

Pre-Course Reading for ESI's Solidification Course

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The primary goal of ESI's Solidification Course is to relate material properties and solidification processing conditions to the development of microstructures and defects. The purpose of this short reading is to familiarize participants with a few basic concepts and nomenclature that will be used during the course.

Definitions

- **Casting** is the industrial process whereby liquid metal is transformed to solid, by filling either a complex-shaped mould (near-net-shape casting), or a simpler-shaped mould (cylindrical or rectangular) to create billets and ingots for further downstream processing.
- **Solidification** is the physical process by which a material changes phase from liquid to solid. Pure materials and compounds, such as water (0°C), aluminum (661°C) or iron (1538°C) solidify at a unique temperature. Mixtures containing more than one component, called **alloys**, solidify over a range of temperatures. Two-component mixtures are called **binary alloys**, and some familiar examples include: water-salt, copper-zinc (brass), and iron-carbon (steels and cast irons). The secondary components (e.g. salt, zinc, carbon) are referred to as the **solute**. We will also discuss three-component **ternary** alloys.
- Alloys begin to solidify at their **liquidus temperature** T_{liq} , and under equilibrium conditions will complete solidification at their **solidus temperature** T_{sol} . When the alloy is at an intermediate temperature $T_{sol} < T < T_{liq}$, it is said to be in the **mushy zone**. This term is used to describe the fact that in this range, the alloy is partially liquid and partially solid. The **solid fraction** f_s increases from 0 at T_{liq} to 1 at T_{sol} . In general, the sum of the solid fraction f_s and the liquid fraction f_ℓ is one, unless a gas phase forms (this will be described in the unit about porosity). The evolution of f_s with temperature T is *never* linear, and this will be discussed at length during the course.

Equilibrium phase diagrams

One of the most important tools for understanding the development of microstructure in alloys is the equilibrium phase diagram (we will usually just say "phase diagram"). In this section, we introduce the nomenclature that will be used throughout the course, in the context of a portion of an idealized binary alloy eutectic phase diagram, shown in Figure 1.

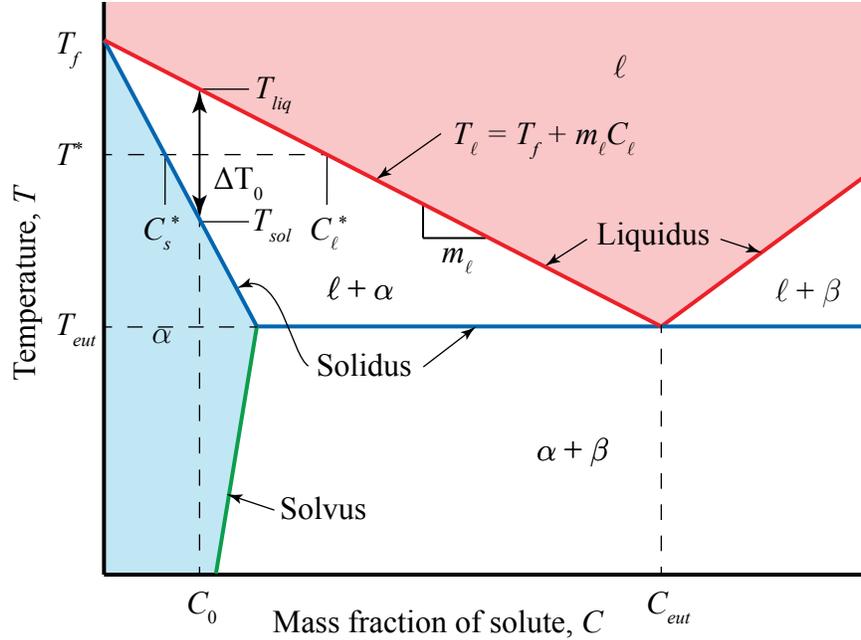


Figure 1: A portion of an idealized binary alloy eutectic equilibrium phase diagram

In a phase diagram, there are several different possibilities for describing the amount of each component present in the alloy (mass fraction, atomic fraction, volume fraction). There are circumstances where one of these is more convenient than the others. For example, when mixing an alloy in the lab, mass fraction is most convenient, whereas when one looks at a microstructure in the microscope, what one sees is volume fraction. For the purposes of this tutorial, we will use mass fraction, for which we use the symbol C .

Referring now to Figure 1, the phase diagram shows which phases are present at a given temperature and composition for this binary alloy system. Above the **liquidus temperature**, indicated in red in the figure, the only phase present is the liquid, denoted by ℓ . Below the **solidus temperature**, indicated in blue, only solid phases are present. The **solid solution** of solute in the primary phase is designated α , and the line corresponding to the maximum solubility of the solute element in this phase is called the **solvus**, indicated in green. To the right of this line, we have a mixture of two solid phases $\alpha + \beta$.

In this tutorial, we will consider just one alloy, which is indicated on the phase diagram as the composition C_0 . Let us consider the evolution of phases for this alloy, starting at a temperature in the fully liquid region, and then gradually cooling. Under equilibrium conditions (we will discuss non-equilibrium conditions extensively during the course), this alloy will begin to freeze at its liquidus temperature T_{liq} , and finish solidification when it reaches its solidus temperature T_{sol} . The **freezing range** for this alloy is defined as $\Delta T_0 = T_{liq} - T_{sol}$. At an intermediate temperature $T_{sol} < T^* < T_{liq}$ the composition of the solid and liquid phases will be C_s^* and C_l^* (see Figure 1). Under equilibrium conditions, the solid fraction f_s can be computed using the **inverse lever rule**:

$$f_s = \frac{C_l^* - C_0}{C_l^* - C_s^*} \quad (1)$$

Note that the difference in composition between the liquid and solid phases, called **partitioning**, is one of the primary factors in the development of microstructure.

We have idealized the phase diagram by assuming the solidus and liquidus lines to be straight lines. The slope of the liquidus line is designated m_ℓ , and thus the equation of the liquidus line is given by

$$T_\ell = T_f + m_\ell C_\ell \quad (2)$$

where T_f is the equilibrium freezing temperature of the pure primary component, called solvent, while the alloying element is the solute. The **partition coefficient** of the solute element, k_0 , is defined as the ratio of the solid and liquid compositions, i.e.,

$$k_0 = \frac{C_s^*}{C_\ell^*} \quad (3)$$

When both the solidus and liquidus temperatures are straight lines, then k_0 is constant. It should be emphasized that none of these approximations (Eqs.1,2,3) are exactly true for almost all real alloy systems because the solidus and liquidus lines are never straight lines. This will be discussed during the course, and is also addressed to some extent in the next section.

Example: The Pb-Sn alloy system

The Pb-Sn binary-alloy eutectic phase diagram is shown in Figure 2, where the tin and lead are completely soluble in each other in the liquid state, but are not very soluble in the solid state. Only a little lead is soluble in the solid tin (up to ≈ 2.5 mass%Pb), while only a moderate amount of tin is soluble in solid lead (up to ≈ 19.2 mass%Sn). Let us identify some important points on the phase diagram.

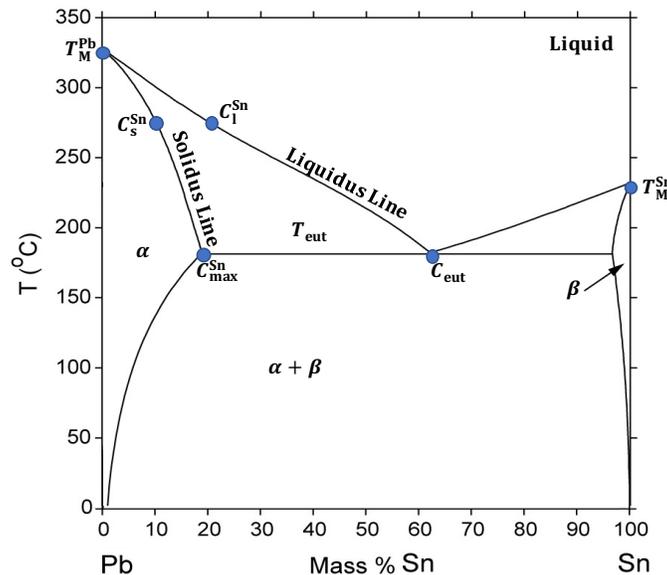


Figure 2: Pb-Sn binary equilibrium phase diagram

- T_f^{Sn} and T_f^{Pb} are the melting temperatures of pure Sn and Pb.
- C_{eut} represents the eutectic composition. This is the composition on the phase diagram where an alloy of Pb and Sn solidify at a unique temperature to form a two-phase solid. At any composition extending from the maximum solubility of Sn in (Pb) and of Pb in (Sn), solidification starts at T_{liq} and finishes at the eutectic temperature T_{eut} .
- T_{eut} represents the eutectic temperature. For any composition extending from the maximum solubility of Sn in (Pb) and of Pb in (Sn), the horizontal line at $T = T_{eut}$ is an invariant: the three phases liquid, solid (Pb) and solid (Sn) coexist.
- m_l represents the slope of the liquidus line, $m_l \approx \frac{T_{eut} - T_f^{\text{Pb}}}{C_{eut}}$, with units $^{\circ}\text{C} / \text{wt.}\%$. The \approx symbol has been used in the equation because the liquidus line is not straight.
- m_s represents the slope of the solidus line, $m_s \approx \frac{T_{eut} - T_f^{\text{Pb}}}{C_{max}^{\text{Sn}}}$, with units $^{\circ}\text{C} / \text{wt.}\%$. The \approx symbol has been used in the equation because the solidus line is not straight.
- The symbol α identifies a solid phase that primarily consists of Pb. It is usually written as (Pb) to denote that this is the crystal structure of pure Pb with some Sn randomly distributed in the solid solution. The symbol β identifies a solid phase that primarily consists of Sn and is also noted as (Sn). The large region in the middle of the phase diagram shown by $\alpha + \beta$ identifies the two-phase region where both the α or (Pb) and β or (Sn) phases are present in the material.

Test yourself!

1. Identify the melting temperature of Pb
2. Identify the melting temperature of Sn
3. Identify the eutectic composition and temperature
4. Calculate the slope of the liquidus line
5. Calculate the slope of the solidus line
6. Calculate the partition coefficient at 275°C
7. Determine the temperature interval over which solidification occurs for an alloy having 90wt.%Pb-10wt.%Sn
8. Determine the temperature interval over which solidification occurs for an alloy having 50wt.%Pb-50wt.%Sn
9. At 100wt.%C, which phases are present?
 - (a) At a composition 95wt.%Pb-5wt.%Sn
 - (b) At a composition 50wt.%Pb-50wt.%Sn
 - (c) At a composition 5wt.%Pb-99wt.%Sn
 - (d) At a composition 1wt.%Pb-99wt.%Sn
10. How does the liquidus line change with temperature?
11. How does the solidus line change with temperature?
12. What is special about the eutectic compositions?

Microstructure

This section introduces the important concepts and terminology that will be used when we discuss microstructures.

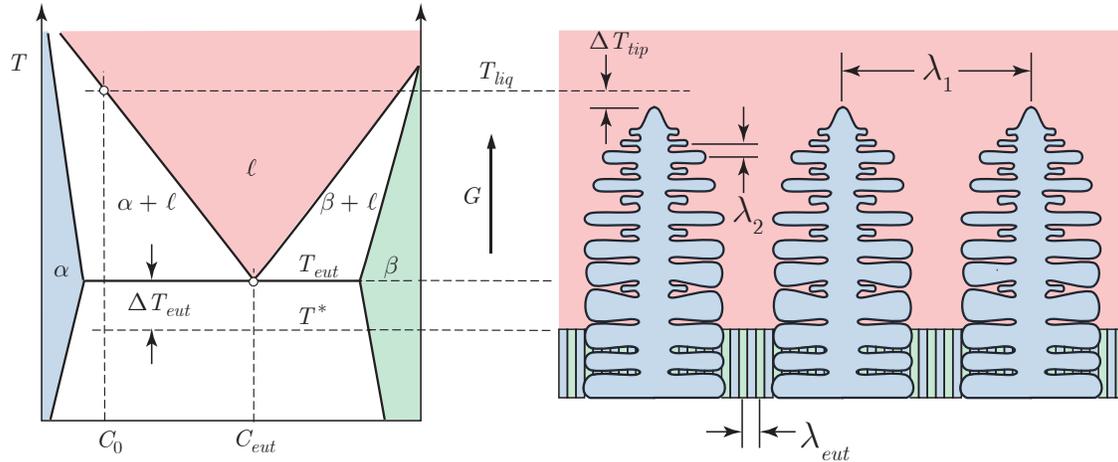


Figure 3: (Left) Eutectic equilibrium phase diagram, indicating the alloy composition C_0 discussed in this section. (Right) Schematic microstructure of the alloy C_0 forming during solidification in a fixed temperature gradient. The liquid is shown in pink, the primary dendrites are blue, and the lamellar eutectic consists of alternating layers of the primary phase (blue) and the secondary phase (green).

Figure 3 shows an idealized binary eutectic phase diagram on the left, and a schematic microstructure for alloy C_0 during solidification in a fixed temperature gradient G . The microstructure consists of **primary dendrites** of phase α , and a **lamellar eutectic** consisting of alternating layers of α and β phases. Solidification of the primary dendrites begins at a temperature slightly below the equilibrium liquidus T_{liq} , and the solidification of the eutectic begins at a temperature slightly below the equilibrium eutectic temperature T_{eut} . The respective **undercoolings** for the two microstructural features, ΔT_{tip} and ΔT_{eut} , are relatively small (typically 0.1°C or less), but they are nevertheless very important to the understanding of the origin of length scales in the microstructure.

Figure 3 also indicates some of the parameters that are used to describe the length scales present in the microstructure. The primary dendrites form in a periodic array, characterized by the **primary dendrite arm spacing (PDAS)** λ_1 . Each primary dendrite also displays **secondary dendrite** arms, whose **secondary dendrite arm spacing (SDAS)** is denoted by λ_2 . The eutectic lamellae also form a periodic array, with **lamellar spacing** λ_{eut} . This structure forms also slightly below the eutectic temperature, for reasons that will be detailed during the course.