3.40 Lecture Summary

November 4, 2009

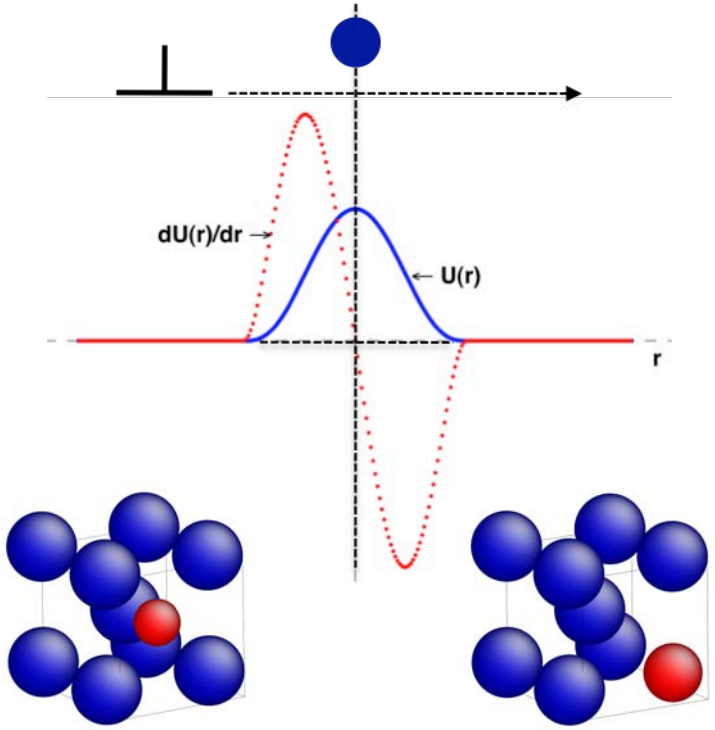
Department of Materials Science and Engineering

Solid Solution Strengthening

The Big Picture

<u>Size Effect</u> – *Asymmetry*

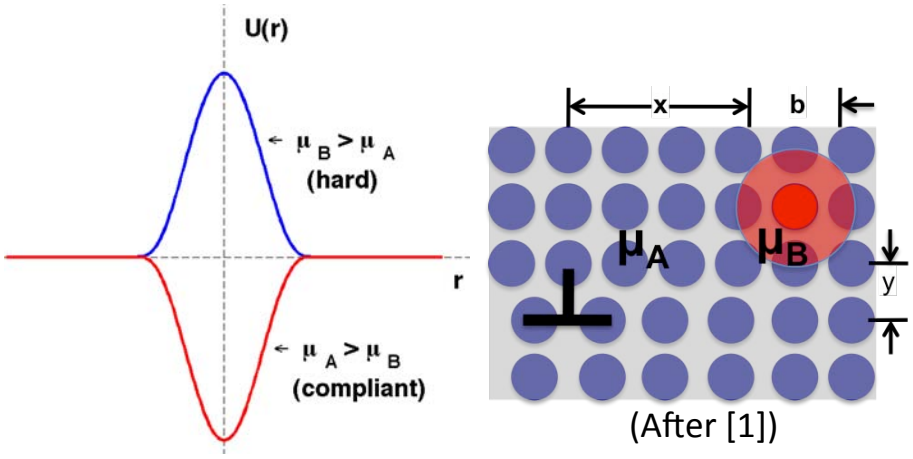
(interstitial over substitutional alloying)



<u>Modulus Effect</u> – *Compliance*

($\mu_{solute} < \mu_{solvent}$)

- Local change in elastic constants
- Dislocation energy changes ($E \approx \mu b^2$)



(After [1])

[1] Fleischer. Acta.Metall. **9** (1961) 996-1000

Solid Solution Strengthening

Size & Modulus Effect Combined

Yield Stress Derivation

$$U(r) \rightarrow \frac{\partial U(r)}{\partial r} \rightarrow Length \;\; Scale \rightarrow \tau_y$$

- Force (substitutional/edge)

$$F_T = \frac{\mu_A b^2 x R^3}{3\pi(1-\nu)(x^2+y^2)^2}\left|g' - 32\varepsilon\right|$$

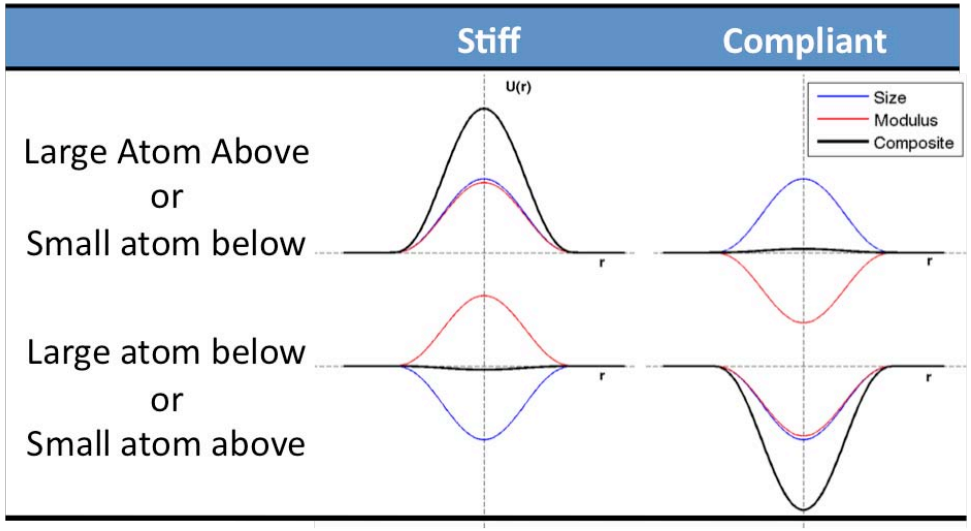
$$g' = \frac{g}{1+1/2|g|}, \; g = \frac{1}{\mu_A}\frac{\partial \mu_A}{\partial c}, \; \varepsilon = \frac{1}{a}\frac{\partial a}{\partial c}$$

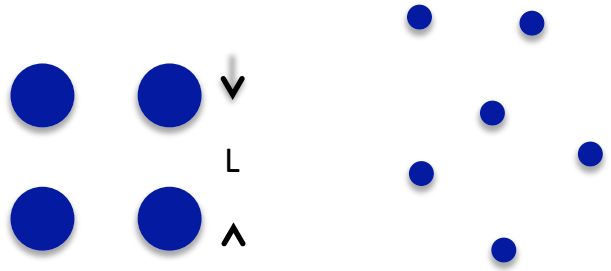
- Length Scale

$$L \approx \frac{b}{\sqrt{c}}$$

- Yield Stress

$$\tau_y \approx \frac{F}{bL} \;\rightarrow\; \tau_y \approx \mu_A \sqrt{c}\, f(g,\varepsilon)$$





[2] Fleischer. Acta.Metall. **11** (1963) 203-209.

Annealing in Solid Solutions

Solute Diffusion

General Annealing Effects

- Recrystallization
- Grain Growth
- Dislocation Climb
- Recovery, polygonization

Solid Solution Annealing Effects

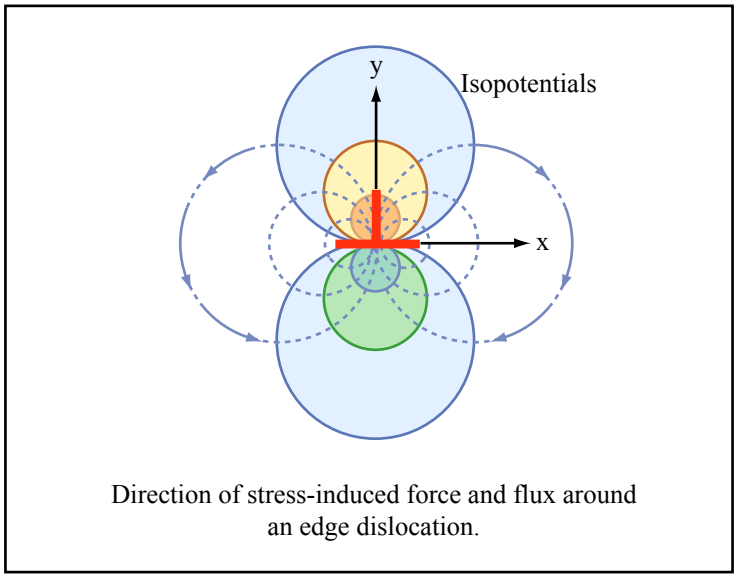
- Solute Diffusion

$$J = -L\nabla\Phi$$

$$\Phi = \mu + \Delta\Omega P,\ P = \frac{\mu(1+\nu)}{3\pi(1-\nu)}\frac{\sin(\theta)}{r}$$

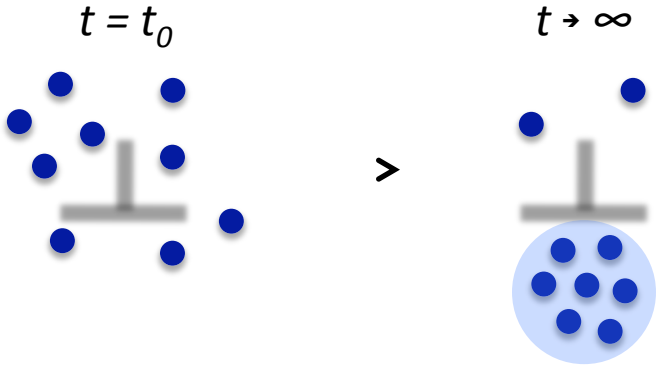
$$J = -D(\nabla c + \frac{c\Delta\Omega}{kT}\nabla P)$$

- Solute Atmosphere



Direction of stress-induced force and flux around an edge dislocation.

Figure by MIT OpenCourseWare. Please also see Fig. 3.8 in Balluffi, Robert W., et al. *Kinetics of Materials*. Hoboken, NJ: Wiley-Interscience,2005.



[3] Balluffi *et al*. Kinetics of Materials (2005).

Annealing in Solid Solutions

Solute Diffusion Kinetics

Cottrel-Bilby Solution

- Fraction Diffused

$$v \approx (D/kT)\cdot F,\ F \approx A/r^2$$

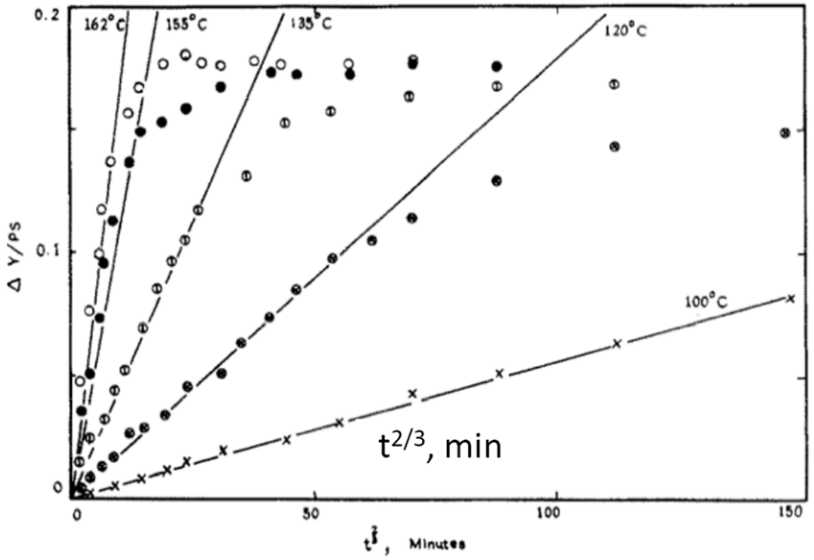
$$t \approx \frac{r^3 kT}{AD}$$

$$f(t) = 3\rho_D\left(\frac{ADt}{kT}\right)^{2/3}$$

Harper Equation

- Solute Diffusion

$$f(t) = 1 - \exp\left[-3\rho_D\left(\frac{ADt}{kT}\right)^{2/3}\right]$$



(Ref. [4])

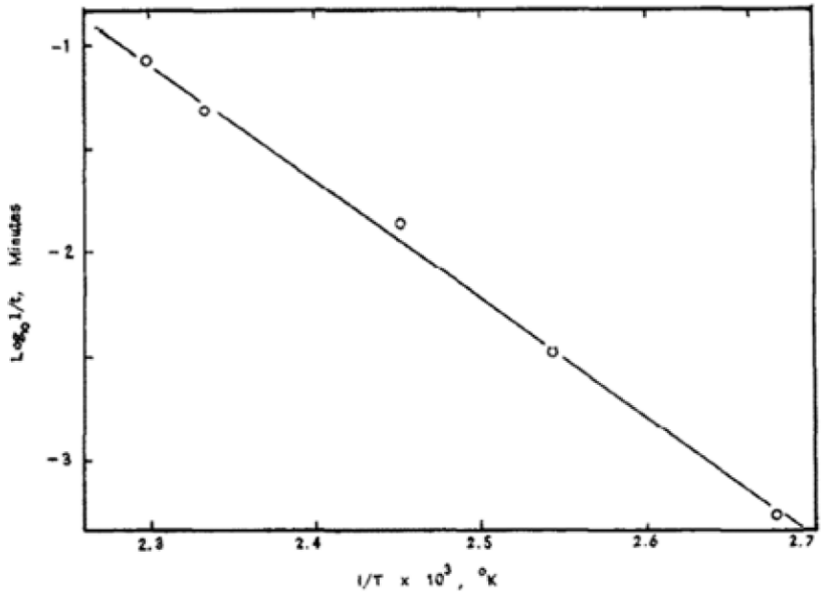


Image removed due to copyright restrictions.
Please see Fig. 9.13 in Reed-Hill, Robert E.,
and Reza Abbaschian. *Physical Metallurgy Principles*·
Boston, MA: PWS Publishing, 1994.

[4] Szkopik and Miodownik. J. Nuc. Mater. **17** (1965) 20.
[5] Abbaschian *et al*. Physical Metallurgy Principles (2009).

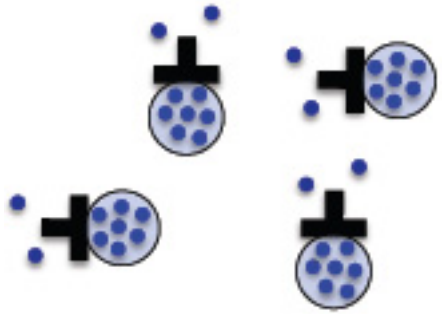
Courtesy of Elsevier, Inc., http://www.sciencedirect.com.
Used with permission.

Annealing in Solid Solutions

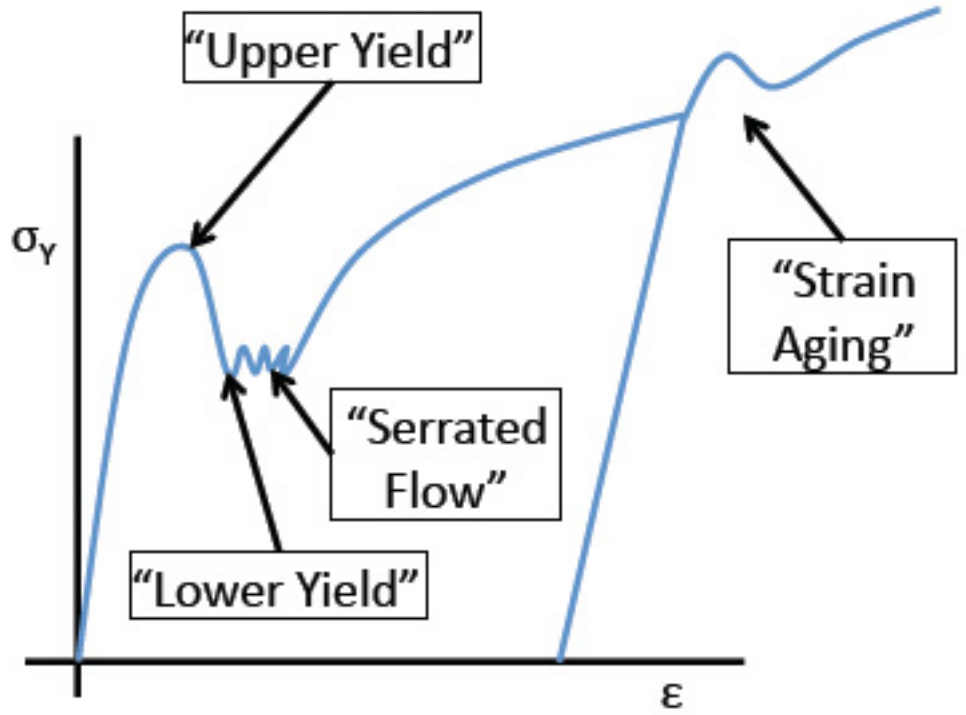
Solute Diffusion Kinetics

Deformation of Solution-Hardened Alloys

- Solute Atmospheres – Dislocation Pinning



- Break-away (Upper Yield)
- Dislocation – Solute Interactions
- Strain Aging



[5] Abbaschian *et al*. Physical Metallurgy Principles (2009).

3.40J / 22.71J / 3.14 Physical Metallurgy

Fall 2009