Phase Transformations: Particle Coarsening

Today's topics:

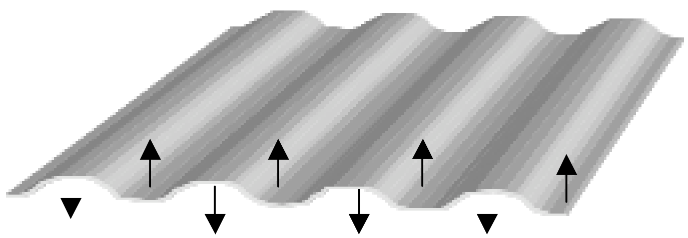
- **Capillarity as a driving force**
- **Particle coarsening in Pb–Sn solid/liquid alloys**
- **The Gibbs–Thomson effect**
- **Particle coarsening kinetics in volume diffusion-controlled regime**

Capillarity as a driving force

- **"Capillarity" refers to a variety of phenomena that result from the properties of interfaces, particularly excess surface free energy, γ, and surface tension forces.**
- **Microstructures containing interfaces are subject to constant adjustments as the material finds ways to reduce interfacial area or in the case of anisotropic interfacial free energy, adopt morphologies that maximize low-energy interfacial orientations.**

Capillarity as a driving force, cont'd

- **Single-phase interfaces such as grain boundaries can reduce their area by local migration toward their center of curvature.**

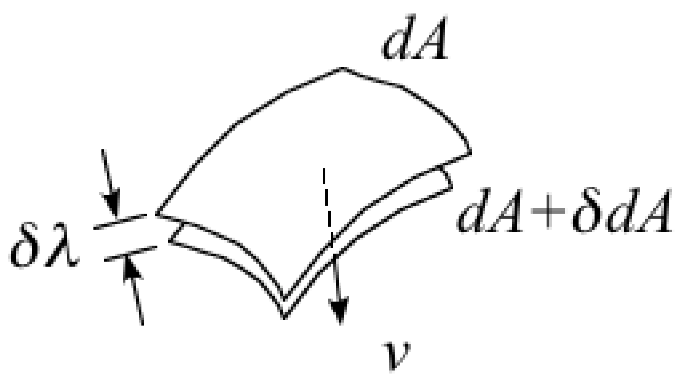


The corrugated surface will tend to smooth…

A curved grain boundary will migrate…

Capillarity as a driving force, cont'd

$$\textbf{Capillary driving force } \Delta f = \frac{\Delta \mathrm{E}}{\text{Volume swept out by interface}}$$



$$\delta dA = (\kappa_1 + \kappa_2) dA\, \delta\lambda$$

$$\Delta f = \frac{\gamma(dA + \delta dA) - \gamma(dA)}{dA\, d\lambda}$$

$$\boxed{\Delta f = \gamma(\kappa_1 + \kappa_2)}$$

The Particle Coarsening Phenomenon

- **Observations of rapidly quenched Pb–Sn solid/liquid mixtures held above eutectic temperature for various times…**

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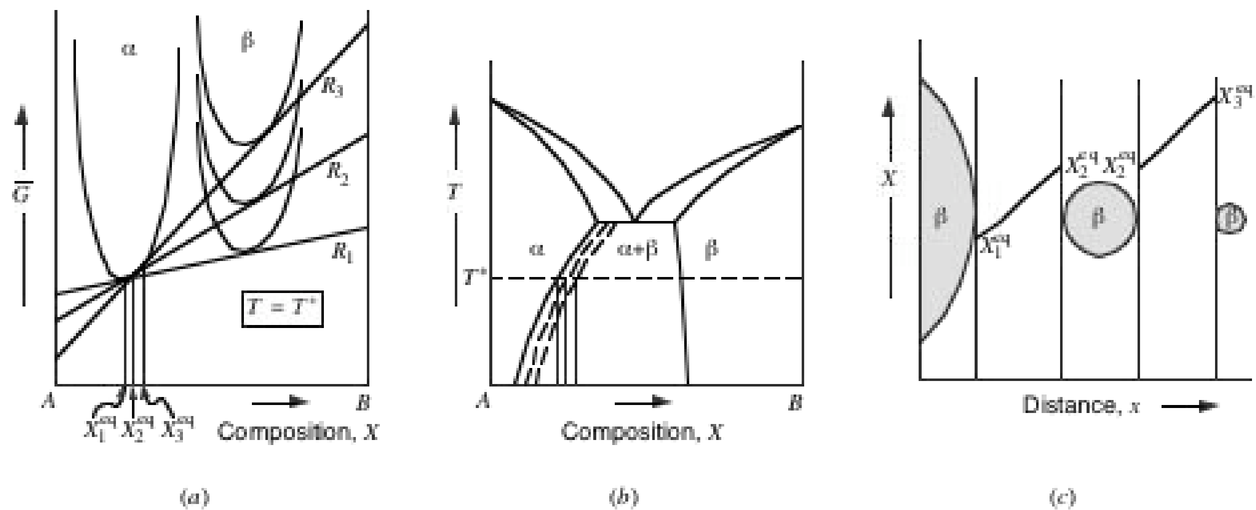
See Figure 15.6 in Balluffi, Robert W., Samuel M. Allen, and W. Craig Carter.
Kinetics of Materials. Hoboken, NJ: J. Wiley & Sons, 2005. ISBN: 0471246891.

Scaled micrographs exhibit *self similarity*.

The Gibbs–Thomson effect

- **Variation of phase equilibrium with particle radius, R:**



Resulting concentration gradients cause small particles to dissolve and larger ones to grow.

The Gibbs–Thomson effect, cont'd

- **Chemical potentials at equilibrium in a two-phase material depend on particle size and in dilute solutions give rise to this relation for the matrix solubility:**

$$c^{\text{eq}}(R) = c^{\text{eq}}(\infty)\exp\left[\frac{2\gamma\Omega}{kTR}\right] \approx c^{\text{eq}}(\infty)\left[1+\frac{2\gamma\Omega}{kTR}\right]$$

At curved particle

At flat interface

Diffusion-controlled coarsening kinetics

- **Rate law is derived from a "mean-field" model that effectively treats the diffusion of a particle of given size R in a surrounding matrix having the concentration corresponding to the mean particle size $\langle R \rangle$**

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See Figure 15.2 in Balluffi, Robert W., Samuel M. Allen, and W. Craig Carter.
Kinetics of Materials. Hoboken, NJ: J. Wiley & Sons, 2005. ISBN: 0471246891.

Particle fate depends on its size relative to $\langle R \rangle$

Diffusion-controlled coarsening kinetics

- **Rate law for evolution of mean size is**

$$\langle R(t)\rangle^3 - \langle R(0)\rangle^3 = \frac{8\tilde{D}\gamma\Omega^2 c^{\mathrm{eq}}(\infty)}{9kT}\, t = \kappa\, t$$

See Figure 15.9 in Balluffi, Robert W., Samuel M. Allen, and W. Craig Carter. *Kinetics of Materials*. Hoboken, NJ: J. Wiley & Sons, 2005. ISBN: 0471246891.

- **"*t*-to-the-one-third" rate law is observed in a wide variety of experiments**