Dispersion Strengthening
And Phase Diagrams

Dispersion Strengthening And Phase Diagrams

when the solubility of a material is exceeded by adding too much of an alloying element or compound, a second phase forms and a two-phase material is produced. The boundary between the two phases, known as the **interphase interface, is a surface where the atomic arrangement is not perfect.**

In metallic materials, this boundary interferes with the slip or movement of dislocations, causing strengthening. The general term for such strengthening by the introduction of a second phase is known as dispersion strengthening.

Principles of Dispersion Strengthening

Most engineered materials are composed of more than one phase, and many of these materials are designed to provide improved strength. In simple dispersion-strengthened alloys, small particles of one phase, usually very strong and hard, are introduced into a second phase, which is weaker but more ductile. The soft phase, usually continuous and present in larger amounts, is called the matrix. The hard-strengthening phase may be called the dispersed phase or the precipitate, depending on how the alloy is formed. In some cases, a phase or a mixture of phases may have a very characteristic appearance—in these cases, this phase or phase mixture may be called a microconstituent. For dispersion strengthening to occur, the dispersed phase or precipitate must be small enough to provide effective obstacles to dislocation movement, thus providing the strengthening mechanism.

There are some general considerations for determining how the characterization of the matrix and precipitate affected the overall properties of alloy (Fig 1)

1. The matrix should be soft and ductile, while the dispersed phase should be hard and strong. The dispersed phase particles interfere with slip, while the matrix provides at least some ductility to the overall alloy.
2. The hard dispersed phase should be discontinuous, while the soft, ductile matrix should be continuous. If the hard and brittle dispersed phase were continuous, cracks could propagate through the entire structure.
3. The dispersed phase particles should be small and numerous, increasing the likelihood that they interfere with the slip process since the area of the interphase interface is increased significantly.

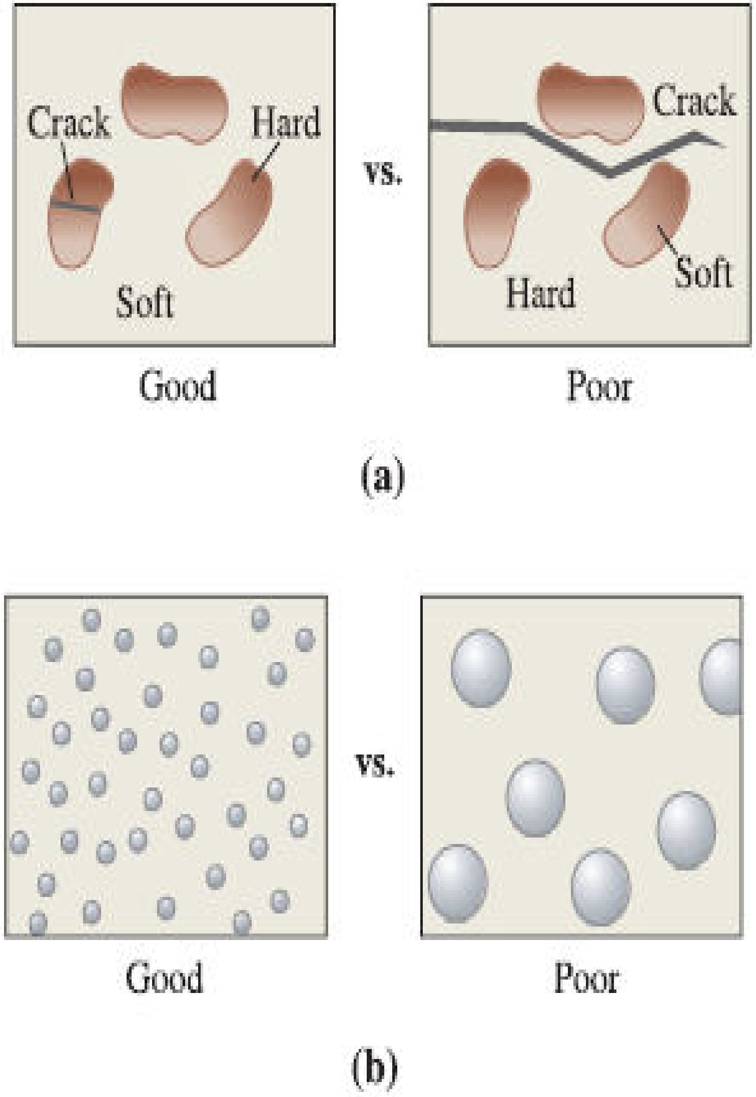
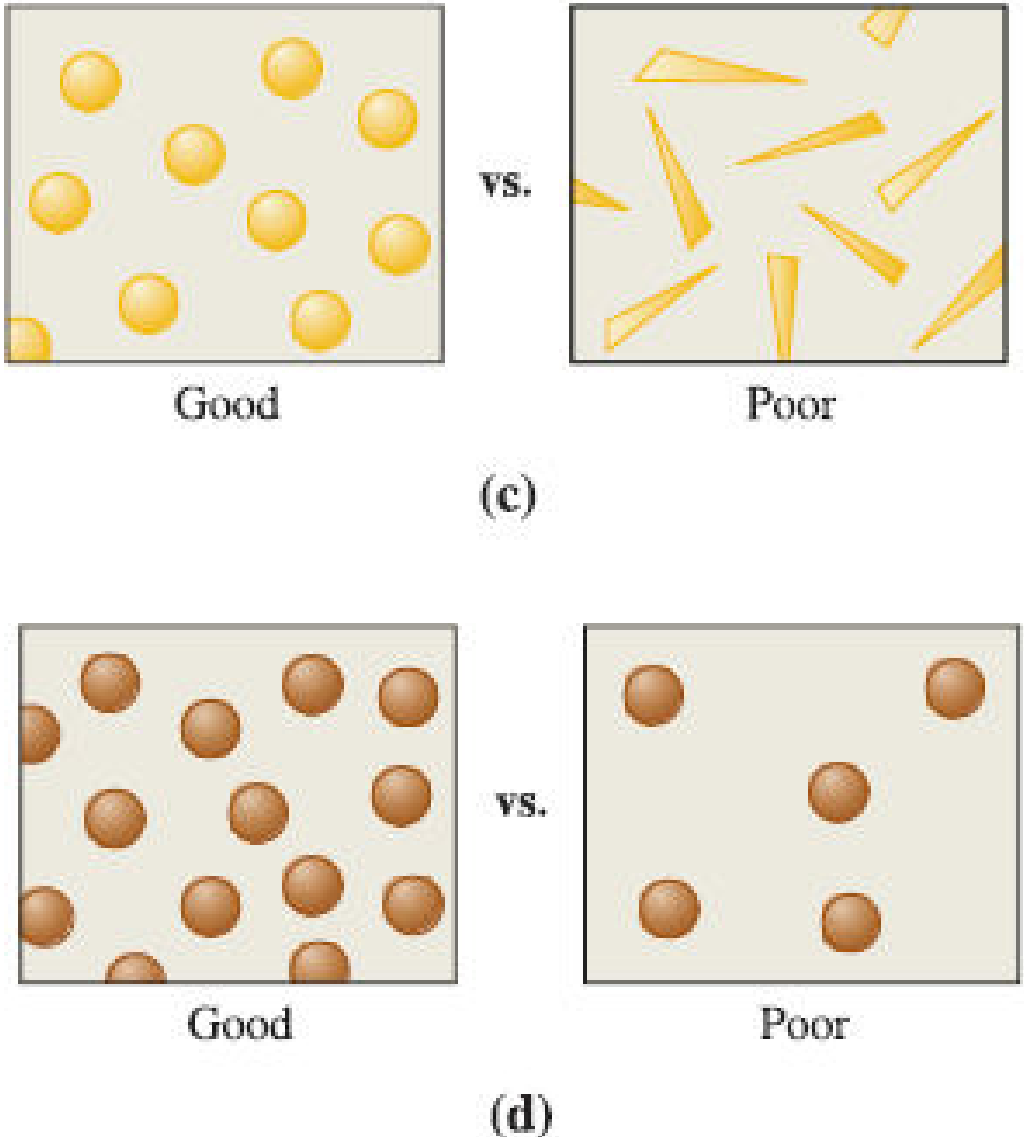


Figure 11-1
Considerations for effective dispersion strengthening: (a) The precipitate phase should be hard and discontinuous, while the matrix should be continuous and soft, (b) the dispersed phase particles should be small and numerous, (c) the dispersed phase particles should be round rather than needle-like, and (d) larger amounts of the dispersed phase increase strengthening.



(c) the dispersed phase particles should be round rather than needle-like, and (d) larger amounts of the dispersed phase increase strengthening.

Intermetallic Compounds

An **intermetallic compound contains two or more metallic elements, producing a new phase** with its own composition, crystal structure, and properties. Intermetallic compounds are almost always very hard and brittle. Intermetallics or intermetallic compounds are similar to ceramic materials in terms of their mechanical properties.

intermetallics is two-fold. First, often dispersion strengthened alloys contain an intermetallic compound as the dispersed phase. Secondly, many intermetallic compounds, on their own (and not as a second phase), are being investigated and developed for high temperature applications.

Stoichiometric intermetallic compounds have a fixed composition. Steels are often strengthened by a stoichiometric compound, iron carbide (Fe3C), which has a fixed ratio of three iron atoms to one carbon atom. Stoichiometric intermetallic compounds are represented in the phase diagram by a vertical line [Figure 11-2(a)]. An example of a useful intermetallic compound is molybdenum disilicide (MoSi2). This material is used for making heating elements for high temperature furnaces. At high temperatures (1000 to 1600°C), MoSi2 shows outstanding oxidation resistance. At low temperatures (500°C and below), MoSi2 is brittle and shows catastrophic oxidation known as pesting.

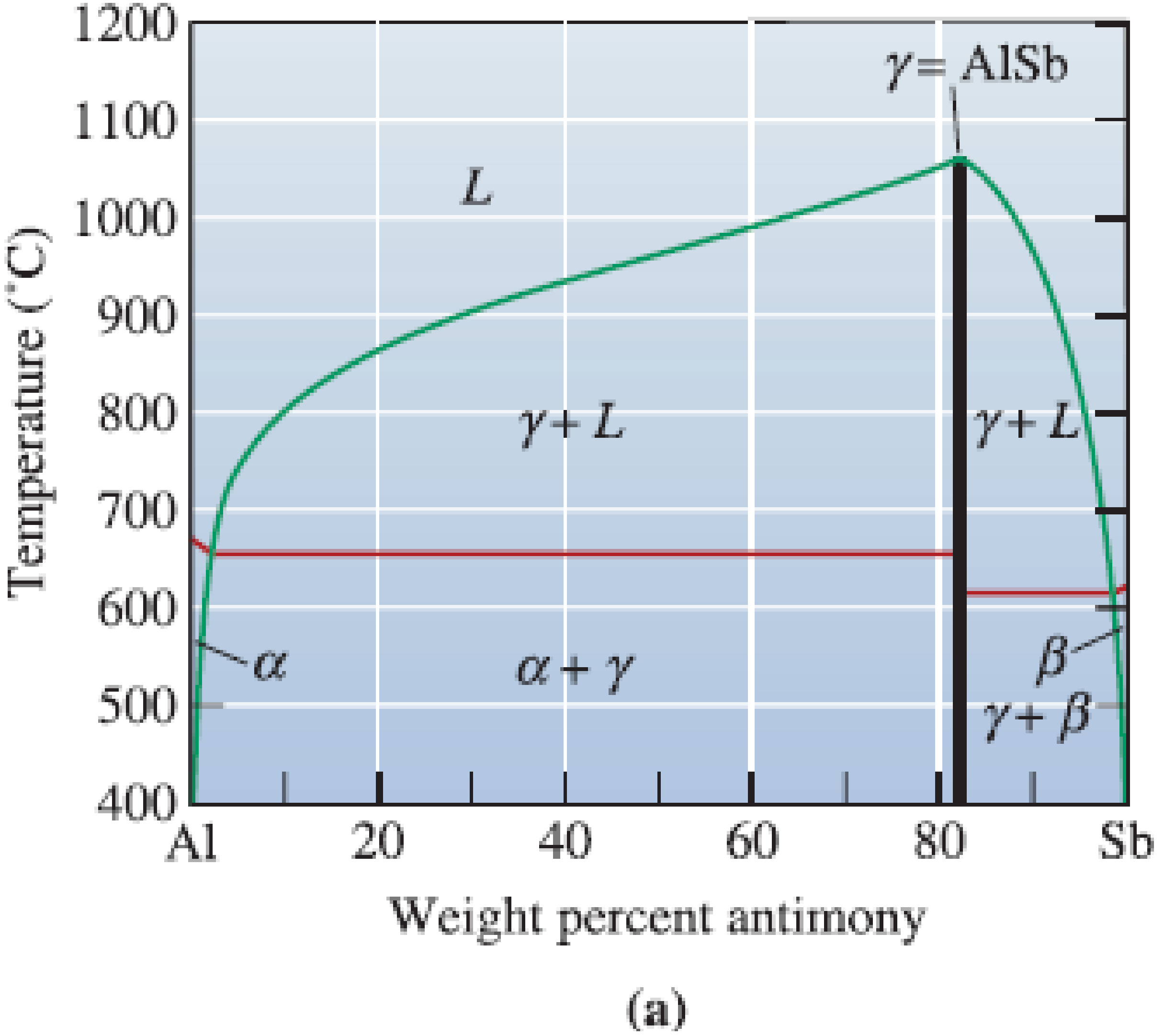
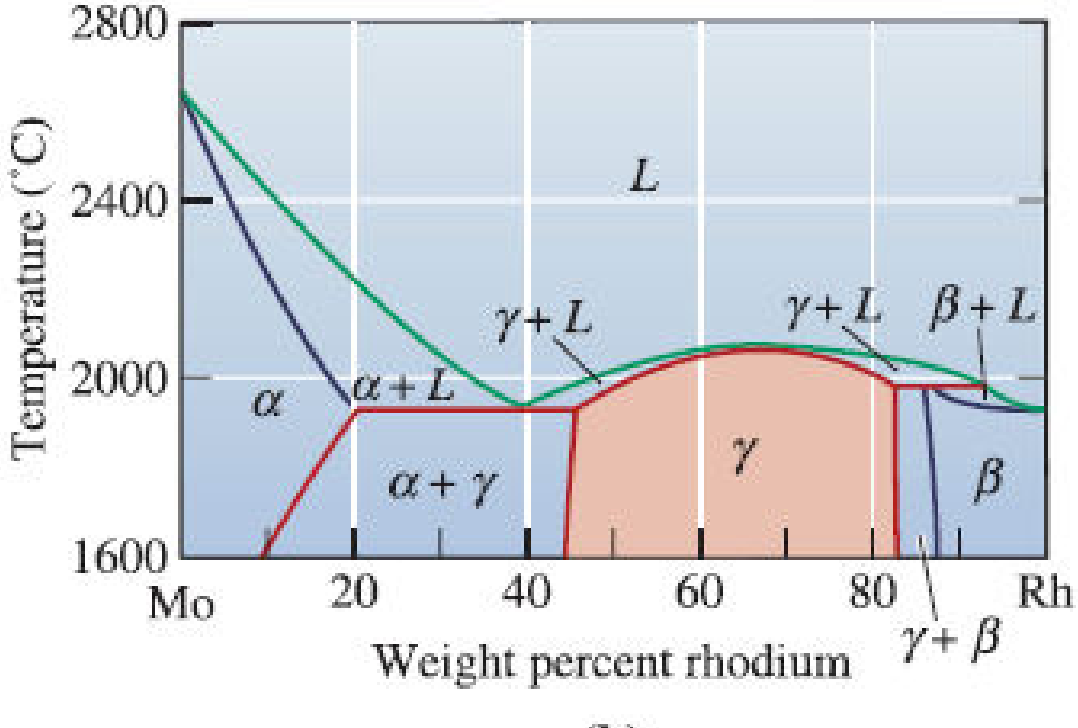


Figure 11-2 (a) The aluminum-antimony phase diagram includes a stoichiometric intermetallic compound γ.

Nonstoichiometric intermetallic compounds have a range of compositions and are sometimes called **intermediate solid solutions**. In the molybdenum–rhodium system, the γ phase is a nonstoichiometric intermetallic compound [Figure 11-2(b)]. Because the molybdenum–rhodium atom ratio is not fixed, the γ phase can contain from 45 wt.% to 83 wt.% Rh at 1600°C. Precipitation of the nonstoichiometric intermetallic copper aluminide $CuAl_2$ causes strengthening in a number of important aluminum alloys.



(b)

(b) The molybdenum-rhodium phase diagram includes a nonstoichiometric intermetallic compound γ.

Phase Diagrams Containing Three-Phase Reactions

Many binary systems produce phase diagrams more complicated than the isomorphous phase diagrams discussed in Chapter 10. The systems we will discuss here contain reactions that involve three separate phases. Five such reactions are defined in Figure 11-4. Each of

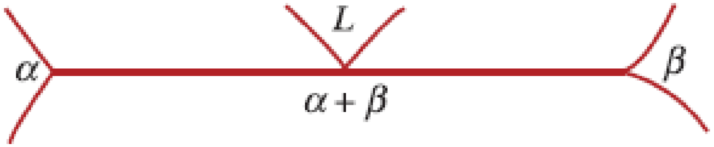
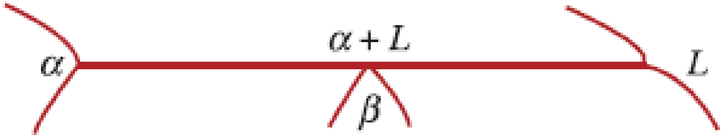
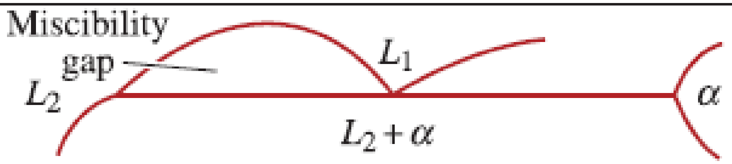
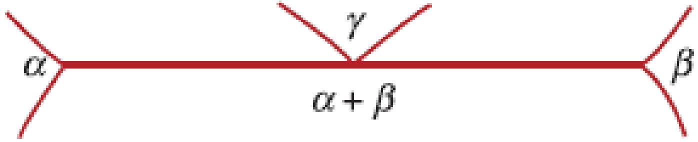
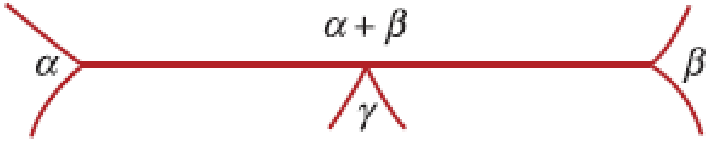
Eutectic	$L \rightarrow \alpha + \beta$	
Peritectic	$\alpha + L \rightarrow \beta$	
Monotectic	$L_1 \rightarrow L_2 + \alpha$	
Eutectoid	$\gamma \rightarrow \alpha + \beta$	
Peritectoid	$\alpha + \beta \rightarrow \gamma$	

Figure 11-4 The five most important three-phase reactions in binary phase diagrams.

these reactions can be identified in a phase diagram by the following procedure.

1. Locate a horizontal line on the phase diagram. The horizontal line, which indicates the presence of a three-phase reaction, represents the temperature at which the reaction occurs under equilibrium conditions.
2. Locate three distinct points on the horizontal line: the two endpoints plus a third point, in between the two endpoints of the horizontal line. This third point represents the composition at which the three-phase reaction occurs. In Figure 11-4, the point in between has been shown at the center; however, on a real phase diagram, this point is not necessarily at the center.
3. Look immediately above the in-between point and identify the phase or phases present; look immediately below the point in between the end points and identify the phase or phases present. Then write the reaction from the phase(s) above the point that are transforming to the phase(s) below the point. Compare this reaction with those in Figure 11-4 to identify the reaction.

The Eutectic Phase Diagram

The lead–tin (Pb–Sn) system contains only a simple eutectic reaction (Figure 11-6). This alloy system is the basis for the most common alloys used for soldering. As mentioned before, because of the toxicity of Pb, there is an intense effort underway to replace lead in Pb–Sn solders. We will continue to use a Pb–Sn system, though, to discuss the eutectic phase diagram. Let's examine four classes of alloys in this system.

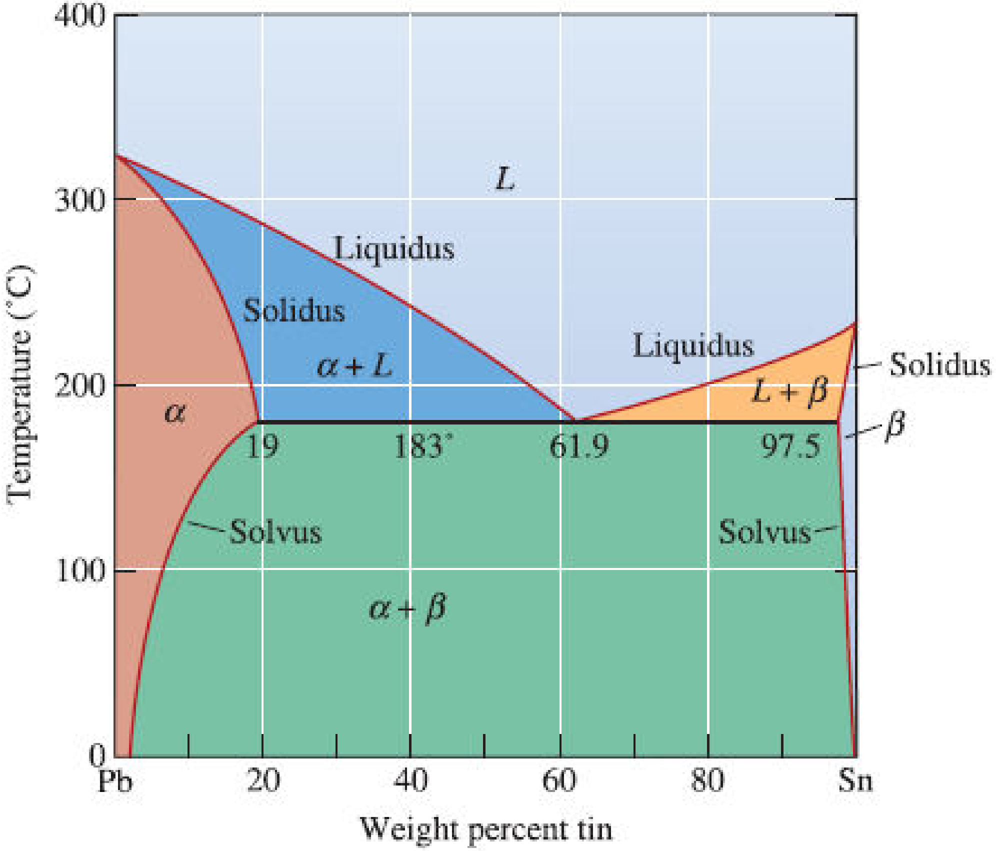


Figure 11-6 The lead–tin equilibrium phase diagram.

Solid-Solution Alloys Alloys that contain 0 to 2% Sn behave exactly like the copper-nickel alloys; a single-phase solid solution α forms during solidification (Figure 11-7). These alloys are strengthened by solid-solution strengthening, strain hardening, and controlling the solidification process to refine the grain structure.

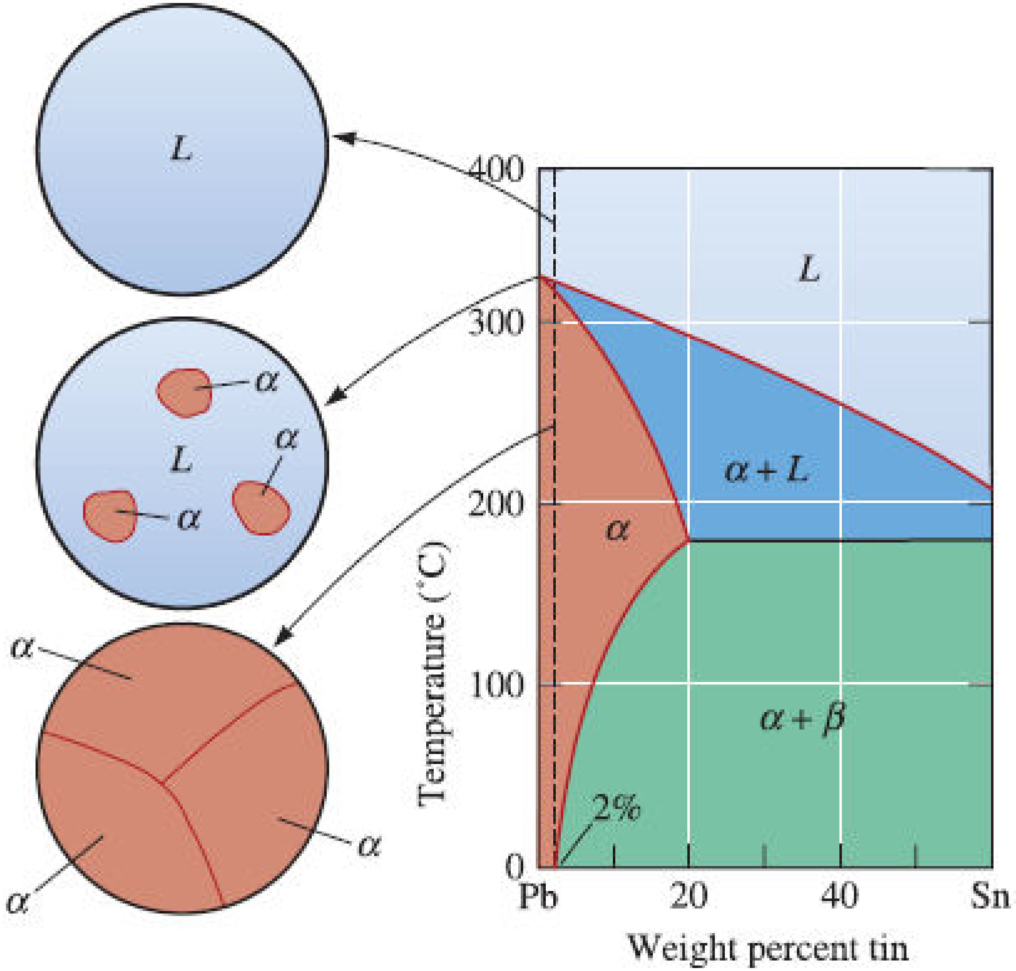


Figure 11-7 Solidification and microstructure of a Pb-2% Sn alloy. The alloy is a single-phase solid solution.

Alloys That Exceed the Solubility Limit Alloys containing between 2% and 19% Sn also solidify to produce a single solid solution *α*; however, as the alloy continues to cool, a solid-state reaction occurs, permitting a second solid phase (*β*) to precipitate from the original *α* phase (Figure 11-8).

On this phase diagram, the *α* is a solid solution of tin in lead; however, the solubility of tin in the *α* solid solution is limited. At 0°C, only 2% Sn can dissolve in *α*. As the

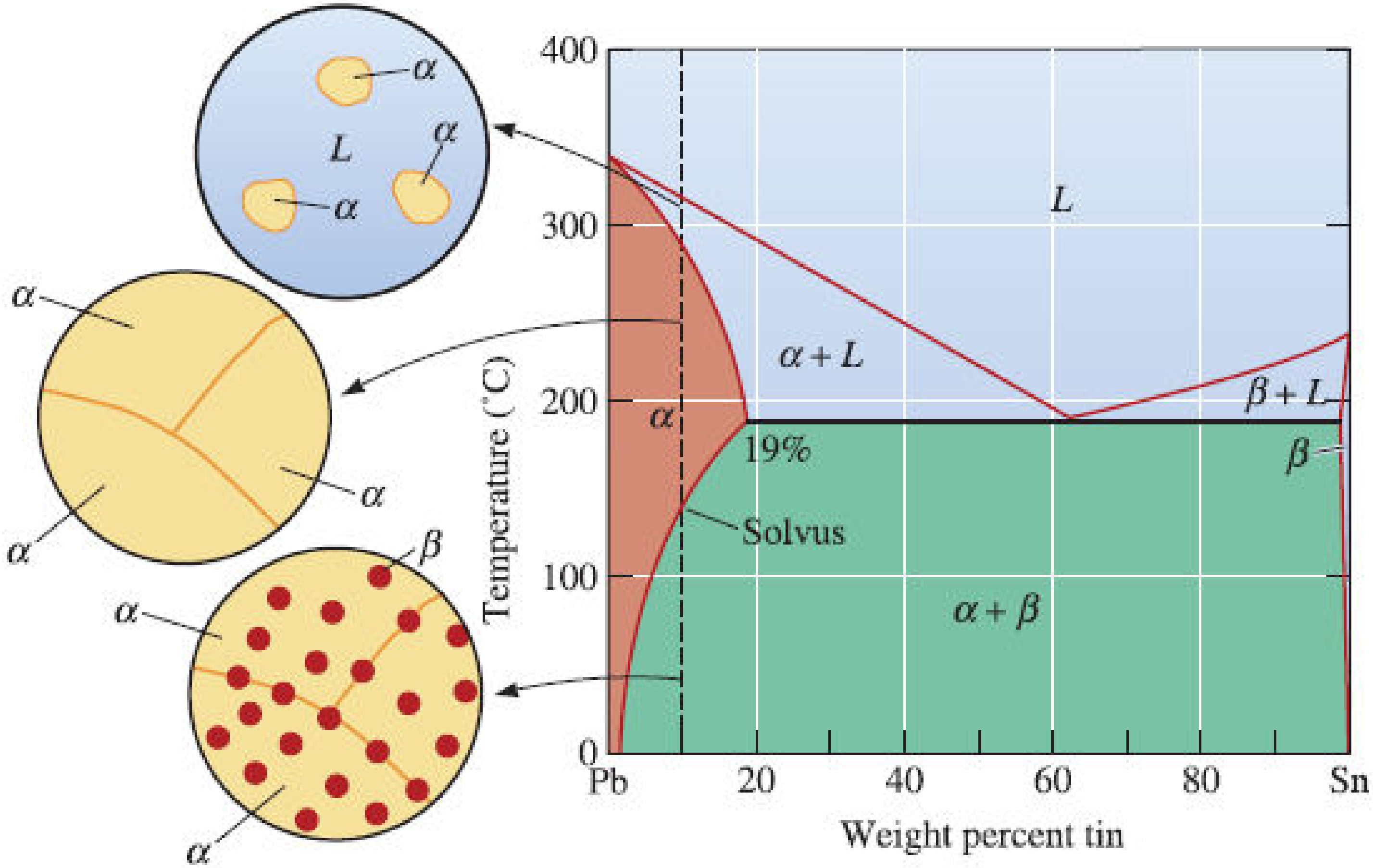


Figure 11-8 Solidification, precipitation, and microstructure of a Pb-10% Sn alloy. Some dispersion strengthening occurs as the *β* solid precipitates.

temperature increases, more tin dissolves into the lead until, at 183°C, the solubility of tin in lead has increased to 19% Sn. This is the maximum solubility of tin in lead. The solubility of tin in solid lead at any temperature is given by the solvus curve. Any alloy containing between 2% and 19% Sn cools past the solvus, the solubility limit is exceeded, and a small amount of β forms.

We control the properties of this type of alloy by several techniques, including solid-solution strengthening of the α portion of the structure, controlling the microstructure produced during solidification, and controlling the amount and characteristics of the β phase.

Example 11-2 *Phases in the Lead–Tin (Pb-Sn) Phase Diagram*

Determine (a) the solubility of tin in solid lead at 100°C, (b) the maximum solubility of lead in solid tin, (c) the amount of β that forms if a Pb-10% Sn alloy is cooled to 0°C, (d) the masses of tin contained in the α and β phases, and (e) the mass of lead contained in the α and β phases. Assume that the total mass of the Pb-10% Sn alloy is 100 grams.

SOLUTION

The phase diagram we need is shown in Figure 11-8. All percentages shown are weight %.

(a) The 100°C temperature intersects the solvus curve at 6% Sn. The solubility of tin (Sn) in lead (Pb) at 100°C, therefore, is 6%.

(b) The maximum solubility of lead (Pb) in tin (Sn), which is found from the tin-rich side of the phase diagram, occurs at the eutectic temperature of 183°C and is 97.5% Sn or 2.5% Pb.

(c) At 0°C, the 10% Sn alloy is in the $\alpha + \beta$ region of the phase diagram. By drawing a tie line at 0°C and applying the lever rule, we find that

$$\% \ \beta = \frac{10 - 2}{100 - 2} \times 100 = 8.2\%$$

Note that the tie line intersects the solvus curve for solubility of Pb in Sn at a non-zero concentration of Sn. We cannot read this accurately from the diagram; however, we assume that the right-hand point for the tie line is 100% Sn. The percent of α would be $(100 - \% \ \beta) = 91.8\%$. This means if we have 100 g of the 10% Sn alloy, it will consist of 8.2 g of the β phase and 91.8 g of the α phase.

(d) Note that 100 g of the alloy will consist of 10 g of Sn and 90 g of Pb. The Pb and Sn are distributed in two phases (i.e., α and β). The mass of Sn in the α phase $= 2\%$ Sn $\times$ 91.8 g of α phase $= 0.02 \times 91.8$ g $= 1.836$ g. Since tin (Sn) appears in both the α and

β phases, the mass of Sn in the β phase will be = (10 – 1.836) g = 8.164 g. Note that in this case, the β phase at 0°C is nearly pure Sn.

(e) Let's now calculate the mass of lead in the two phases. The mass of Pb in the α phase will be equal to the mass of the α phase minus the mass of Sn in the α phase = 91.8 g – 1.836 g = 89.964 g. We could have also calculated this as

$$\begin{aligned}\text{Mass of Pb in the } \alpha \text{ phase} &= 98\%\ \text{Pb} \times 91.8\,\text{g of } \alpha \text{ phase} = 0.98 \times 91.8\,\text{g} \\ &= 89.964\,\text{g}\end{aligned}$$

We know the total mass of the lead (90 g), and we also know the mass of lead in the α phase. Thus, the mass of Pb in the β phase = 90 – 89.964 = 0.036 g. This is consistent with what we said earlier (i.e., the β phase, in this case, is almost pure tin).

Eutectic Alloys The alloy containing 61.9% Sn has the eutectic composition (Figure 11-9). The word eutectic comes from the Greek word *eutectos* that means easily fused. Indeed, in a binary system showing one eutectic reaction, an alloy with a eutectic composition has the lowest melting temperature. This is the composition for which there is no freezing range (i.e., solidification of this alloy occurs at one temperature, 183°C in the Pb-Sn system). Above 183°C, the alloy is all liquid and, therefore, must contain 61.9% Sn. After the liquid cools to 183°C, the eutectic reaction begins:

$$L_{61.9\%\,\mathrm{Sn}} \rightarrow \alpha_{19\%\,\mathrm{Sn}} + \beta_{97.5\%\,\mathrm{Sn}}$$

Two solid solutions—α and β—are formed during the eutectic reaction. The compositions of the two solid solutions are given by the ends of the eutectic line.

During solidification, growth of the eutectic requires both removal of the latent heat of fusion and redistribution of the two different atom species by diffusion. Since

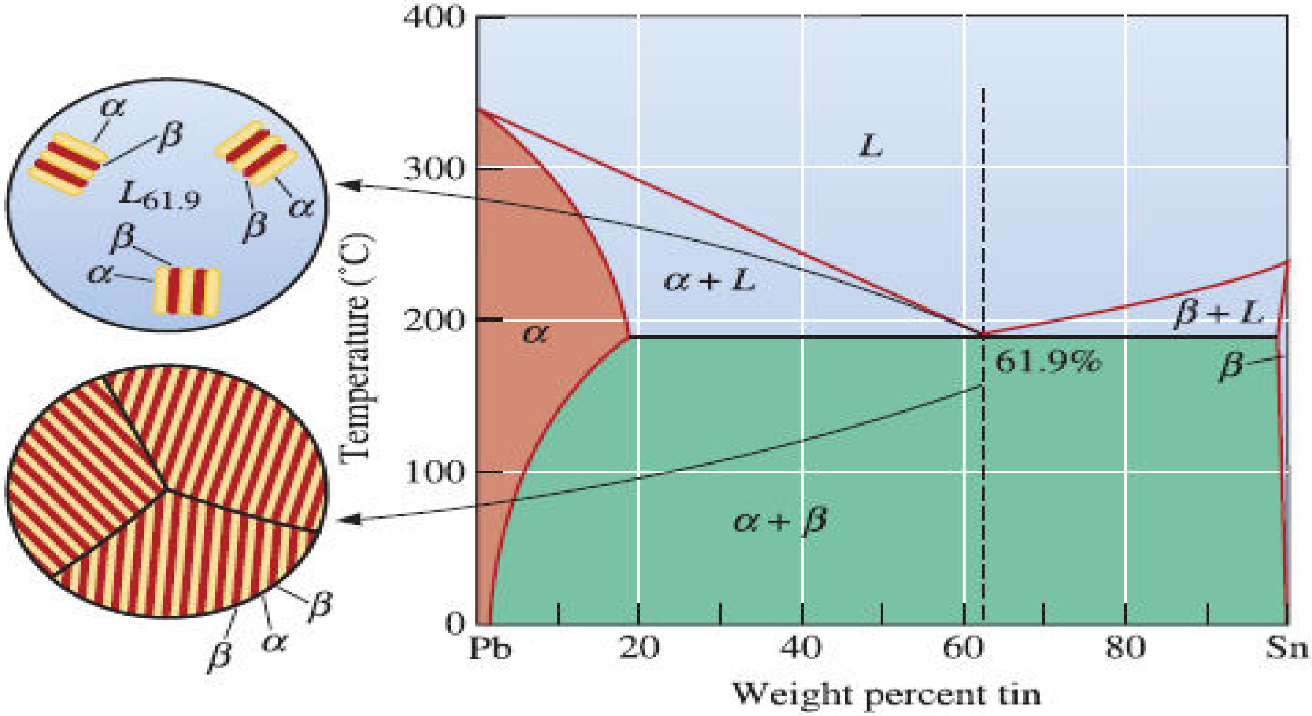


Figure 11-9 Solidification and microstructure of the eutectic alloy Pb-61.9% Sn.

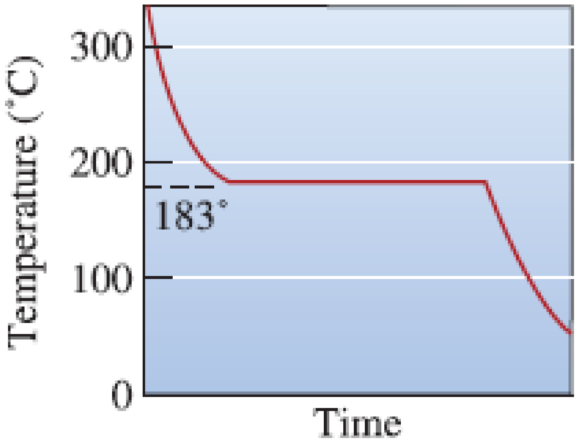


Figure 11-10
The cooling curve for an eutectic alloy is a simple thermal arrest, since eutectics freeze or melt at a single temperature.

solidification occurs completely at 183°C, the cooling curve (Figure 11-10) is similar to that of a pure metal; that is, a thermal arrest or plateau occurs at the eutectic temperature. In Chapter 9, we stated that alloys solidify over a range of temperatures (between the liquidus and solidus) known as the freezing range. Eutectic compositions are an exception to this rule since they transform from a liquid to a solid at a constant temperature (i.e., the eutectic temperature).

As atoms are redistributed during eutectic solidification, a characteristic microstructure develops. In the lead-tin system, the solid α and β phases grow from the liquid in a **lamellar**, or plate-like, arrangement (Figure 11-11). The lamellar structure permits the lead and tin atoms to move through the liquid, in which diffusion is rapid, without having to move an appreciable distance. This lamellar structure is characteristic of numerous other eutectic systems.

The product of the eutectic reaction has a characteristic arrangement of the two solid phases called the **eutectic microconstituent**. In the Pb-61.9% Sn alloy, 100% of the eutectic microconstituent is formed, since all of the liquid goes through the reaction.

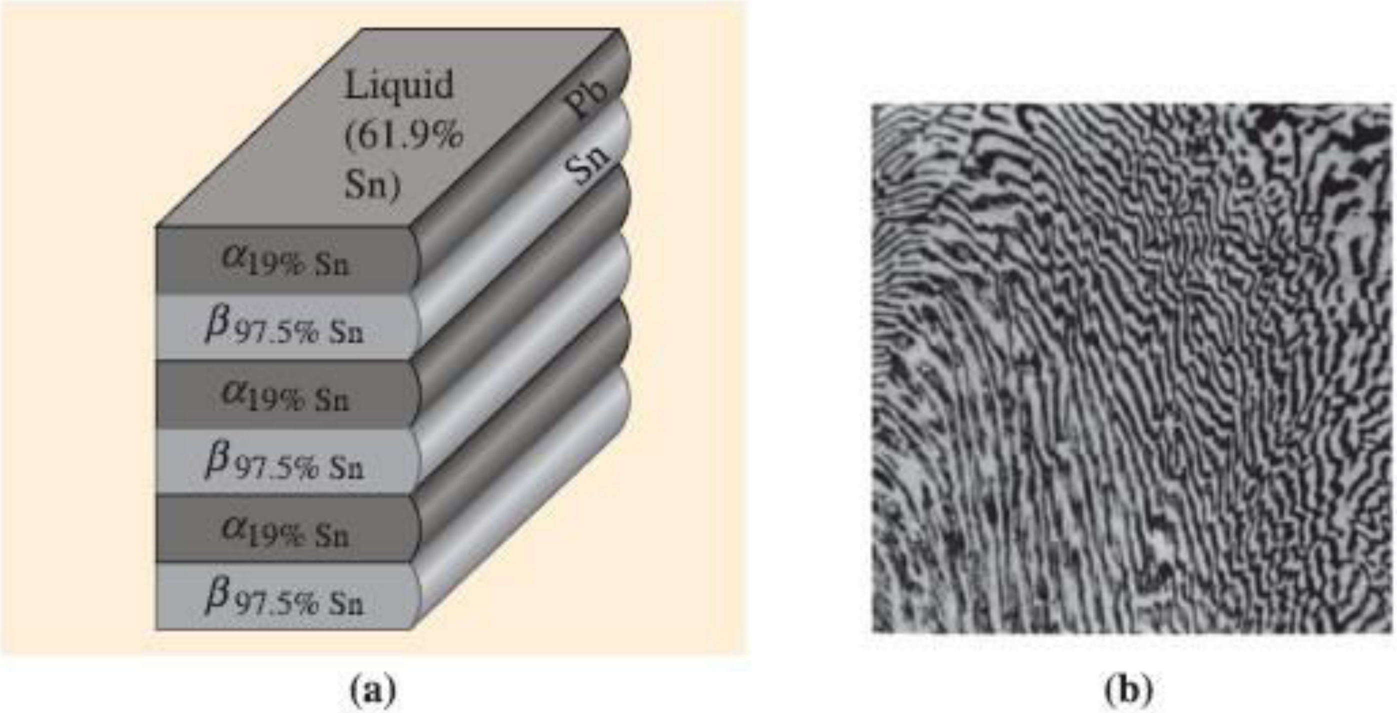


Figure 11-11 (a) Atom redistribution during lamellar growth of a lead–tin eutectic. Tin atoms from the liquid preferentially diffuse to the β plates, and lead atoms diffuse to the α plates. (b) Photomicrograph of the lead-tin eutectic microconstituent (× 400). *(Reprinted Courtesy of Don Askeland.)*

Hypoeutectic and Hypereutectic Alloys

A hypoeutectic alloy is an alloy with a composition between that of the left-hand end of the tie line defining the eutectic reaction and the eutectic composition. As a hypoeutectic alloy containing between 19% and 61.9% Sn cools, the liquid begins to solidify at the liquidus temperature, producing solid α; however, solidification is completed by going through the eutectic reaction (Figure 11-13). This solidification sequence occurs for compositions in which the vertical line corresponding to the original composition of the alloy crosses both the liquidus and the eutectic.

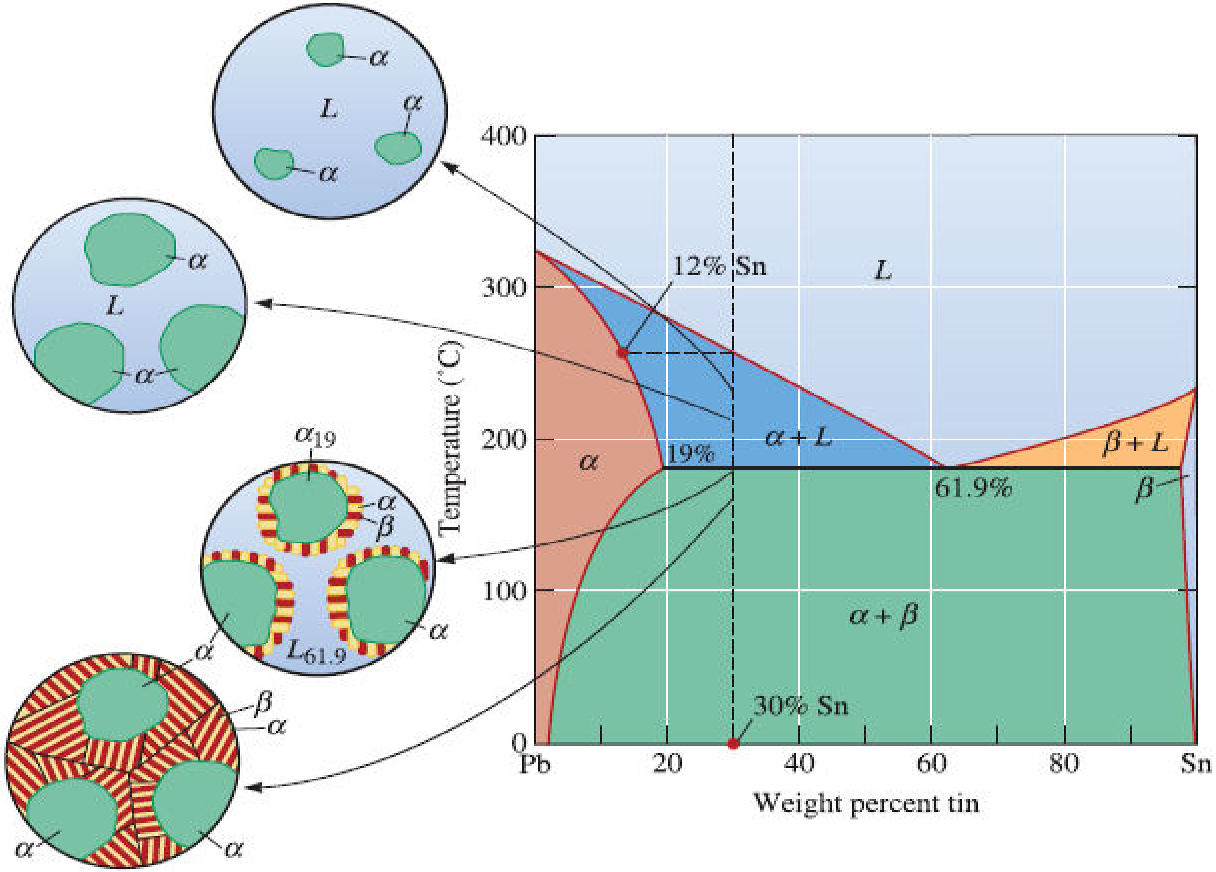


Figure 11-13 The solidification and microstructure of a hypoeutectic alloy (Pb-30% Sn).

An alloy composition between that of the right-hand end of the tie line defining the eutectic reaction and the eutectic composition is known as a **hypereutectic alloy**. In the Pb-Sn system, any composition between 61.9% and 97.5% Sn is hypereutectic.

Let's consider a hypoeutectic alloy containing Pb-30% Sn and follow the changes in structure during solidification (Figure 11-13). On reaching the liquidus temperature of 260°C, solid α containing about 12% Sn nucleates. The solid α grows until the alloy cools to just above the eutectic temperature. At 184°C, we draw a tie line and find that the solid α contains 19% Sn and the remaining liquid contains 61.9% Sn. We note that at 184°C, the liquid contains the eutectic composition! When the alloy is cooled below 183°C, all of the remaining liquid goes through the eutectic reaction and transforms to a lamellar mixture of α and β.

the eutectic microconstituent surrounds the solid α that formed between the liquidus and eutectic temperatures. The eutectic microconstituent is continuous

We call the solid α phase that forms when the liquid cools from the liquidus to the eutectic the **primary** or **proeutectic microconstituent**. This solid α does not take part in the eutectic reaction. Thus, the morphology and appearance of this α phase is distinct from that of the α phase that appears in the eutectic microconstituent. Often we find that the amounts and compositions of the microconstituents are of more use to us than the amounts and compositions of the phases.

The cooling curve for a hypoeutectic alloy is a composite of those for solid-solution alloys and "straight" eutectic alloys (Figure 11-15). A change in slope occurs at the liquidus as primary α begins to form. Evolution of the latent heat of fusion slows the cooling rate as the solid α grows. When the alloy cools to the eutectic temperature, a thermal arrest is produced as the eutectic reaction proceeds at 183°C. The solidification sequence is similar in a hypereutectic alloy, giving the microstructure shown in Figure 11-14(b).

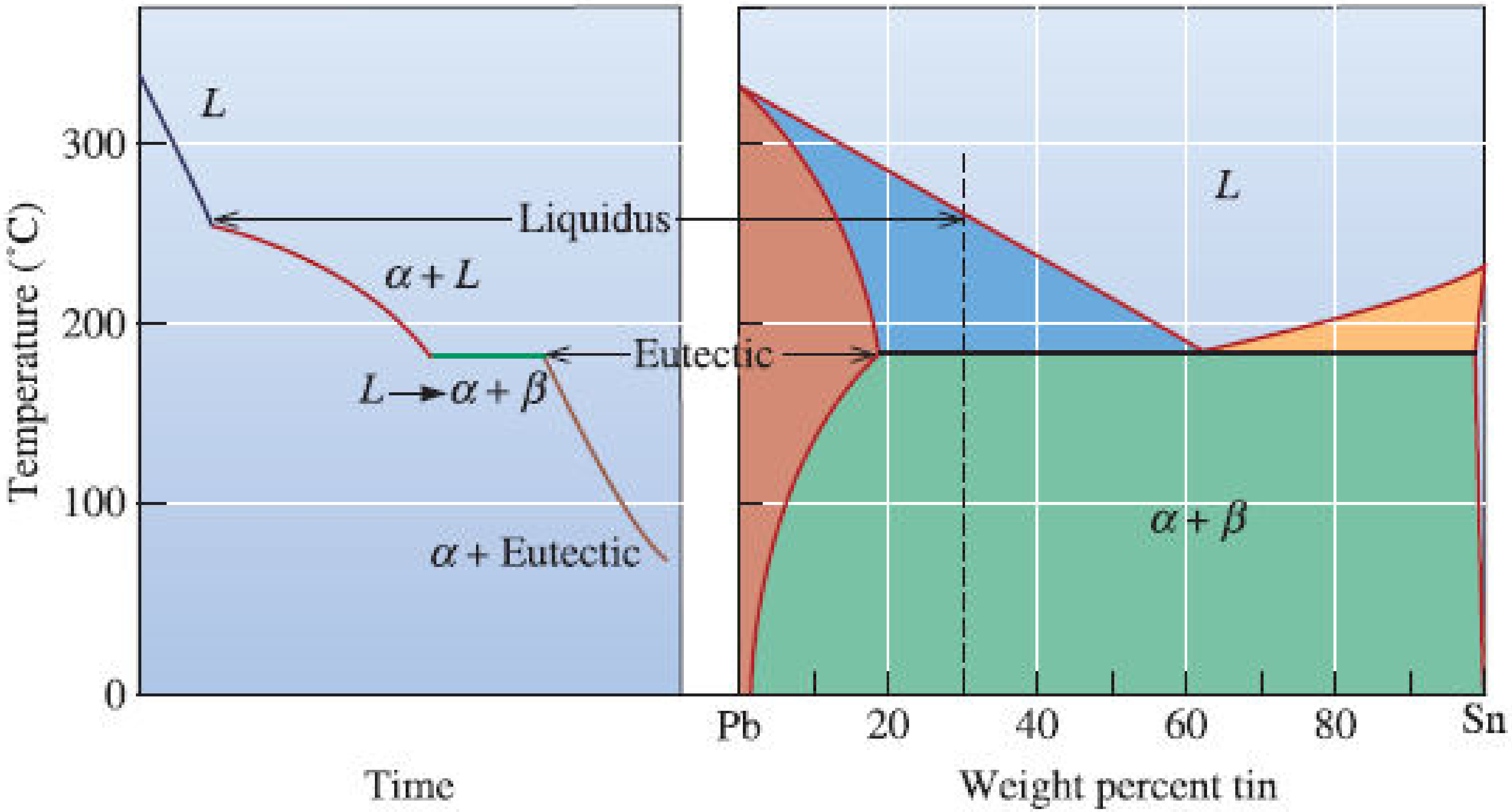


Figure 11-15 The cooling curve for a hypoeutectic Pb-30% Sn alloy.

Thank you for your attentions