ENGINEERING MATERIALS

Lecture No. 1

Phase Diagrams

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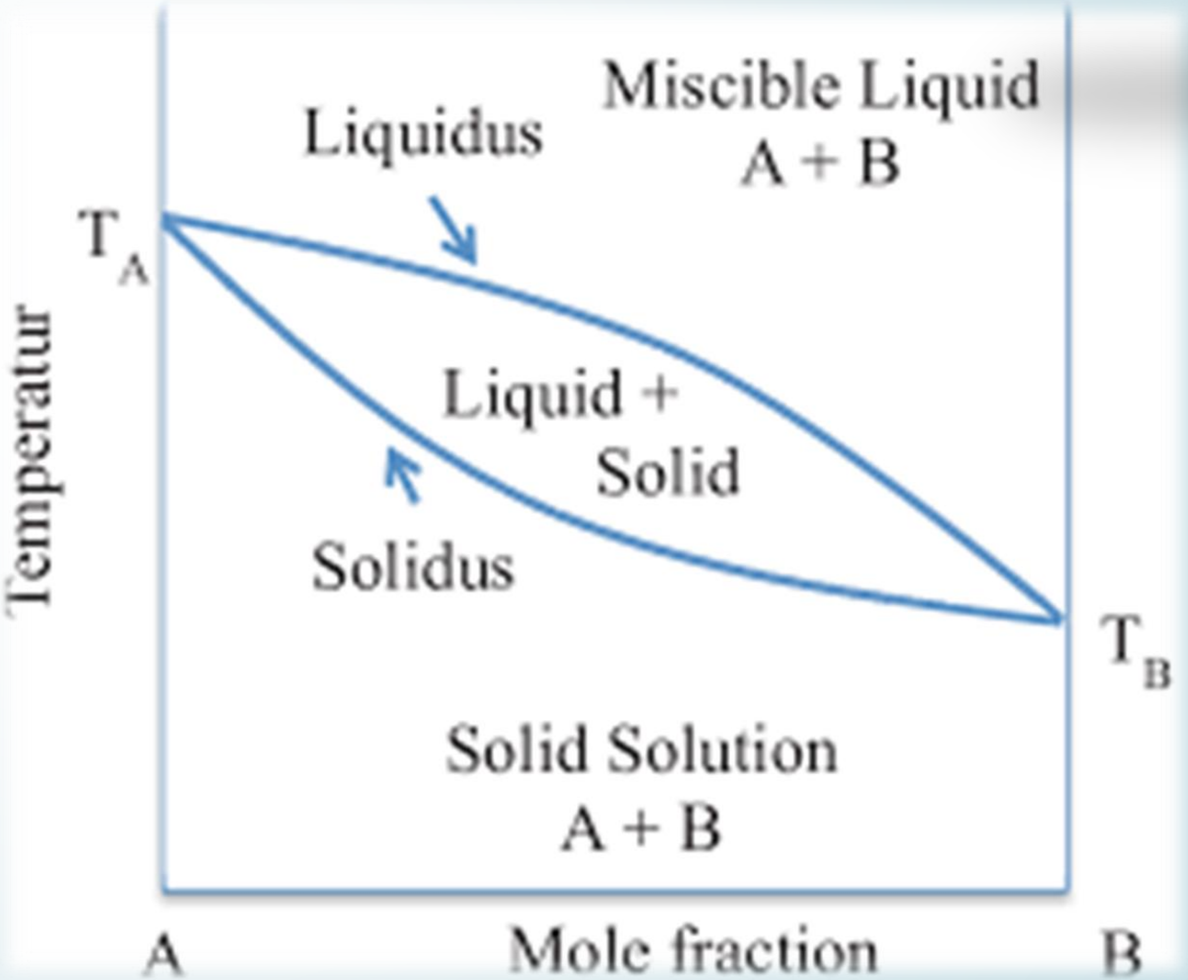
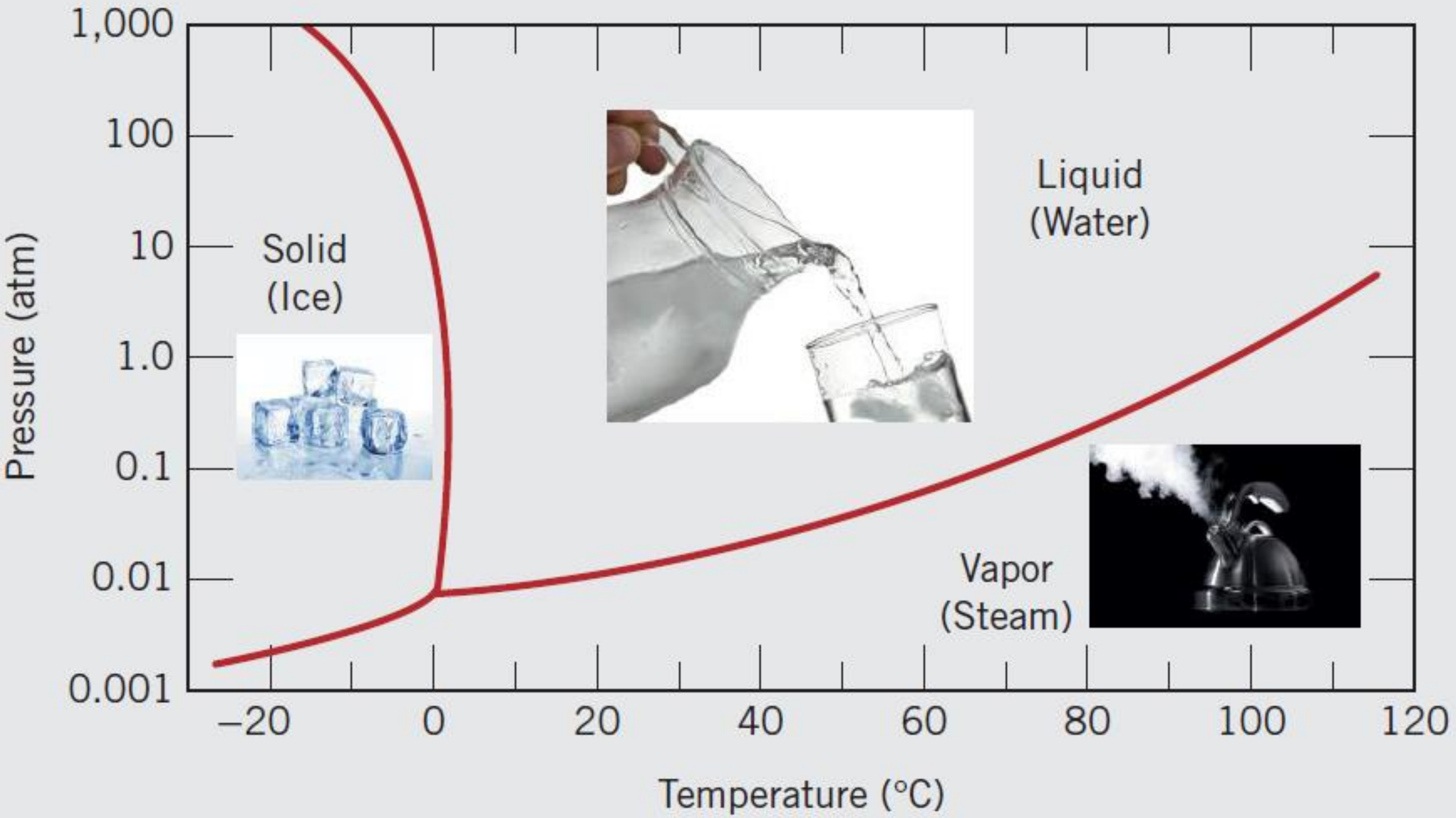



1,000
100
10
1.0
0.1
0.01
0.001
Pressure (atm)
Solid
(Ice)
Liquid
(Water)
Vapor
(Steam)
−20
0
20
40
60
80
100
120
Temperature (°C)

Alloys and Phase Diagrams

Although some metals are important as pure elements (e.g., gold, silver, copper), most engineering applications require the improved properties obtained by alloying. Through alloying, it is possible to enhance strength, hardness, and other properties compared with pure metals.

ALLOYS

An alloy is a metal composed of two or more elements, at least one of which is metallic.

The two main categories of alloys are

(1) solid solutions and

(2) intermediate phases

Solid Solutions

A solid solution is an alloy in which one element is dissolved in another to form a single-phase structure. The term ***phase*** describes any homogeneous mass of material, such as a metal in which the grains all have the same crystal lattice structure. In a solid solution, the solvent or base element is metallic, and the dissolved element can be either metallic or nonmetallic. Solid solutions come in two forms, shown in Figure 1. The first is a ***substitutional solid solution***, in which atoms of the solvent element are replaced in its unit cell by the dissolved element. Brass is an example, in which zinc is dissolved in copper.

Solid Solutions

To make the substitution, several rules must be satisfied :

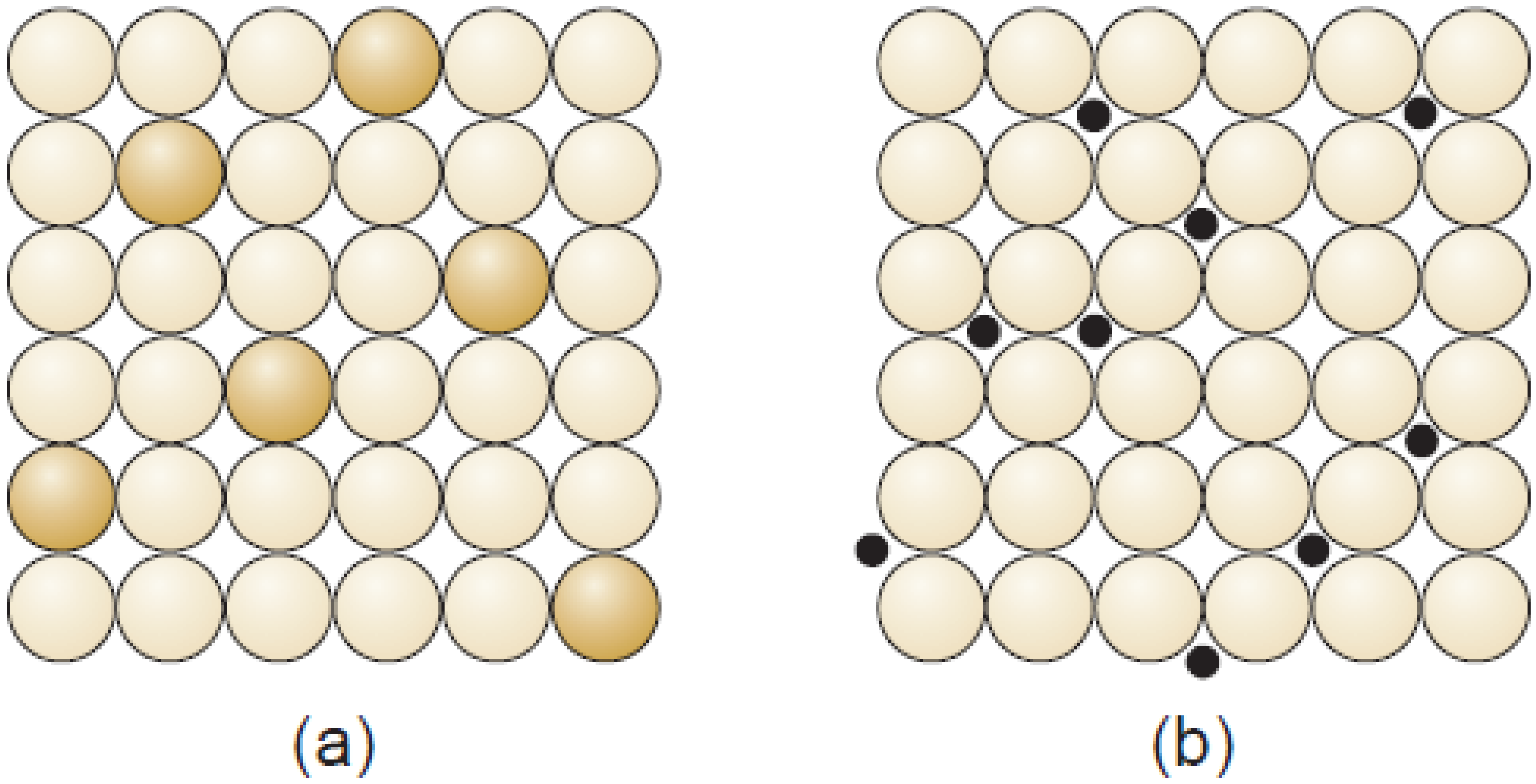
(1) the atomic radii of the two elements must be similar, usually within 15%;

(2) their lattice types must be the same;

(3) if the elements have different valences, the lower valence metal is more likely to be the solvent; and

(4) if the elements have high chemical affinity for each other, they are less likely to form a solid solution and more likely to form a compound.

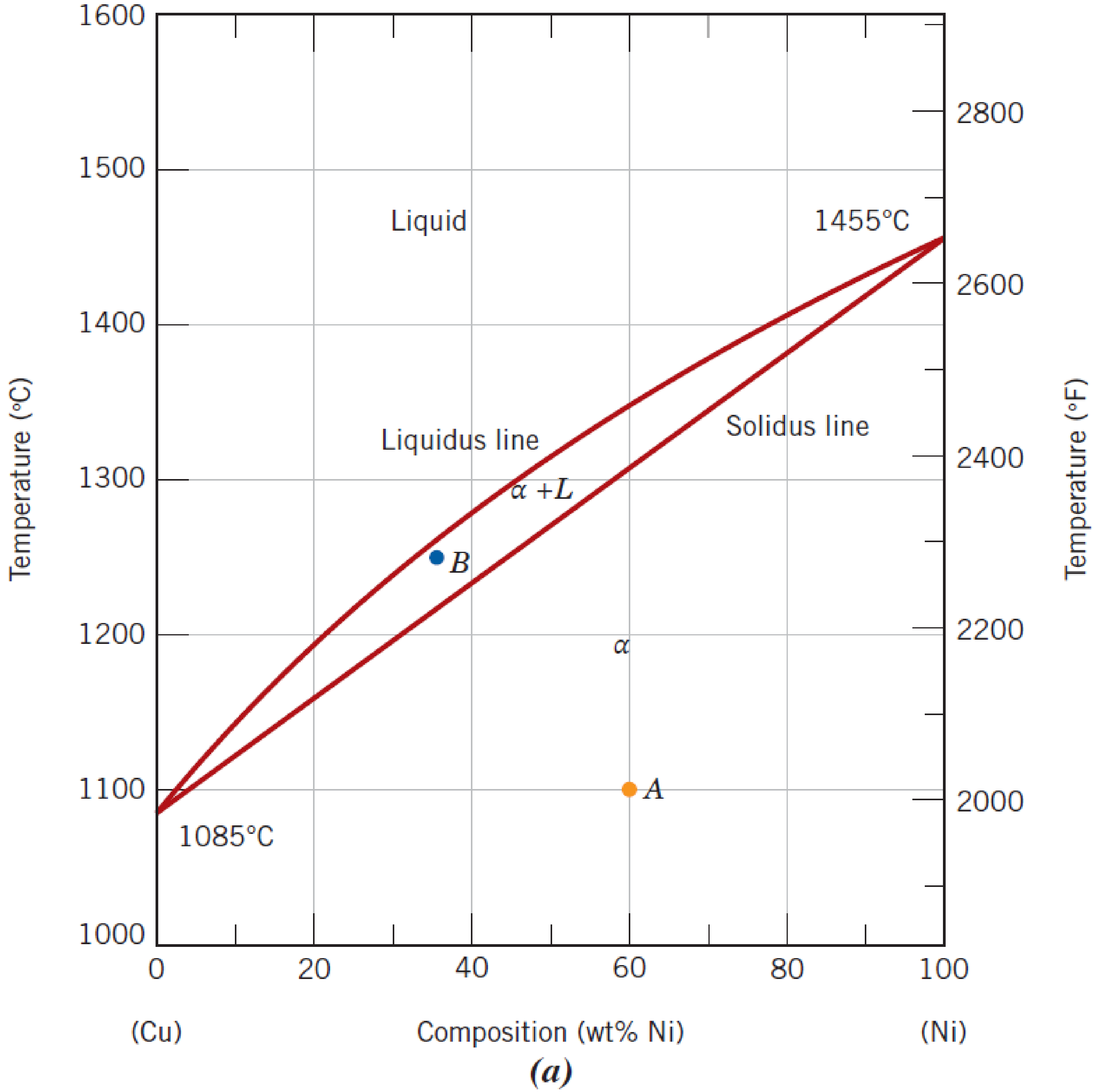
The second type of solid solution is an ***interstitial solid solution***, in which atoms of the dissolving element fit into the vacant spaces between base metal atoms in the lattice structure. It follows that the atoms fitting into these interstices must be small compared with those of the solvent metal. The most important example of this second type is carbon dissolved in iron to form steel. In both forms of solid solution, the alloy structure is generally stronger and harder than either of the component elements.



Two forms of solid solutions: (a) substitutional solid solution, and (b) interstitial solid solution

PHASE DIAGRAMS

As the term is used in this text, a phase diagram is a graphical means of representing the phases of a metal alloy system as a function of composition and temperature. Discussion of the diagram will be limited to alloy systems consisting of two elements at atmospheric pressures. This type of diagram is called a ***binary phase diagram***.


1600
1500
1400
1300
1200
1100
1000
Temperature (°C)
2800
2600
2400
2200
2000
Temperature (°F)
Liquid
1455°C
Liquidus line
Solidus line
α + L
B
α
A
1085°C
0
20
40
60
80
100
(Cu)
Composition (wt% Ni)
(Ni)

(a)

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.

To illustrate this concept, consider the sugar–water ($C_{12}H_{22}O_{11}$–H_2O) 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. At this time, the solution is not capable of dissolving any more 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.

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. There are several different varieties; in the present discussion, we will concern ourselves with binary alloys—those that contain two components. If more than two components are present, phase diagrams become extremely complicated and difficult to represent. An explanation of the principles governing, and the interpretation of phase diagrams can be demonstrated using binary alloys even though most alloys contain more than two components.

Binary phase diagrams are maps that represent the relationships between temperature and the compositions and quantities of phases at equilibrium, which influence the microstructure of an alloy. Many microstructures develop from phase transformations, the changes that occur when the temperature is altered (typically upon cooling). This may involve the transition from one phase to another or the appearance or disappearance of a phase. Binary phase diagrams are helpful in predicting phase transformations and the resulting microstructures, which may have equilibrium or nonequilibrium character.

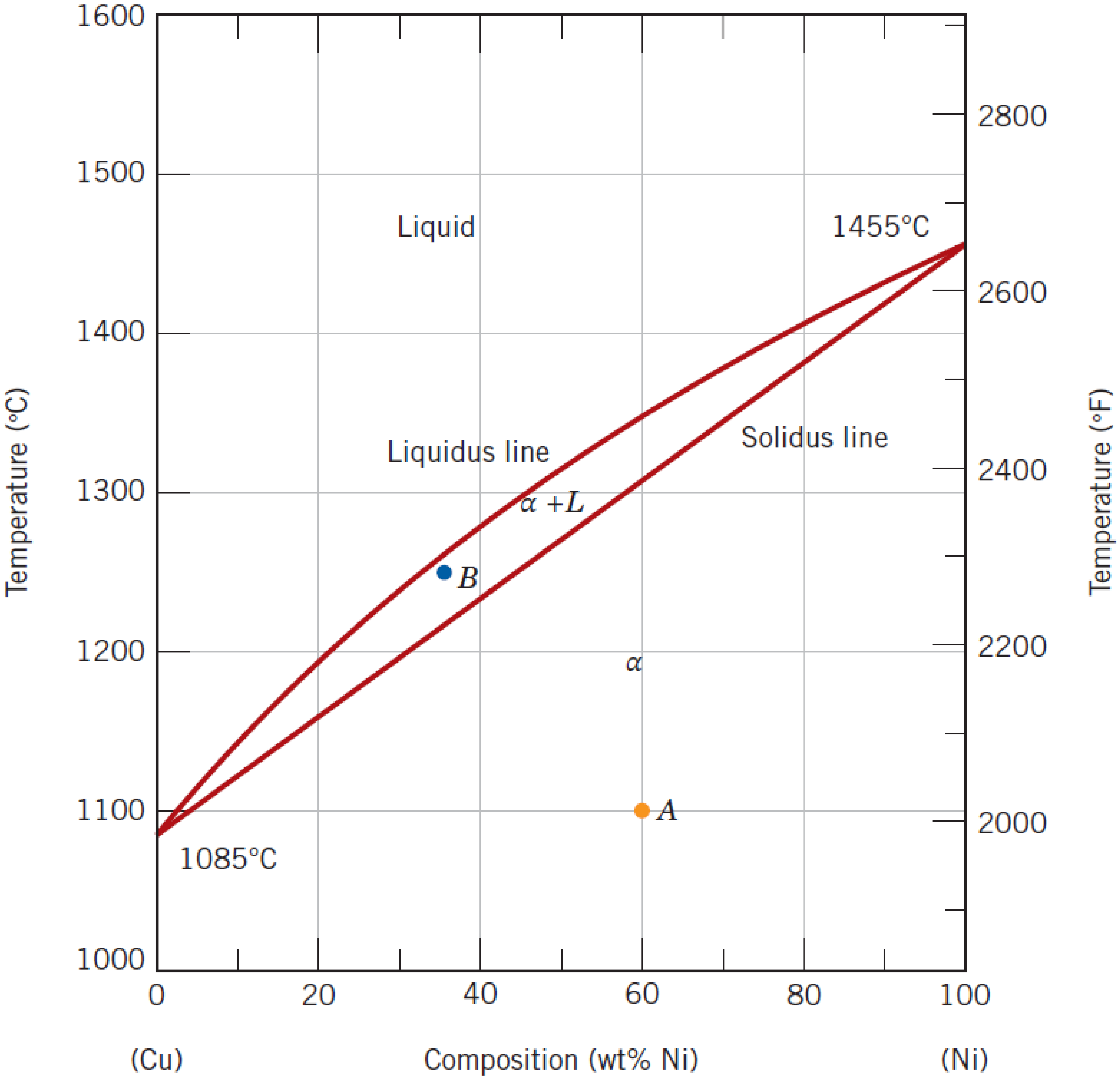
Possibly the easiest type of binary phase diagram to understand and interpret is the type that is characterized by the copper–nickel system (Figure 2). Temperature is plotted along the ordinate, and the abscissa represents the composition of the alloy, in weight percent of nickel. The composition ranges from 0 wt% Ni (100 wt% Cu) on the far left horizontal extreme to 100 wt% Ni (0 wt% Cu) on the right. 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. Each region is defined by the phase or phases that exist over the range of temperatures and compositions delineated by the phase boundary lines.

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 has 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. This complete solubility is explained by the fact that both Cu and Ni have the same crystal structure (FCC), nearly identical atomic radii and electronegativities, and similar valences. The copper–nickel system is termed **isomorphous** because of this complete liquid and solid solubility of the two components.

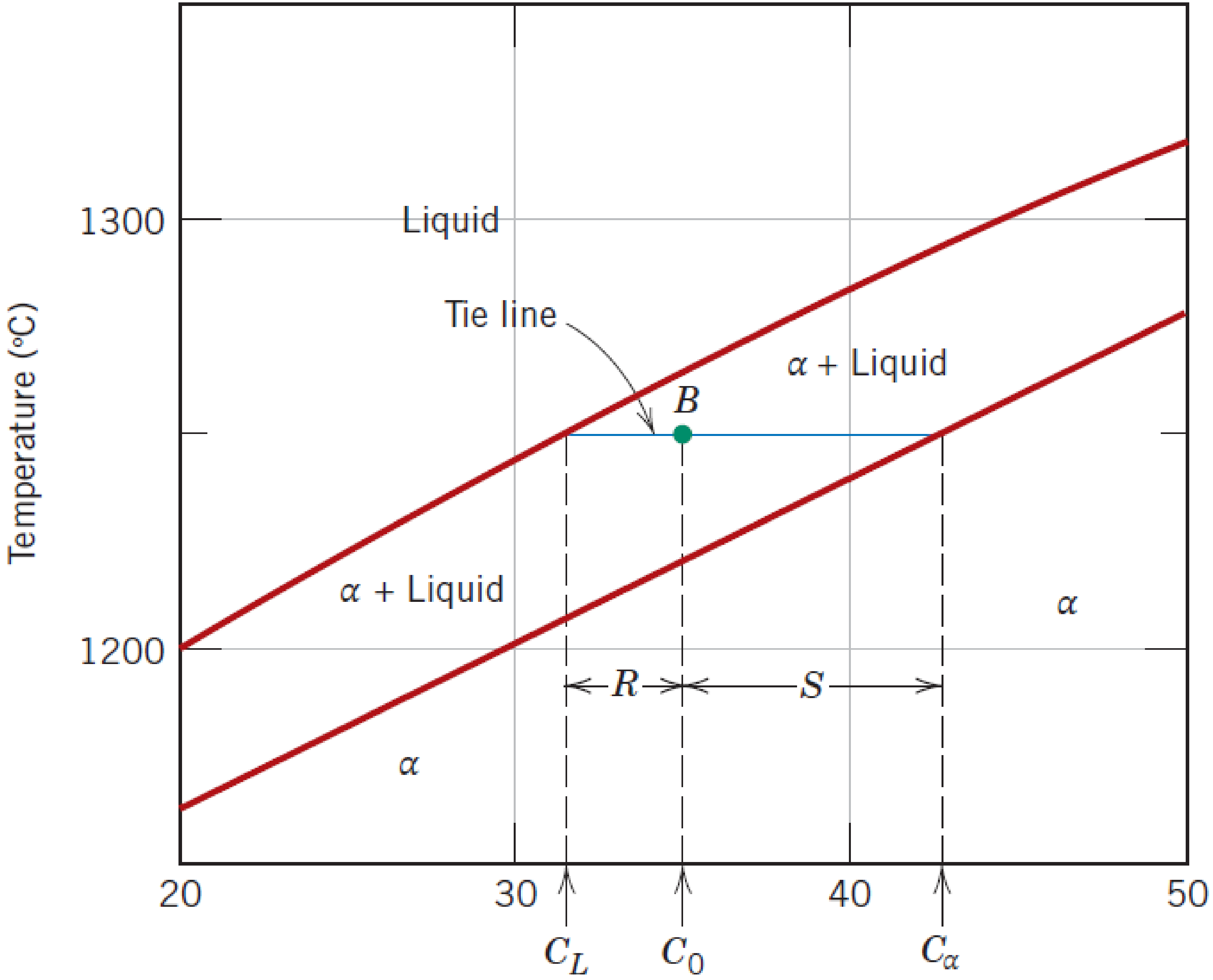
Some comments are in order regarding nomenclature: First, for metallic alloys, solid solutions are commonly designated by lowercase Greek letters (α, β, γ, etc.). With regard to phase boundaries, the line separating the L and $\alpha + L$ phase fields is termed the *liquidus line*, as indicated in Figure2*a*; the liquid phase is present at all temperatures and compositions above this line. The *solidus line* is located between the α and $\alpha + L$ regions, below which only the solid α phase exists.

For Figure 2*a*, the solidus and liquidus lines intersect at the two composition extremes; these correspond to the melting temperatures of the pure components. For example, the melting temperatures of pure copper and nickel are 1085°C and 1455°C, respectively.

Heating pure copper corresponds to moving vertically up the left-hand temperature axis. Copper remains solid until its melting temperature is reached. The solid-to-liquid transformation takes place at the melting temperature, and no further heating is possible until this transformation has been completed. For any composition other than pure components, this melting phenomenon occurs over the range of temperatures between the solidus and liquidus lines; both solid α and liquid phases are in equilibrium within this temperature range. For example, upon heating of an alloy of composition 50 wt% Ni–50 wt% Cu (Figure 2 *a*), melting begins at approximately 1280°C ; the amount of liquid phase continuously increases with temperature until about 1320°C, at which point the alloy is completely liquid.


1600
1500
1400
1300
1200
1100
1000
Temperature (°C)
2800
2600
2400
2200
2000
Temperature (°F)
Liquid
1455°C
Liquidus line
α +L
Solidus line
B
α
A
1085°C
0
20
40
60
80
100
(Cu)
Composition (wt% Ni)
(Ni)

(a)



Temperature (°C)
1300
1200
Liquid
Tie line
α + Liquid
B
α + Liquid
α
α
R
S
20
30
40
50
C_L
C_0
C_α
Composition (wt% Ni)

(b)

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

(1) the phases that are present,

(2) the compositions of these phases, and

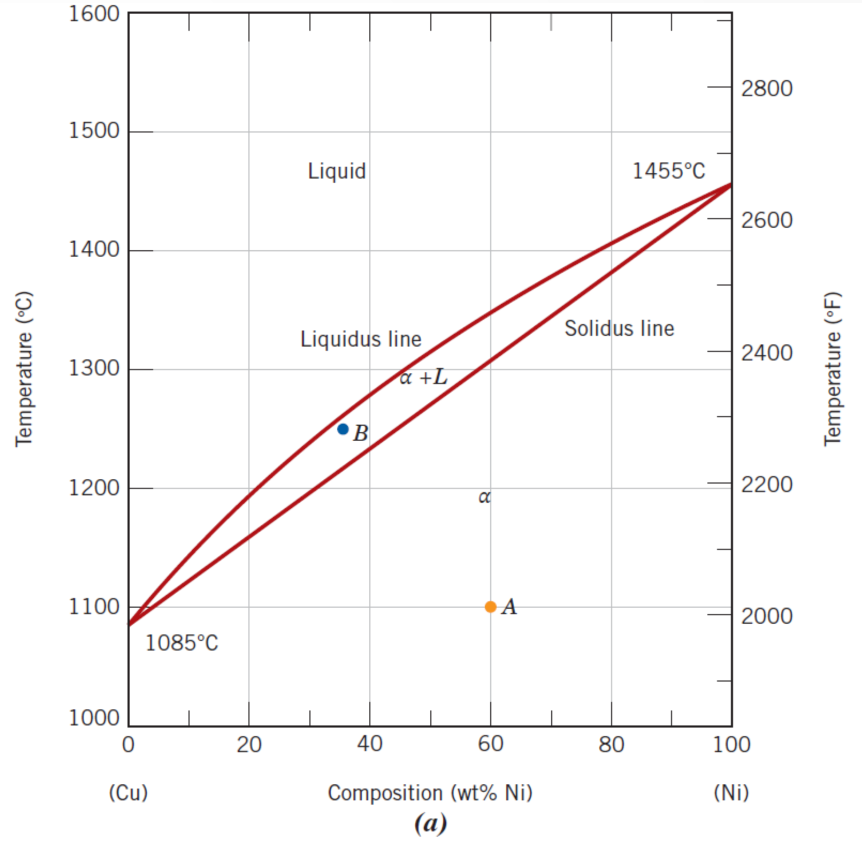
(3) the percentages or fractions of the phases.

The procedures for making these determinations will be demonstrated using the copper–nickel system .

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 2 *a*; because this is within the α region, only the single α phase will be present. However, a 35 wt% Ni–65 wt% Cu alloy at 1250°C (point *B*) consists of both α and liquid phases at equilibrium.

Thank you for listening



(a)