

Solidification

Solidification is a phase transformation in which the liquid turns into a solid when temperature is lowered below its freezing point. Many characteristics of the casting such as macro and microstructure, internal defects and solute distribution are defined during solidification, therefore very important to control solidification to obtain high quality products in practical casting processes.

various stages in the solidification of a polycrystalline specimen are represented schematically in Figure 1. Initially, small crystals or nuclei form at various positions. These have random crystallographic orientations, as indicated by the square grids. The small grains grow by the successive addition from the surrounding liquid of atoms to the structure of each

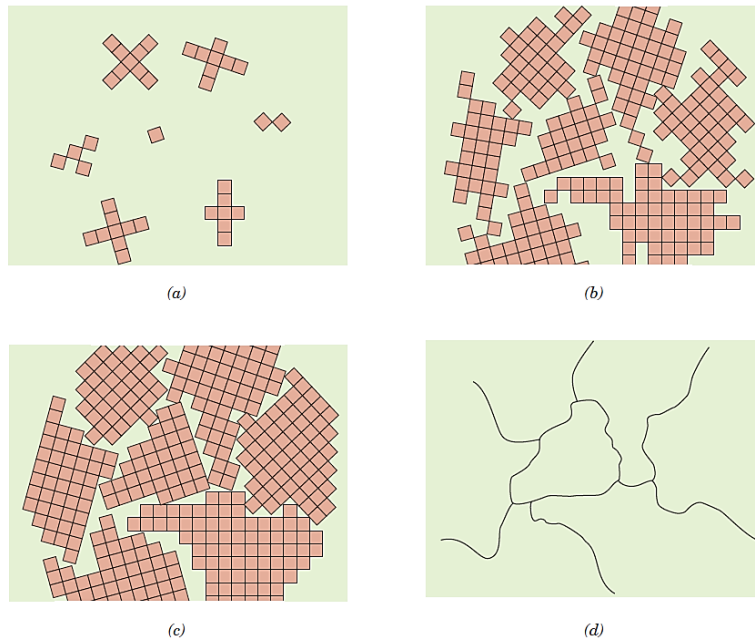


Figure 1 Schematic diagrams of the various stages in the solidification of a polycrystalline material; the square grids depict unit cells

During solidification, the atomic arrangement changes from at best a short-range order to a longer-range order, or crystal structure. Solidification requires two steps:

- 1- Nucleation
- 2- Growth

Nucleation

Nucleation occurs when a small piece of solid forms from the liquid. The solid must achieve a certain minimum critical size to be stable.

Simply, let us first consider the solidification of a pure material, and assumed that each nucleus is spherical in geometry and has a radius r (figure 2). The critical free energy change and the critical nucleus radius (r^*) are presented in figure 3.

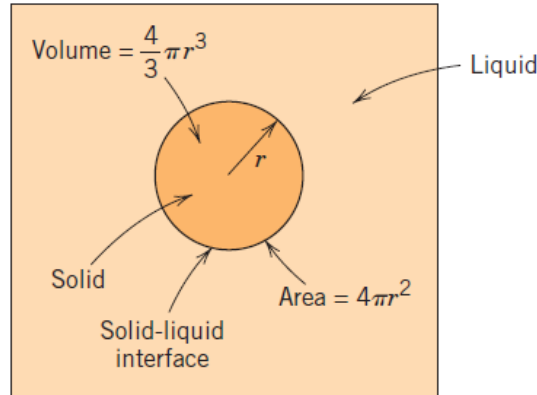
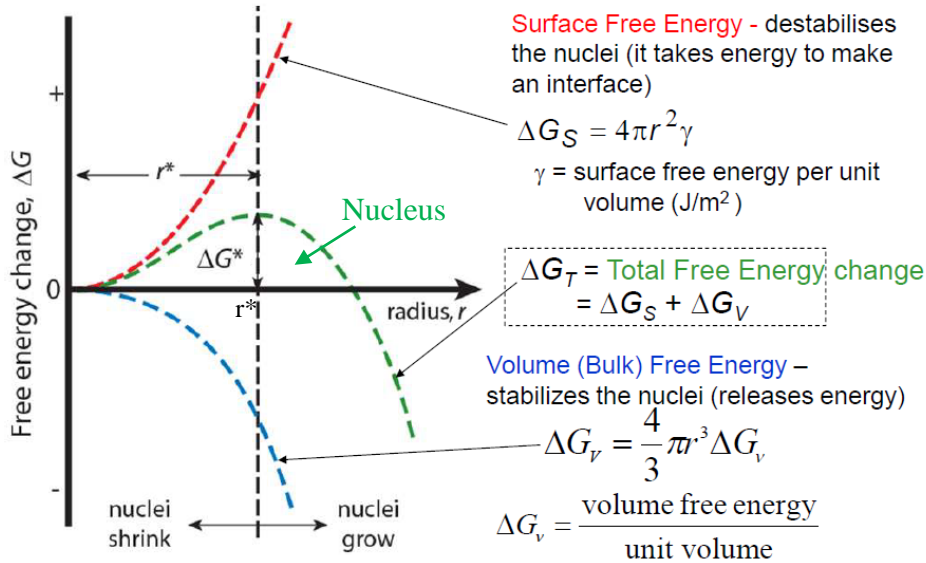


Figure 2 Schematic diagram showing the nucleation of a spherical solid particle in a liquid

Homogeneous Nucleation & Energy Effects 2



$r^* = \text{critical nucleus: for } r < r^* \text{ nuclei shrink; for } r > r^* \text{ nuclei grow (to reduce energy)}$

Figure 3 Schematic plot of free energy versus embryo/nucleus radius, on which is shown the critical free energy change and the critical nucleus radius (r^*).

Nucleation Types

1- Homogeneous nucleation

- nuclei forms in the bulk of liquid metal
- requires considerable super-cooling (typically 80-300°C)

2- Heterogeneous nucleation

- much easier since stable “nucleating surface” is already present (mold, wall, impurities in liquid phase)
- only very slight supercooling (0.1-10°C)

Table 3.1: Comparison of Homogeneous and Heterogeneous nucleation

Homogeneous nucleation	Heterogeneous nucleation
Occurs in pure metals	Occurs in alloys
Nucleation is by deposition of atoms from its own melt	Nucleation is by the influence of foreign particles
Requires some amount of undercooling for nucleation.	Undercooling is less as compared to homogeneous nucleation.
Starts below the equilibrium freezing temperature	Starts comparatively at much higher temperature

Growth

Growth of the solid occurs as atoms from the liquid are attached to the tiny solid until no liquid remains, figure 4 presents the growth types

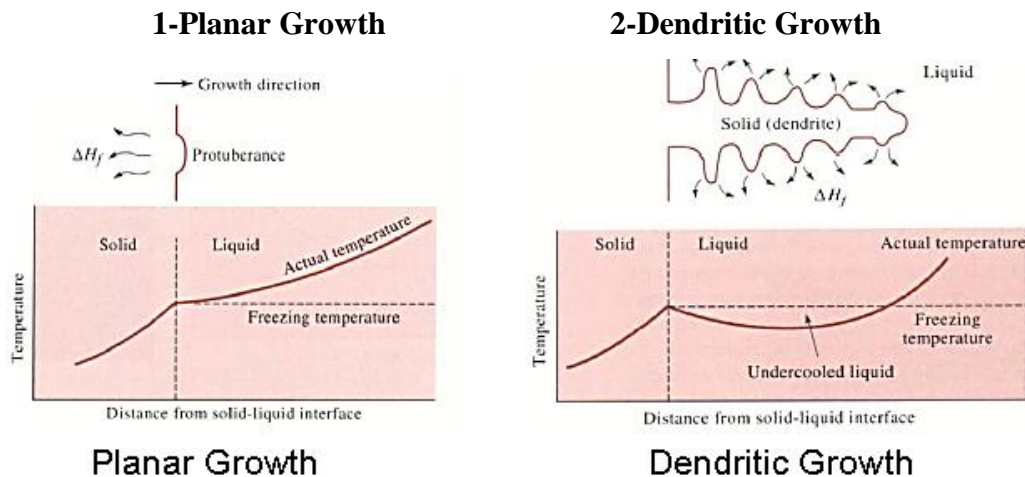
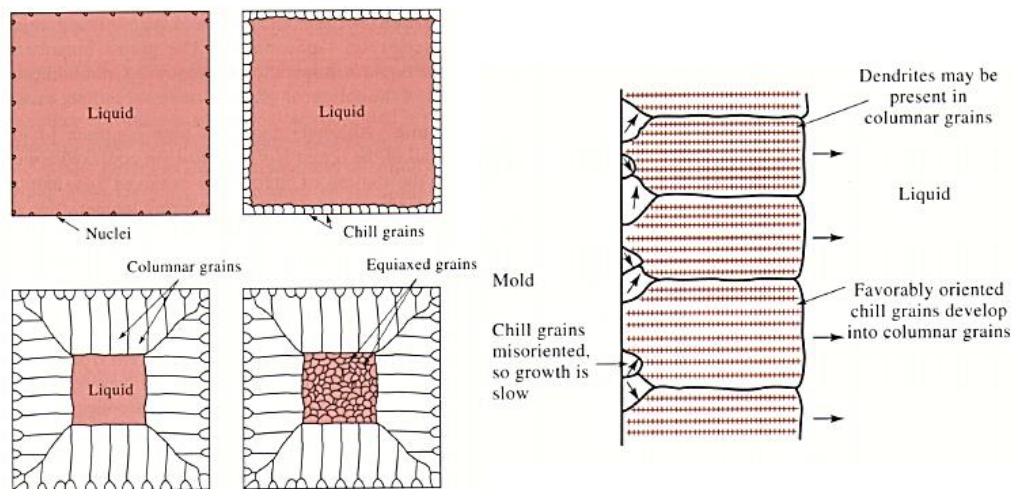


Figure 4 growth types

In pure metals, the nature of the growth of the solid during solidification depends on how heat is removed from the solid –liquid system. Two types of heat must be removed:

- **The specific heat of the liquid** *is the heat required to change the temperature of a unit weight of the material by one degree.* The specific heat must be removed first, either by radiation into the surrounding atmosphere or by conduction into the surrounding mold, until the liquid temperature decreases to the freezing temperature.
- **The latent heat of fusion** *is the amount of energy required to change a unit mass of liquid into solid.* Pure metal and eutectic alloys have a sharp distinction between the solid and liquid phases, i.e. the phase changes at constant temperature. While in a conventional alloy the phase change take place over a temperature range.

Casting or Ingot Structure



Solidification Time

Time required to completely solidify for a simple casting (t_s) :

$$t_s = B \left(\frac{V}{A} \right)^n$$

Chvorinov's rule

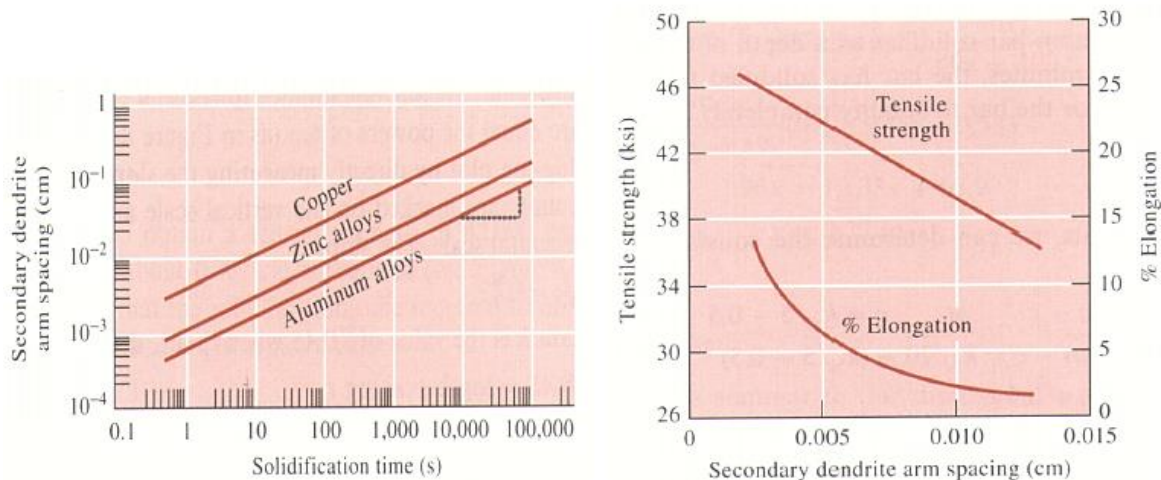
B = mold constant, depending on the properties and initial temperature of both the metal and the mold

V = volume of the casting

A = surface area of the casting in contact with the mold

n = constant (usually about 2)

Effect on Structure and Properties (con.)



Aluminum casting alloy

Solidification of Pure Metal (cooling curve)

Pure metals melt and freeze (or solidify) at the same temperature. Under equilibrium conditions, the metal is completely solid below this temperature. Cooling curves can be drawn to show that the metal cools quite rapidly to the freezing or solidification point, where the temperature remain constant while the metal losses its heat of fusion. Further cooling occurs only after the pure metal is completely solidified. Figure (5) shows a cooling curve of a pure metal.

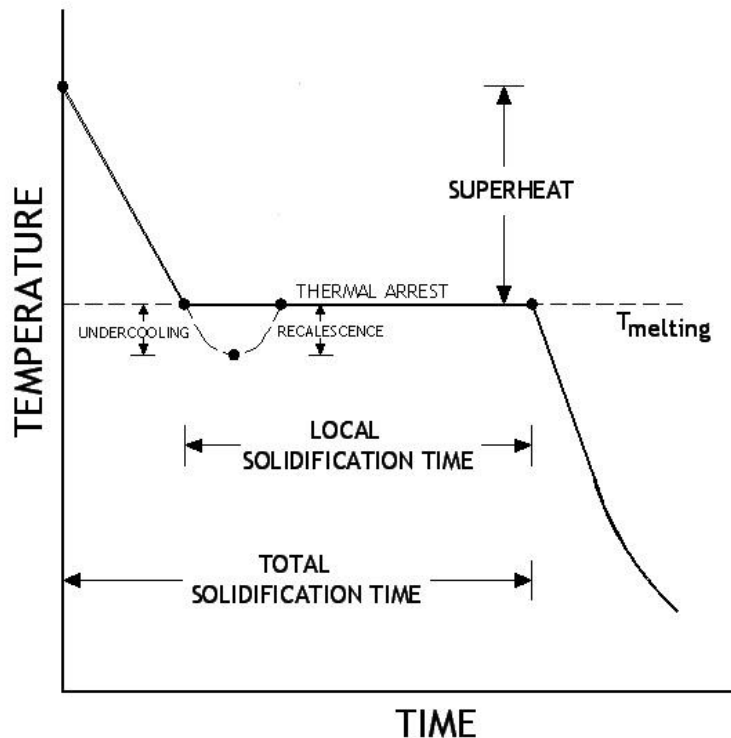


Figure (5) Typical of cooling curve for pure metals.

Solidification of Binary Alloys (cooling curve)

In contrast to a pure substance which changes phase isothermally, alloys solidify over a temperature range as shown in figure (6), in which the solid and liquid co-exist in thermodynamic equilibrium.

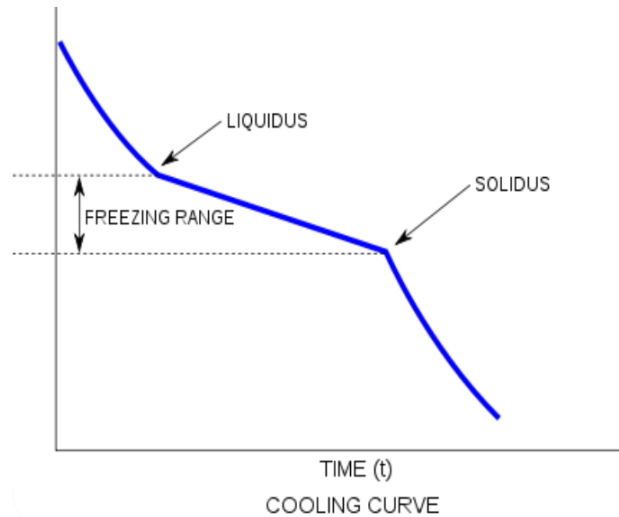
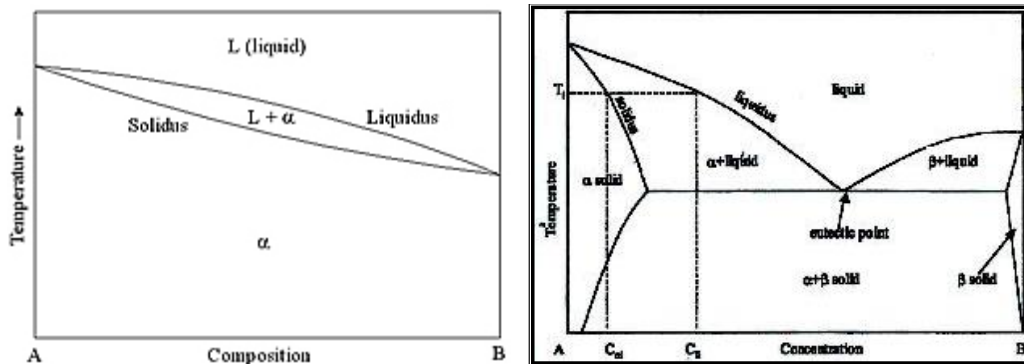


Figure (6) Typical of cooling curve for alloys.

Figure (7) shows a typical equilibrium phase diagram of a fictitious eutectic-forming binary system A-B. At temperature above the liquidus lines, a single liquid phase exists as a solution of constituents A and B.



It is important, in solidification modeling, to take into account these

Figure (7) Typical phase diagram for a binary alloy system A-B

Microscopic interfacial features, because they ultimately determine the microstructure, which strongly affects the mechanical properties of the material. There are essentially two basic growth morphologies that can exist during alloy solidification. These are dendritic and eutectic morphology.

Figure (8)

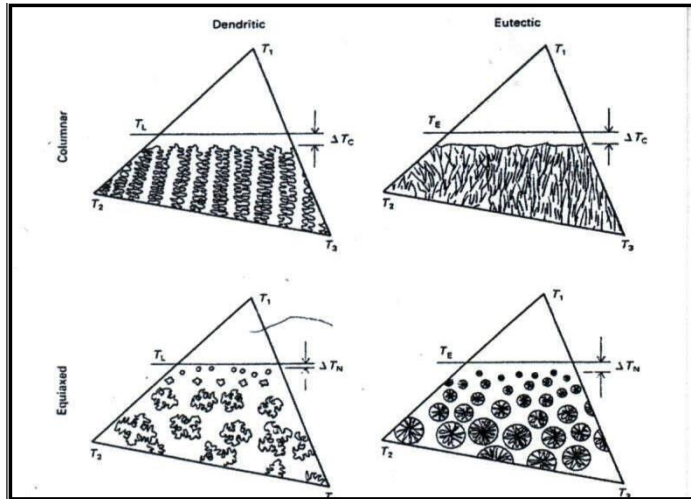


Figure (8) Schematic of columnar and equiaxed growth of dendritic and eutectic alloys in a thermal gradient G

- Dendrites grow with a very large specific surface area and irregular solid-liquid interface. In the macroscopic sense, such growth is virtually irresolvable. Hence, the mushy zone, which is comprised of solid dendrites and interdendritic liquid, is treated as a porous solid structure which is saturated with interdendritic liquid.

- Eutectic growth is much simpler than that of dendrites because the eutectic grain maintains a simple geometric interface shape. Generally, both morphologies develop together.

Imperfections in Solids

1- Point defects: Point defects are localized disruptions in otherwise perfect atomic or ionic arrangements in a crystal structure.

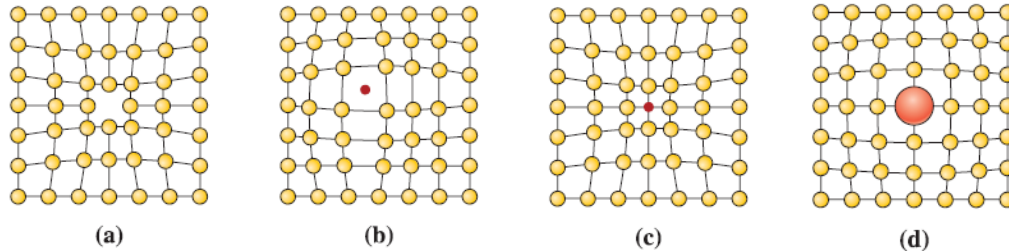


Figure 9: Point defects: (a) vacancy, (b) interstitial atom, (c) small substitutional atom, (d) large substitutional atom

- **Vacancies:** A vacancy is produced when an atom or an ion is **missing** from its normal site in the crystal structure as in Figure 9 (a).
- **Interstitial Defects:** An interstitial defect is formed when an extra atom or ion is **inserted** into the crystal structure at unoccupied position, as in Figure 9(b).
- **Substitutional Defects:** A substitutional defect is introduced when one atom or ion is **replaced** by a different type of atom or ion as in Figure 9(c) and (d).

2- Dislocation is a linear or one-dimensional defect around which some of the atoms are misaligned. Dislocations typically are introduced into a crystal during solidification of the material or when the material is deformed permanently. It can identify three types of dislocations:

- 1- The screw dislocation
- 2- The edge dislocation
- 3- The mixed dislocation.

Figure 10 present an edge dislocation

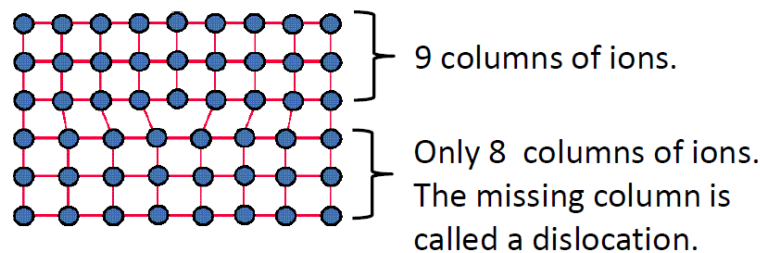


Figure 10 edge dislocation