

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

It is critical to note that binary phase diagrams typically do not incorporate different colors to indicate different phases. We have chosen to do so, however, for the Pb-Sn phase diagrams in this chapter to help you visualize the various microstructures that form during solidification. The single-phase regions of the Pb-Sn diagrams are colored, while the two-phase regions are white. All other phase diagrams are presented as a single color so that you are also comfortable with the more conventional presentation.

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.

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 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 (Figure 11-6). As any alloy containing between 2% and 19% Sn cools below 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. These types of compositions, which form a single solid phase at high temperatures and two solid phases at lower temperatures, are suitable for age or precipitate hardening. In Chapter 12, we will learn how nonequilibrium processes are needed to make precipitation hardened alloys. A vertical line on a phase diagram (e.g., Figure 11-8) that shows a specific composition is known as an isopleth. Determination of reactions that occur upon the cooling of a particular composition is known as an isoplethal study. The following example illustrates how certain calculations related to the composition of phases and their relative concentrations can be performed.

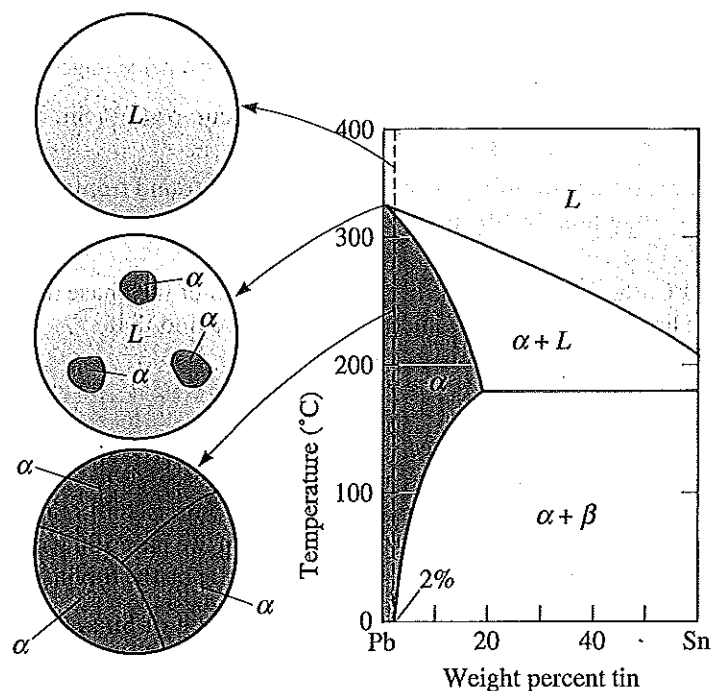


Figure 11-7 Solidification and microstructure of a Pb-2% Sn alloy. The alloy is a single-phase solid solution.

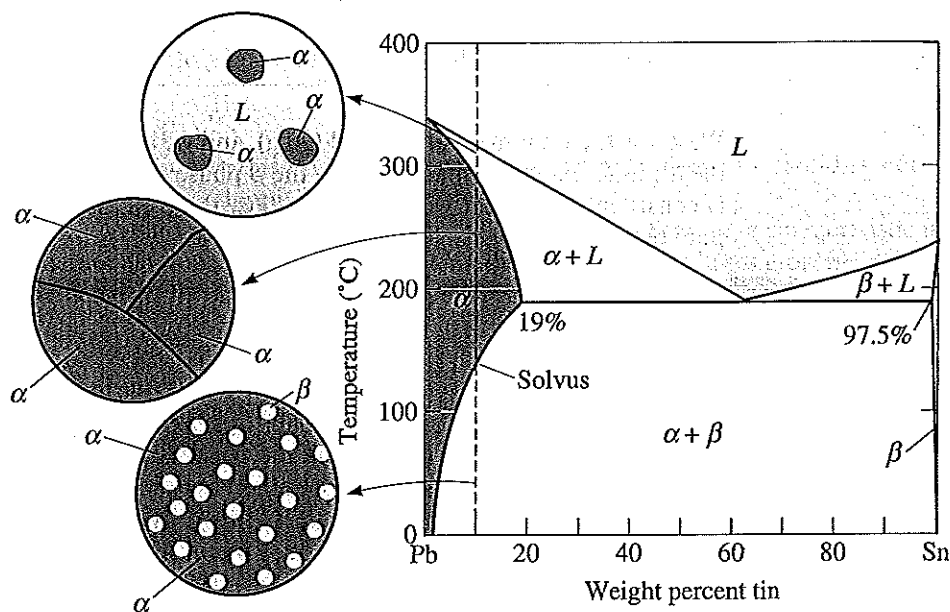


Figure 11-8 Solidification, precipitation, and microstructure of a Pb-10% Sn alloy. Some dispersion strengthening occurs as the β solid precipitates.

Example 11-2 Phases in the Lead-Tin Phase Diagram

Determine (a) the solubility of tin in solid lead at 100°C and (b) the maximum solubility of lead in solid tin. Also if a Pb-10% Sn alloy is cooled to 0°C, determine (c) the amount of β that forms, (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 %.

- The 100°C temperature intersects the solvus curve at 6% Sn. The solubility of tin in lead at 100°C, therefore, is 6%.
- The maximum solubility of lead in tin, 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.
- 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; thus, 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.

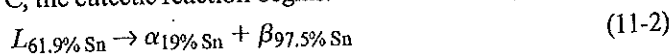
- Note that 100 g of the alloy will consist of 10 g of Sn and 90 g of Pb. The Pb and Sn are distributed in two phases (i.e., α and β). The mass of Sn in the α phase = $(2\% \text{ Sn})(91.8 \text{ g of } \alpha \text{ phase}) = (0.02)(91.8 \text{ g}) = 1.836 \text{ g}$. Since tin appears in both the α and β phases, the mass of Sn in the β phase will be $= (10 - 1.836) \text{ g} = 8.164 \text{ g}$. Note that in this case, the β phase at 0°C is nearly pure Sn.

- 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 = $91.8 \text{ g} - 1.836 \text{ g} = 89.964 \text{ g}$. We could have also calculated this as

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

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 = $90 - 89.964 = 0.036 \text{ g}$. 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 the 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:



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 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

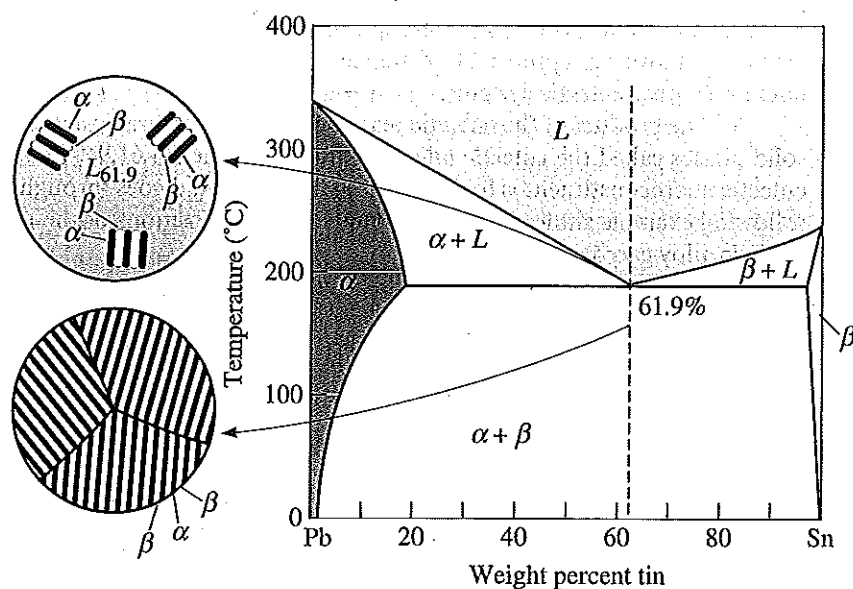


Figure 11-9 Solidification and microstructure of the eutectic alloy Pb-61.9% Sn.

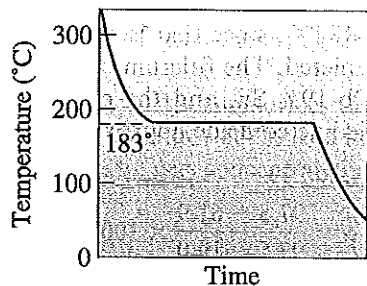
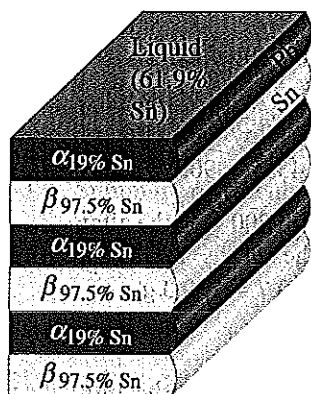


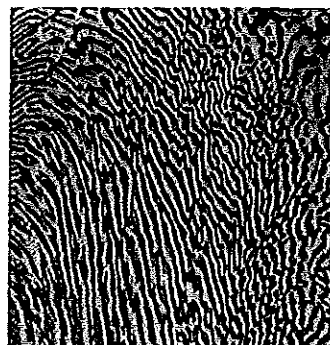
Figure 11-10 The cooling curve for a eutectic alloy is a simple thermal arrest, since eutectics freeze or melt at a single temperature.

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



(a)



(b)

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 ($\times 400$). (Reprinted Courtesy of Don Askeland)

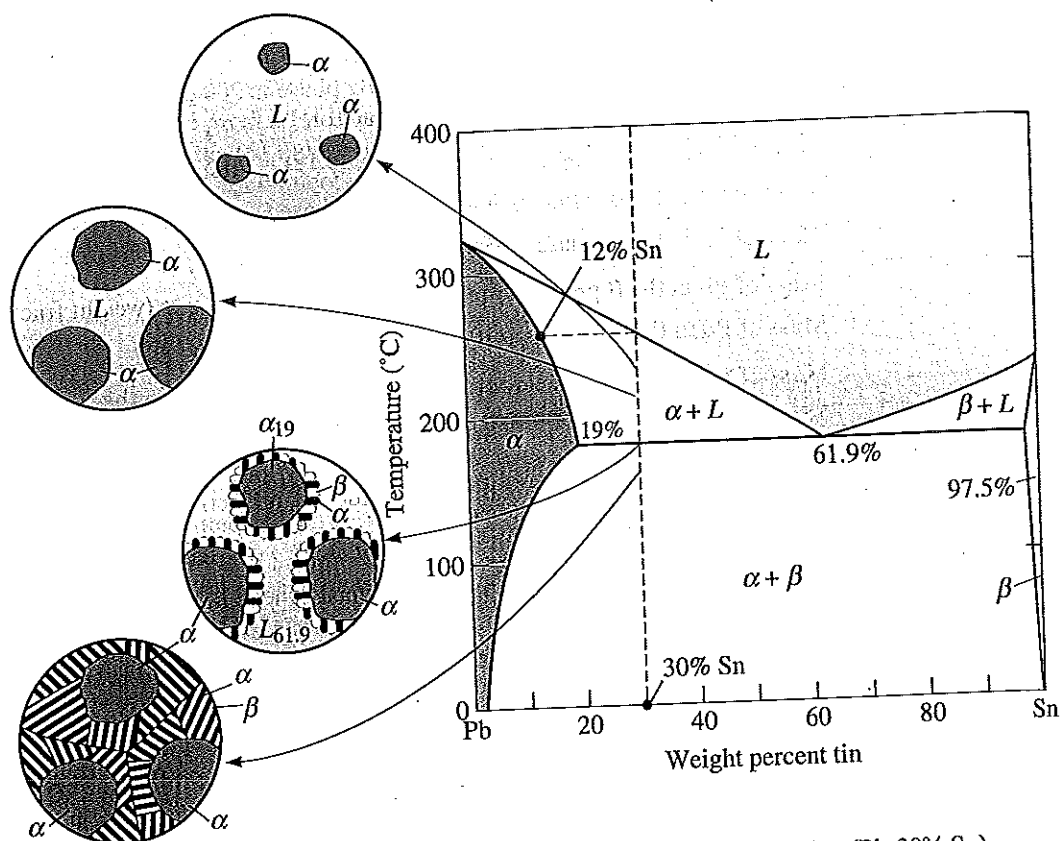


Figure 11-13 The solidification and microstructure of a hypoeutectic alloy (Pb-30% Sn).

the vertical line corresponding to the original composition of the alloy crosses both the liquidus and the eutectic.

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 microstructure shown in Figure 11-14(a) results. Notice that the eutectic microconstituent surrounds the solid α that formed between the liquidus and eutectic temperatures. The eutectic microconstituent is continuous and the primary phase is dispersed between the colonies of the eutectic microconstituent.

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.

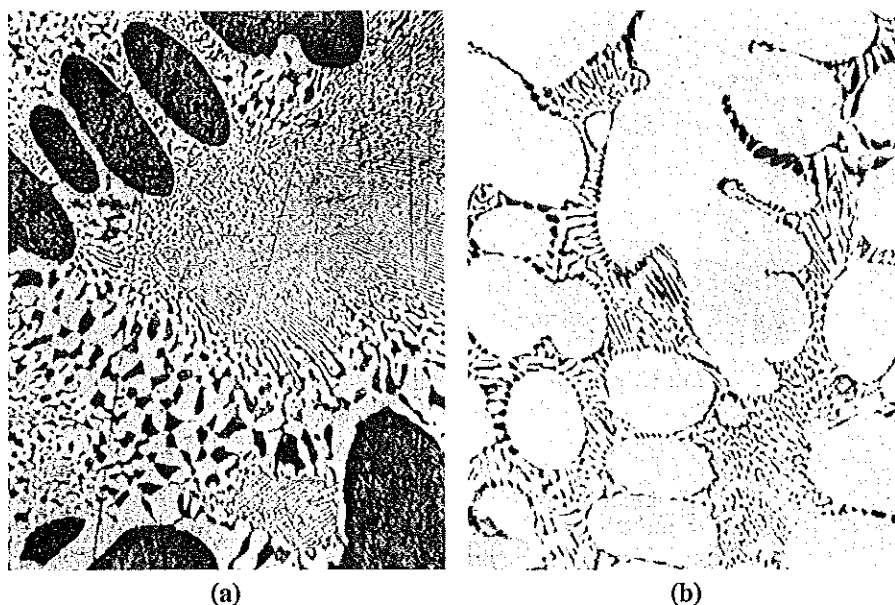


Figure 11-14 (a) A hypoeutectic lead-tin alloy. (b) A hypereutectic lead-tin alloy. The dark constituent is the lead-rich solid α ; the light constituent is the tin-rich solid β ; and the fine plate structure is the eutectic ($\times 400$). (Reprinted Courtesy of Don Askeland)

Example 11-4

Determination of Phases and Amounts in a Pb-30% Sn Hypoeutectic Alloy

For a Pb-30% Sn alloy, determine the phases present, their amounts, and their compositions at 300°C, 200°C, 184°C, 182°C, and 0°C.

SOLUTION

Temperature (°C)	Phases	Compositions	Amounts
300	L	L : 30% Sn	$L = 100\%$
200	$\alpha + L$	L : 55% Sn	$L = \frac{30 - 18}{55 - 18} \times 100 = 32\%$
		α : 18% Sn	$\alpha = \frac{55 - 30}{55 - 18} \times 100 = 68\%$
184	$\alpha + L$	L : 61.9% Sn	$L = \frac{30 - 19}{61.9 - 19} \times 100 = 26\%$
		α : 19% Sn	$\alpha = \frac{61.9 - 30}{61.9 - 19} \times 100 = 74\%$
182	$\alpha + \beta$	α : 19% Sn	$\alpha = \frac{97.5 - 30}{97.5 - 19} \times 100 = 86\%$
		β : 97.5% Sn	$\beta = \frac{30 - 19}{97.5 - 19} \times 100 = 14\%$
0	$\alpha + \beta$	α : 2% Sn	$\alpha = \frac{100 - 30}{100 - 2} \times 100 = 71\%$
		β : 100% Sn	$\beta = \frac{30 - 2}{100 - 2} \times 100 = 29\%$

Note that in these calculations, the fractions have been rounded off to the nearest %. This can pose problems if we were to calculate masses of different phases, in that you