes

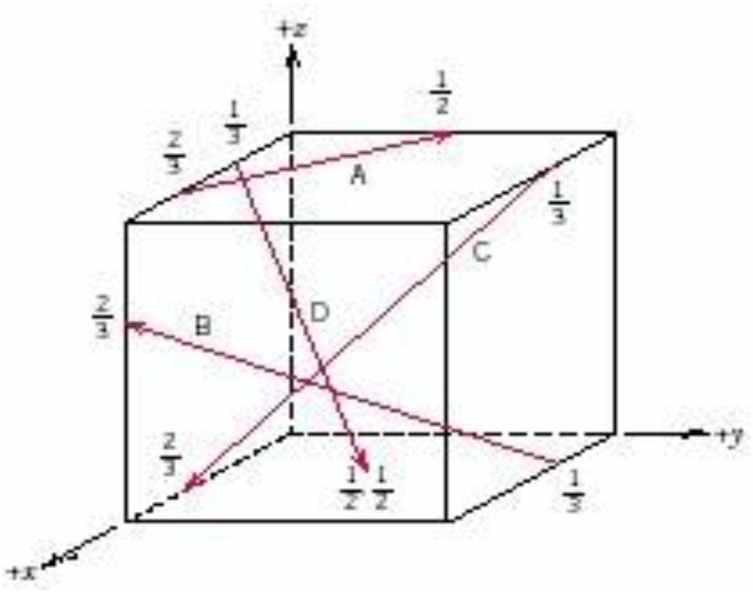
Experiment requirements:

Objective: The Objective of the study is to Construct and identify different types of crystallographic planes and directions in crystal structure models

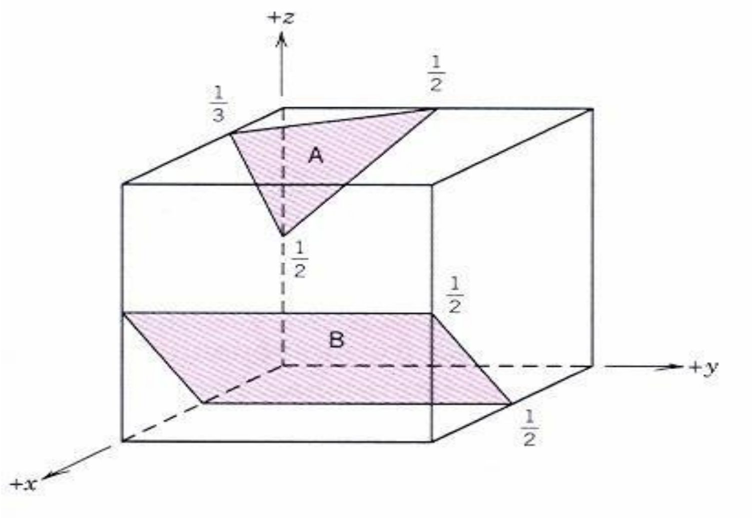
Lab work:

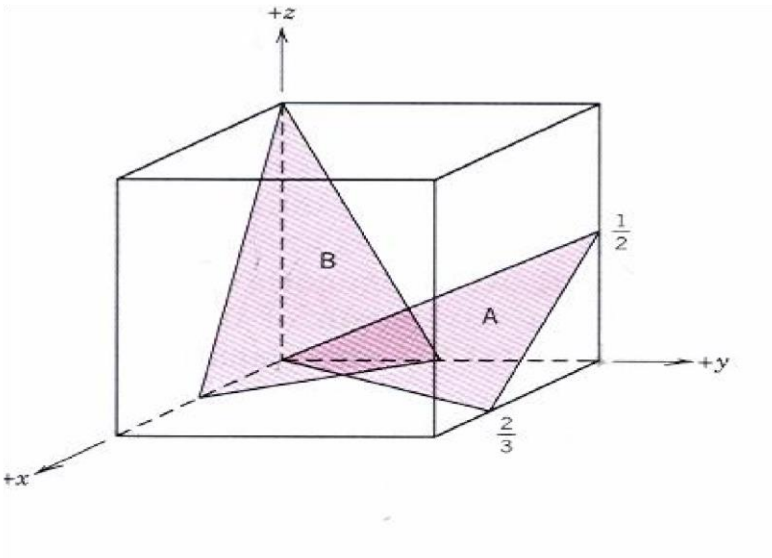
1. Draw crystallographic directions: $[001]$,$[02\bar{1}]$,$[\bar{1}21]$,$[101]$, (200)

2. Determining the indices of line directions.



3. Determine the Miller indices of planes A and B:





3. Calculate Planar density for a Simple cubic system of (100) plane where lattice parameter (a=3.03A^{o})

4. Find the angle between two planes (111) and (1-1 1)

Assignments:

1. Explain the importance of FCC, BCC and HCP structures
2. Sketch the following direction:[110], [120], [-1 0 2]

Experiment No: 05

Experiment Name: Metallography Specimen Preparation and Microscopic Examination

Objectives:

1. To learn and gain experience in the preparation of metallographic specimens.
2. Familiarize yourself with different types of work materials for specimen preparation.

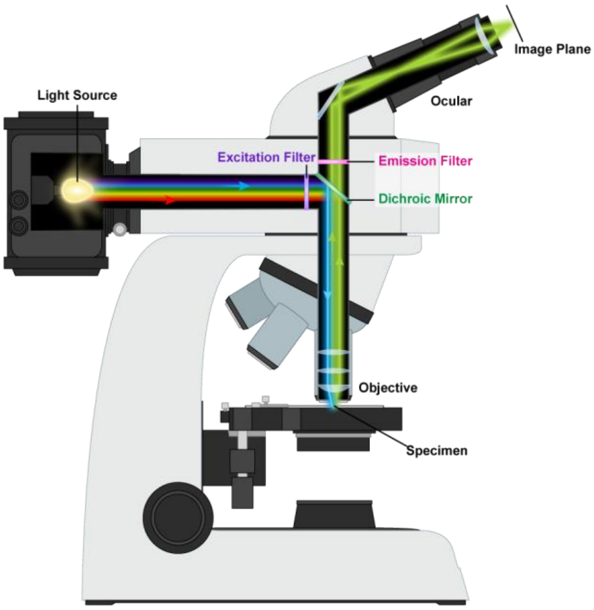
Abstract

Proper preparation of metallographic specimens to determine microstructure and content requires that a rigid step-by-step process be followed. In sequence, the steps include sectioning, mounting, coarse grinding, fine grinding, polishing, etching and microscopic examination. Specimens must be kept clean and preparation procedure carefully followed in order to reveal accurate microstructures. Each group of students will prepare and examine the given sample for metallographic examination.

The basic techniques can be learned through patient persistence in a matter of hours. This module takes the student through the metallographic sample preparation process step-by-step with demonstrations and explanations of sectioning, mounting, coarse & fine grinding, polishing, etching and microscopic examination.

Apparatus

Emery Paper
Acetone
Cotton wool
Etching Reagent
Wet Polishing Machine
Alumina Powder



s the etchant commonly utilized with common irons and steels. Nital is dripped onto the specimen using an eyedropper or cotton swab. Ten seconds to one minute, depending on the sample and nital concentration, is usually sufficient for proper etching.

Materials	Composition	Application Procedure
Iron & Steel	1-5 Parts Nitric Acid 100 Parts Alcohol	Immerse/Swab
Copper & Brass	1 Part Ammonium Hydroxide 1 Part 3% Hydrogen Peroxide 1 Part Water	Swab
Copper & Brass	5 g Ferric Chloride, 10 ml Hydrochloric Acid 100 ml Water	Immerse
Aluminum	5-10 g Ammonium Persulphate 1 ml Hydrofluoric Acid 99 ml Water	Immerse
Aluminum	10 g Sodium Hydroxide, 100 ml Water	Immerse
Stainless Steels	10 g Oxalic Acid 100 ml Water	Use Electrolytically
Stainless Steels	5 ml Sulfuric Acid 100 ml Water	Use Electrolytically

Experiment Requirements:

Each group of students will prepare the given specimen for microscopic observation. Prepare a metallographic specimen by going through the coarse grinding, fine grinding, polishing, and etching stages of specimen preparation. Clearly label your specimen and submit it with the lab write-up; the quality of your specimen will be graded.

* Attach the microscopic image of the prepared specimen with the report.

Assignments:

1. **What is the purpose of using etchants in metallographic examination? Name any two etchants and specify the materials they are commonly used for.**

2. **Why is it important to keep the specimen clean during the grinding, polishing, and etching processes? What could happen if this step is neglected?**

Experiment No: 06
Experiment Name: Constructing Material Property Charts Using ANSYS-Granta EduPack

Objective:

To understand the process of selecting materials based on their properties by constructing material property charts using ANSYS-Granta EduPack.

Apparatus/Software Required:

- Computer with ANSYS-Granta EduPack installed
- Notebook for observations

Theory:

Material selection is a critical step in mechanical design. Engineers use material property charts to compare materials based on different properties, such as density, strength, stiffness, and thermal conductivity. ANSYS-Granta EduPack provides a database of materials and tools for creating these charts.

Procedure:

1. **Launch ANSYS-Granta EduPack**
    - Open the software and select the appropriate database (e.g., Level 1 for beginners).
2. **Exploring Material Properties**
    - Navigate through different material categories (Metals, Polymers, Ceramics, Composites).
    - Observe key properties such as Young’s modulus, tensile strength, and thermal conductivity.
3. **Constructing a Material Property Chart**
    - Go to the **Chart** option in the toolbar.
    - Select two properties (e.g., Density vs. Young’s modulus).
    - Generate the chart and observe material distribution.
4. **Analyzing the Chart**
    - Identify trends among different material classes.
    - Compare materials based on specific design requirements.
5. **Saving & Reporting**
    - Save the generated chart.

- Write a brief report discussing key observations.

Observations & Discussion:

- How do different material families compare in strength-to-weight ratio?
- What materials are most suitable for lightweight structural applications?

Conclusion:

This experiment introduces students to material selection using ANSYS-Granta EduPack, helping them visualize and compare material properties efficiently.

Assignment: Understanding Material Families and Their Properties

Aim: To explore different material families and analyze their properties using ANSYS-Granta EduPack.

Task:

1. Open ANSYS-Granta EduPack and explore the material families (Metals, Polymers, Ceramics, and Composites).
2. Select any **five materials** from different families and note down the following properties:
   a. Density
   b. Young's modulus
   c. Tensile strength
   d. Thermal conductivity

3. Compare and contrast these materials in a tabular (make a table in Word) format.

4. Answer the following questions from your prepared table:

   a) Which material has the highest stiffness-to-weight ratio?
   b) Which material is most suitable for applications requiring high thermal conductivity?

Submission: A table with material properties and a short (200-word) explanation of observations