

EPFL

Physics of Materials

Chapter 8: Dislocation Kinetics

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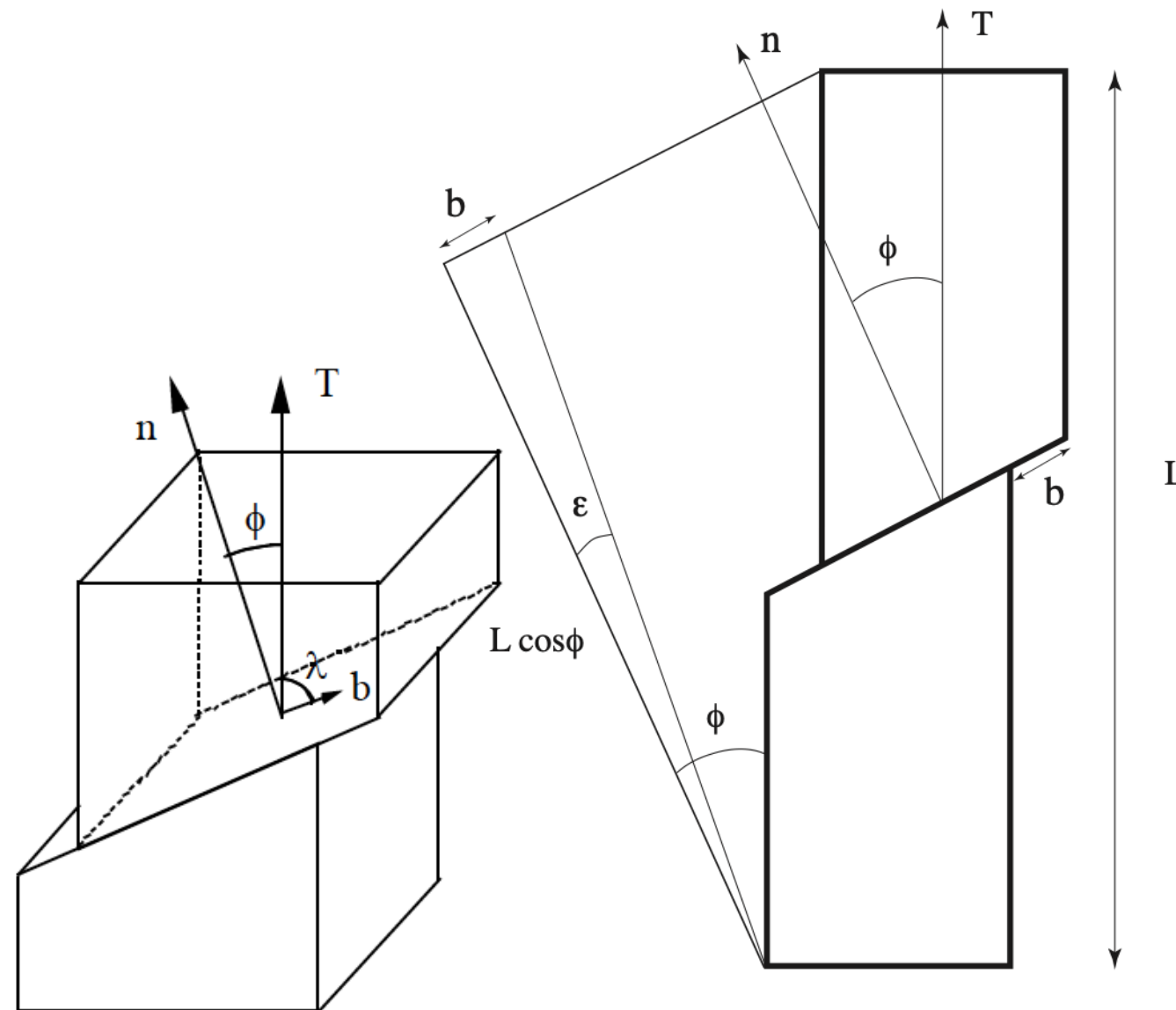


Masters Course PHYS-307

Fall 2024

Orowan equation

$$\dot{\epsilon} = \Lambda b \dot{u} = \Lambda b v$$



Elongation of the test-sample $\gamma = \frac{dL}{L}$

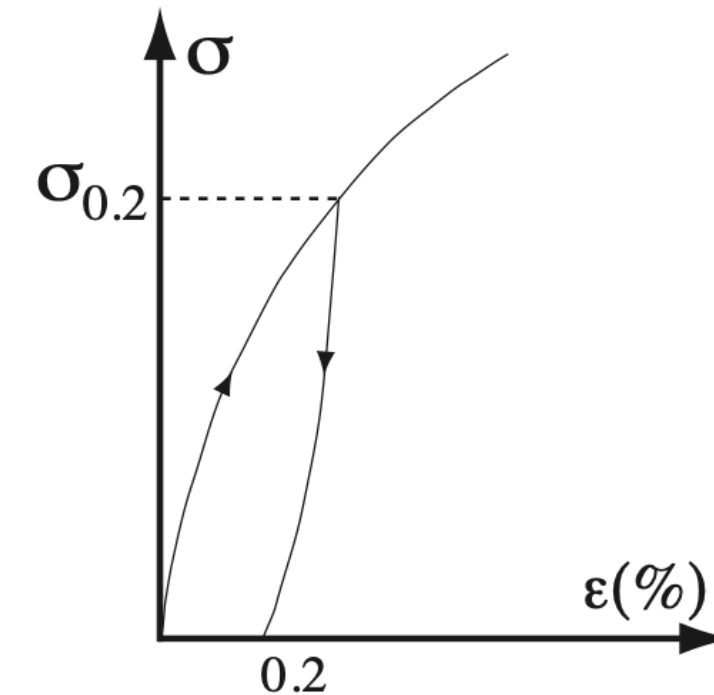
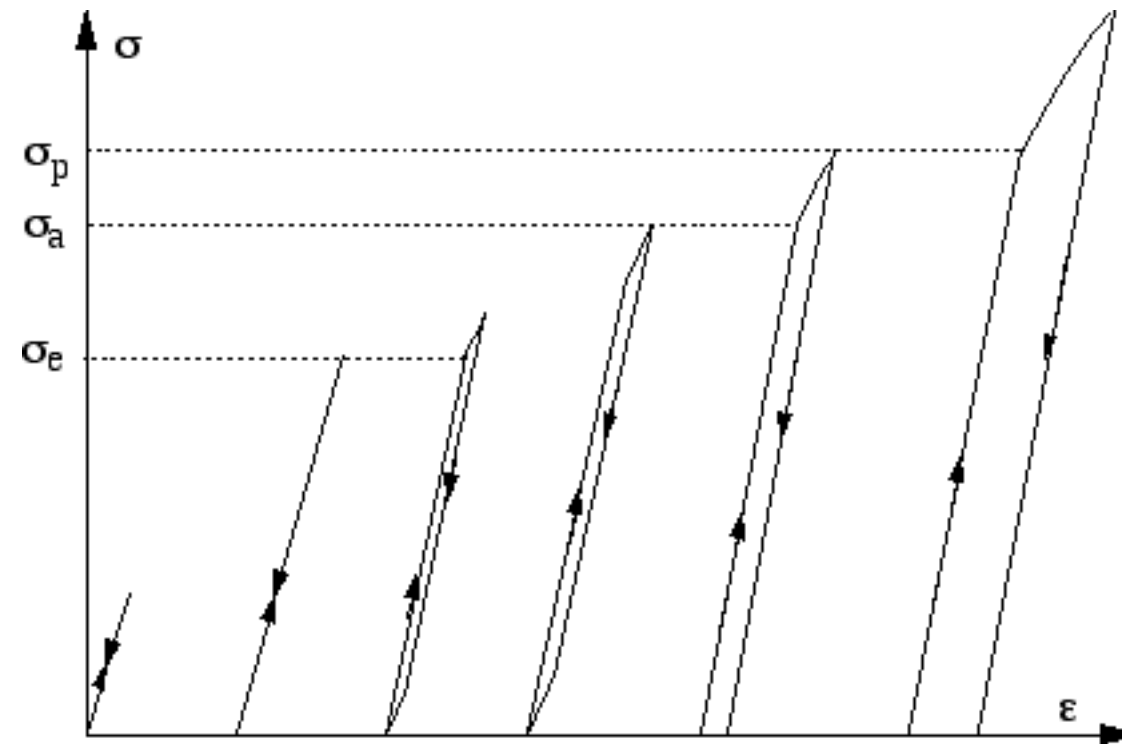
$$\epsilon = \frac{b}{L \cos \phi} \quad \gamma = \frac{b \cos \lambda}{L}$$



$$\gamma = \cos \lambda \cos \phi \cdot \epsilon = m \cdot \epsilon$$

m is the Schmid factor

Deformation curve

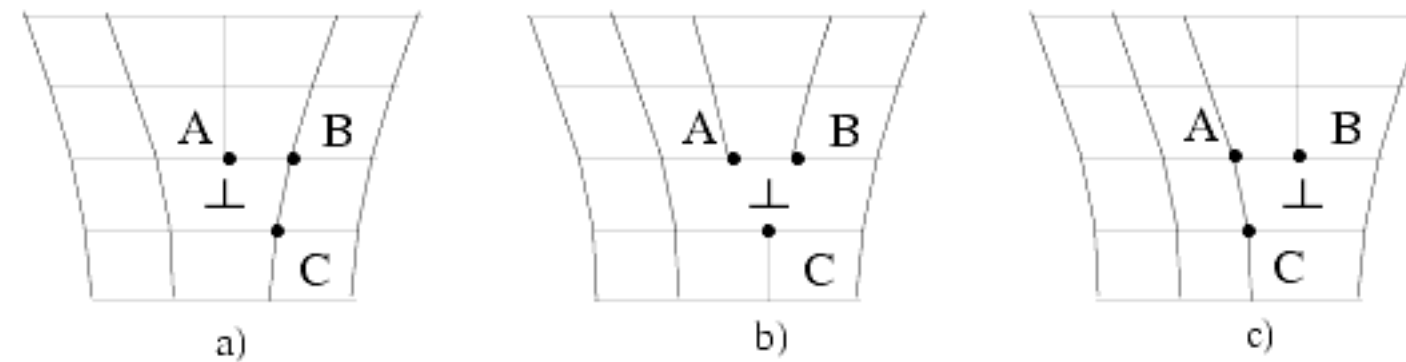


Yield stress

The dislocations movement is controlled by:

- 1) interactions with the lattice (Peierls-Nabarro Force)
- 2) interactions with other dislocations (and image forces)
- 3) interaction with point defects (solute drag)
- 4) interactions with extended defects (precipitates, grain boundaries)

Interaction of dislocations with the crystal lattice



Free energy $\Delta G = W(x) - \sigma b x$

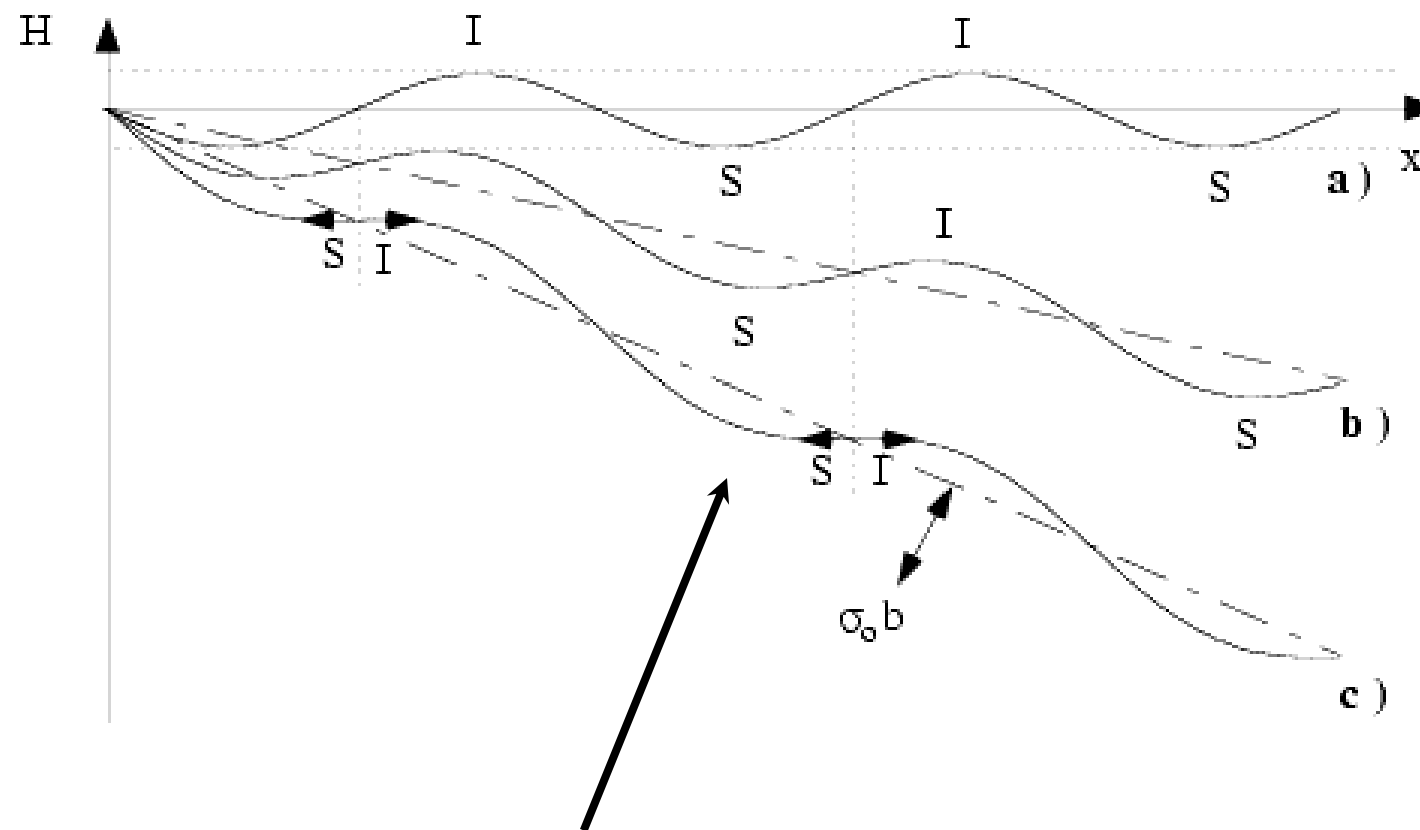
There is movement if:

$$\frac{\partial W(x)}{\partial x} - \sigma_0 b = 0$$

Potential

$$W(x) = -\left(\frac{\tau_I - \tau_S}{2}\right) \sin \frac{2\pi x}{a}$$

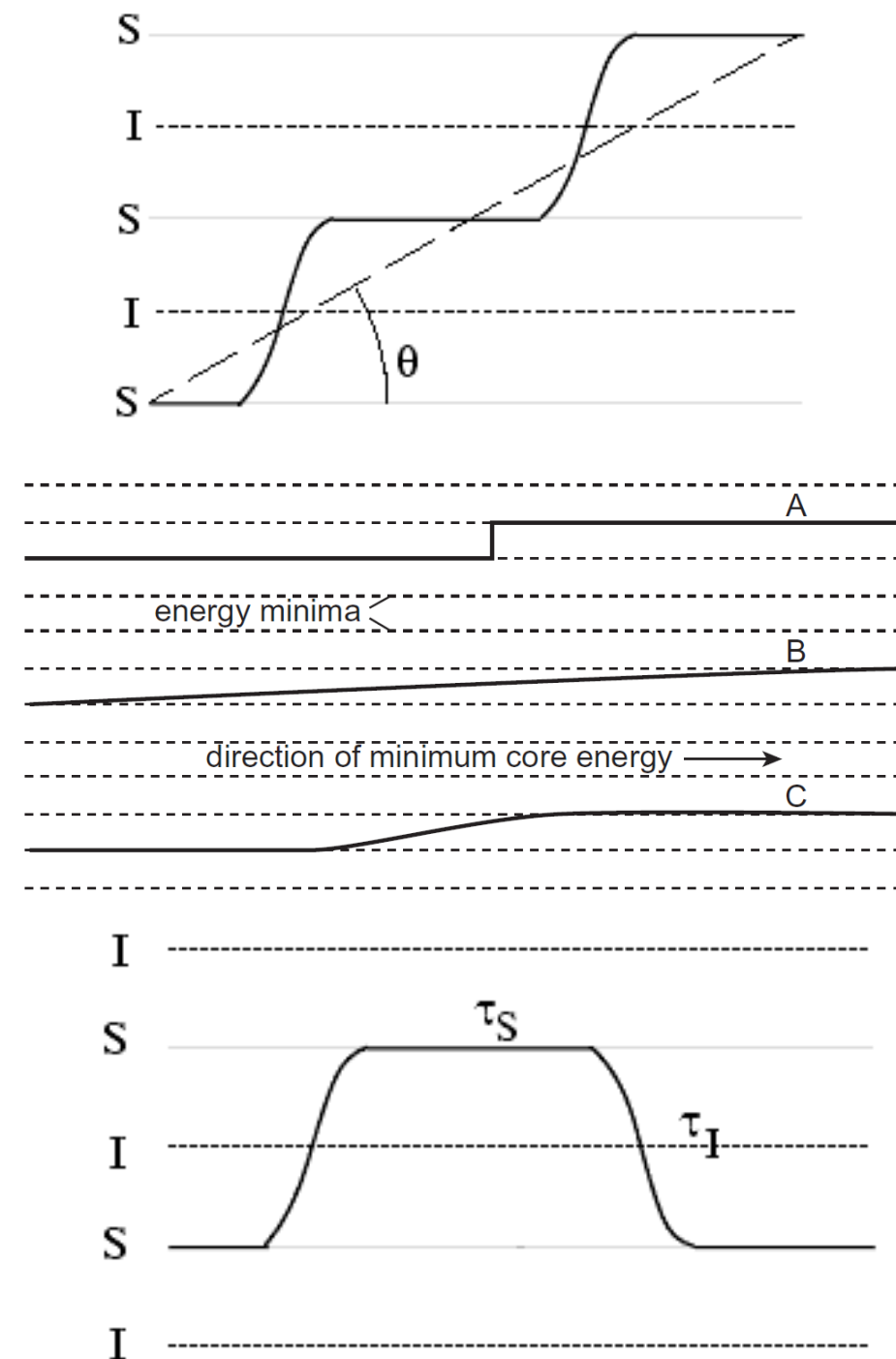
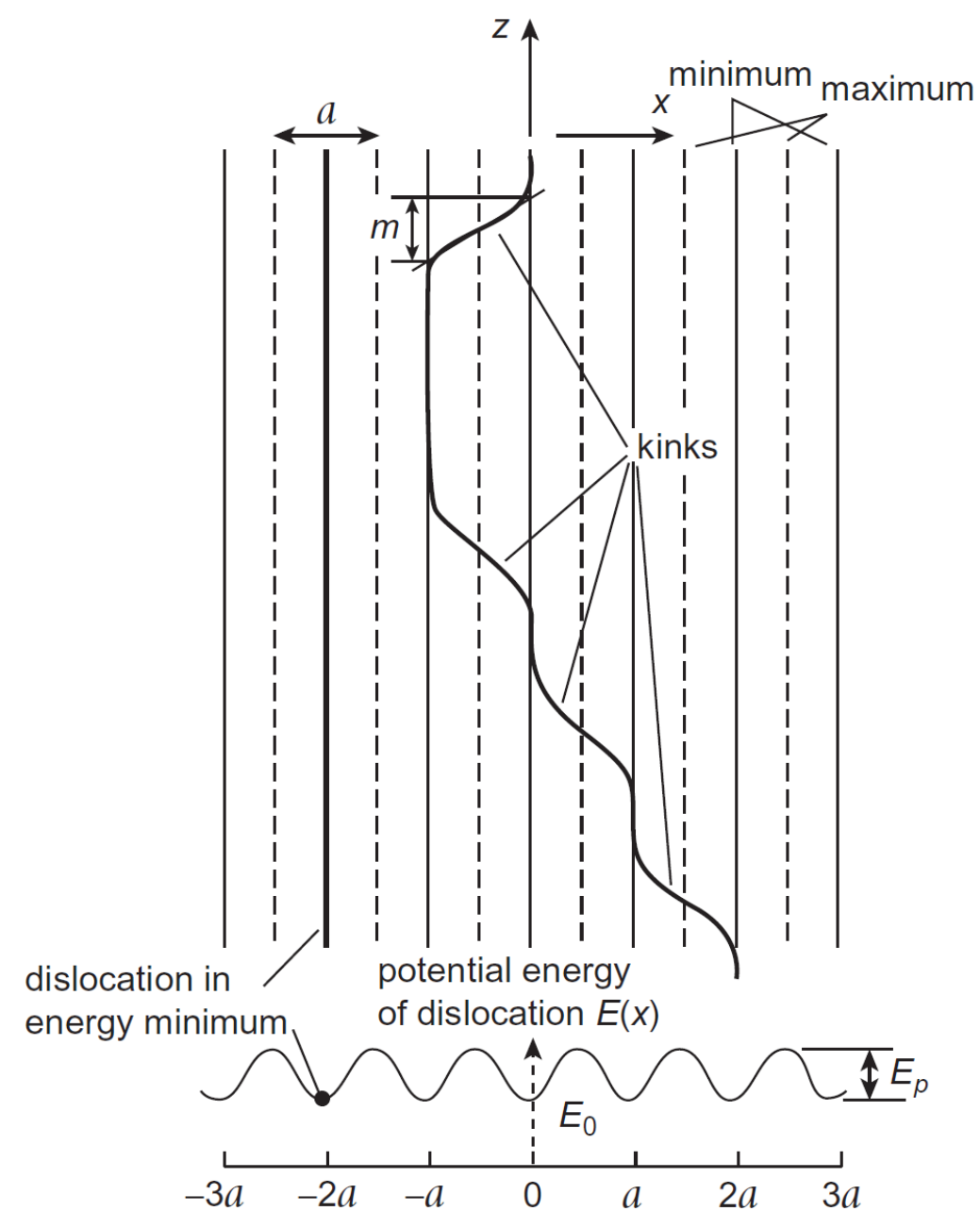
$$\frac{\partial W(x)}{\partial x} = -\frac{\pi}{a} (\tau_I - \tau_S) \cos \frac{2\pi x}{a}$$



Horizontal tangent:

$$\frac{2\pi x}{a} = \pi \quad \sigma_0 b = \frac{\pi}{a} (\tau_I - \tau_S) \quad \sigma_0 = \frac{\pi}{ab} (\tau_I - \tau_S)$$

Kinks

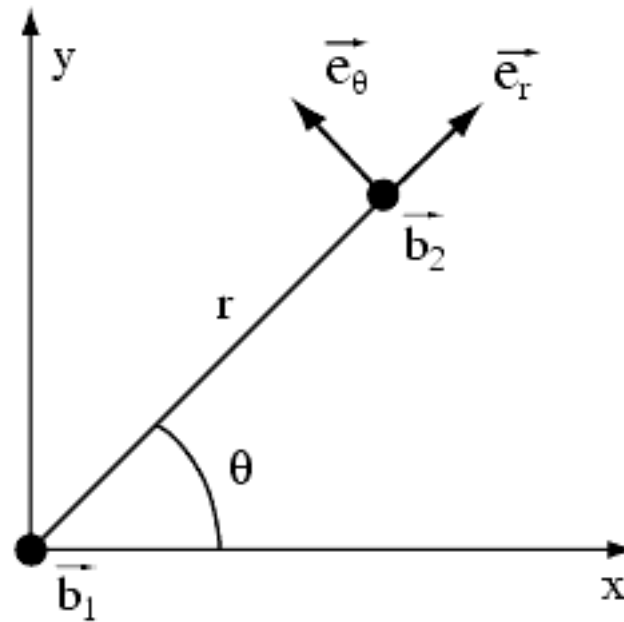


Double Kink
mechanism

We get a Peierls stress of order $\frac{\mu}{1000}$

Interaction between dislocations

Two parallel screw dislocations



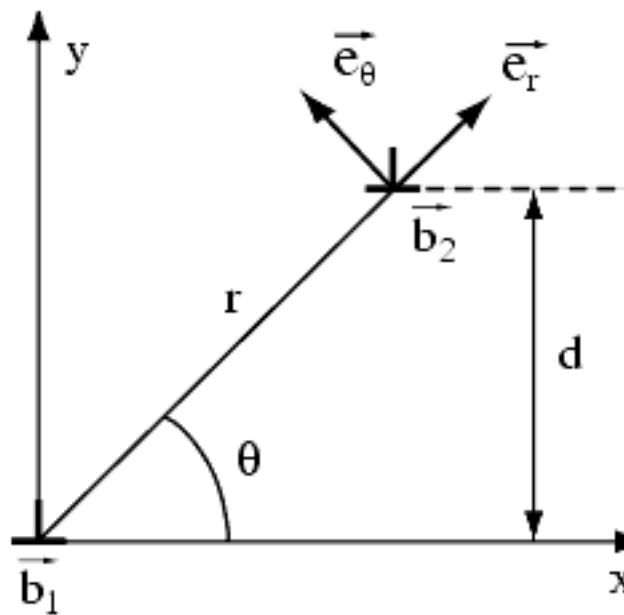
$$\vec{b}_1 = (0, 0, b_1)$$

$$\vec{b}_2 = (0, 0, b_2)$$

$$\sigma_{\theta z} = \frac{\mu b_1}{2\pi r}$$

$$F_r = b_2 \sigma_{\theta z} = \frac{\mu b_1 b_2}{2\pi r} = \pm \frac{\mu b^2}{2\pi r}$$

Two parallel edge dislocations



$$\vec{b}_1 = (b_1, 0, 0)$$

$$\vec{b}_2 = (b_2, 0, 0)$$

$$F_x = b_2 \sigma_{xy}$$

$$F_y = -b_2 \sigma_{xx}$$

$$D = \frac{\mu b}{2\pi(1-\nu)}$$

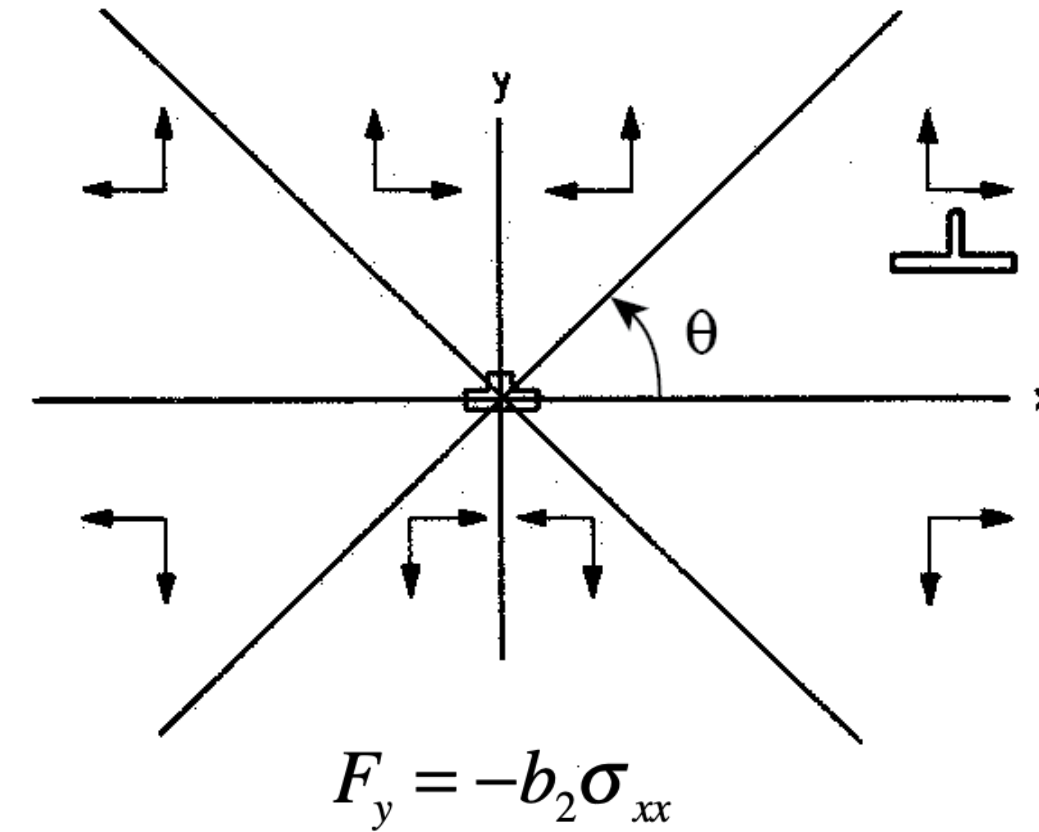
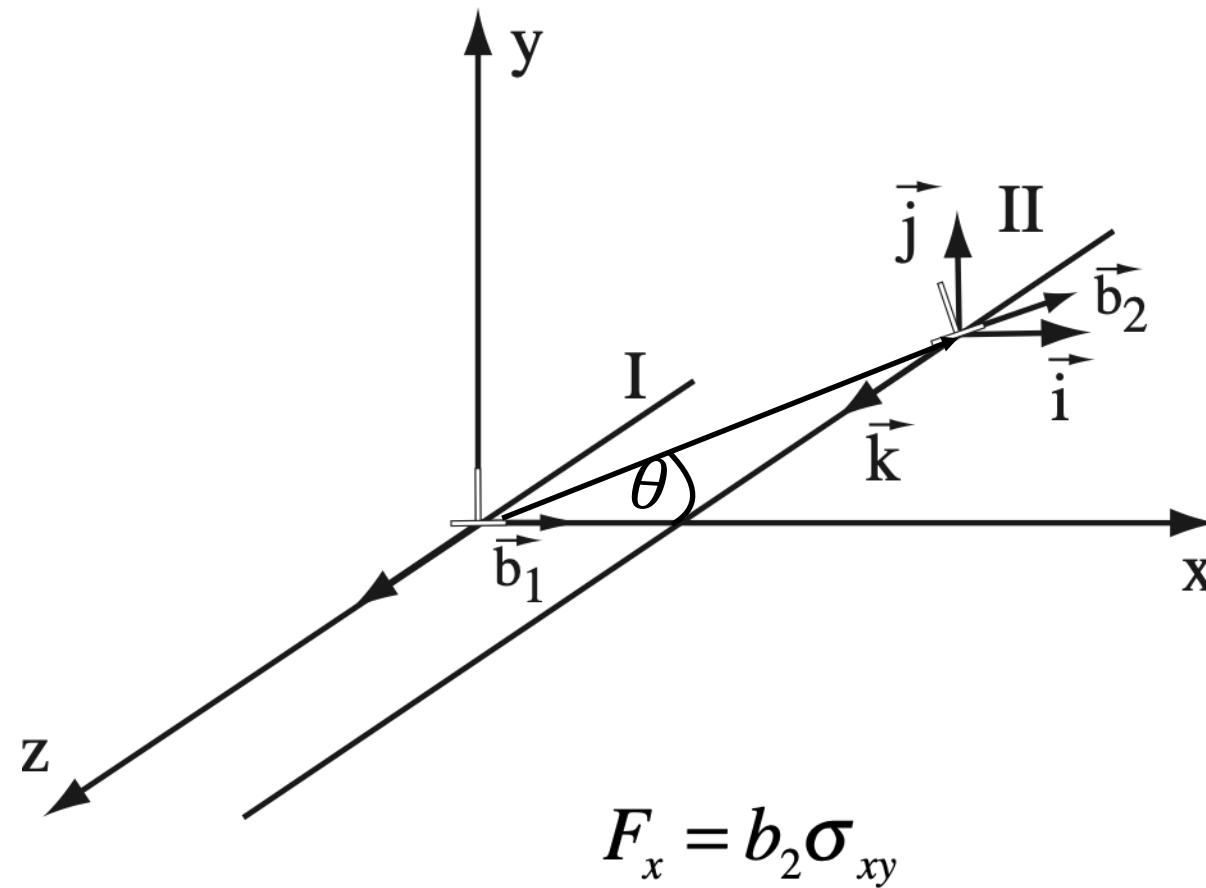
$$\sigma_{xy} = D \frac{\cos \theta \cos 2\theta}{r}$$

$$\sigma_{xx} = -D \frac{\sin \theta (2 + \cos 2\theta)}{r}$$

$$F_x = \frac{\mu b_1 b_2}{2\pi(1-\nu)} \frac{\cos \theta \cos 2\theta}{r}$$

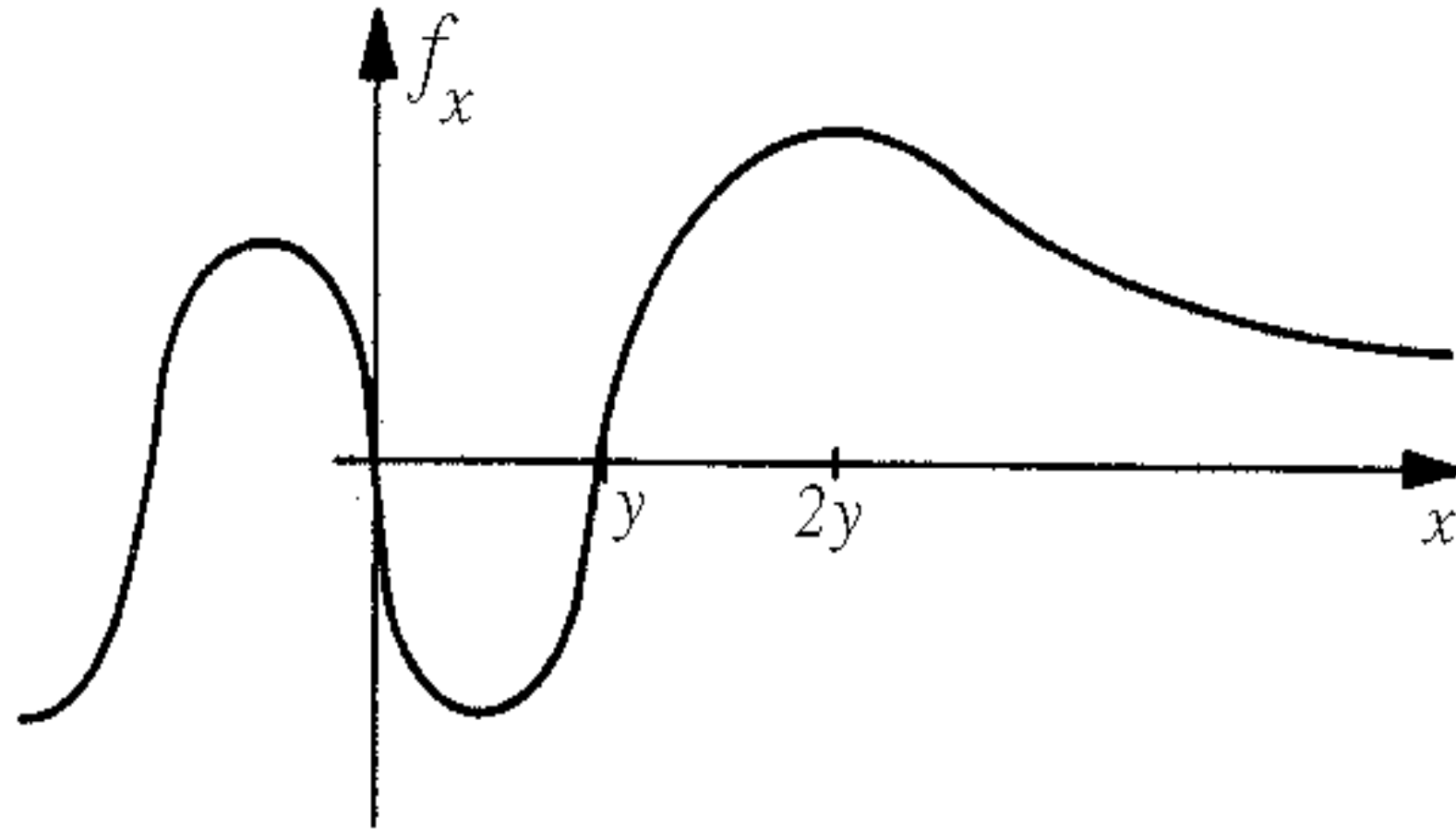
$$F_y = \frac{\mu b_1 b_2}{2\pi(1-\nu)} \frac{\sin \theta (2 + 2 \cos 2\theta)}{r}$$

Solution of the problem: 2 edge dislocations interaction

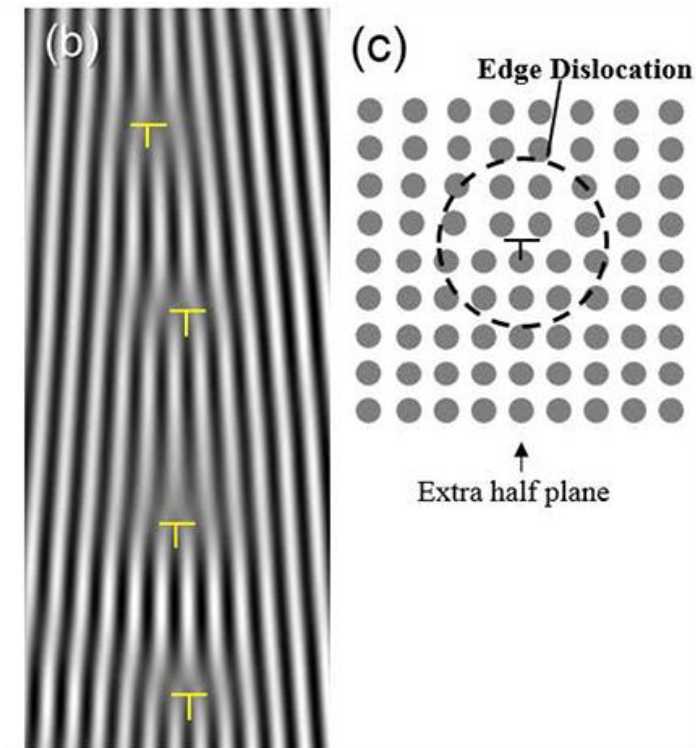
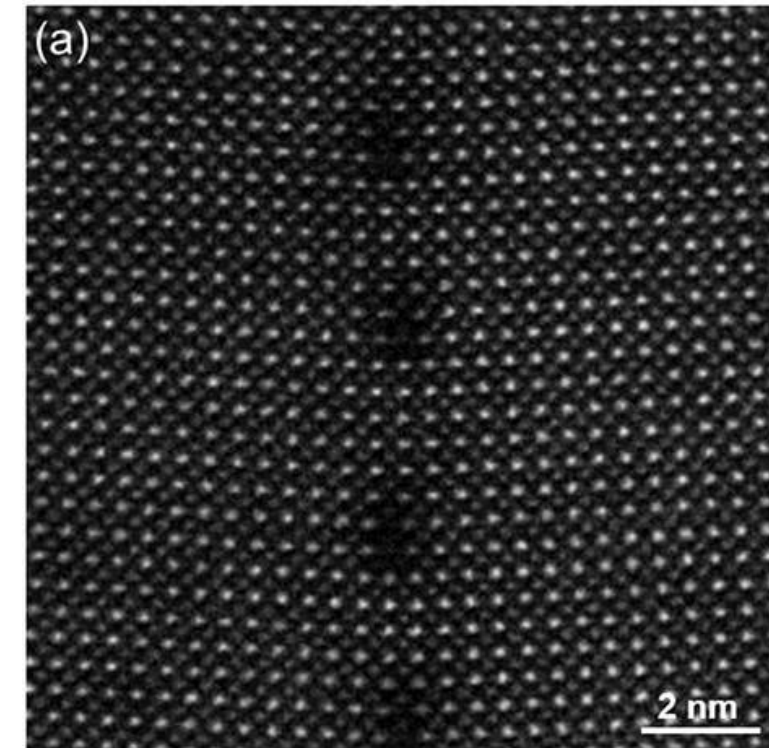


$$f_x = \frac{\mu b_1 b}{2\pi(1-\nu)} \cdot \frac{\cos\theta \cos 2\theta}{r} \quad \text{and} \quad f_y = \frac{\mu b_1 b}{2\pi(1-\nu)} \cdot \frac{\sin\theta (2+\cos 2\theta)}{r}$$

The Peach Koehler Force between edges dislocation explains small angle grain boundary formation



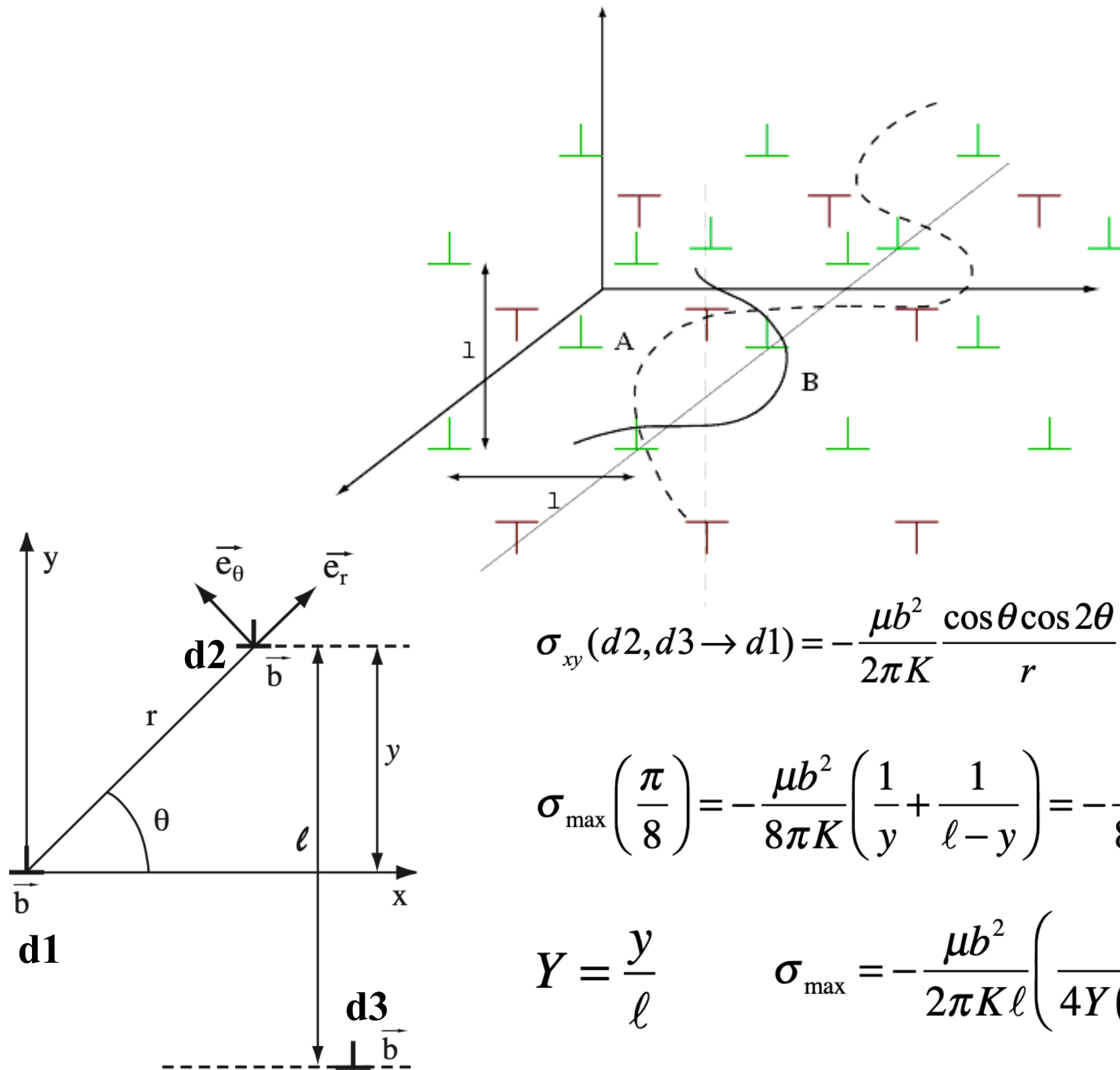
$$f_x = \frac{\mu b_1 b}{2\pi(1-\nu)} \frac{x(x^2 - y^2)}{(x^2 + y^2)^2}$$



Dislocations: long distance interaction

Frank Network

e.g., contains parallel edge dislocation lying on parallel (111) glide planes (green same $\vec{b}$ and black opposite $-\vec{b}$)

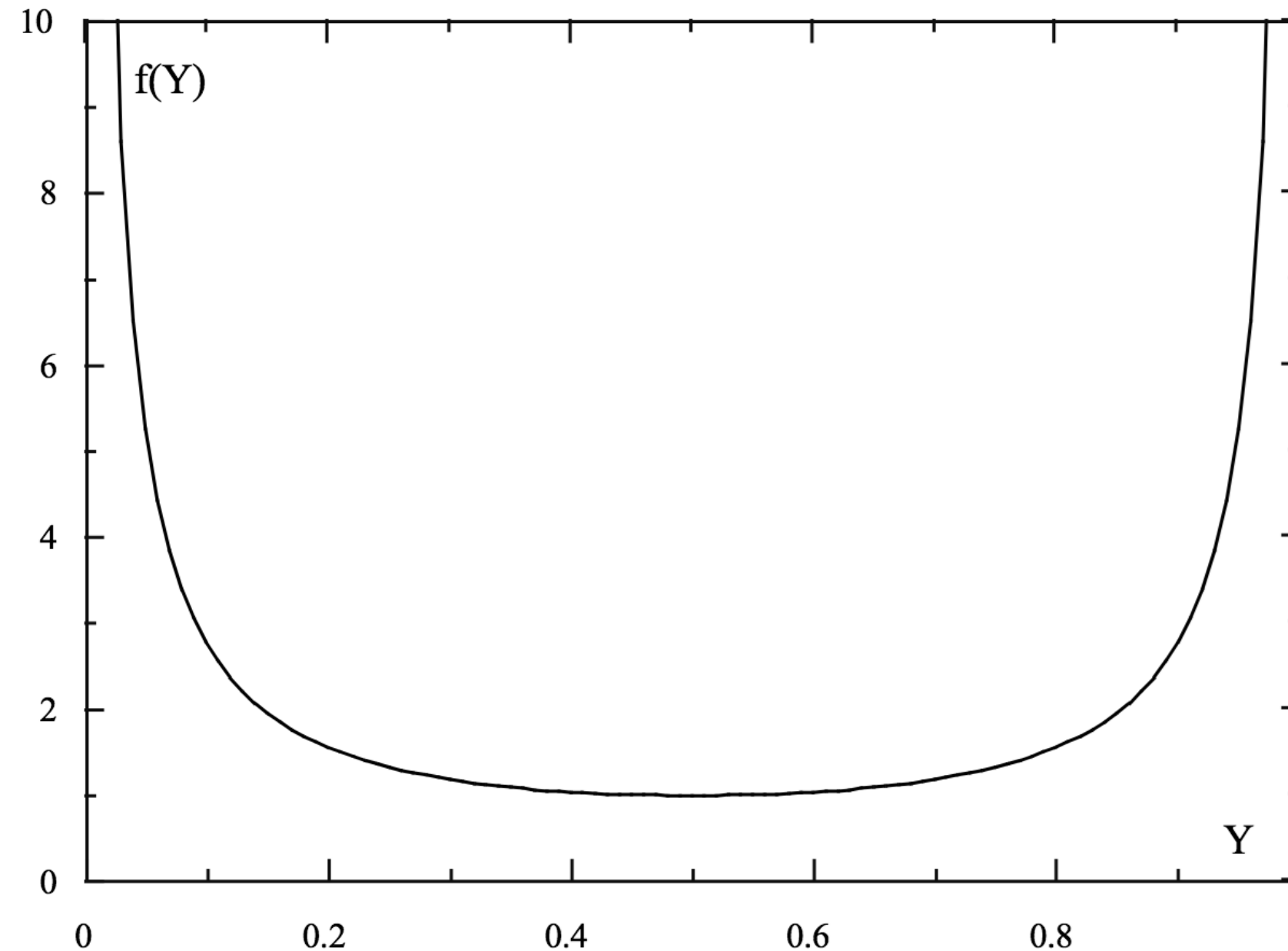


$$\sigma_{xy}(d2, d3 \rightarrow d1) = -\frac{\mu b^2}{2\pi K} \frac{\cos \theta \cos 2\theta}{r} = -\frac{\mu b^2}{4\pi K} \frac{\sin 2\theta \cos 2\theta}{y} = -\frac{\mu b^2}{8\pi K} \frac{\sin 4\theta}{y}$$

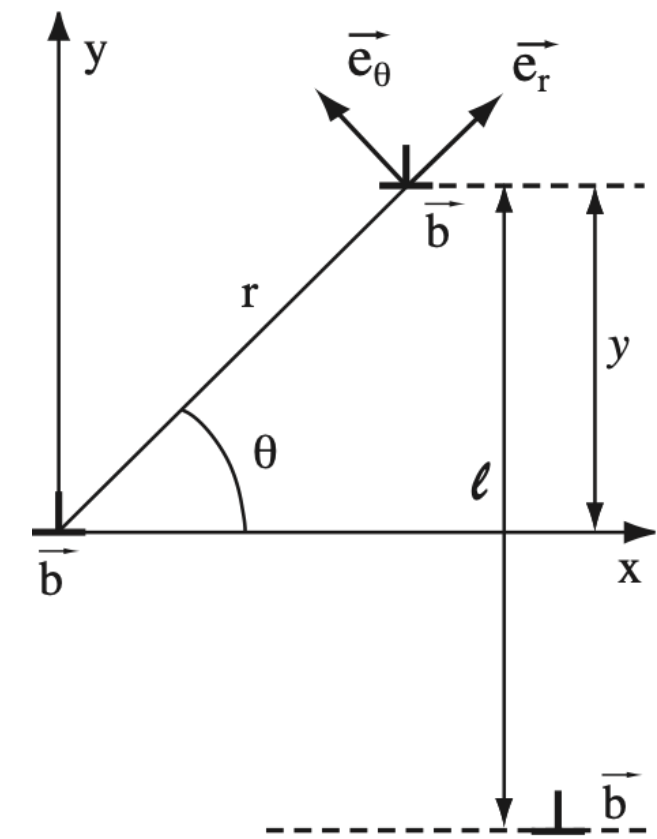
$$\sigma_{\max}\left(\frac{\pi}{8}\right) = -\frac{\mu b^2}{8\pi K} \left(\frac{1}{y} + \frac{1}{\ell - y}\right) = -\frac{\mu b^2}{8\pi K \ell} \left(\frac{\ell}{y(1 - y/\ell)}\right) \quad K = \frac{1 - \nu}{1 - \nu \cos^2 \psi}$$

$$Y = \frac{y}{\ell} \quad \sigma_{\max} = -\frac{\mu b^2}{2\pi K \ell} \left(\frac{1}{4Y(1 - Y)}\right) = -\frac{\mu b^2}{2\pi K \ell} f(Y)$$

Dislocations: long distance interaction

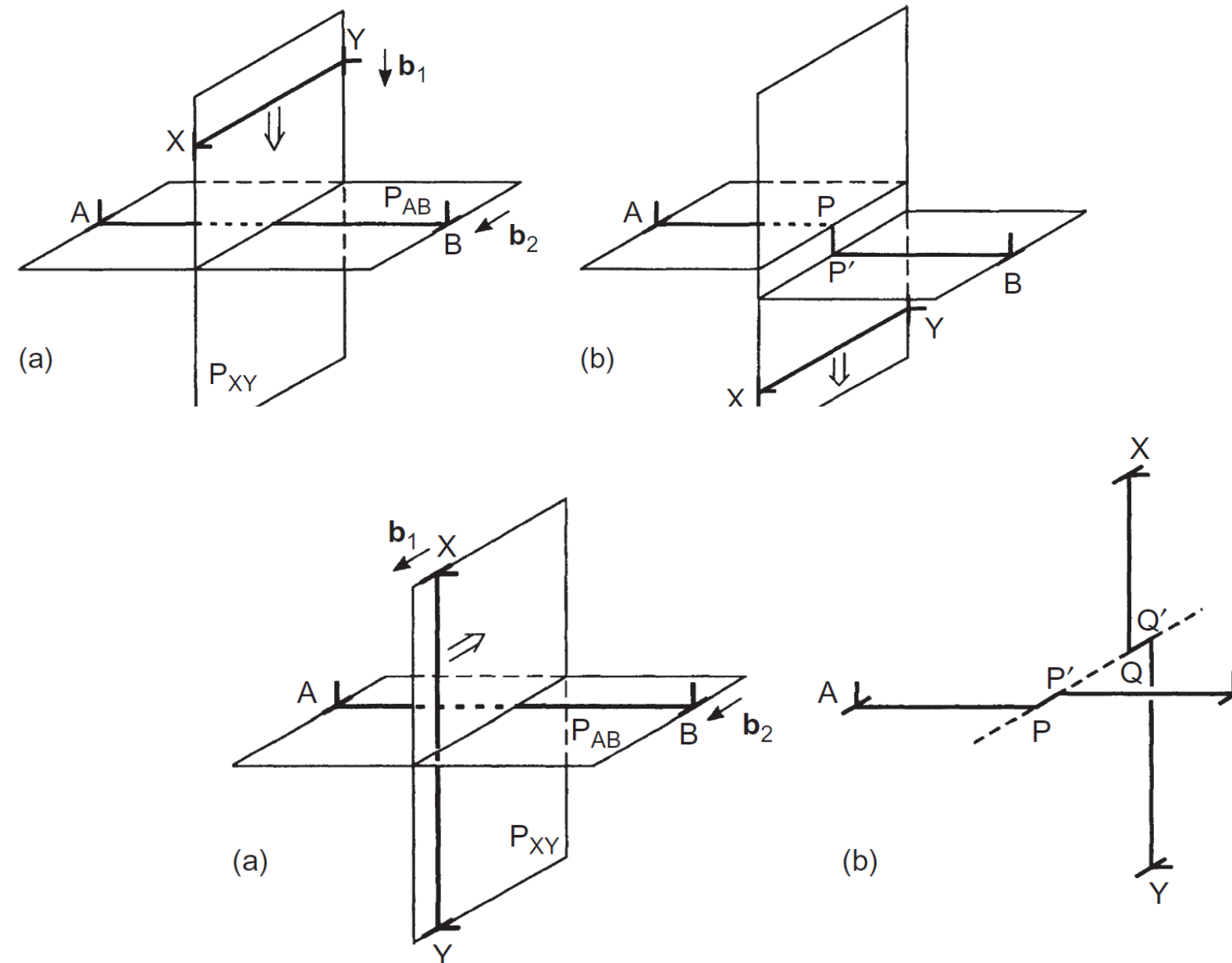


$$\sigma_{\max} = -\frac{\mu b^2}{2\pi K \ell} \left(\frac{1}{4Y(1-Y)} \right) = -\frac{\mu b^2}{2\pi K \ell} f(Y) \quad Y = \frac{y}{\ell}$$



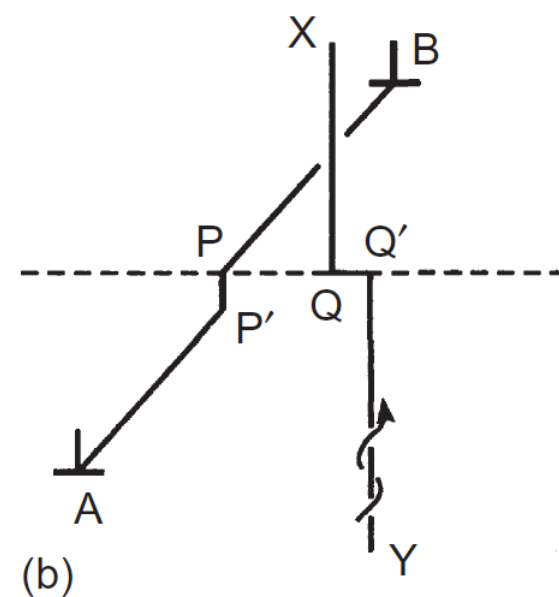
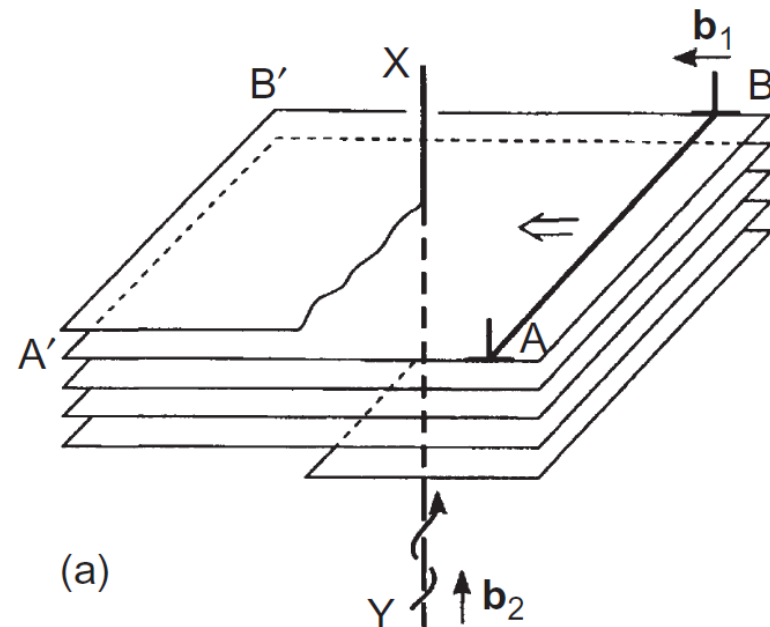
Dislocations: short distance interaction “Jogs”

edge-edge type

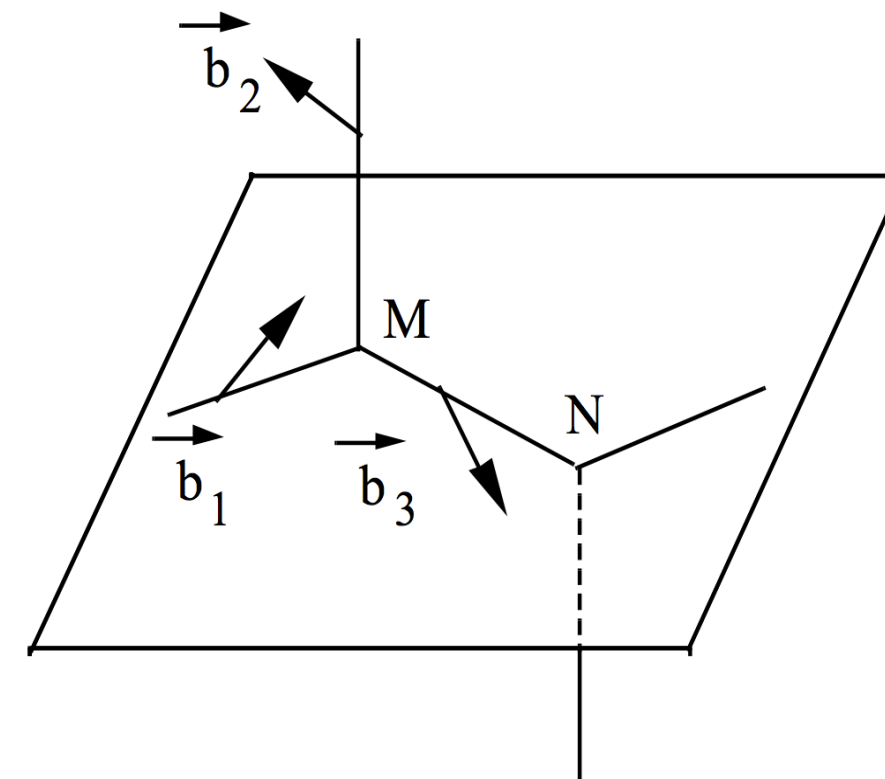


Dislocations: short distance interaction

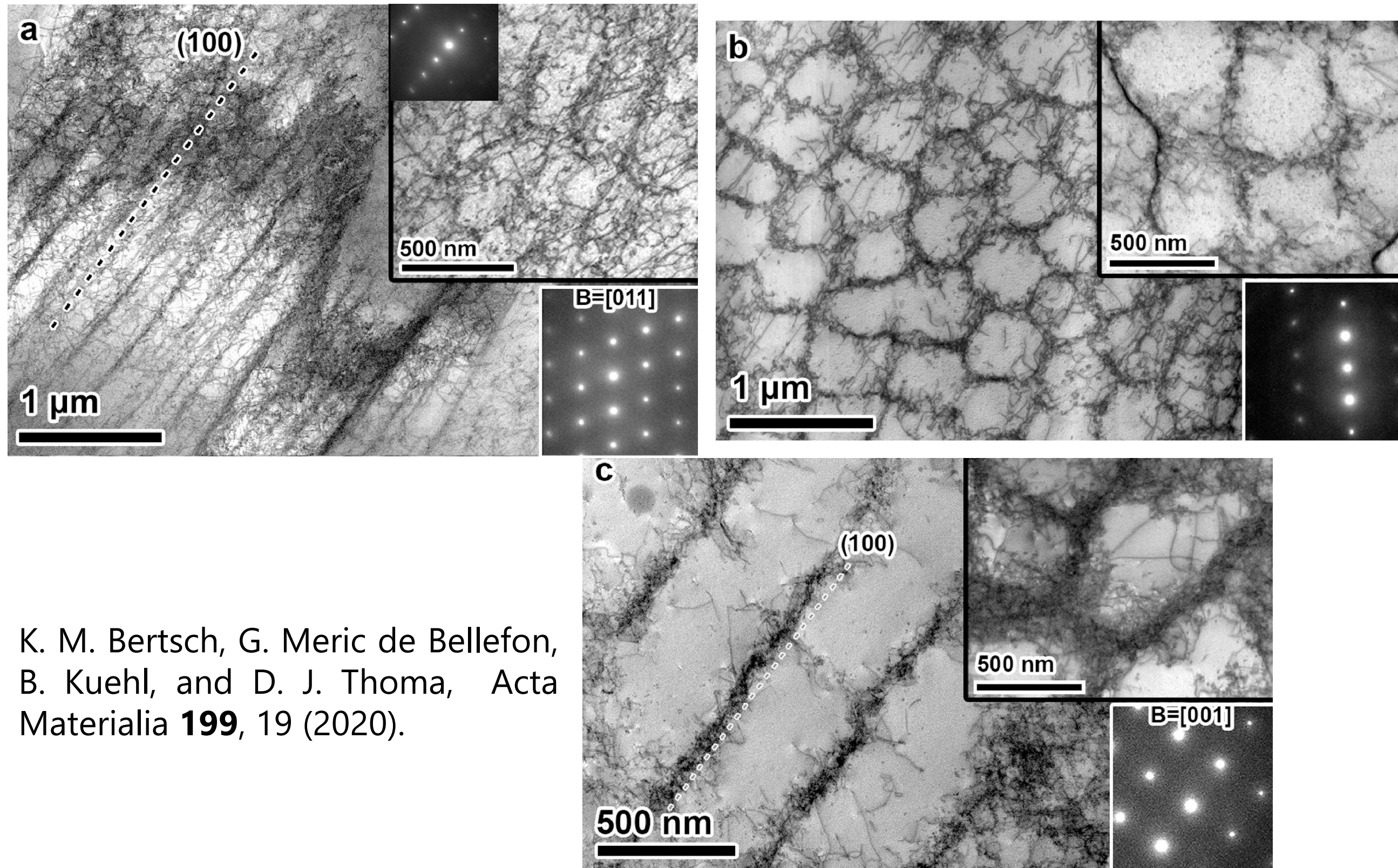
edge-screw



tree

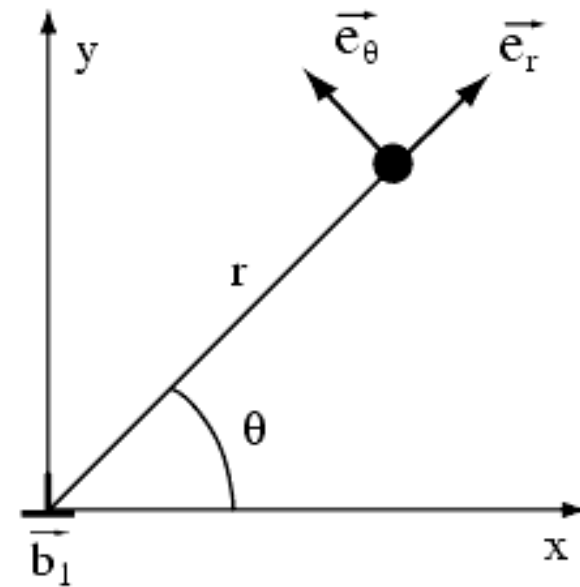


Forests dislocations and Cells



K. M. Bertsch, G. Meric de Bellefon, B. Kuehl, and D. J. Thoma, *Acta Materialia* **199**, 19 (2020).

Elastic interaction with point defects



$$\sigma_p = \frac{1}{3}(\sigma_{11} + \sigma_{22} + \sigma_{33}) = \frac{1}{3}Tr(\sigma)$$

$$\Delta\Omega = \eta\Omega$$

Hydrostatic pressure exerted by the dislocation on the impurity:

$$p = \frac{1}{3} \sum_i \sigma_{ii} = -\frac{\mu b (1+\nu)}{3\pi (1-\nu)} \frac{\sin\theta}{r}$$

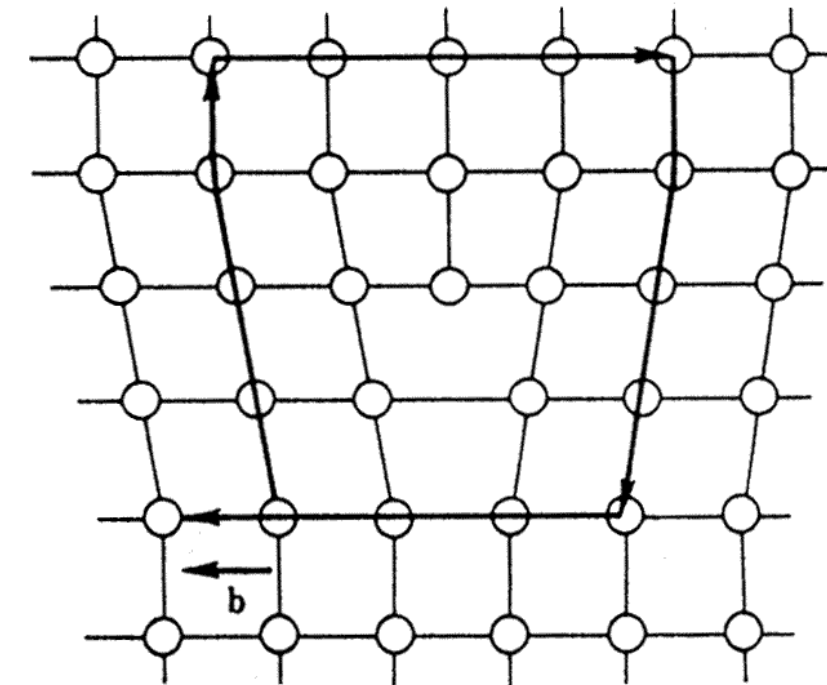
Energy variation from infinite distance:

$$W_\infty - W_I = -p\eta\Omega = \eta\Omega \frac{\mu b (1+\nu)}{3\pi (1-\nu)} \frac{\sin\theta}{r}$$

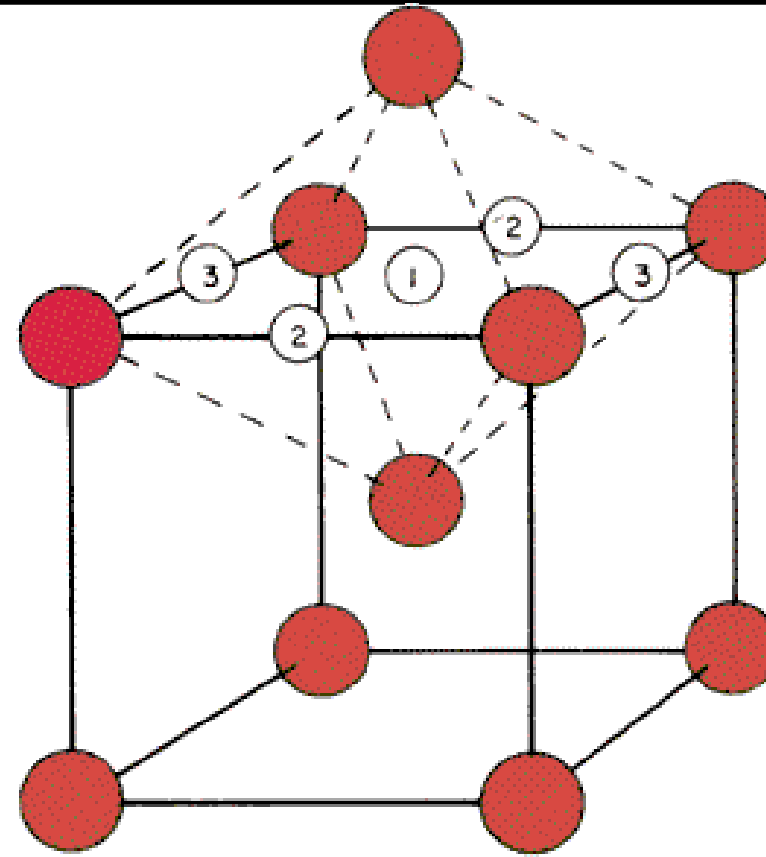
$$\eta < 0 \Rightarrow \sin\theta > 0$$

$$\eta > 0 \Rightarrow \sin\theta < 0$$

lower energy



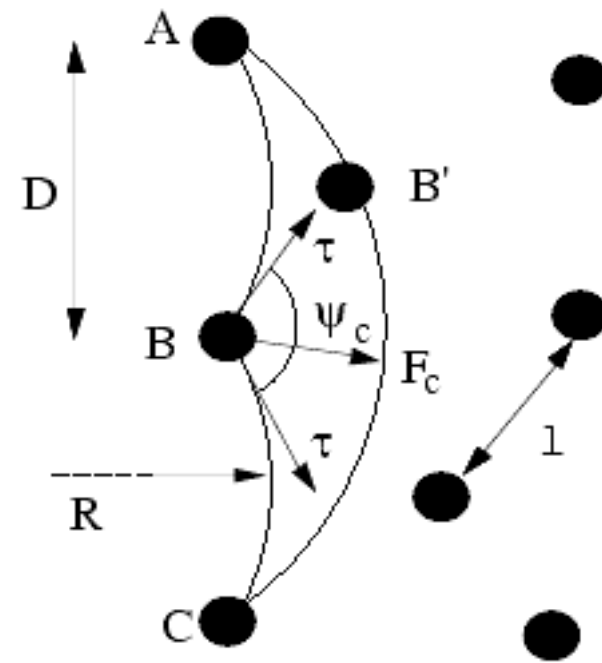
Tetrahedral effect: shear-stress force in BCC



Effect on screw dislocations
e.g., ferritic steel and interaction with
interstitial carbon in bcc Fe lattice

$$W_{tetragonal} > W_{size} > W_{module} > W_{electrostatic}$$

Movement of the dislocation through a distribution of point defects

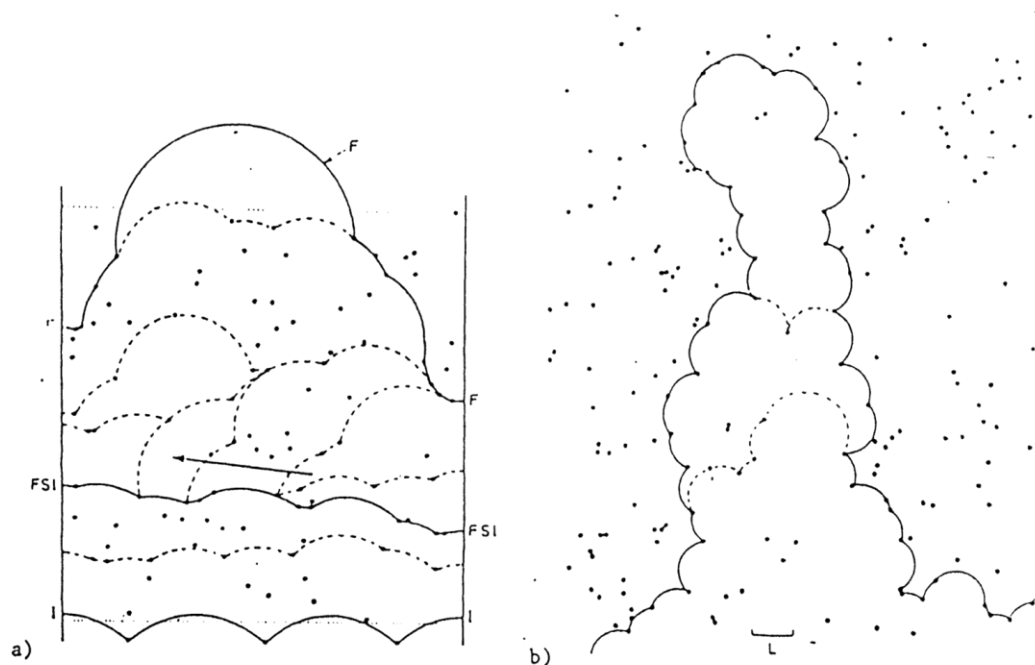


$$R = \frac{\tau}{\sigma b}$$

$$F_c = 2\tau \cos \frac{\psi}{2} = \beta\tau \quad 0 < \beta < 2$$

$\beta \approx 0 \Rightarrow \psi \approx \pi$ weak obstacles

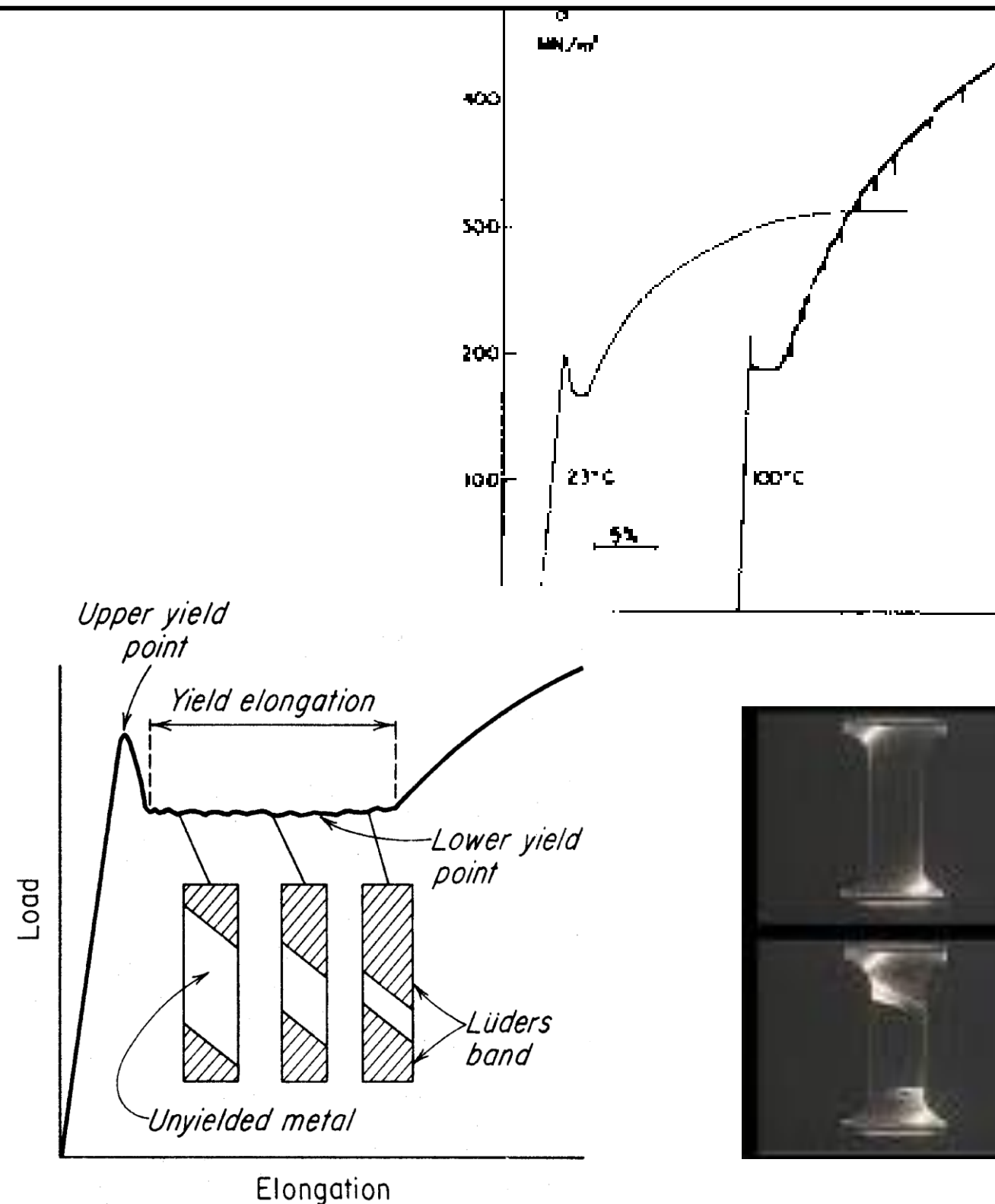
$\beta \approx 2 \Rightarrow \psi \approx 0$ strong obstacles



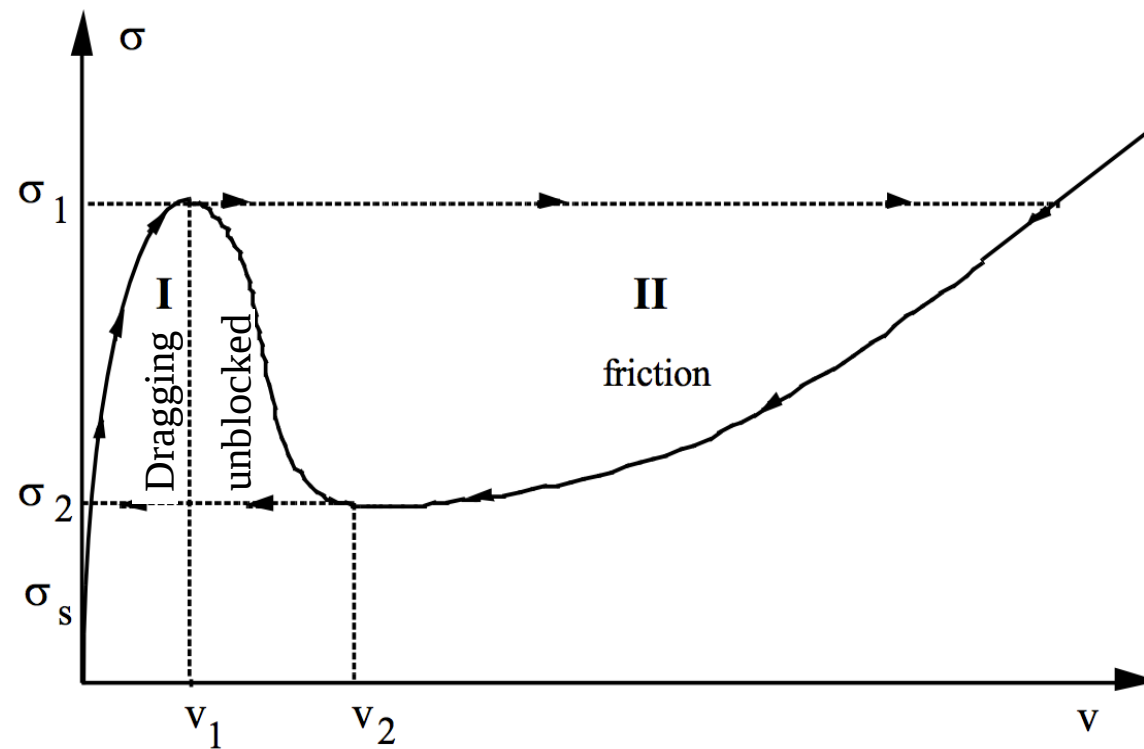
Instabilities in deformation curves

Piobert - Lüders

Slip band propagation due to dislocation multiplication followed by hardening due to interaction with point defects (e.g., carbon atoms in steel)

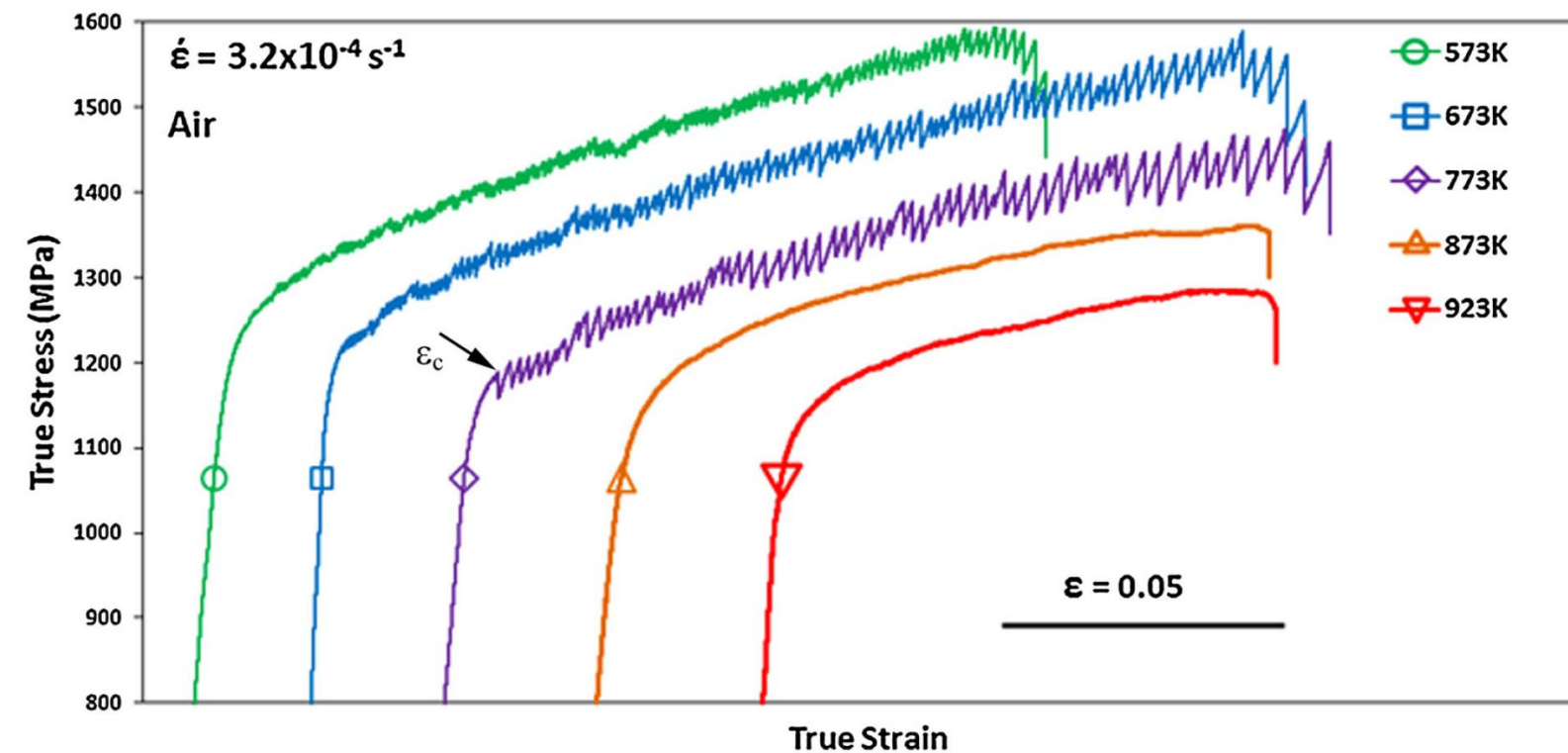


Instabilities in deformation curves



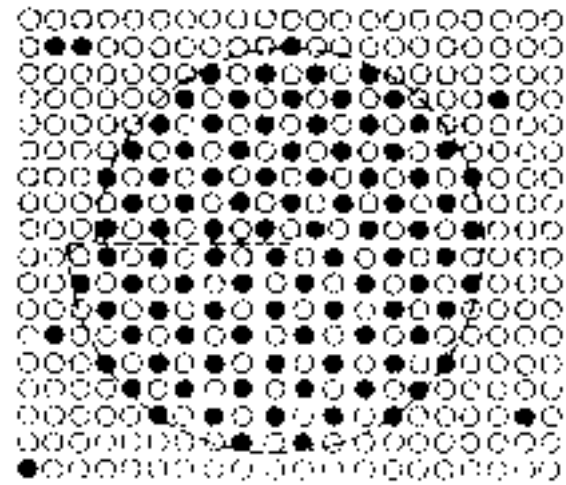
Portevin - Le Châtelier effect

Instabilities in the flow stress due to pinning and depinning of dislocations from point defects (e.g., diffusion (pipe) of solute atoms to the dislocation core) that change their velocities

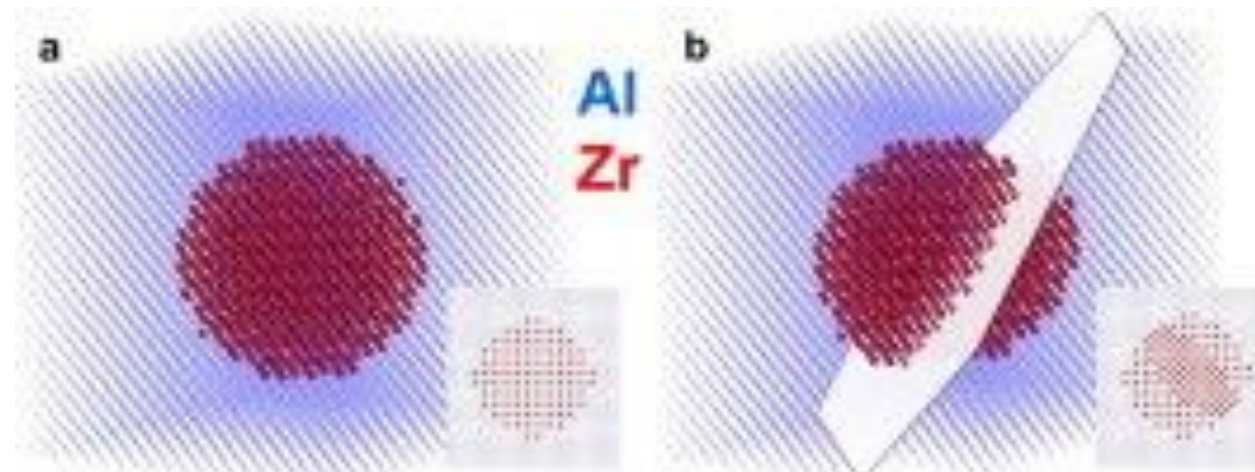


Interactions with precipitates

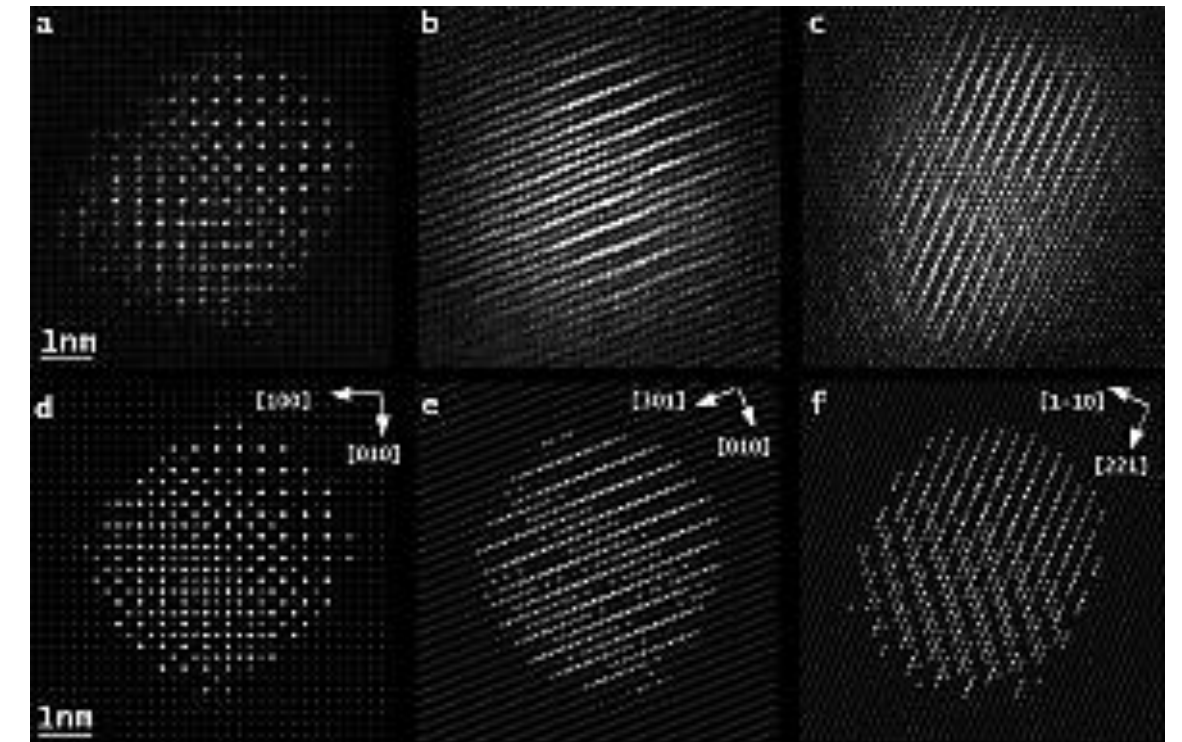
Cutting



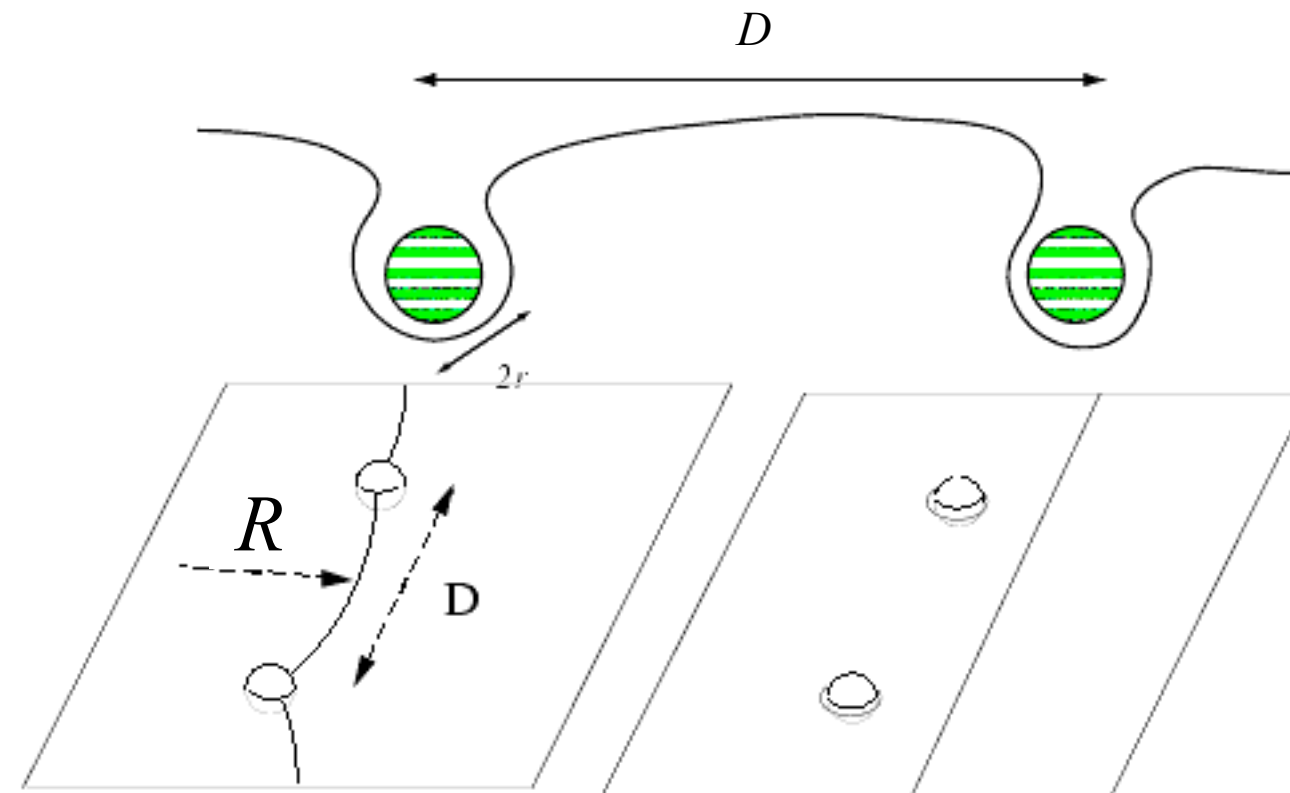
$$\sigma_c \sim \frac{\alpha \gamma_P^{2/3} f^{1/2} r^{1/2}}{\mu^{1/2} b^2}$$



W. Lefebvre et al. / Scripta Materialia 70 (2014) 43–46



Bypass



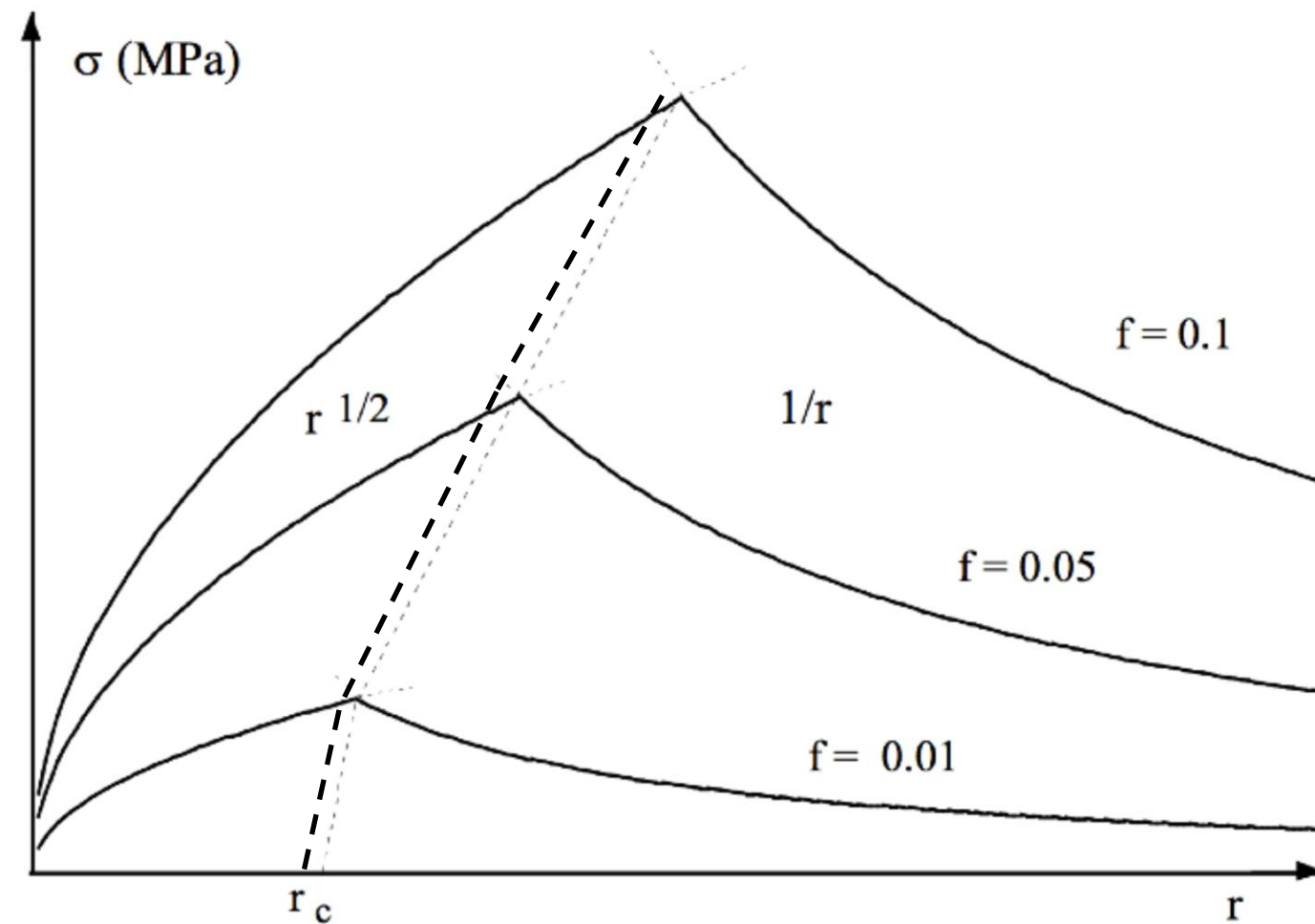
$$\tau \approx \frac{1}{2} \mu b^2$$

$$\sigma_c \approx \frac{\tau}{rb} \approx \frac{\mu b}{2r}$$

$$\sigma_c \approx \frac{\tau}{Rb} = \frac{2\tau}{Db} \approx \frac{\mu b}{D}$$

$$D \propto \frac{r}{\sqrt{f}} \Rightarrow \sigma_c \approx \frac{\mu b \sqrt{f}}{r}$$

Competition cutting-bypass

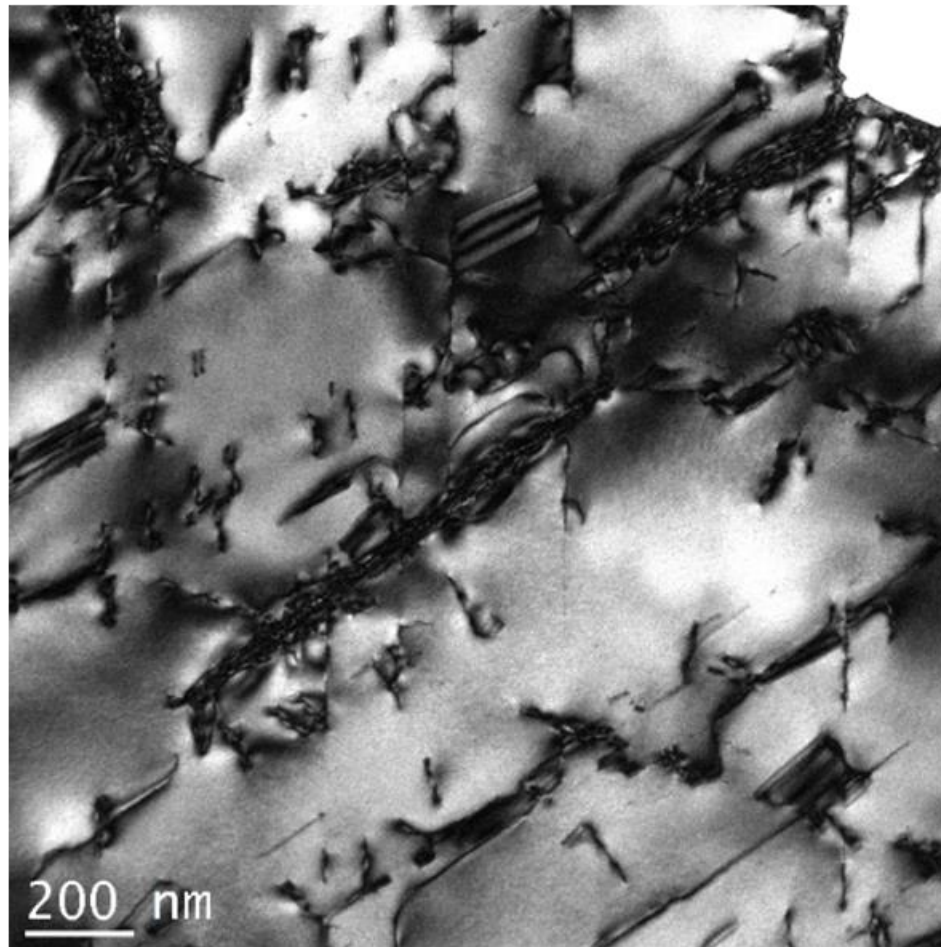


$$\sigma_c \approx \frac{\alpha \gamma_p^{2/3} f^{1/2} r^{1/2}}{\mu^{1/2} b^2}$$

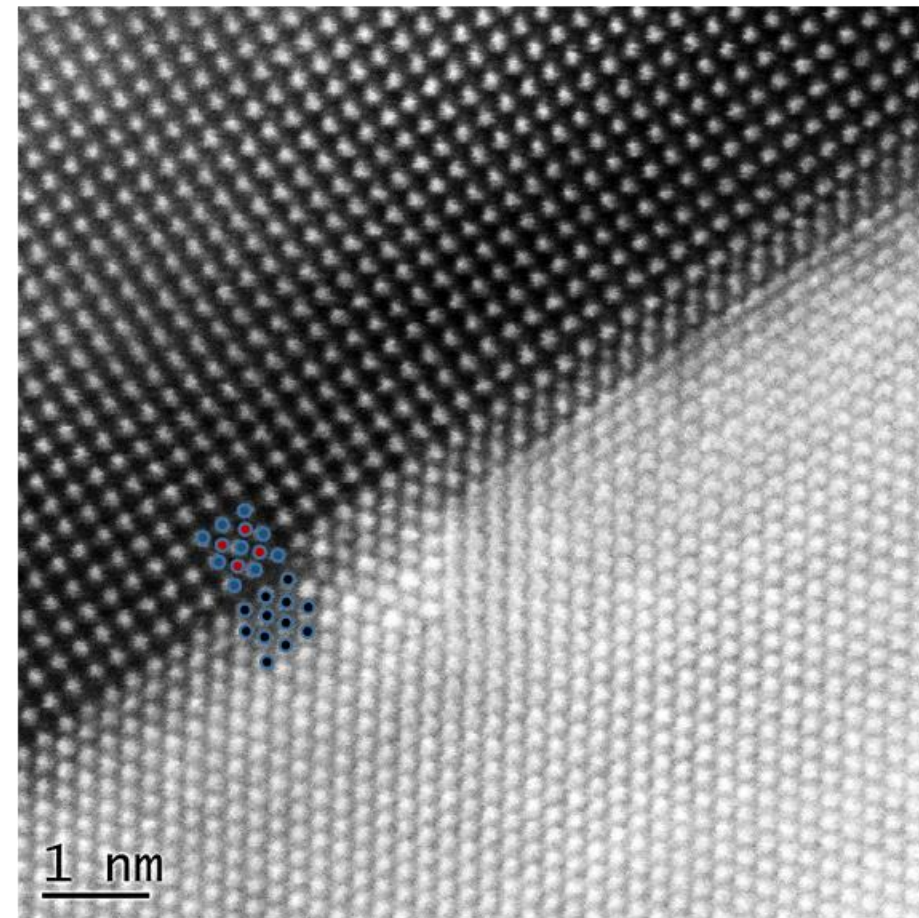
$$\sigma_c \approx \frac{\mu b \sqrt{f}}{r}$$

Coherent NiBe precipitates in CoCr superalloys

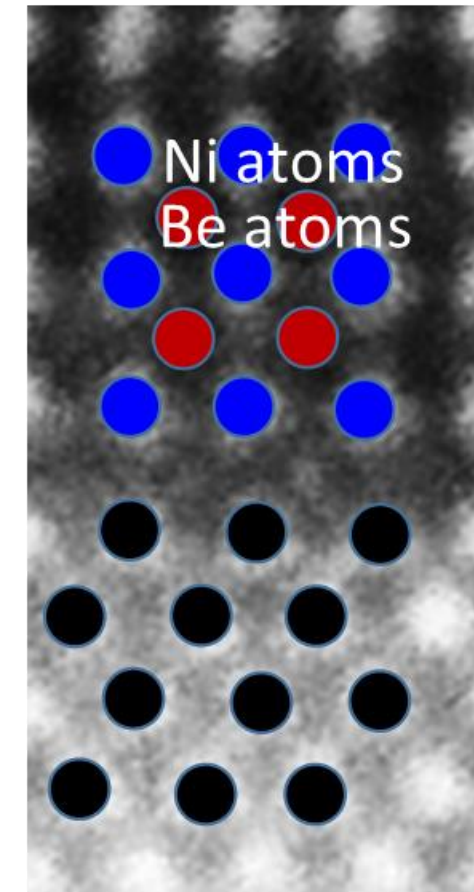
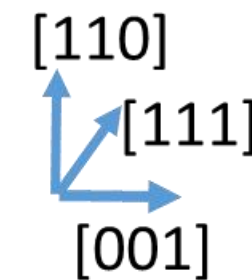
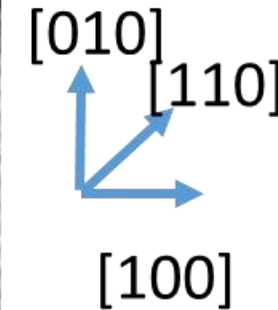
Brightfield TEM



HR-STEM HAADF



Atomic Structure of the interface



NiBe B2 ordered intermetallic [100] Z.A.

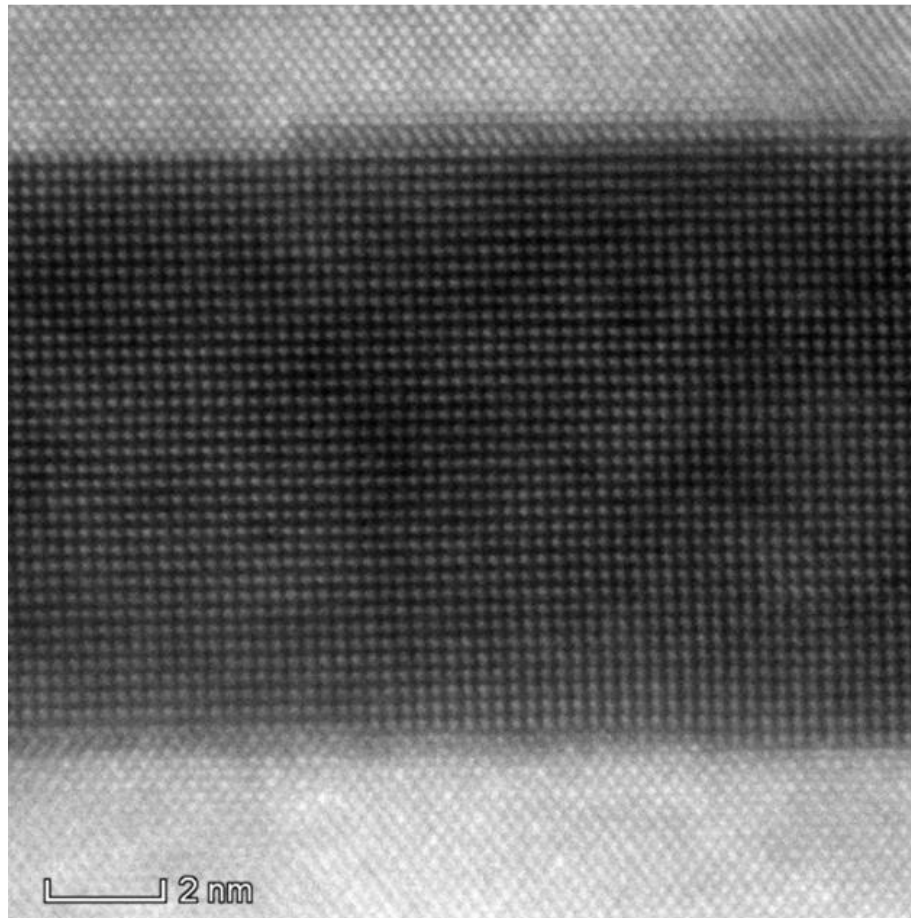
Be atomic columns being low Z are barely visible

CoCr fcc alloy
Solid solution with limited ordering
[110] Z.A.

Bain Orientation $\{100\}\text{NiBe} \parallel \{100\}\text{CoCr}$ and $\langle 010 \rangle \text{NiBe} \parallel \langle 110 \rangle \text{CoCr}$

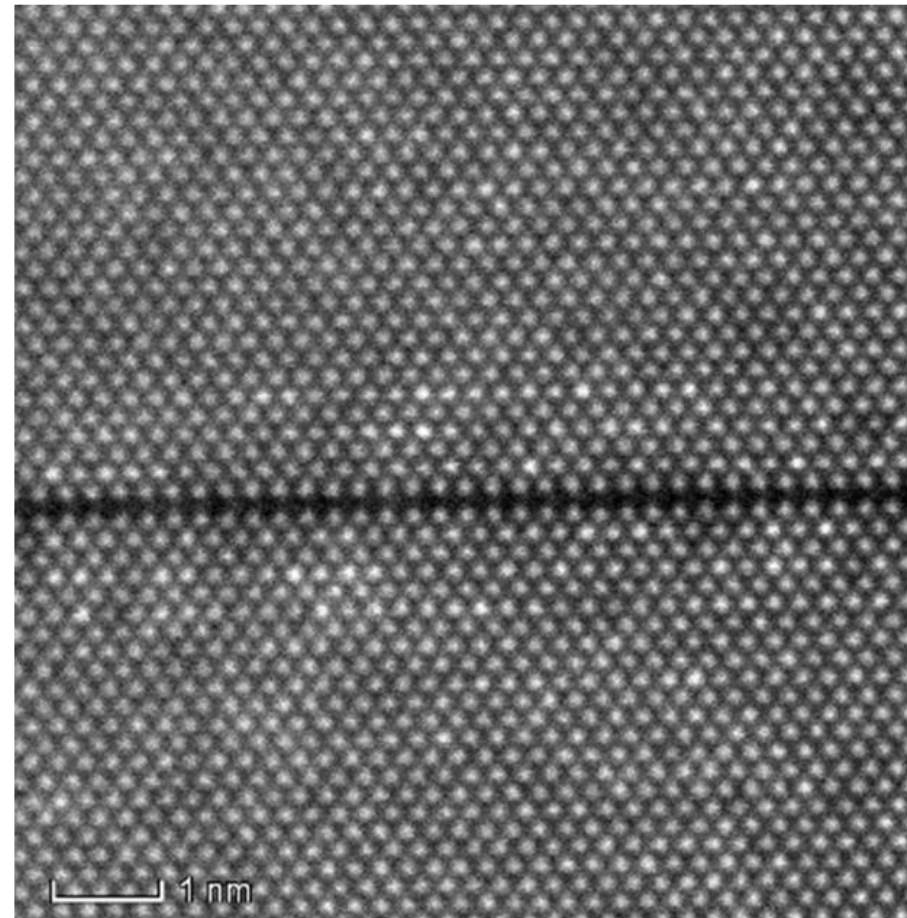
Aging of NiBe precipitates in CoCr superalloys

Semi-coherent
precipitate



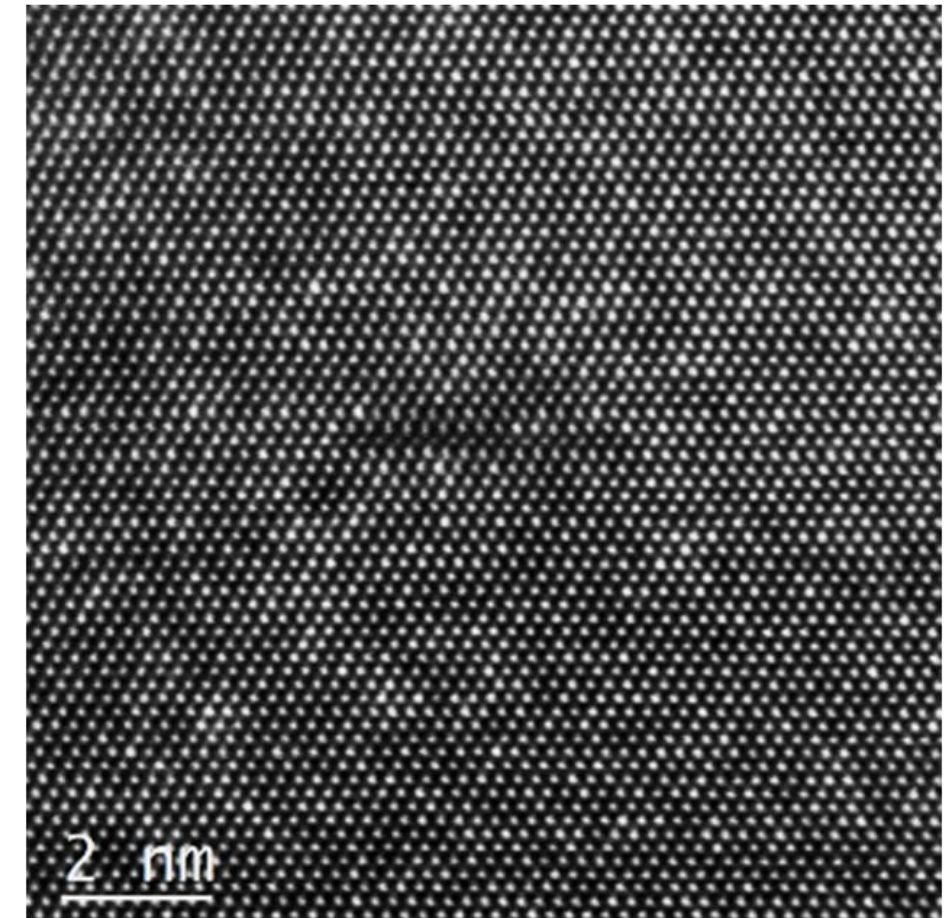
Bypass-cutting
mechanism

Coherent Be GP zone



Cutting mechanism

Be Interstitial cluster

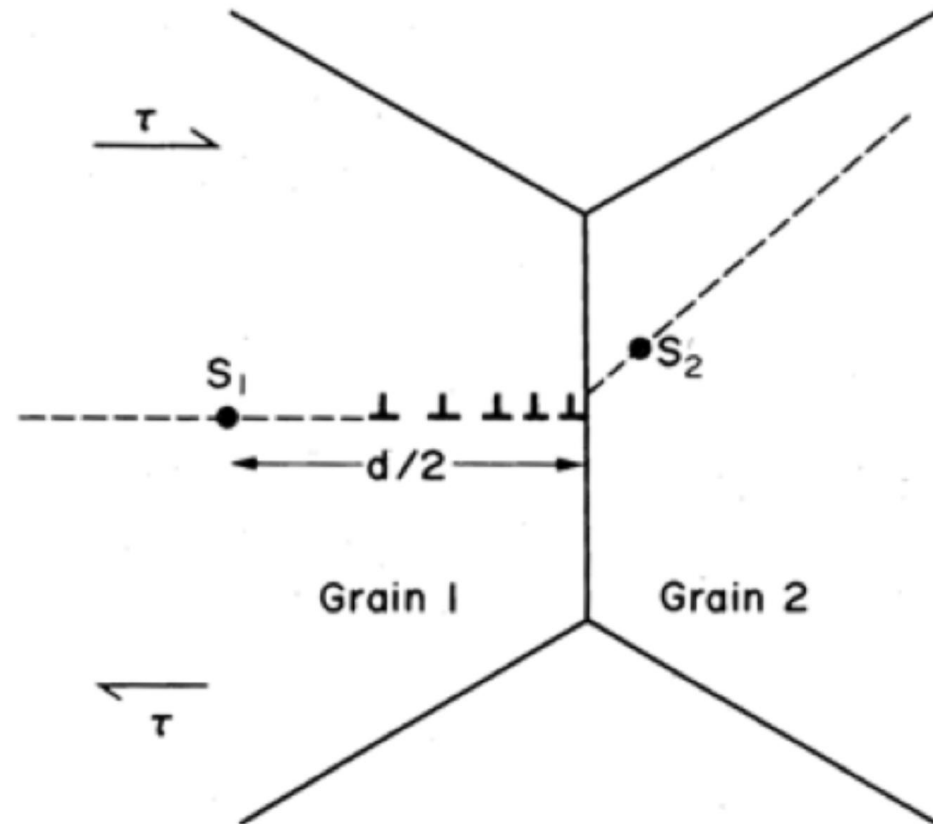


Defect Pinning/ dragging
and increased Peierls
stress

Hall-Petch law

$$\sigma_y = \sigma_0 + \frac{k}{\sqrt{d}}$$

Model based on the stacking of dislocations to grain boundaries



Stress applied on the shear-stress plane: τ

Stress on the leading dislocation: τ_1

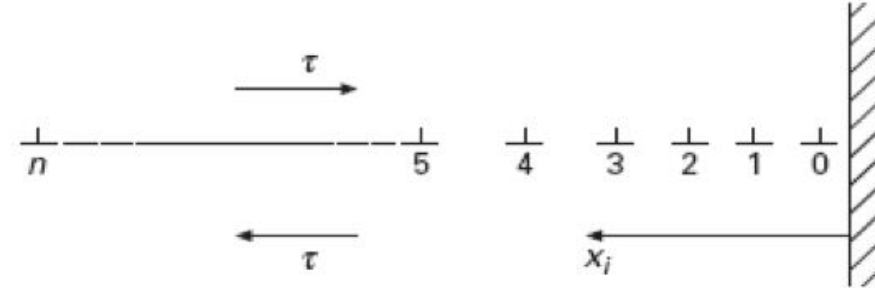
$$\tau_1 = n\tau$$

$$\tau = \frac{\mu b^2}{2\pi(d/2)} = n \frac{\mu b^2}{\pi d} = n \frac{A}{d}$$

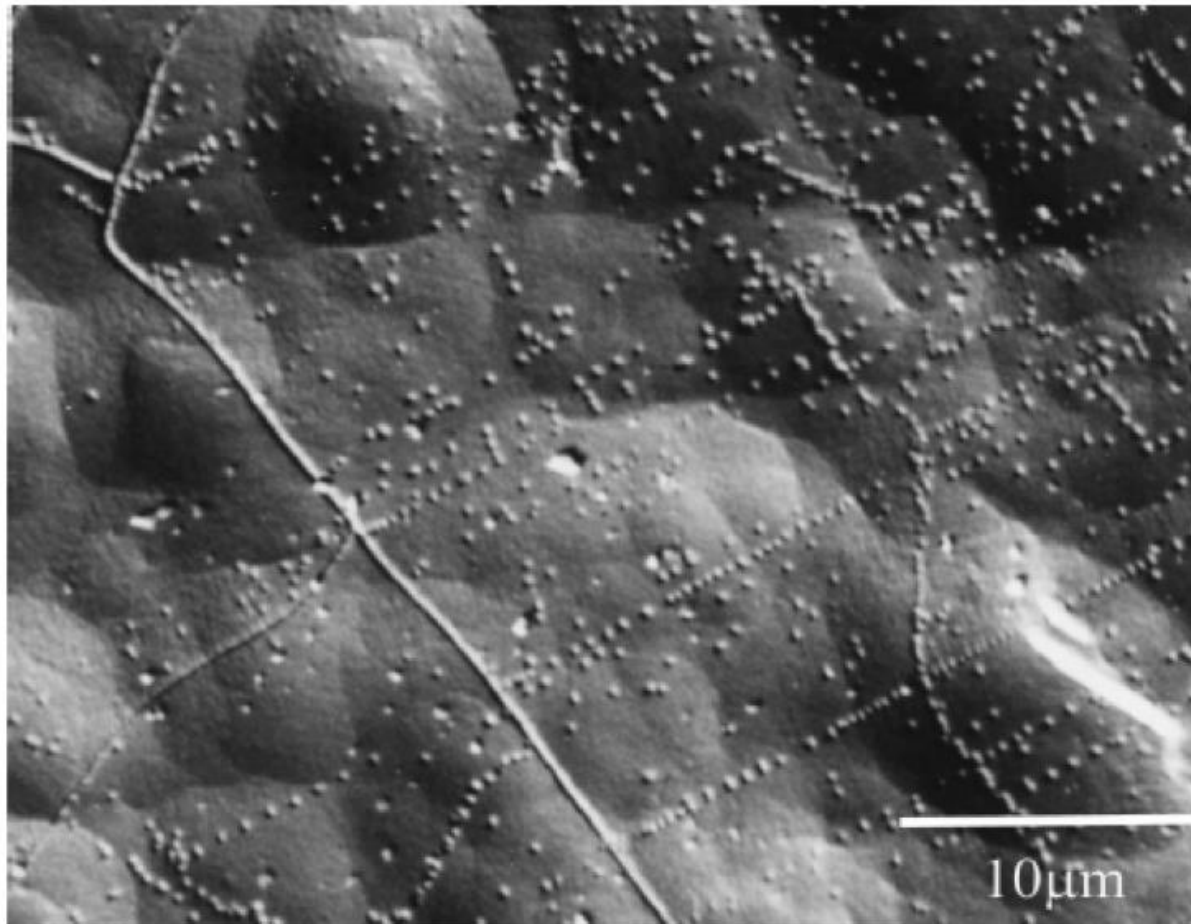
$$\tau_1 = n\tau = n^2 \frac{A}{d} = \frac{d}{A} \tau^2$$

Critical stress $\tau_1^* = \frac{d}{A} \tau^2 \Rightarrow \tau = \sqrt{\tau_1^* \frac{A}{d}} \Rightarrow \sigma_y = \frac{k}{\sqrt{d}} \quad k = \frac{\sqrt{\tau_1^* A}}{m} \text{ Schmid factor}$

Hall-Petch law



$$\sigma_y = \sigma_0 + \frac{k}{\sqrt{d}}$$



Pile-up of dislocations in
Cu observed by etch-pitting