Mechanical Behaviour of Materials

Chapter 03-3 Material Strengthening mechanisms-Strengthening mechanisms

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Introduction to Alloy Strengthening

- Hardening by solute atoms

  -Solid solution strengthening

  (interaction between solute atoms and dislocations)

- Hardening by second phases

  -Precipitation-Hardening

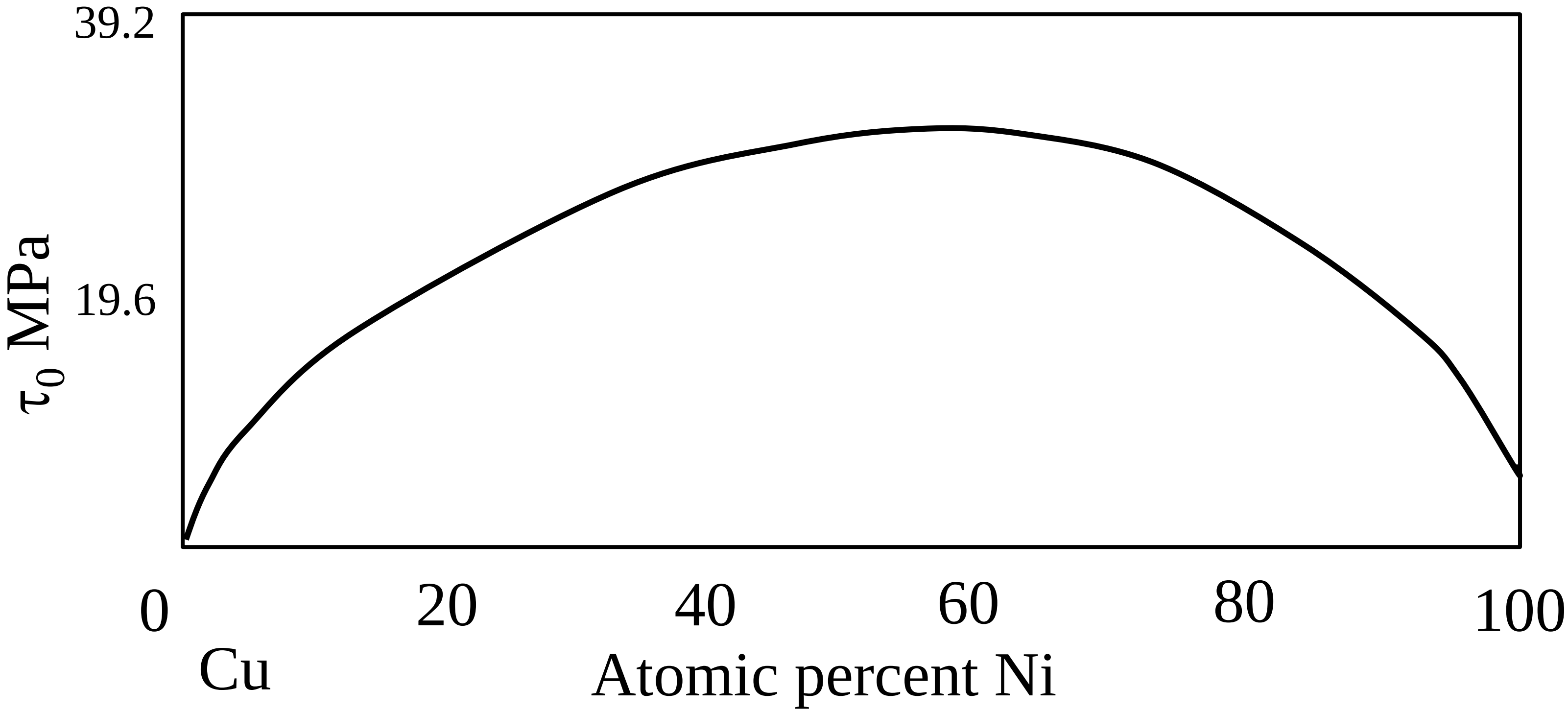
  (interaction between precipitation phases and dislocations)

  -Dispersion-Hardening

  (interaction between dispersion phases and dislocations)

Solid solution strengthening:
0 dimension defects

Effect of alloying on strengthening a material



Critical shear stress of Cu-Ni solid solution crystals:

a) Formation of an internal stress due to the size and modulus effect and b) interaction with dislocations

Cited from Osswald, Z. Phys. 83(1933) 55

Solid solution strengthening

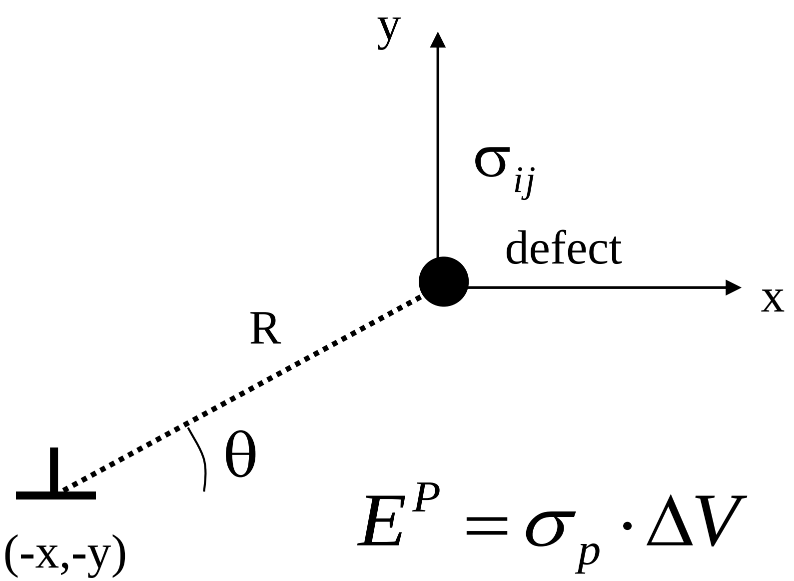
In addition to elastic misfit interaction, there are other sources of dislocation-solute interactions:

1. Parelastic interaction (lattice parameter effect)
2. Dielastic interaction (shear modulus effect)
3. Chemical interaction (Suzuki effect)

However, their contributions are less important than the size effect.

Parelastic interaction (Lattice parameter effect)

Dislocations also interact with point defects, such as vacancies, interstitial and substitutional impurity atoms. Work is done, if a foreign atom is placed in a crystal.



$$E^P = \sigma_p \cdot \Delta V$$

$$\sigma_p = \frac{1}{3}\left(\sigma_{xx} + \sigma_{yy} + \sigma_{zz}\right)$$

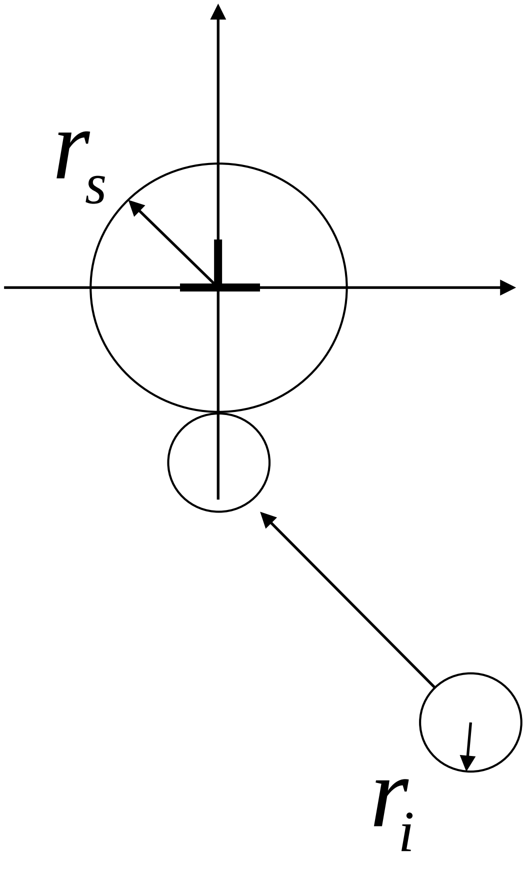
$$\sigma_p = -\frac{Gb}{3\pi}\left(\frac{1+\nu}{1-\nu}\right)\frac{\sin\theta}{R}$$

σ_p the hydrostatic pressure of the stress field associated with an edge dislocation

Interaction energy

We replace the solvent atom by a solute atom of radius r_0. This changes the radius of sphere by a small amount εr_0 with

$$\varepsilon = \frac{r - r_0}{r_0}$$



The interaction energy between the dislocation and the impurity

$$E_p = \frac{4}{3}\left(\frac{1+\nu}{1-\nu}\right) Gb\varepsilon r^3 \frac{\sin\theta}{R} \qquad \text{for } R > r$$

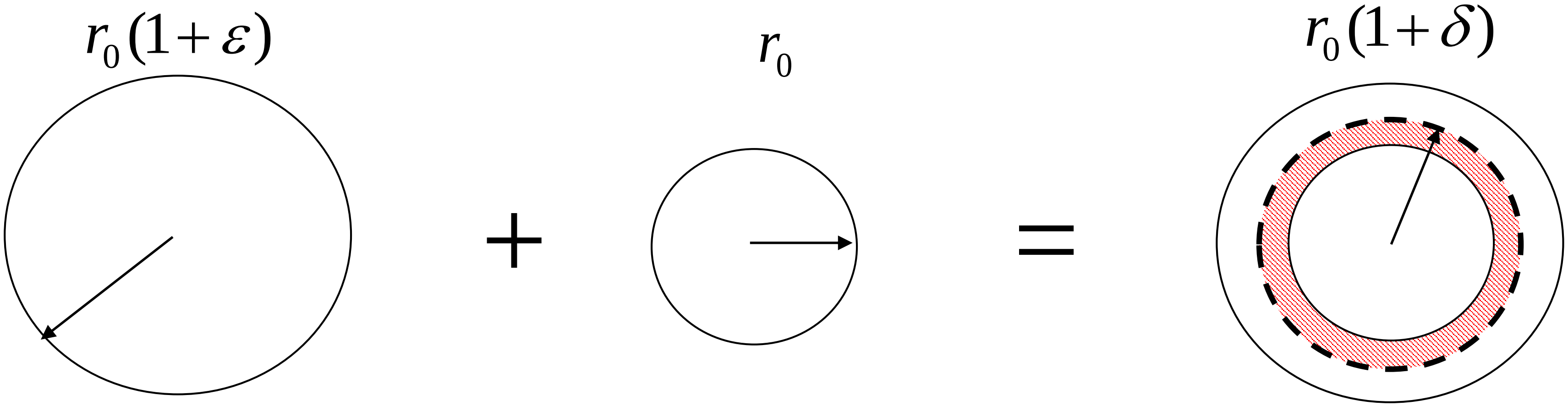
This energy will be positive for sites above the slip plane and negative below the plane, called the positions of attraction and repulsion. Therefore, a vacancy will be attracted to regions of compression.

$$E_p = \frac{1}{3\pi}\left(\frac{1+\nu}{1-\nu}\right) G\left|\Delta V\right|$$

Misfit volume

Misfit volume: ΔV_{mis}

Distortion induced by point defects



$$V_s = \left(\frac{4}{3}\right)\pi r_0^3 (1+\delta)^3$$

the volume of a spherical cavity of radius $r_0(1+\varepsilon)$

$$V_h = \frac{4}{3}\pi r_0^3$$

the volume in an elastic matrix of radius r_0

Radius of a hole : $r_0(1+\varepsilon)$

Equilibrium radius : r_0

Initial radius of defect: $r_0(1+\delta)$

Expanded volume

Misfit volume between the two volume

$$\Delta V_{mis}(free) = V_s - V_h$$

$$= \left(\frac{4}{3}\right)\pi r_0^3 (1+\varepsilon)^3 - \frac{4}{3}\pi r_0^3$$

$$= 4\pi \varepsilon r_0^3$$

On inserting the sphere into the hole, the radius of the hole around the defect is expanded and the change in the volume is given by

$$\Delta V_h(deformed) = \left(\frac{4}{3}\right)\pi r_0^3 (1+\delta)^3 - \frac{4}{3}\pi r_0^3$$

$$= 4\pi \delta r_0^3$$

$$\Delta V_h(deformed) = \frac{(1+\nu)}{3(1-\nu)}\Delta V_{mis}(free) \qquad \delta = \frac{(1+\nu)}{3(1-\nu)}\varepsilon$$

Elastic Interaction force

$$E_p = \frac{4}{3}\left(\frac{1+\nu}{1-\nu}\right) Gb\varepsilon r^3 \frac{\sin\theta}{R}$$

$$= \frac{Gb}{3\pi}\left(\frac{1+\nu}{1-\nu}\right)\left(4\pi\varepsilon r^3\right)\frac{\sin\theta}{R}$$

$$= \frac{Gb}{3\pi}\left(\frac{1+\nu}{1-\nu}\right)\Delta V_{mis} \frac{\sin\theta}{R}$$

$$= \frac{Gb}{3\pi}\Delta V_h \frac{\sin\theta}{R}$$

$$F^P = \frac{dE^P}{dx}$$

$$= \frac{d}{dx}\left[\frac{Gb}{3\pi}\Delta V_h \frac{\sin\theta}{R}\right]$$

$$= \frac{d}{dx}\left[\frac{Gb}{3\pi}\frac{x}{x^2+y^2}\Delta V_h\right]$$

$$= \frac{Gb}{3\pi}\Delta V_h \frac{d}{dx}\left[\frac{x}{x^2+y^2}\right]$$

$$= \frac{Gb}{3\pi}\Delta V_h \left[\frac{y^2-x^2}{\left(x^2+y^2\right)^2}\right]$$

Elastic Interaction force-conti.

$$F^P = \frac{Gb}{3\pi}\Delta V_h\left[\frac{y^2 - x^2}{\left(x^2 + y^2\right)^2}\right]$$

$$\Delta V_h = \left(a(1+\delta)\right)^3 - a^3$$

$$\delta = \frac{da}{dc}\frac{1}{a} = \frac{d\ln a}{dc}$$

δ is a factor of lattice change and *c* the concentration

F^P is maximum, when $x = \frac{y}{\sqrt{3}}$

$$y = \frac{b}{\sqrt{3}} \qquad x = \frac{b}{3}$$

$$F^P_{\max} = \frac{3}{8}\frac{G}{b\pi}\Delta V_h$$

$$= \frac{9}{8}\frac{G}{b\pi}3\delta a^3$$

$$= \frac{27}{8\pi}\delta G b^2$$

$$\approx \delta G b^2$$

δ is small and *b* is equal to *a*

The interaction force of substitutional atoms leads to a linear dependence on the lattice distortion.

Dielastic Interactions (shear modulus effect)

$$E^d = \frac{Gb^2}{8\pi^2 r^2}\Omega\eta$$

$$F^d_{\max} \approx \frac{1}{20}Gb^2|\eta|$$

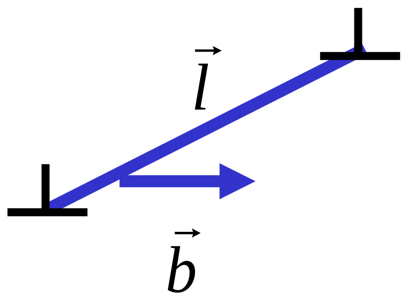
$$\eta = \frac{dG}{dc}\frac{1}{G} = \frac{d\ln G}{dc}$$

Peach-Koehler Equation

The critical shear stress for solid solution strengthening according Peach-Koehler Eq.

$$\vec{F}_{def-dis} = (\sigma_{ij}^{def} \cdot \vec{b}_X) \times \vec{l}_Z$$

$$\vec{F}_{def-dis} = \begin{pmatrix} \sigma_{xy} b \\ -\sigma_{xx} b \\ 0 \end{pmatrix}$$



$$F_{\max} = \Delta \tau_c b_X l_Z$$

Critical shear stress of solid solution strengthening

The maximum possible interaction force $F_{\max} = F_{\max}^{d} + F_{\max}^{p}$

The critical shear stress for solid solution strengthening according Peach-Koehler Eq.

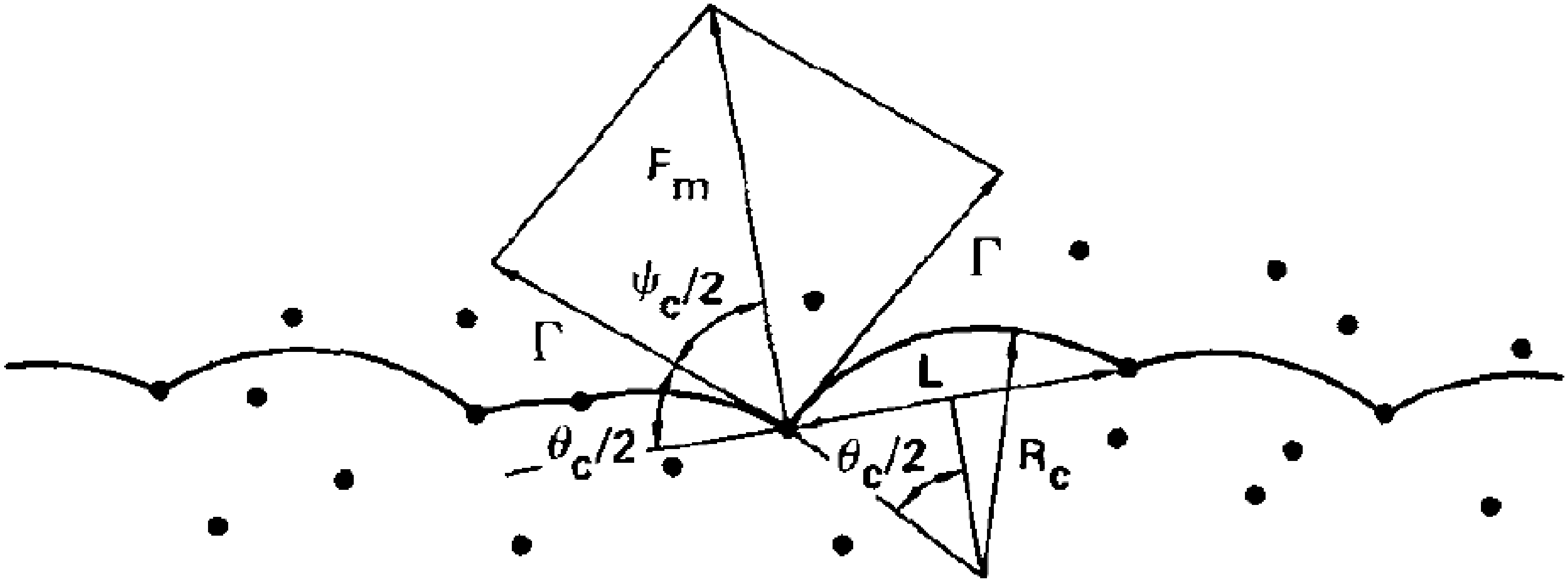
$$F_{\max} = \Delta\tau_c b l_F$$

The Friedel length l_F is the effective obstacle spacing using Friedel statistics and Λ^2 is the area of the glide plane per obstacle.

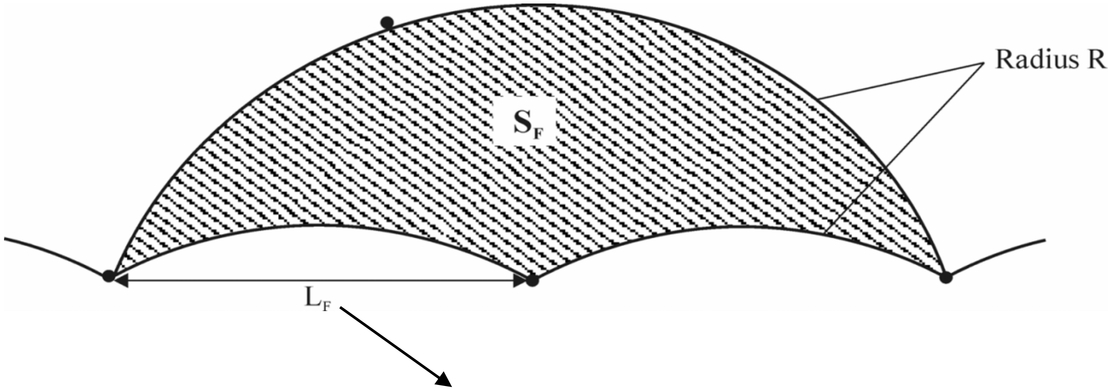
$$\Lambda^2 = \frac{\Delta\tau_c \cdot l_F^3}{Gb} = \frac{1}{c_F} \qquad l_F = \left(\frac{Gb}{\Delta\tau_c \cdot c_F}\right)^3$$

If we consider the obstacle to be solute atoms with a concentration c_F atoms/m^2.

Schematic illustration of the penetration of a random array of point obstacles by a dislocation



Solid Solution Strengthening: Elastic Interactions



average free dislocation length

$$F_{\max} = \Delta\tau_c b l_F$$

$$\Delta\tau_c = \frac{F_{\max}^{3/2}\sqrt{c_F}}{b\sqrt{G}} \approx \sqrt{c_F}$$

$$l_F = \left(\frac{Gb}{\Delta\tau_c \cdot c_F}\right)^{1/3}$$

Increase in the critical shear stress due to the solid solution strengthening is proportional to $\sqrt{c_F}$.

Solid Solution Strengthening: Elastic Interactions

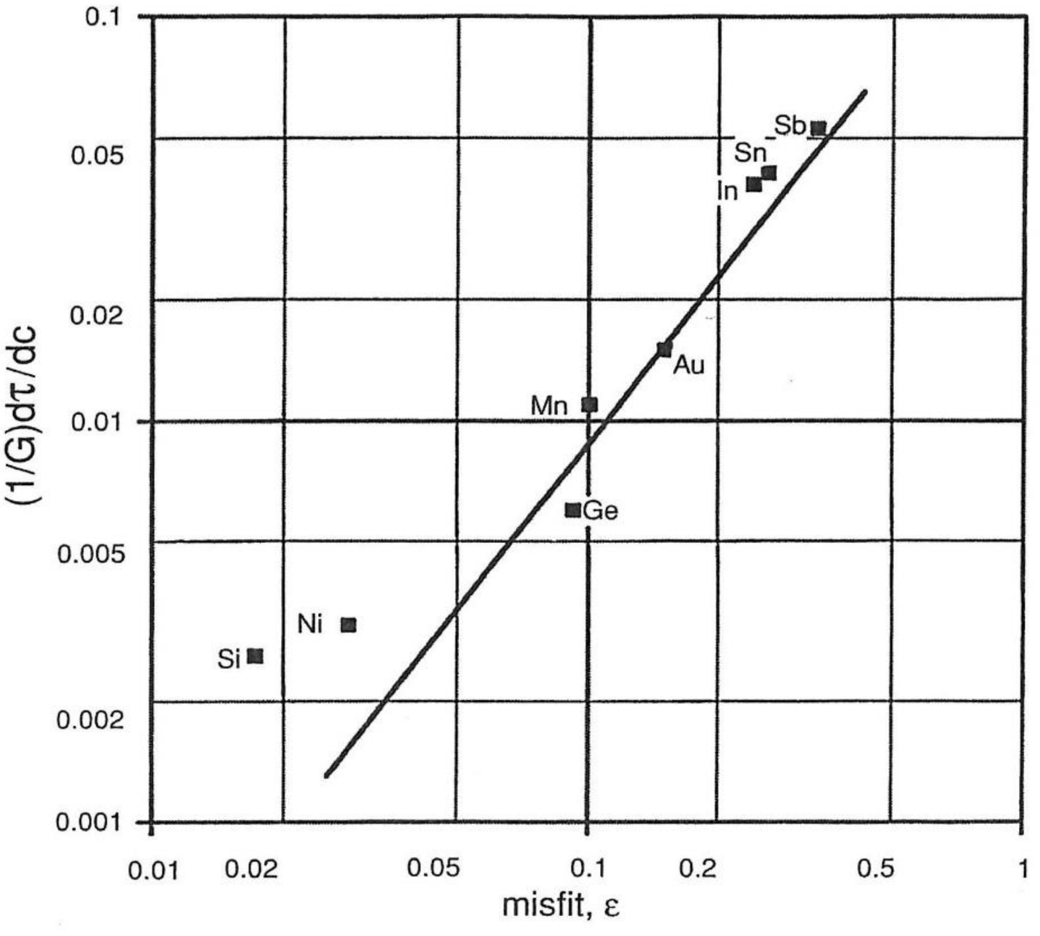
$$F_{\max} = F_{\max}^{d} + F_{\max}^{p}$$

$$\Delta\tau_c = \frac{\left(Gb^2\right)^{3/2}\left(|\delta| + \frac{1}{20}|\eta|\right)^{3/2}\sqrt{c_F}}{b\sqrt{G}}$$

$$\Delta\tau_c = Gb^2\sqrt{c_F}\left(|\delta| + \frac{1}{20}|\eta|\right)^{3/2}$$

The slope of the curve $\Delta\tau_c - \sqrt{c_F}$

Solid solution strengthening



$\delta =$
-0.1 to 0 for vacancies
-0.15 to +0.15 for substitutional solute
0.1 to 1.0 for interstitutal solute

Why is the difference of Solid Solution Strengthening between substitutional and interstitial solution?

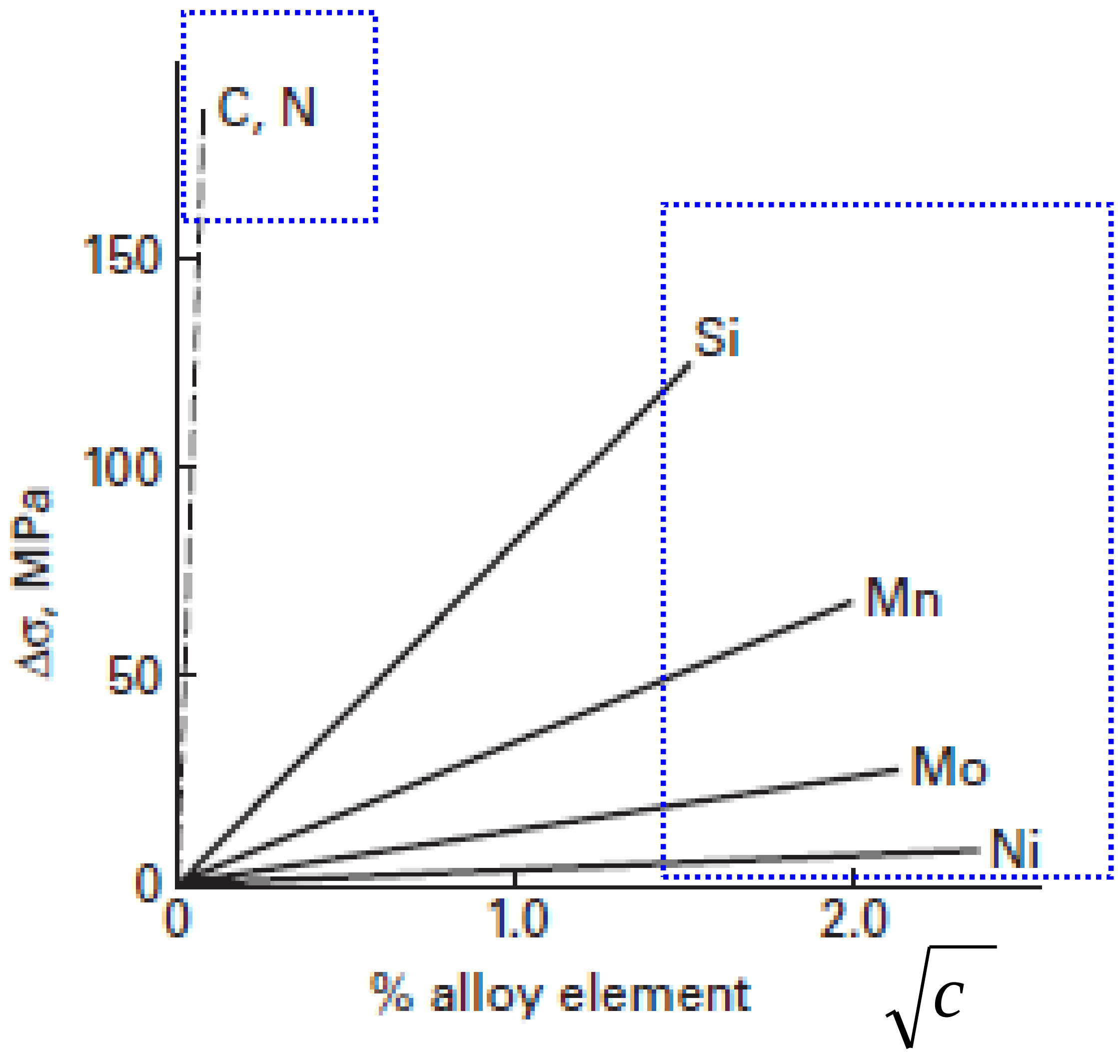
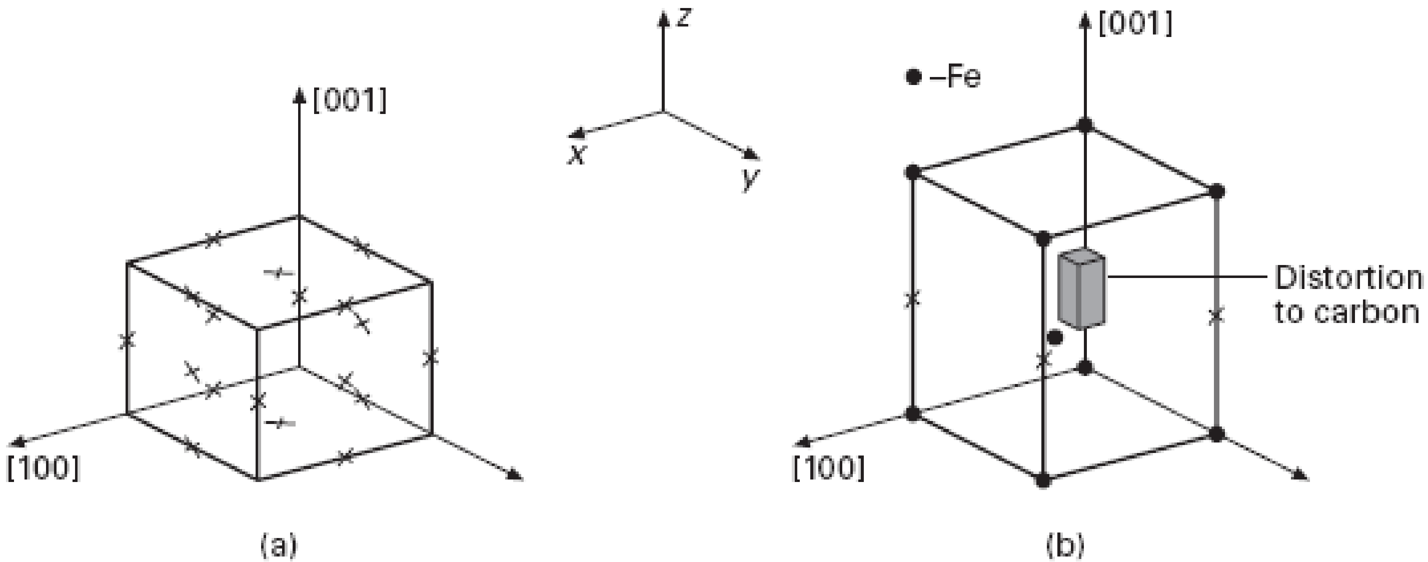


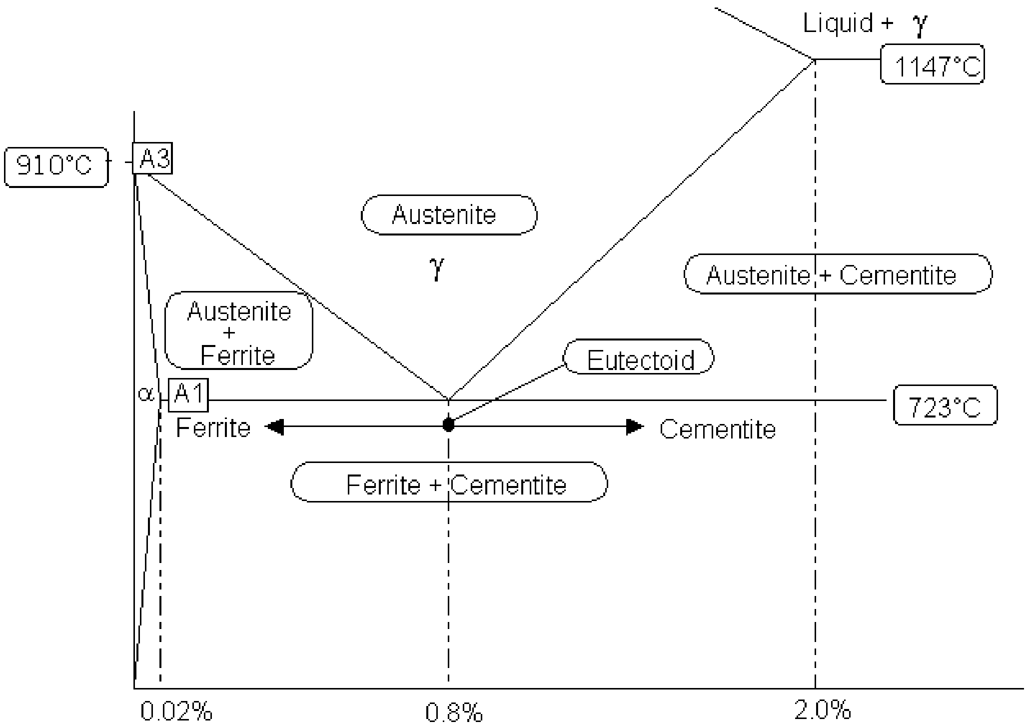
Figure 12.10. The effect of the solute misfit parameter, $e = (1/a)da/dc$, on the solute hardening of copper. The solid line is Equation (12.7) with $C = 0.215$. Data from F. McClintock and A. Argon, *ibid*.

Where are positions of Interstitial Atoms in the Cubic Lattice?



(a) Positions of interstitial atoms in the cube. (b) Carbon atom shown as a producer of a tetragonal distortion.

Question?



$a_C = 1.54$ A

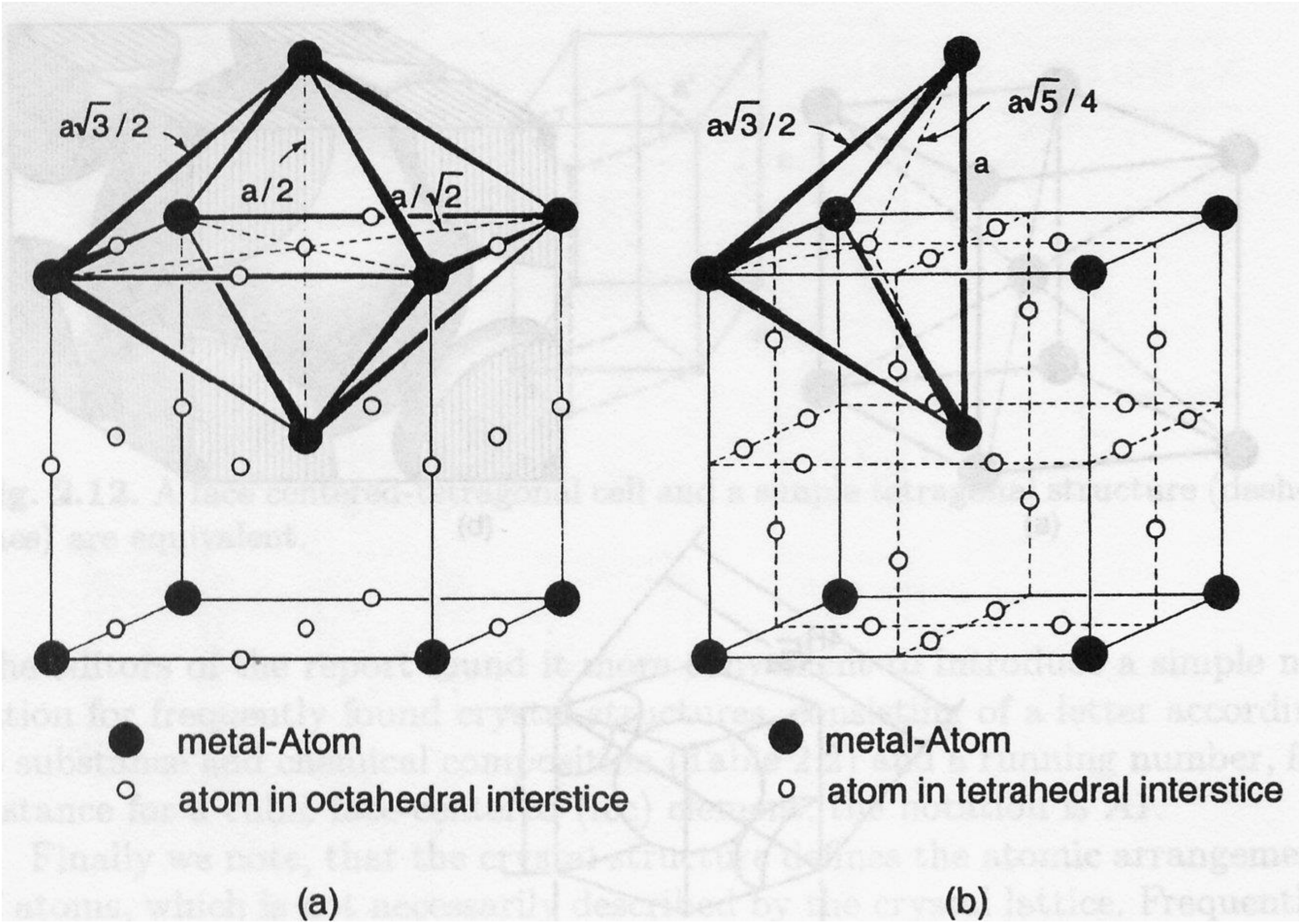
$a_{Fe} = 2.52$ A

$R_C/R_{Fe} = 0.61$

Octahedral	Tetrahedral
$r/R_{fcc} = 0.41$	$r/R_{fcc} = 0.22$
$r/R_{bcc} = 0.16$	$r/R_{bcc} = 0.29$

Bcc

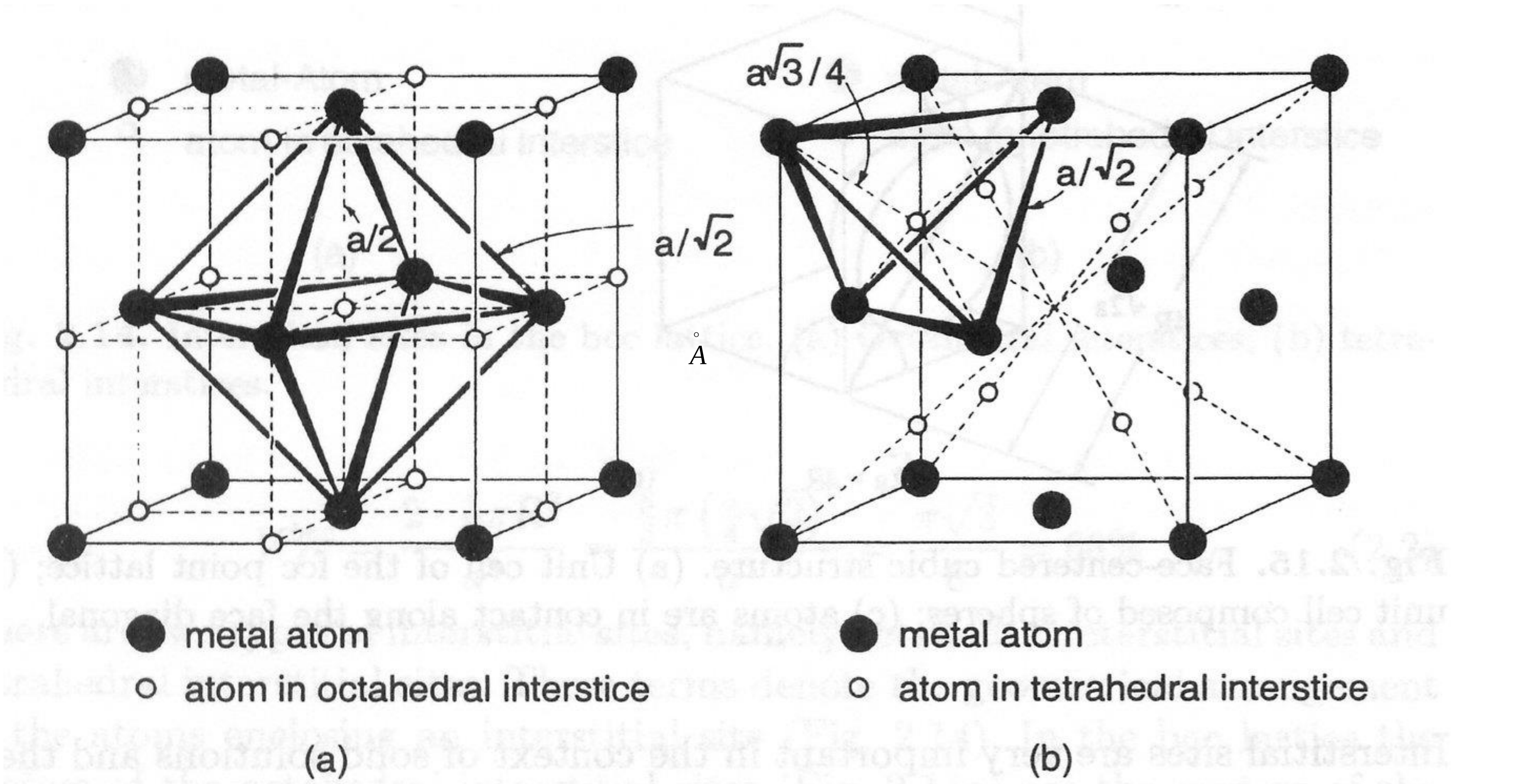
$R_C/R_{Fe} = 0.61$



r/R = 0.155 r/R = 0.291

Fcc

$D_C = 1.54$ A
$D_{Fe} = 2.52$ A



Å

r/R = 0.41

r/R = 0.22

$R_C/R_{Fe} = 0.61$

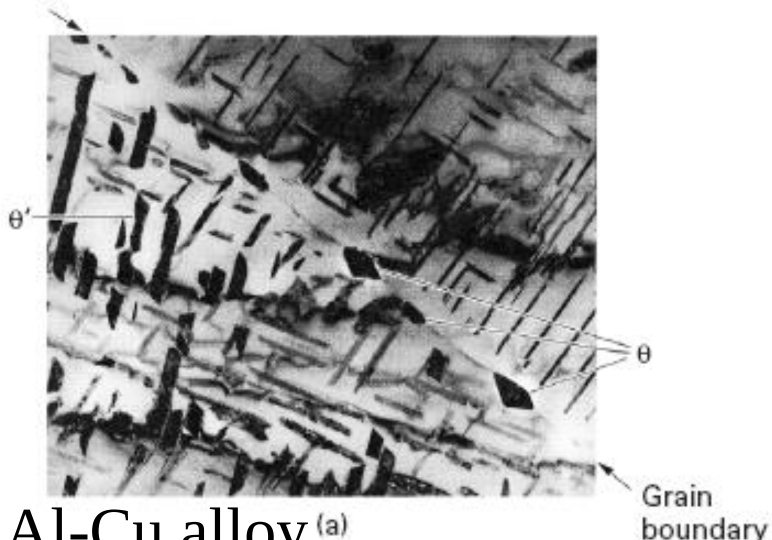
Strengthening mechanism:
3 dimension defects

Second Phases: Precipitation and Dispersion

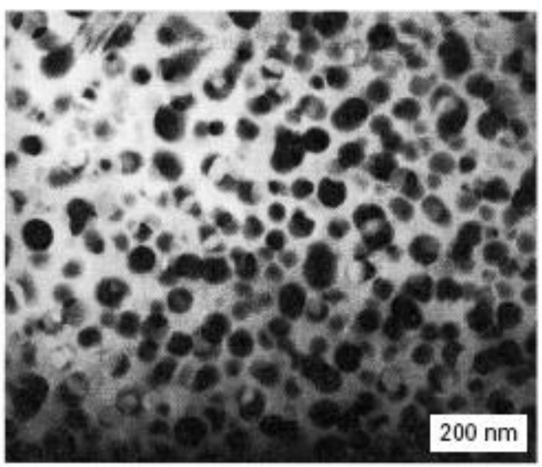
Two alloy systems using this strengthening technique are aluminum alloys and nickel-based superalloys.

Precipitation: precipitation of precipitates out from a homogenous, supersaturated solid solution.

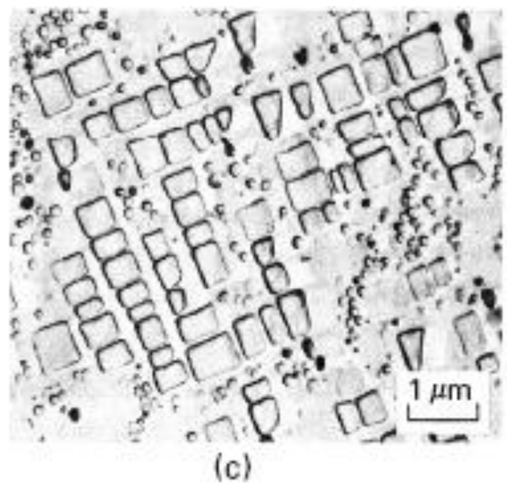
Dispersion: incorporated hard, insoluble second phases in a soft metallic matrix with a maximum volume fraction of 3-4%.



Al-Cu alloy



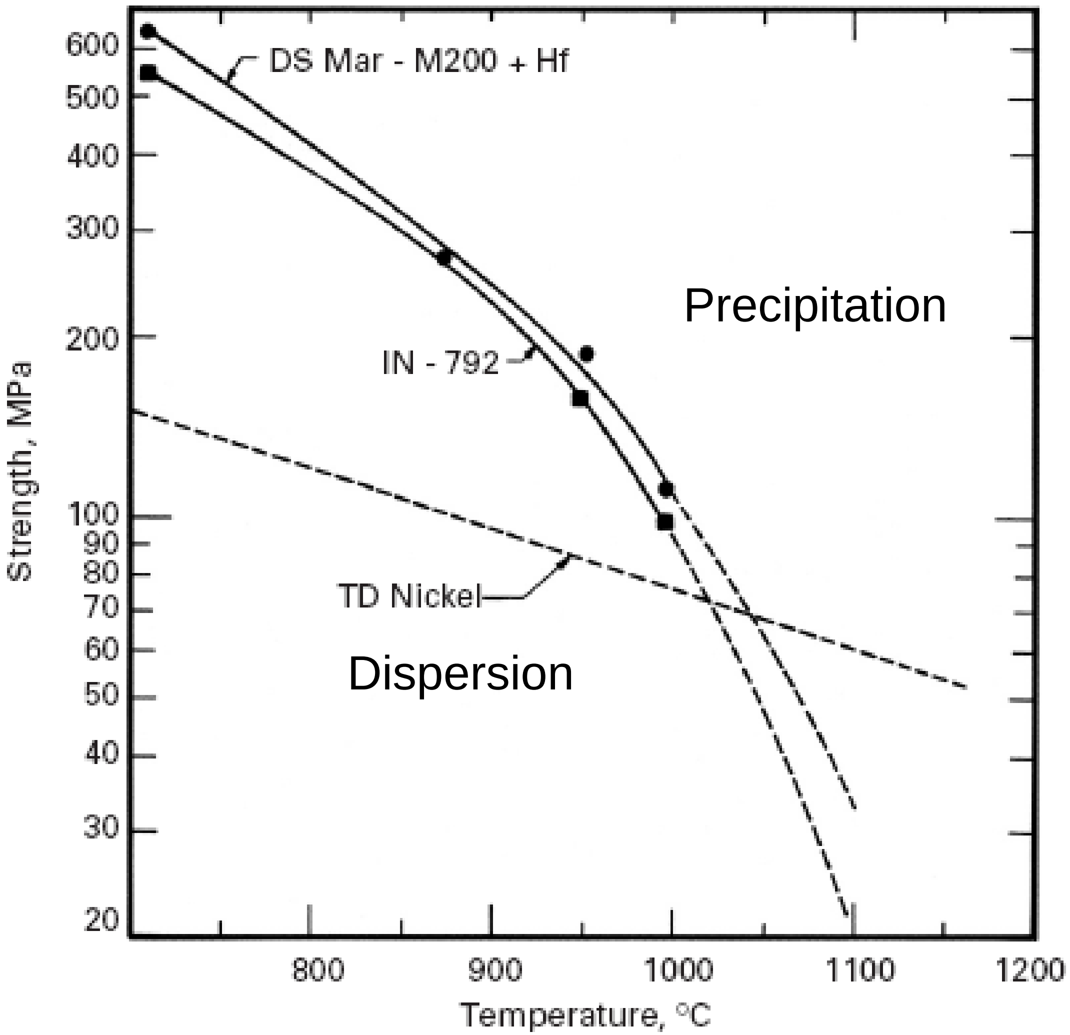
Al-Li alloy



superalloy

(a) θ precipitates (at grain boundaries) and θ precipitates (in grain interior) in Al–Cu alloy. (Courtesy of K. S. Vecchio.) (b) Al3Li precipitates in Al–Li alloy (TEM, dark field). (Courtesy of K. S. Vecchio.) (c) γ precipitates and aged carbides in a superalloy. (Courtesy of R. N. Orava.)

Yield Strength Superalloys and TD Nickel



Comparison of yield strength of dispersion-hardened
thoria-dispersed (TD) nickel with
two nickel-based superalloys strengthened by precipitates (IN-792) and directionally solidified (DS) MAR M 200.

Yield Strength of copper and copper alloys

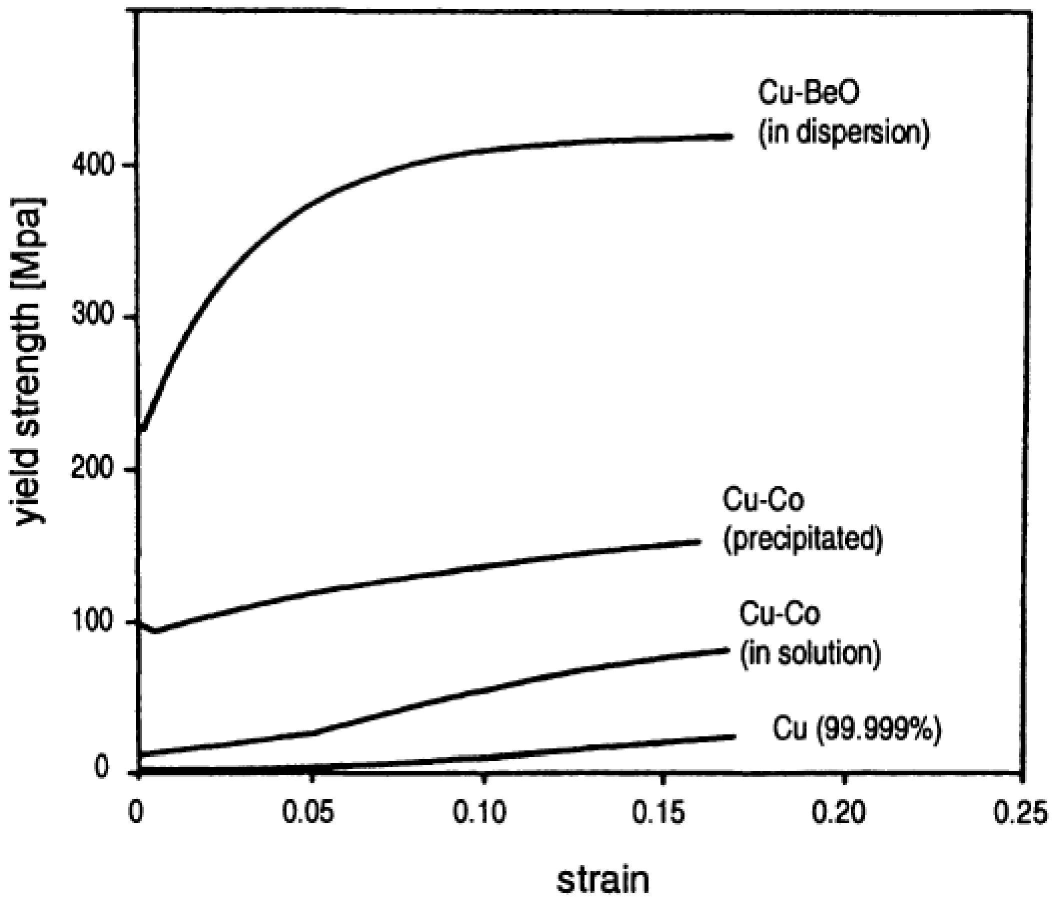


Fig. Hardening curves of high purity copper and copper alloys. In CuCo particles are shearable, in BeO they are not (after [6.24]).

Dispersion strengthening: by-passing

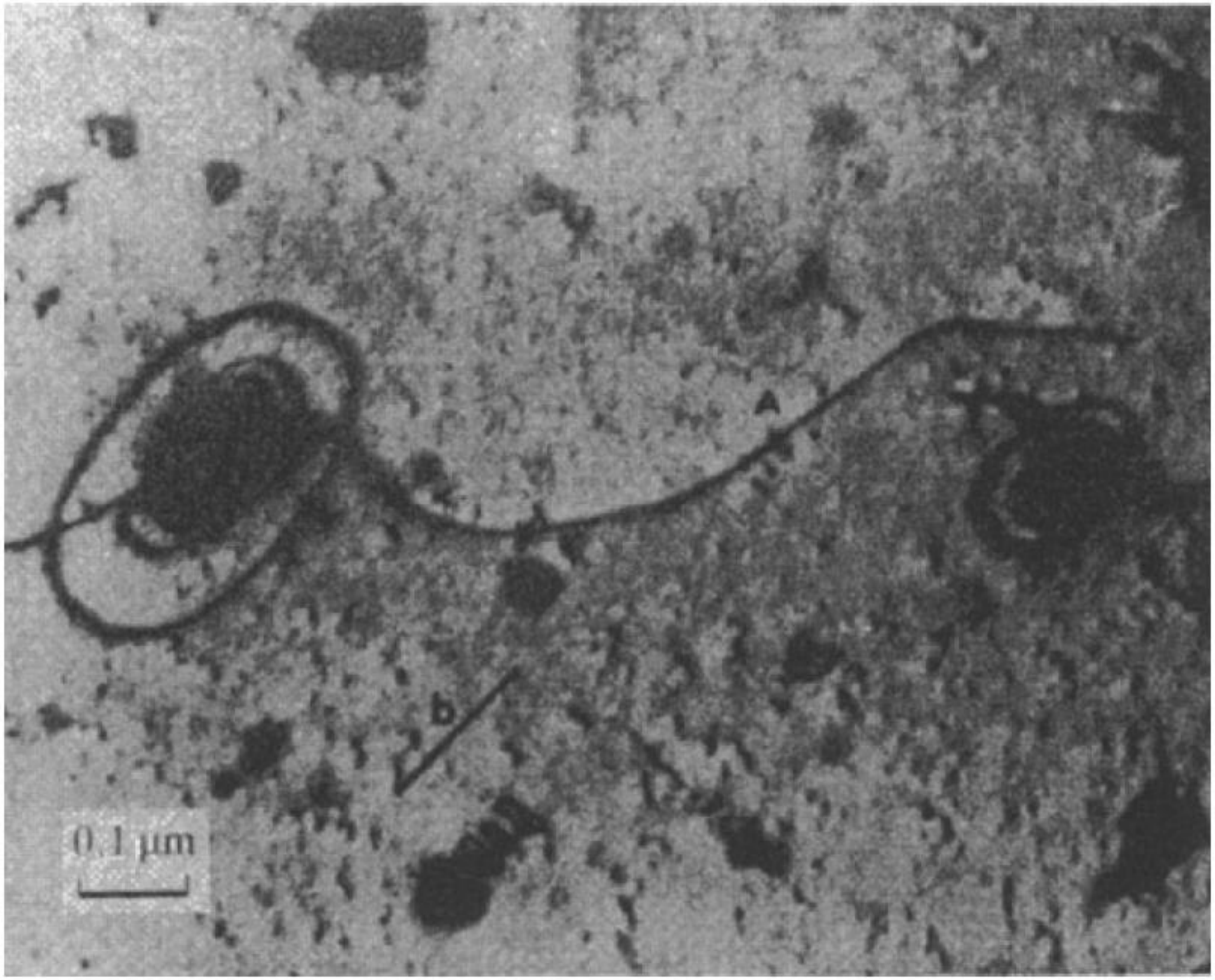
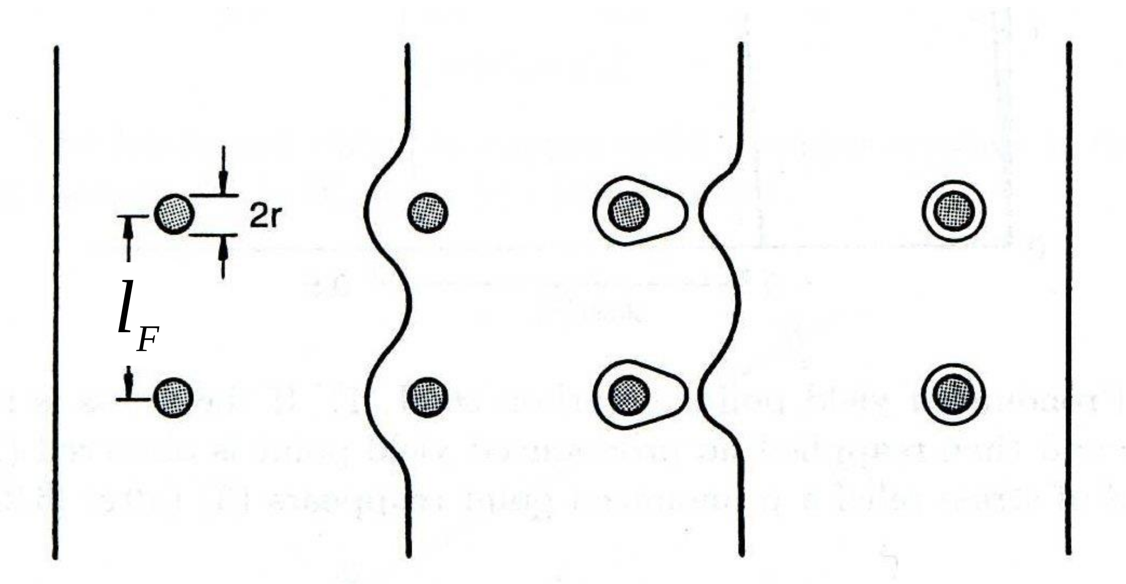


Fig. Orowan loops around Al2O3 particles in Cu30%Zn [6.23].

Bowing (Orowan) mechanism: Orowan stress

The only possible deformation mechanism is the Orowan stress:
Dislocations circumnavigating around the particles in the slip plane



$$\Delta\tau_{OR} b l_F =$$

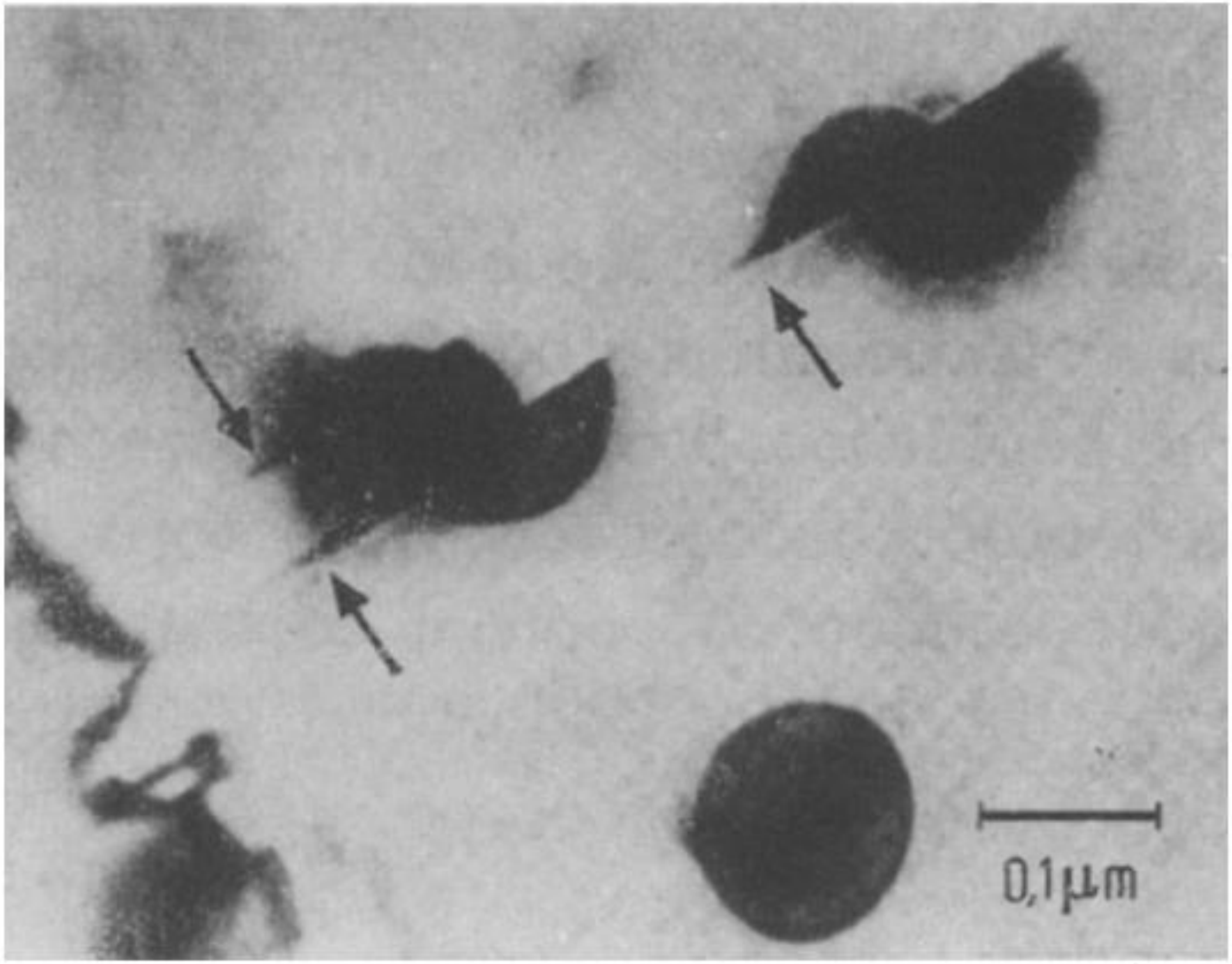
$$l_S^2 = \frac{\Delta\tau_c \cdot l_F^3}{Gb}$$

$$l_S = r \cdot \left(\frac{2\pi}{3f}\right)^{1/2}$$

$$\Delta\tau_{OR} = \sqrt{\frac{3}{16\pi}} \cdot Gb \cdot \frac{\sqrt{f}}{r} \cdot \sin^{3/2}\left(\frac{\theta_c}{2}\right)$$

$$\Delta\tau_{OR} \approx \frac{\sqrt{f}}{r}$$

Cutting mechanism: Fleischer stress

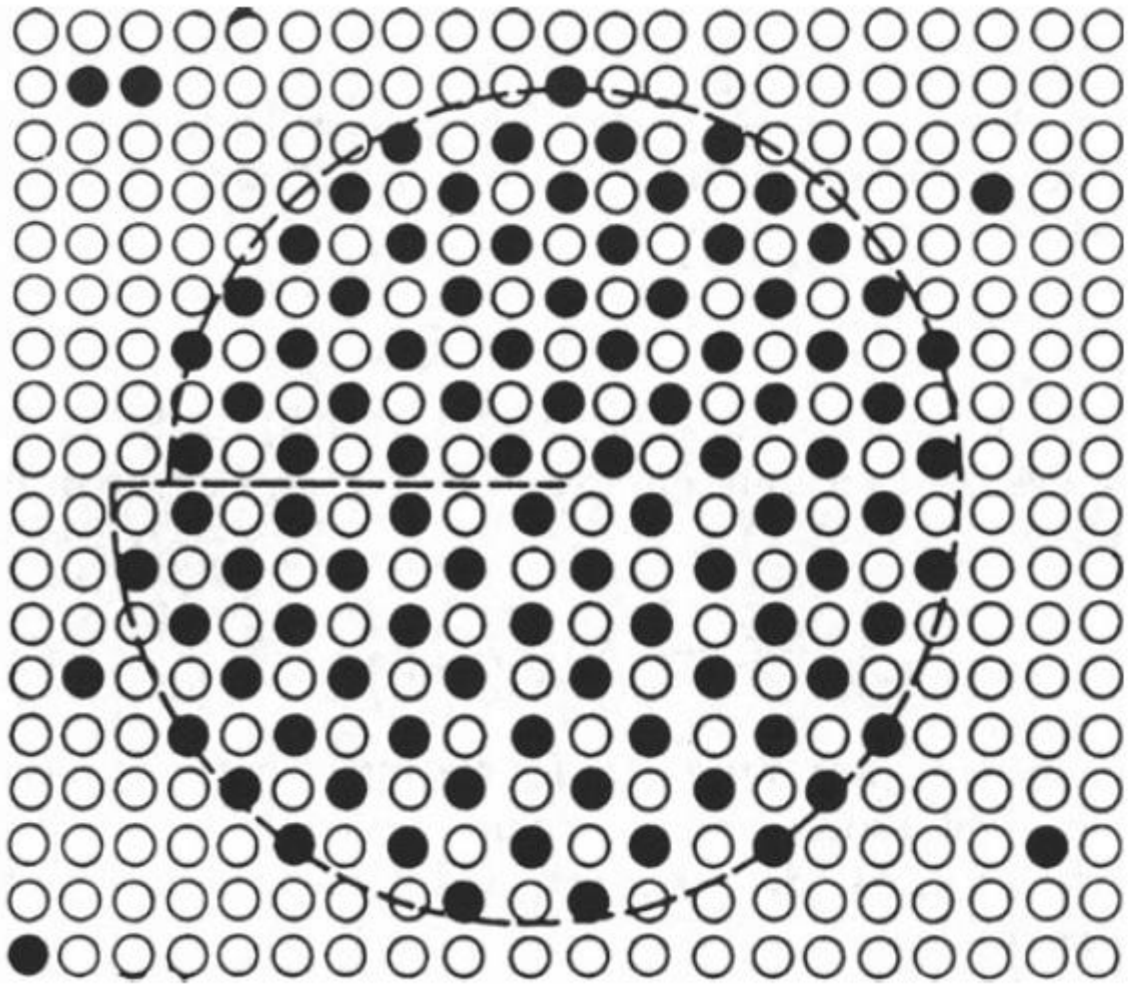


$$F_{pre} = \gamma_{pre} \cdot r$$

(N/m)

Fig. If a dislocation cuts a particle, the particle shears off. (a) Schematic; (b) observed in Ni19%Cr6%Al (aged 540h at 750°C and deformed 2% [6.25]).

Interface strengthening: antiphase boundary

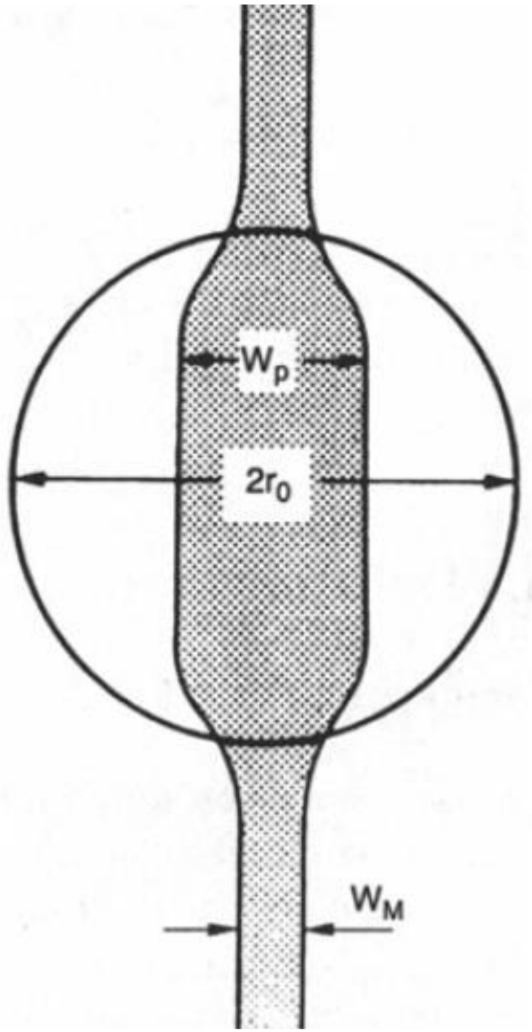


$$F_{anti} = \gamma_{anti} \cdot r$$

(N/m)

Fig. Intersecting an ordered particle produces an antiphase boundary.

Interface strengthening: stacking fault



$$F_{st} = \gamma_{st} \cdot r$$

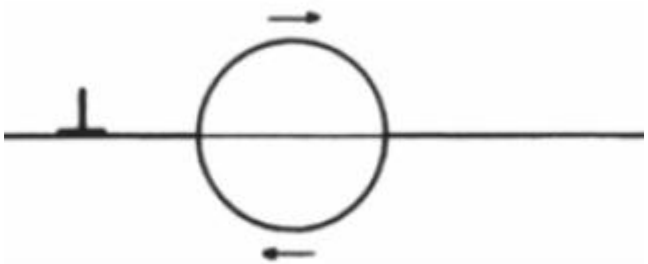
(N/m)

Fig. Change in dissociation width in a particle of different stacking fault energy.

Critical shear stress of cutting

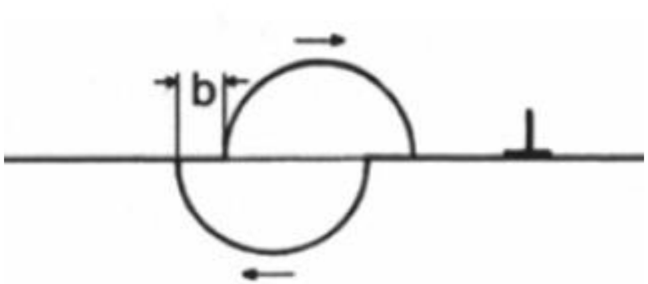
$$F_{\max} = F_{\max}^{pre} + F_{\max}^{anti} + F_{\max}^{st}$$

The presence of grain boundaries has an additional effect on the deformation behaviour of a material by serving as an effective barrier to the movement of glide dislocations.



$$F_{\max} = \Delta\tau_c \cdot b l_F$$

$$l_F = \left(\frac{Gb}{\Delta\tau_c \cdot c_F} \right)^{1/3}$$

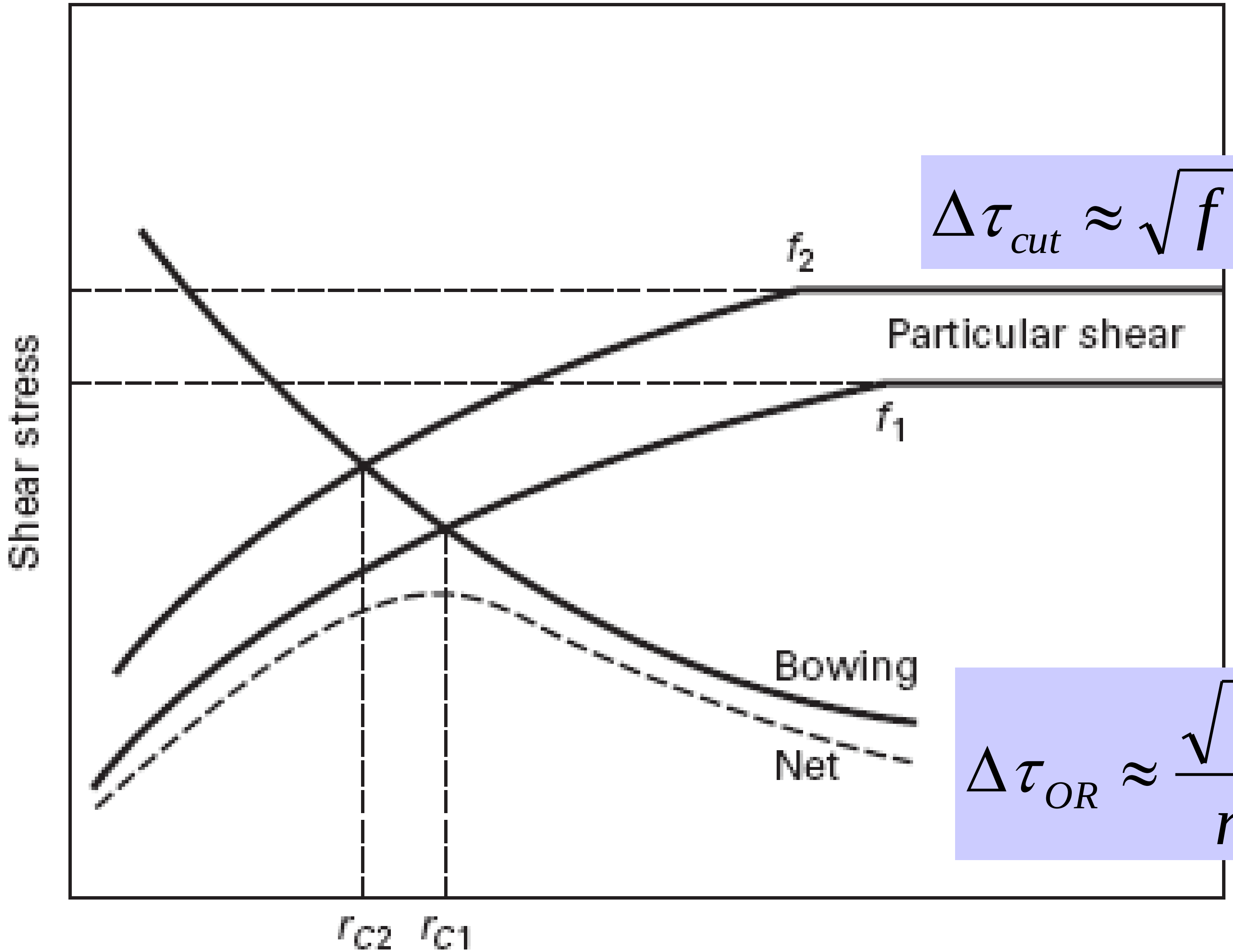


$$c_F = \frac{1}{l_F^2} = \frac{3f}{2\pi r^2}$$

$$\Delta\tau_{cut} \approx \sqrt{f}\sqrt{r}$$

$$\Delta\tau_{cut} = \sqrt{\frac{3}{2\pi}} \cdot \sqrt{\frac{\gamma^3}{G}} \cdot \frac{1}{b^2} \cdot \sqrt{f \cdot r}$$

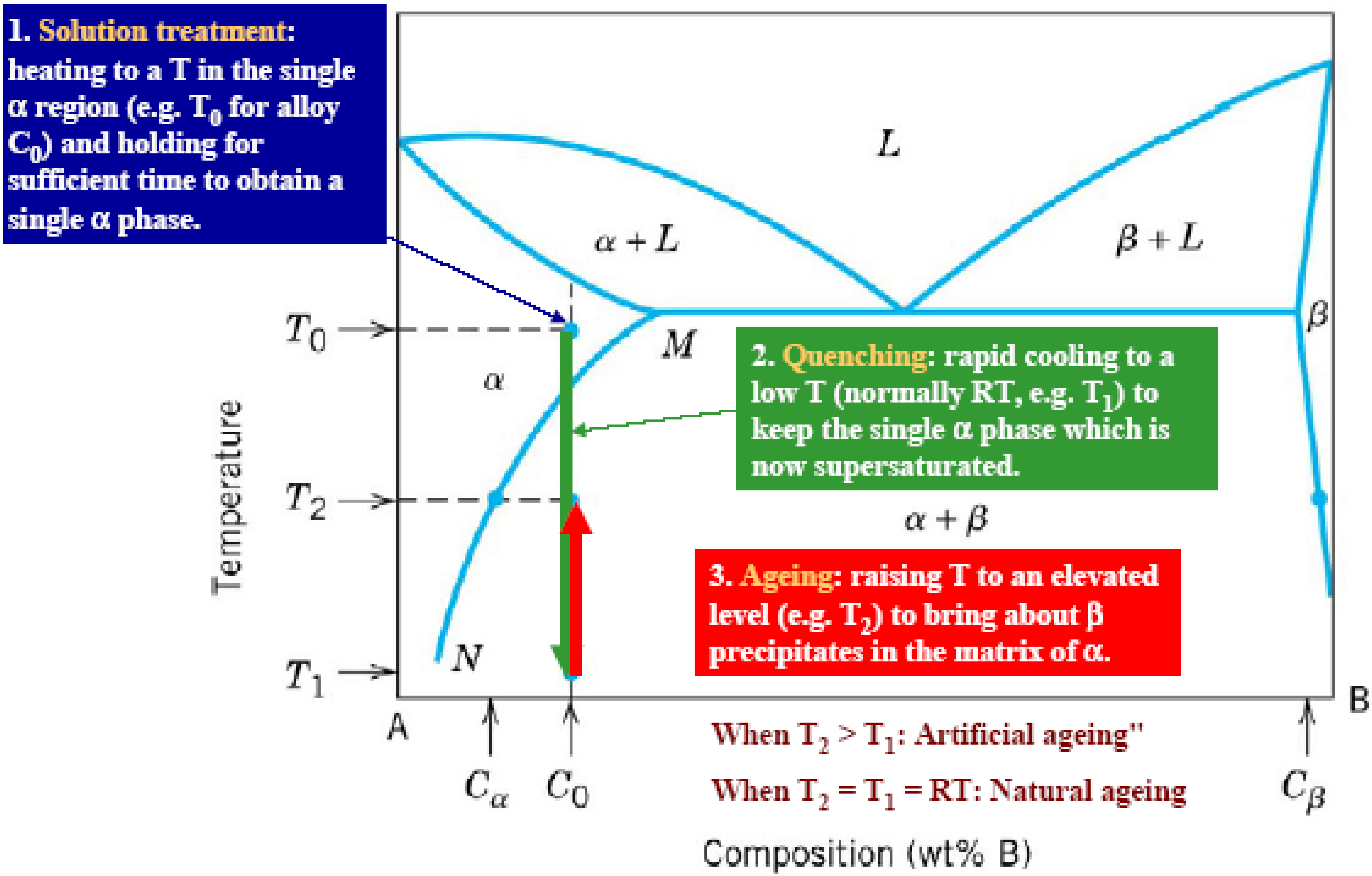
By-passing and cutting mechanism



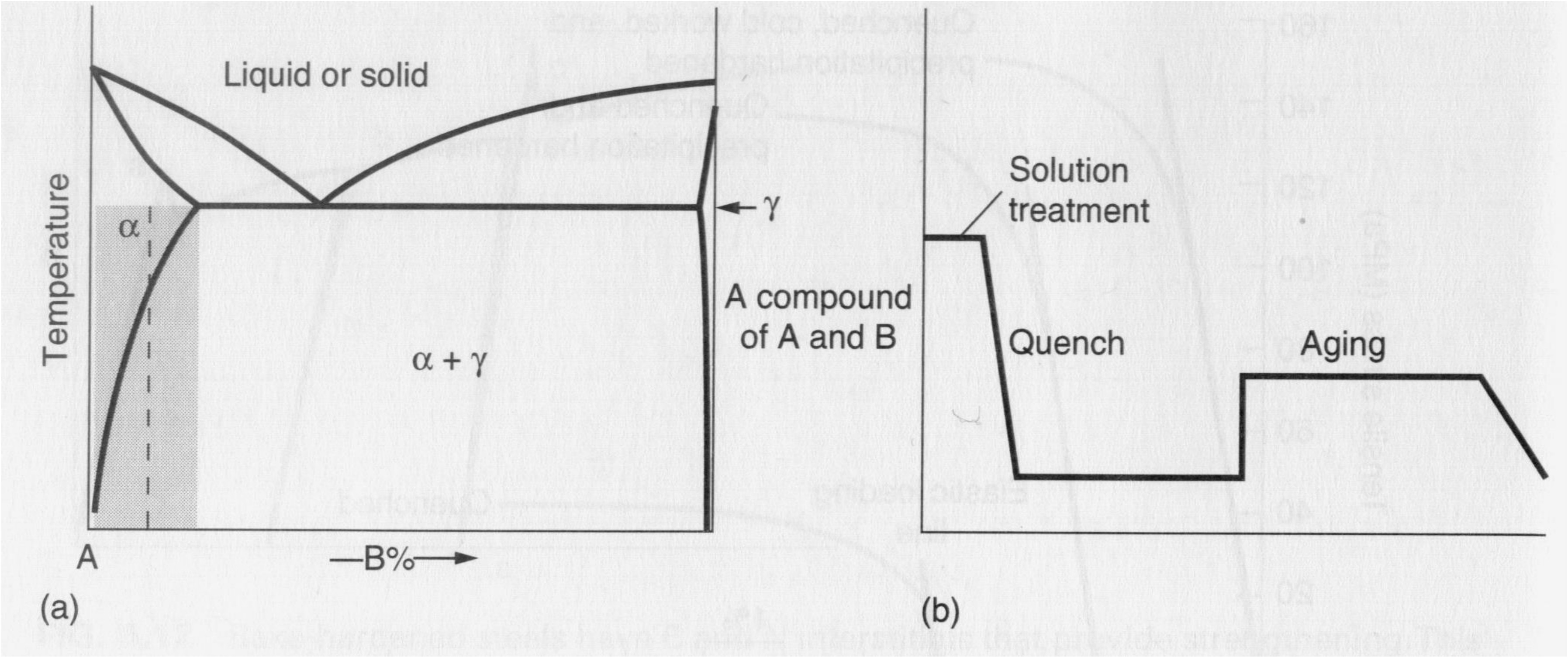
$$\Delta\tau_{cut} \approx \sqrt{f}\sqrt{r}$$

$$\Delta\tau_{OR} \approx \frac{\sqrt{f}}{r}$$

Precipitation treatment



Precipitation treatment



From K. Bowman, “mechanical behavior of materials”, John Wiley & Sons Inc, 2004.

Precipitation treatment

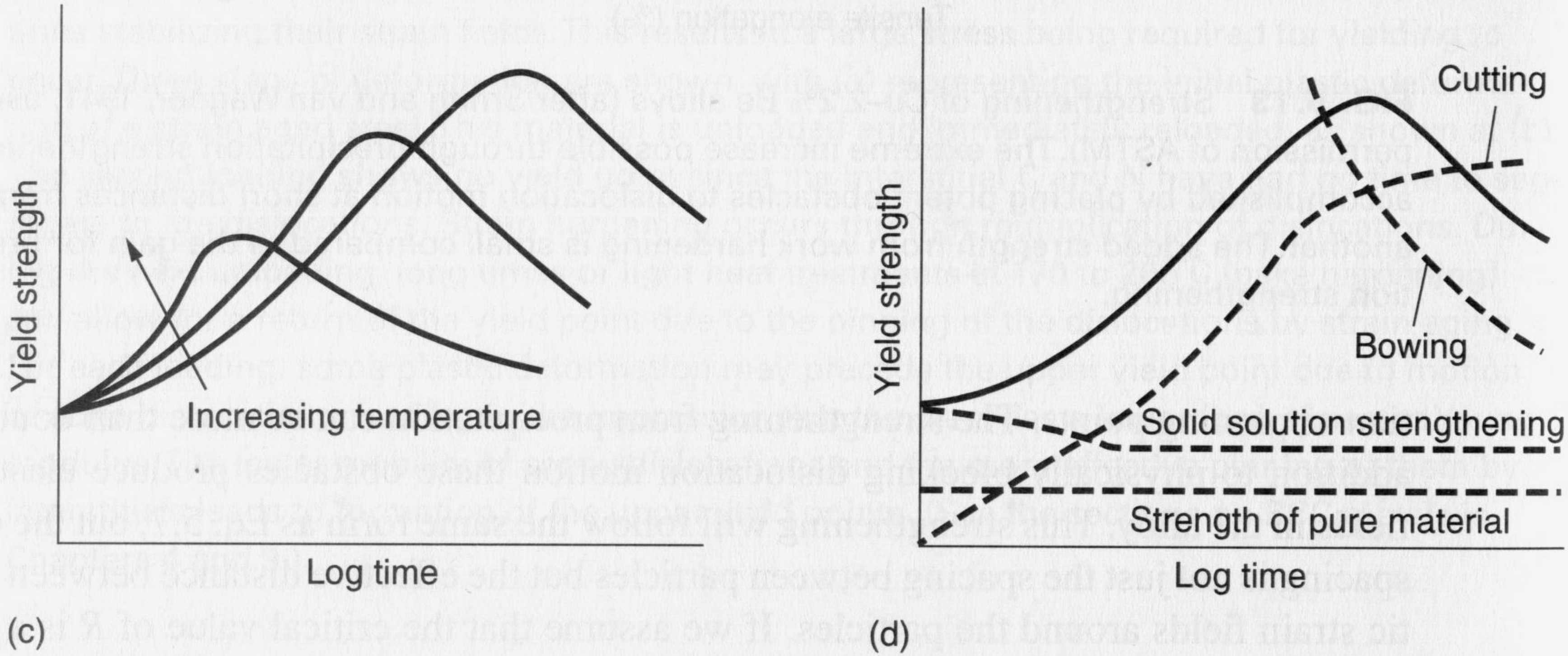


FIG. 5.14 (a) Typical phase diagram for the potential of precipitation strengthening with γ being an intermetallic of elements A and B. (b). A possible process map for the alloy designated with a dashed line in part (a). (c) The effect of aging temperature on the time to peak strength in precipitation strengthened alloys. (d) The contributions from different strengthening mechanisms given as dashed lines add up to the total strength as a function of aging time.

From K. Bowman, “mechanical behavior of materials”, John Wiley & Sons Inc, 2004.

Al-Cu Phase diagram

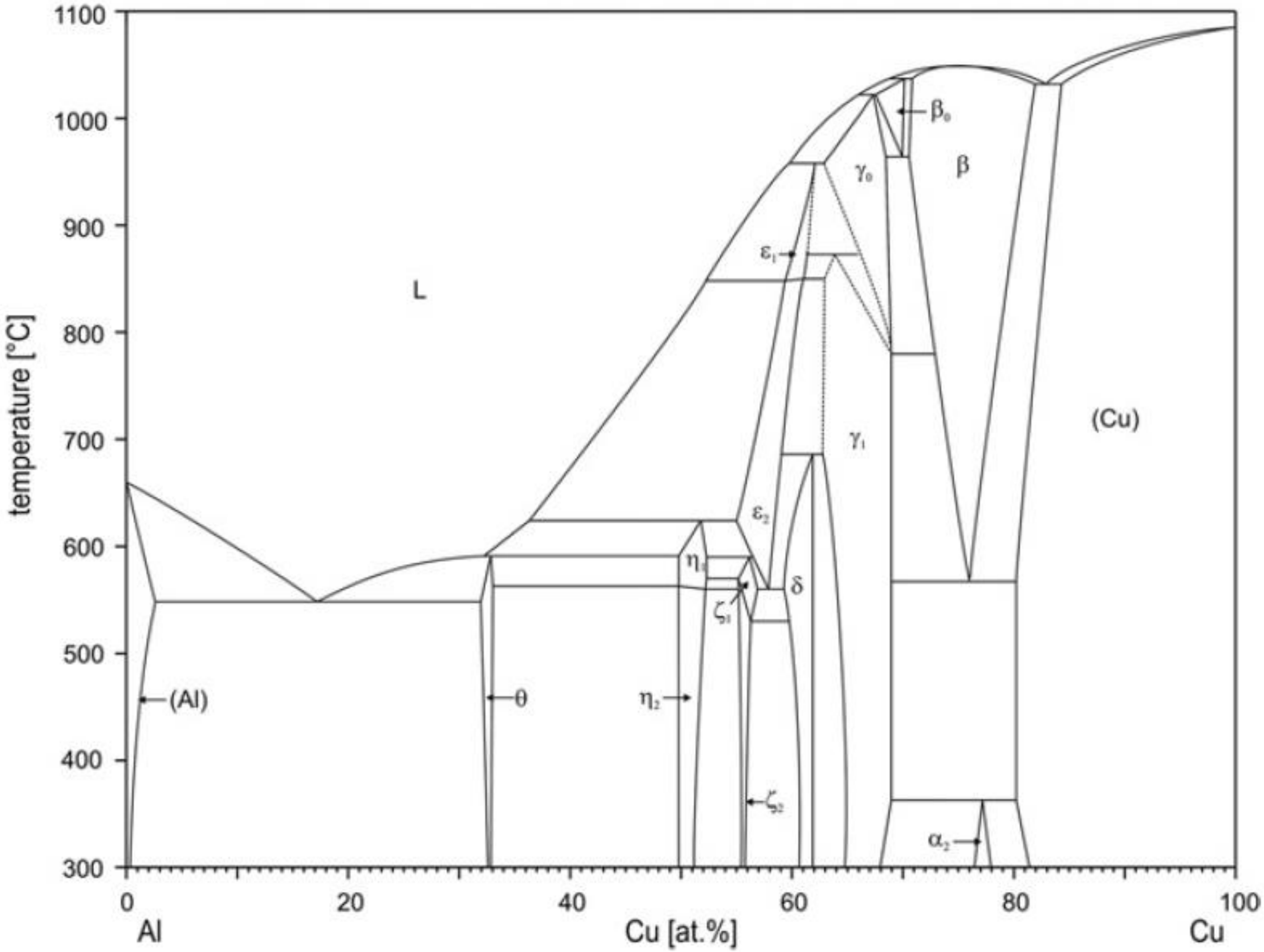
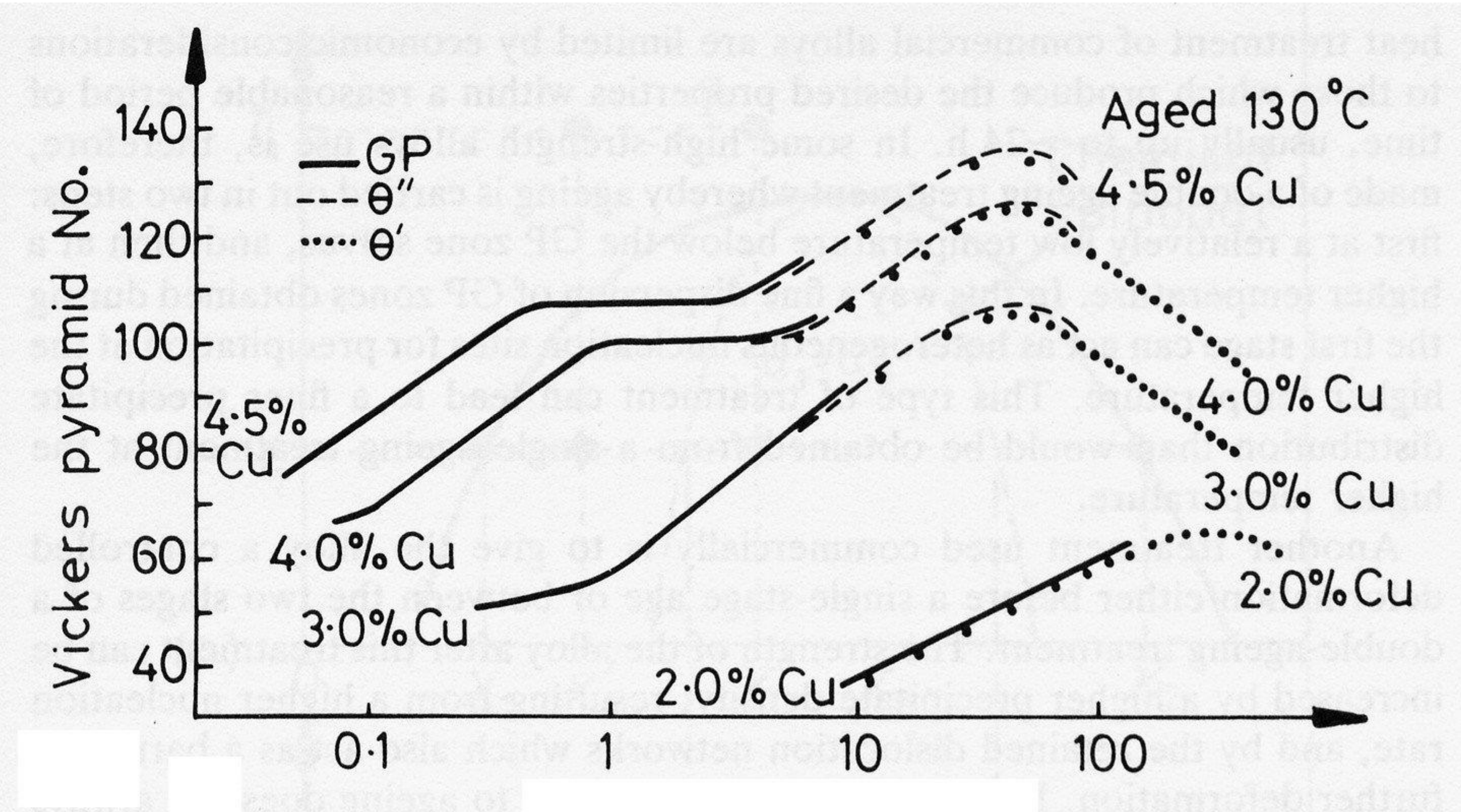


Fig. 1. The Al–Cu phase diagram according to Murray [1].

Al-Cu Precipitation



Summary of Strengthening mechanisms

- Zero dimensional defect: Solid Solution strengthening

  solute atoms –dislocations interaction

$$\Delta\tau_{sol} \approx \varepsilon \cdot \Delta c$$

- 1 dimensional defect: Cold working strengthening

  dislocations –dislocations interaction

$$\Delta\tau_{dis} = \alpha G b \sqrt{\rho}$$

- 2 dimensional defect: Grain boundary strengthening

  grain boundary –dislocations interaction

$$\Delta\tau_{gb} = k d^{-1/2}$$

- 3 dimensional defect: Second phase strengthening

  Precipitation/ Dispersion –dislocations interaction

$$\Delta\tau_{c} \approx \sqrt{f}\sqrt{r}$$

$$\Delta\tau_{OR} \approx= \frac{\sqrt{f}}{r}$$