EPFL

Physics of Materials

Chapter 6: Plastic Deformation:
Introduction to the Dislcolation model

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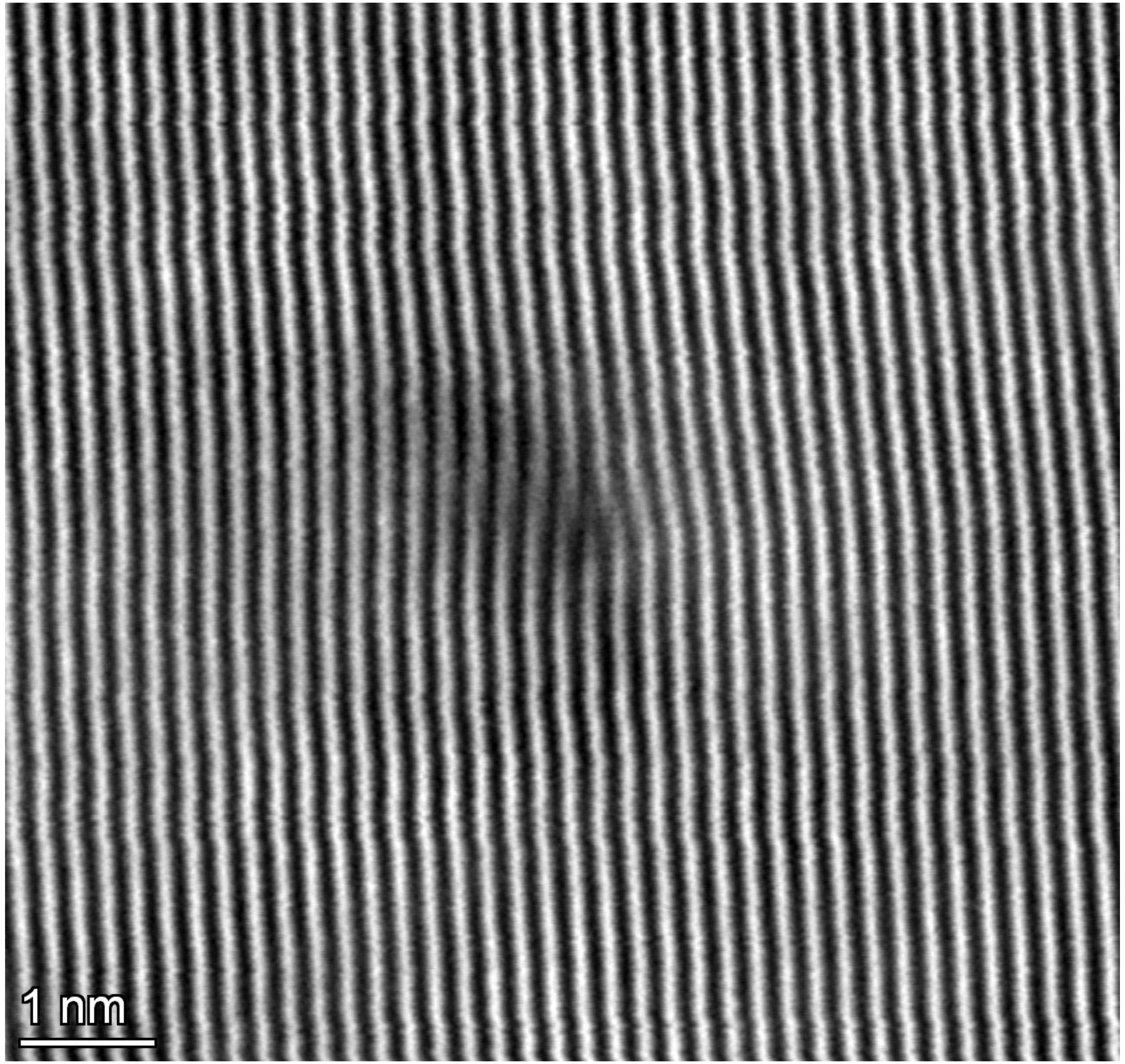
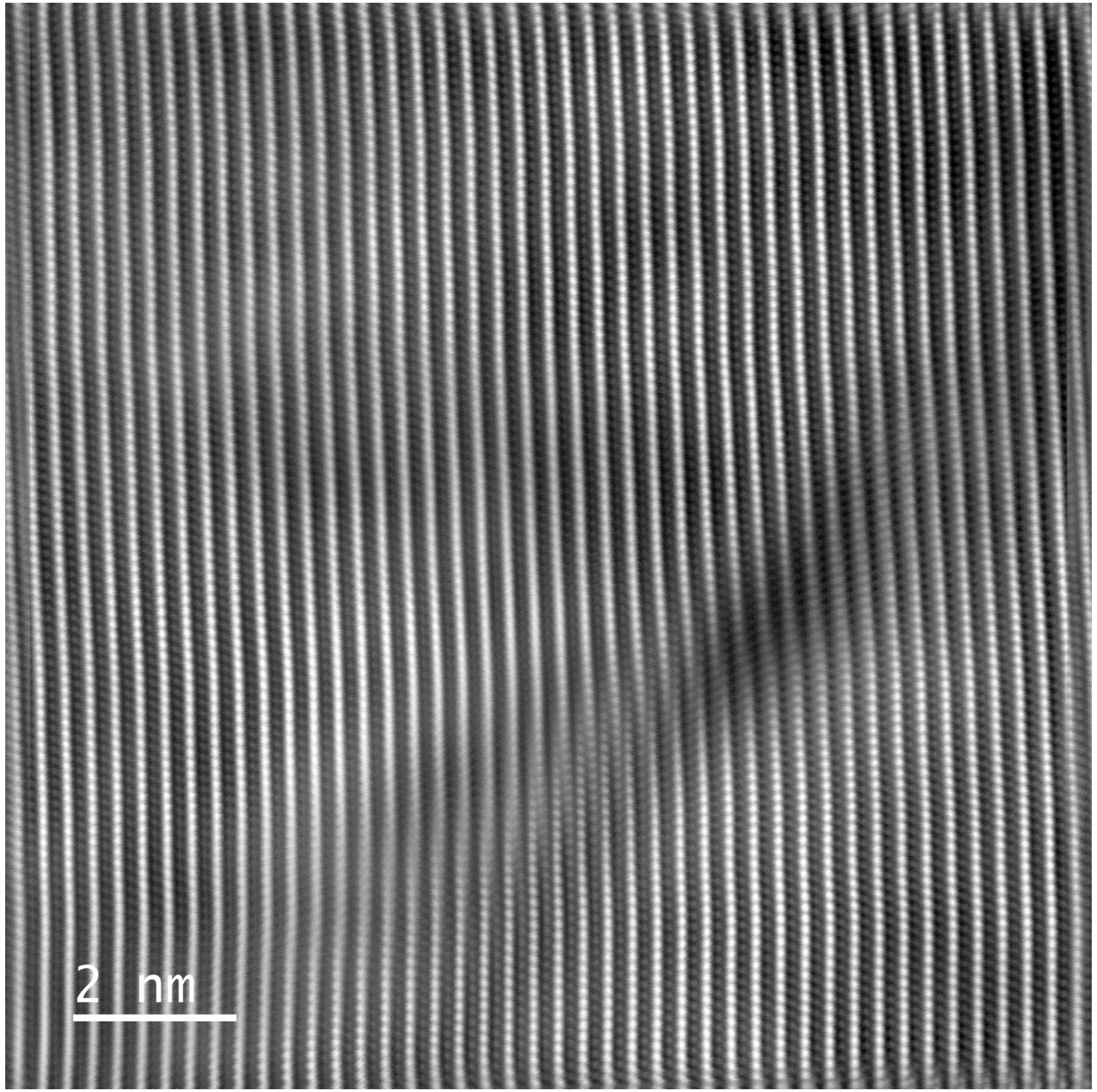
LUMES

Masters Course PHYS-307

Fall 2024

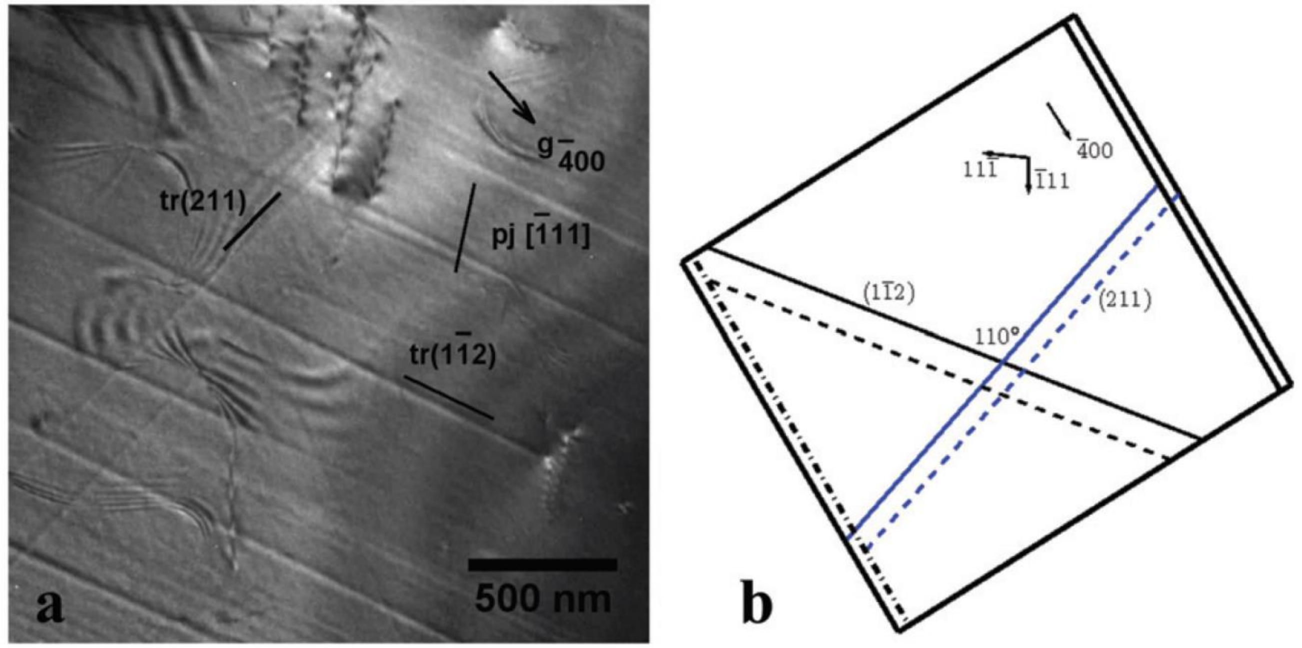
Dislocations

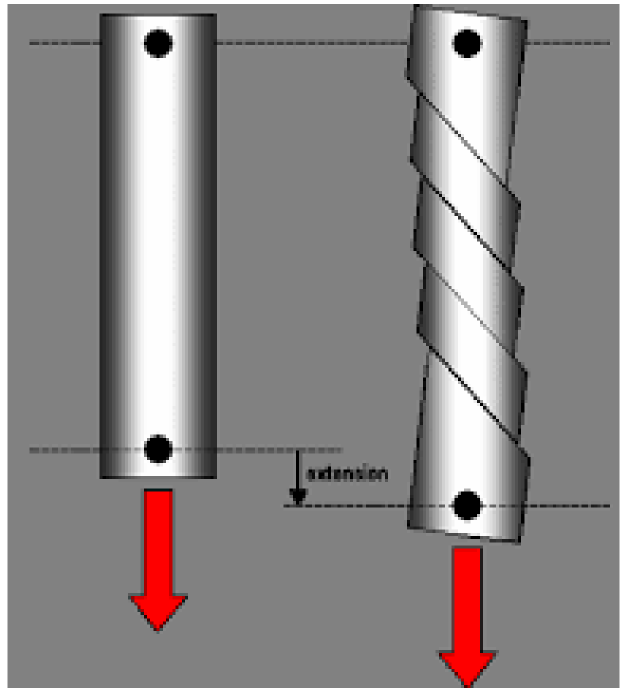


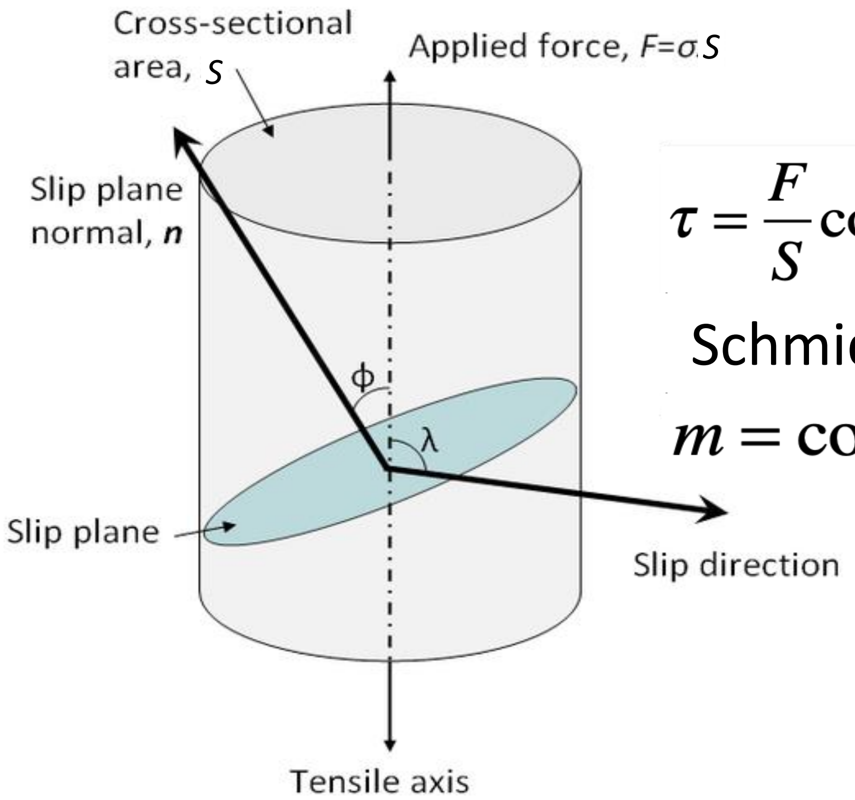


Dislocations were first observed in Single Crystals

Slip lines in a single-crystal



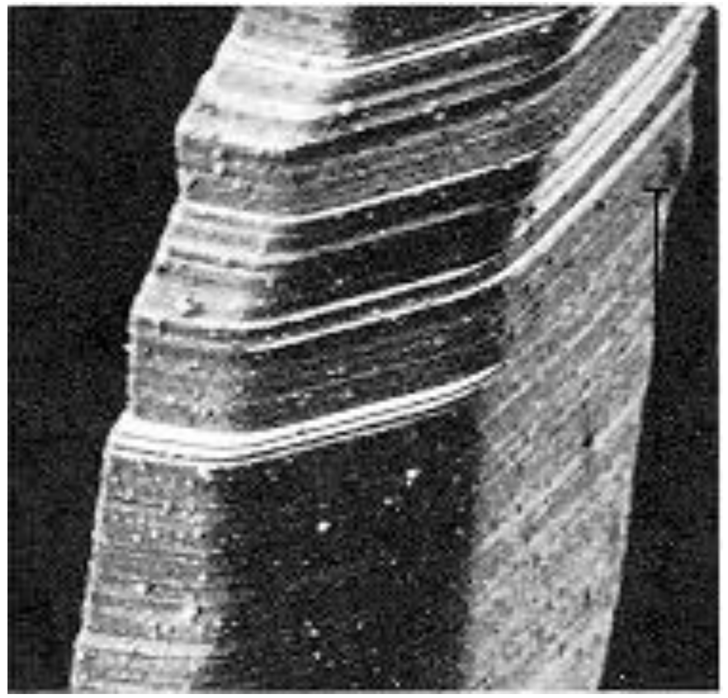




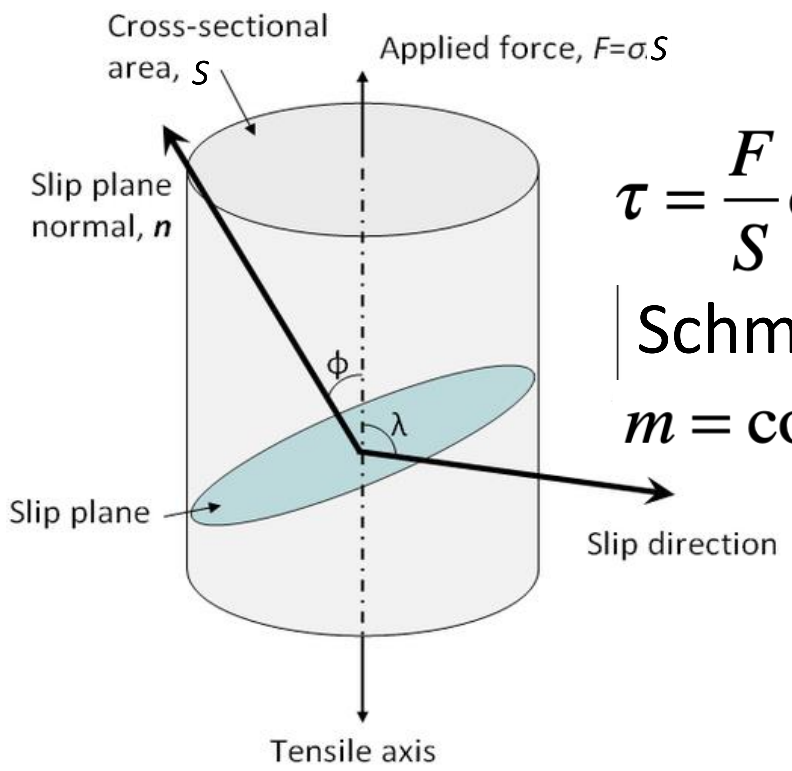
$$\tau = \frac{F}{S}\cos\phi\cos\lambda$$

Schmid factor

$$m = \cos\phi\cos\lambda$$



On the track of dislocations



$$\tau = \frac{F}{S}\cos\phi\cos\lambda$$

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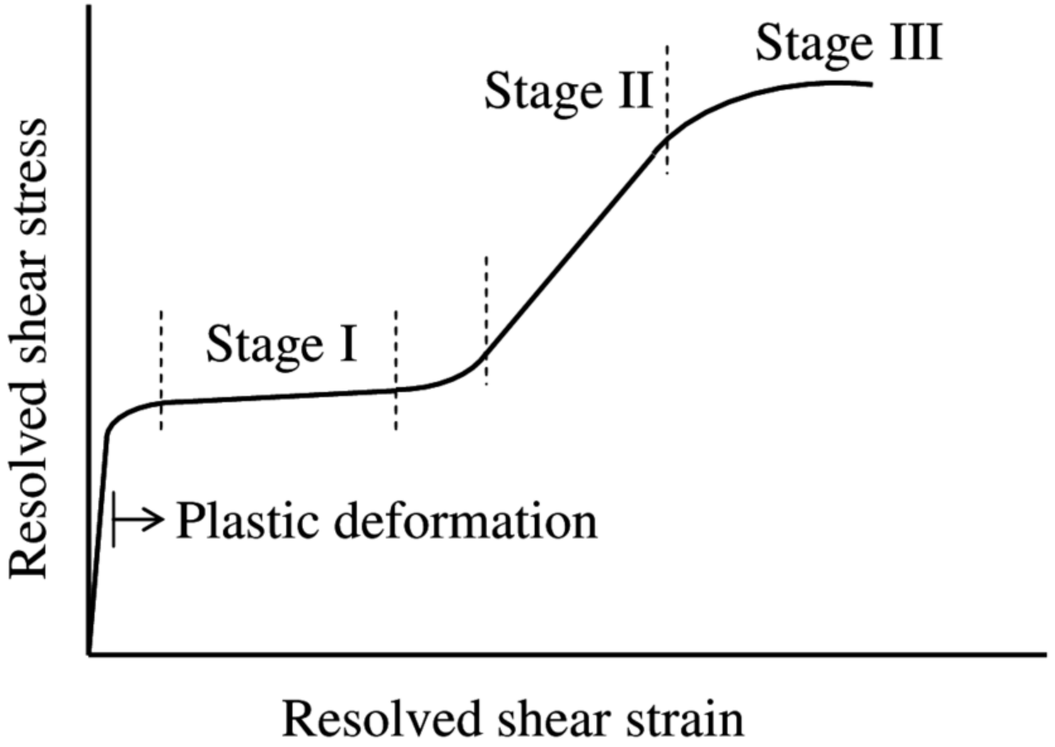
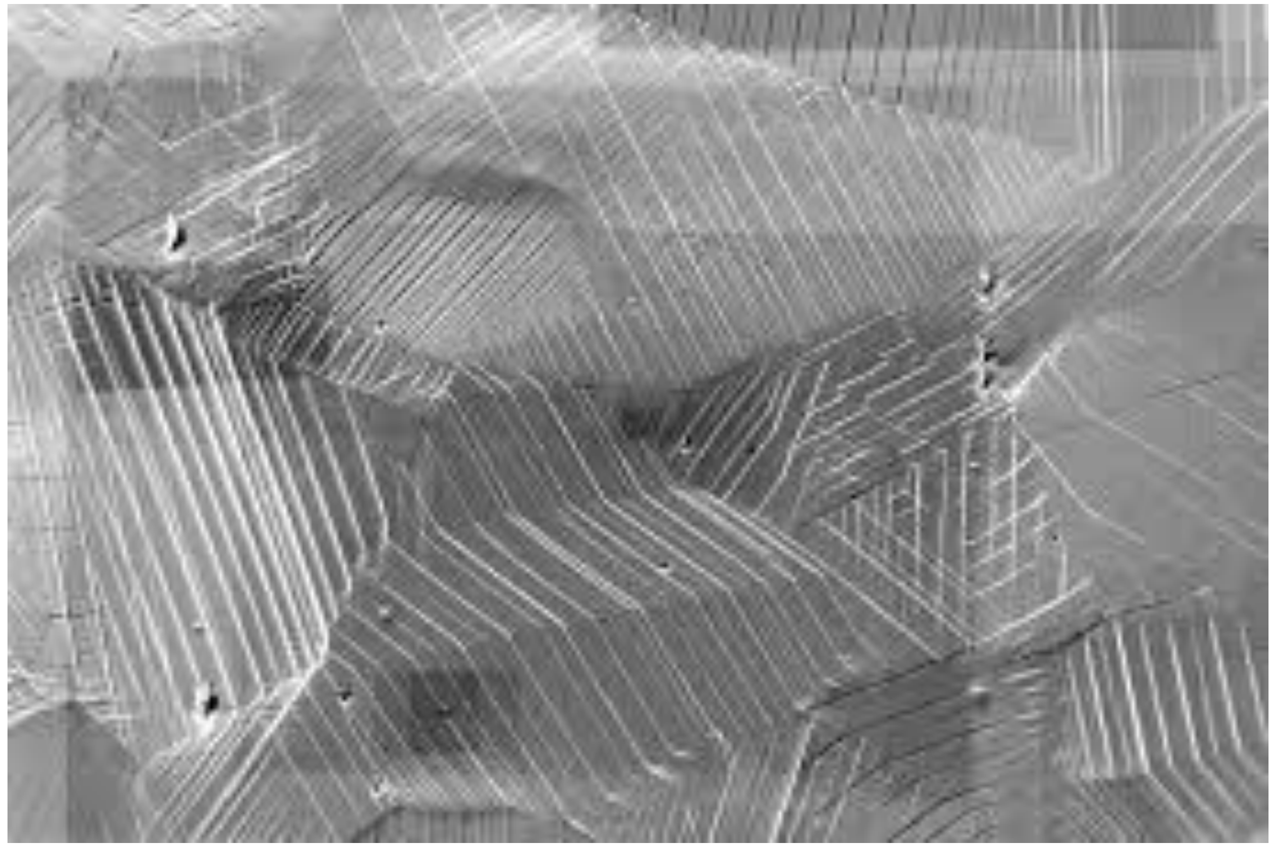


Slip lines in a polycrystal



- Stage 1: easy glide, dislocation motion
- Stage 2: Hardening from dislocations (with the highest Schmid factor) pile-ups
- Stage 3: hardening from activation of other slip systems and dislocations cutting through each other

Mechanical annealing

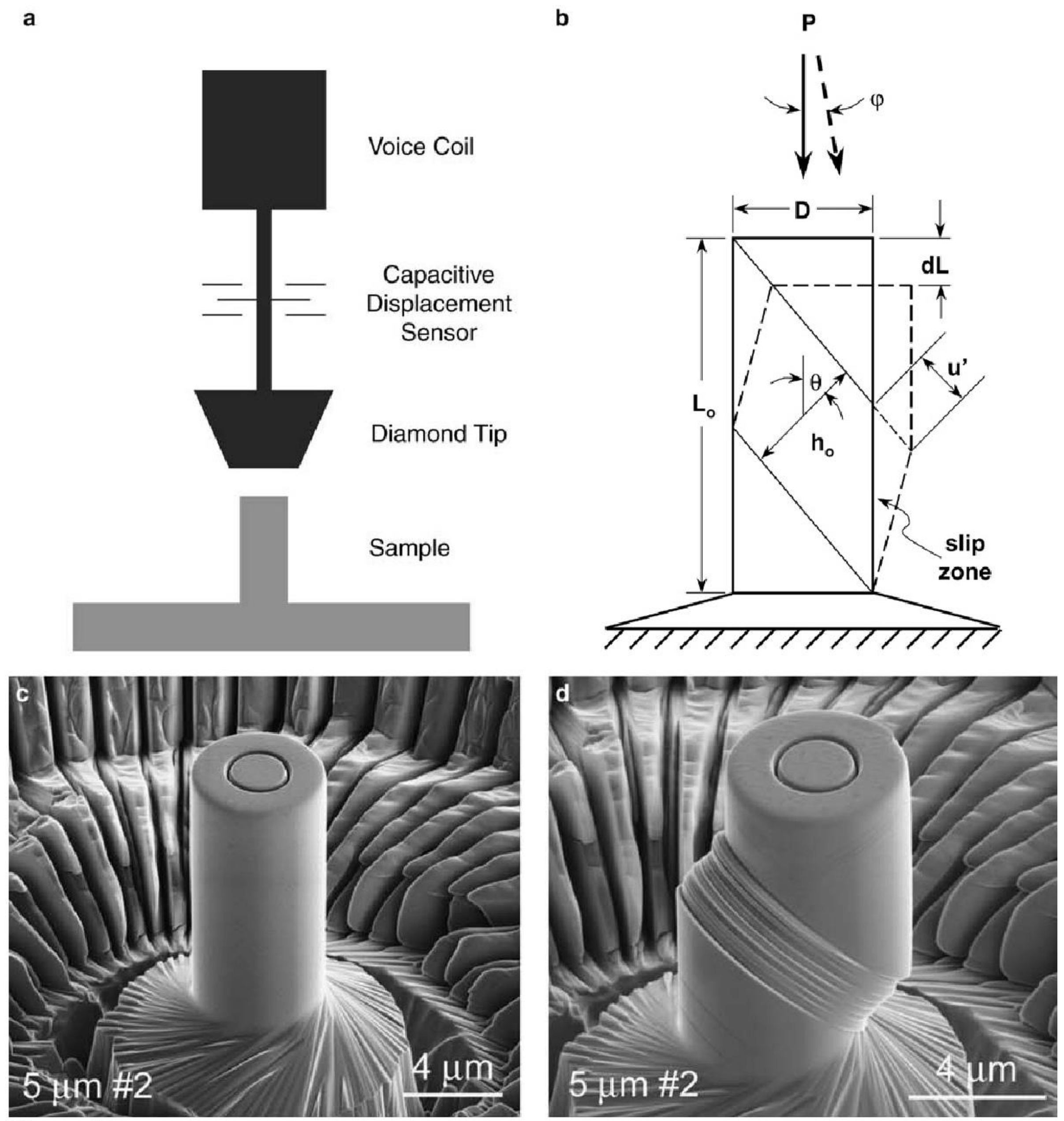
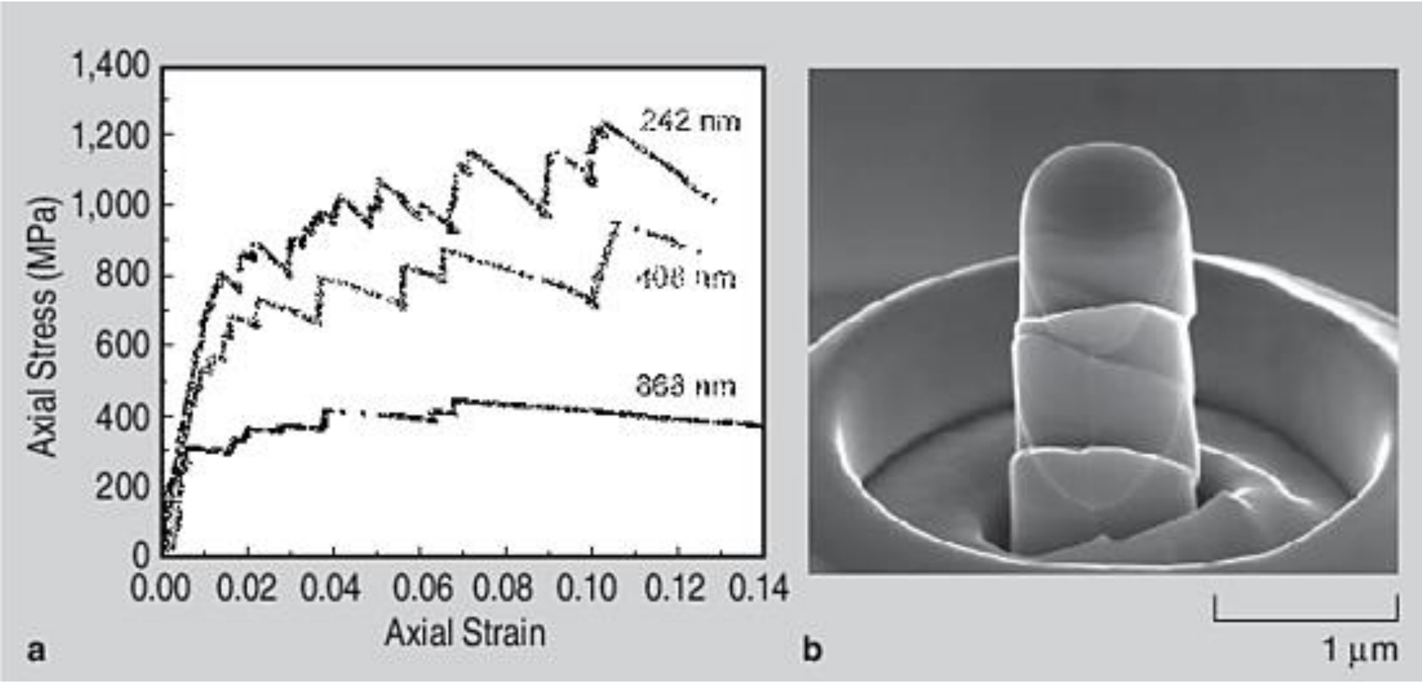
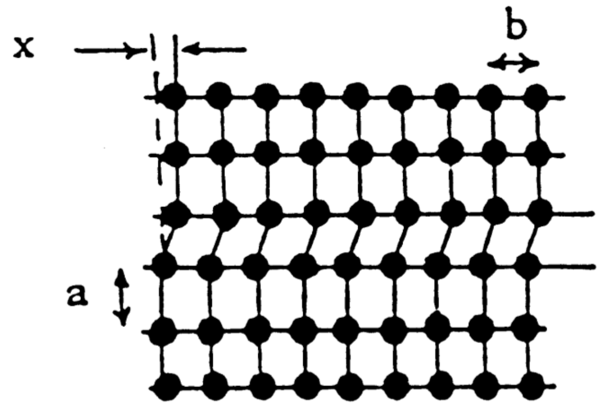


Figure 1

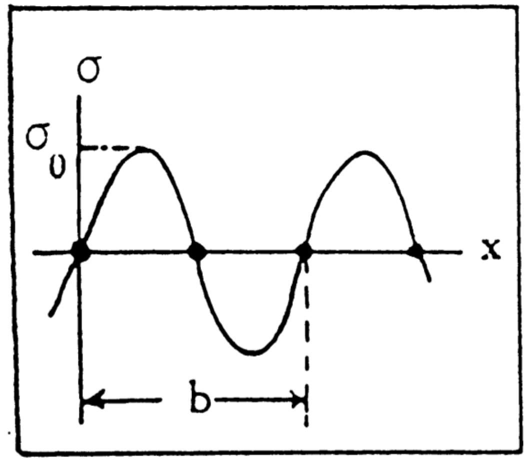


Serrated plasticity relates to the nucleation of dislocation proceeded by the gliding (at lower energy) on the slip plane (activated slip system) associated with the highest Schmid factor for this crystal system and orientation.

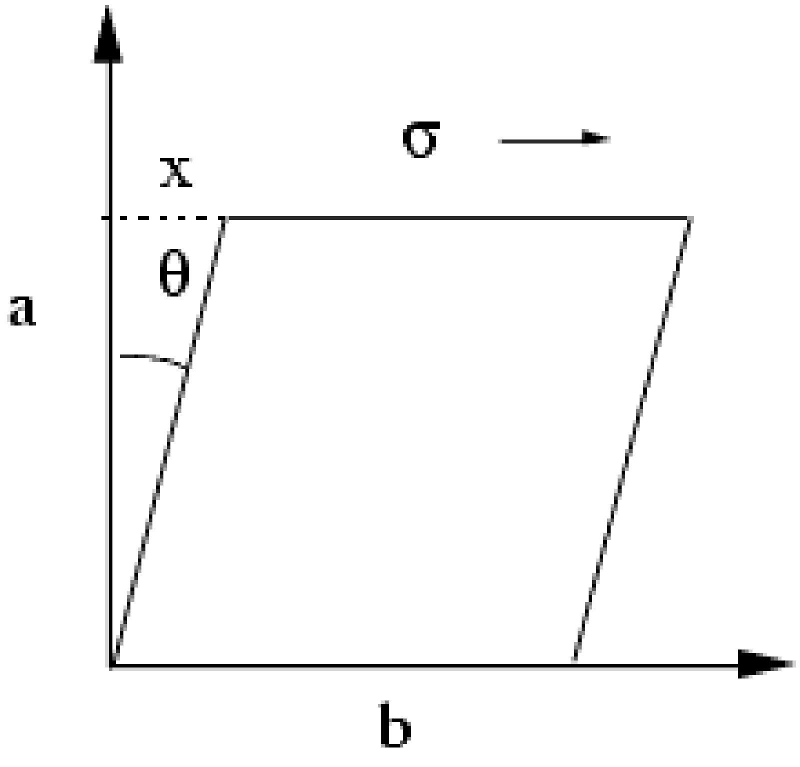
Shear-stress on a crystalline plane



a)



b)



$$\sigma = \sigma_0 \sin\left(\frac{2\pi x}{b}\right) \approx \sigma_0 \frac{2\pi x}{b}$$

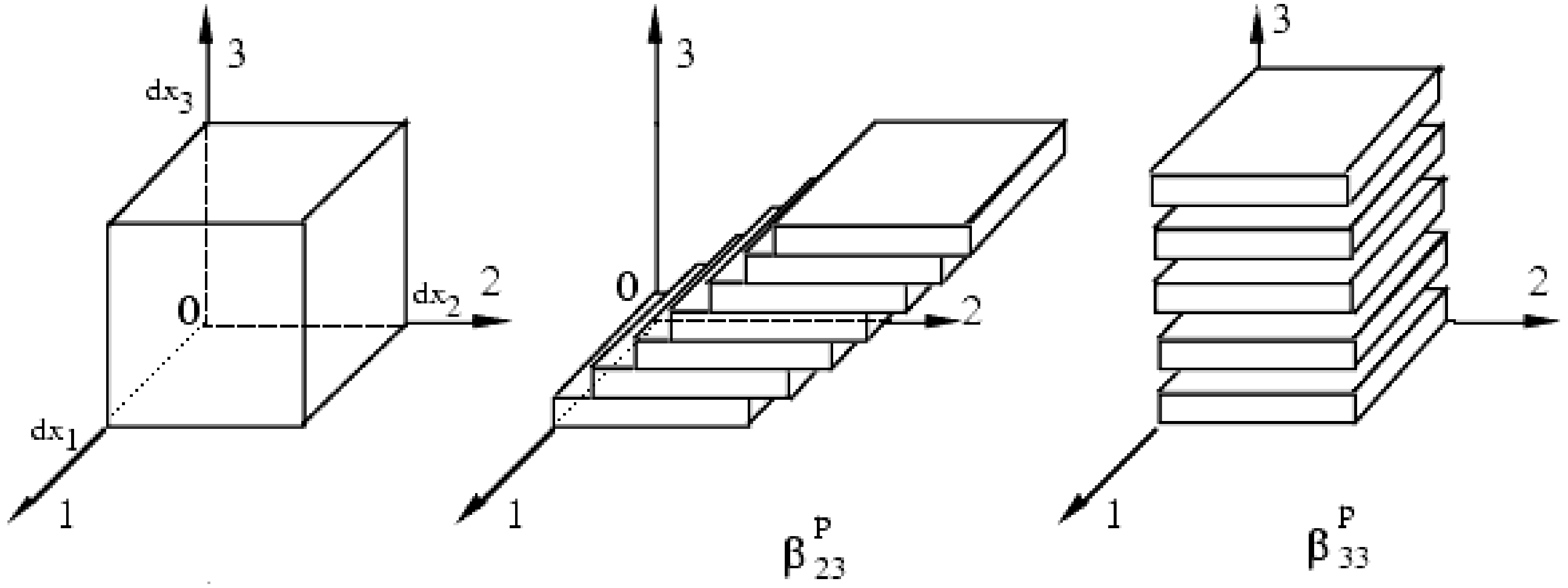
$$\sigma = \mu\theta = \mu\frac{x}{a} \approx \sigma_0 \frac{2\pi x}{b} \qquad \sigma_0 = \frac{\mu b}{2\pi a}$$

$$\sigma = \frac{\mu b}{2\pi a} \sin\left(\frac{2\pi x}{b}\right)$$ Maximum at x $= {}^{b}/_{4}, a > b$

For copper

$$\sigma_{cr} \sim \frac{\mu}{10} = 4.5\ GPa\ but\ \sigma_y \sim 30\ MPa$$

Plastic distortion



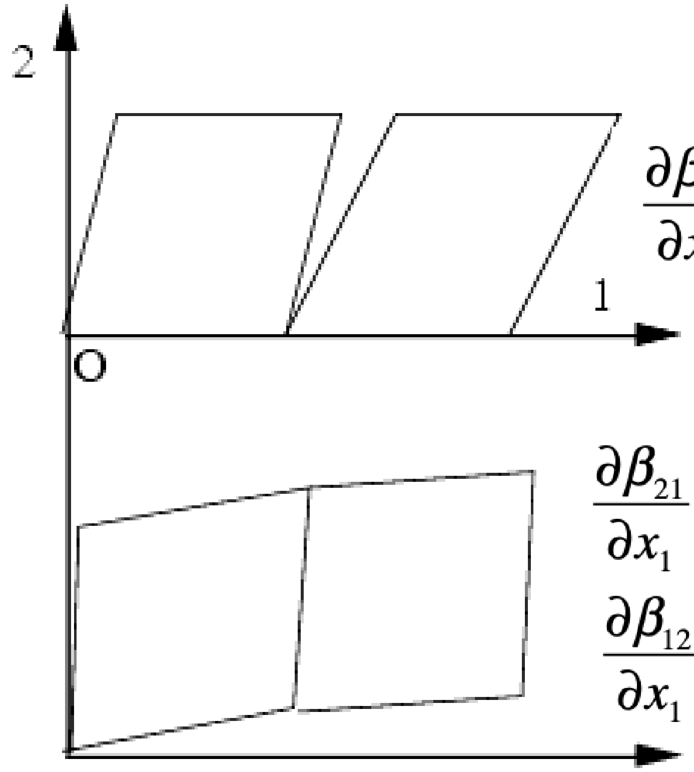
$$du_i^p = \int_0^{dx_j} \left(\frac{\partial u_i^p}{\partial x_j}\right) \partial x_j = \left(\frac{\partial u_i^p}{\partial x_j}\right) dx_j \qquad du_i^p = \beta_{i1}^p dx_1 + \beta_{i2}^p dx_2 + \beta_{i3}^p dx_3 \qquad d\vec{u}^{\,p} = \overline{\overline{\beta}}^{\,p} d\vec{x}$$

$$d\vec{u} = d\vec{u}^{\,p} + d\vec{u}^{\,e}$$

Incompatible distortion: cracks

Compatible distortion= no cracks

$$\frac{\partial \beta_{21}}{\partial x_1} = \frac{\partial \beta_{31}}{\partial x_1} = 0$$



$$\frac{\partial \beta_{12}}{\partial x_1} \neq 0$$

$$\frac{\partial \beta_{21}}{\partial x_1} = 0$$

$$\frac{\partial \beta_{12}}{\partial x_1} \neq 0$$

Plastic distortion

$d\vec{u}$ is an exact total differential thus:

$$d\vec{u} = \frac{\partial \vec{u}}{\partial x_j} dx_j = \vec{\beta}_j dx_j$$

Cauchy identity $\frac{\partial \vec{\beta}_j}{\partial x_k} = \frac{\partial \vec{\beta}_k}{\partial x_j}$ if $j \neq k$

$$\downarrow$$

Physical meaning, the creation of defects during plastic deformation creates residual internal stresses

$$\begin{bmatrix} \frac{\partial \vec{\beta}_3}{\partial x_2} - \frac{\partial \vec{\beta}_2}{\partial x_3} \\ \frac{\partial \vec{\beta}_1}{\partial x_3} - \frac{\partial \vec{\beta}_3}{\partial x_1} \\ \frac{\partial \vec{\beta}_2}{\partial x_1} - \frac{\partial \vec{\beta}_1}{\partial x_2} \end{bmatrix} = 0 = \overrightarrow{rot}\,\overline{\overline{\beta}}$$

No cracks!

$$\overrightarrow{rot}\,\overline{\overline{\beta^e}} = -\overrightarrow{rot}\,\overline{\overline{\beta^p}} = \overline{\overline{\alpha}}$$

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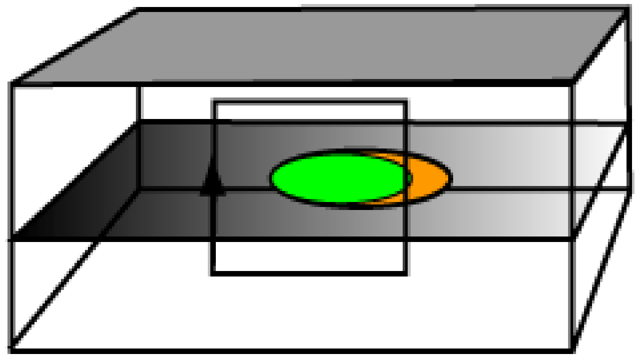
Compatibility

$$\overline{\overline{\alpha}} = \overrightarrow{rot}\,\overline{\overline{\beta^e}} = -\overrightarrow{rot}\,\overline{\overline{\beta^p}}$$

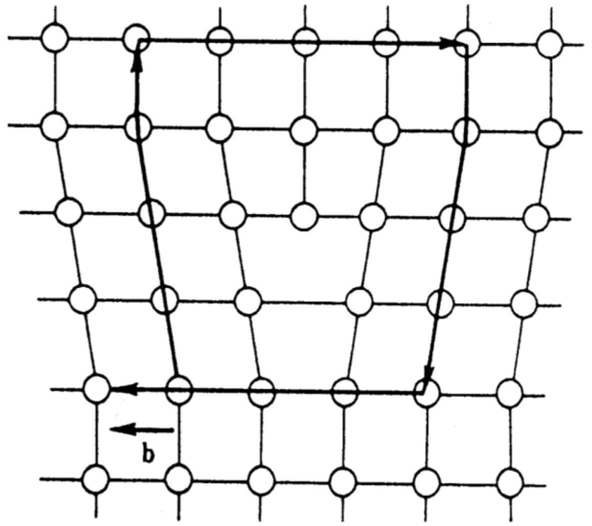
$$\iint \overline{\overline{\alpha}}\, d\vec{S} = \iint \overrightarrow{rot}\,\overline{\overline{\beta^e}}\, d\vec{S} = \oint \overline{\overline{\beta^e}}\, d\vec{x} = \oint \vec{\beta}^{e}_{j} dx_j = \oint d\overrightarrow{u^e}$$

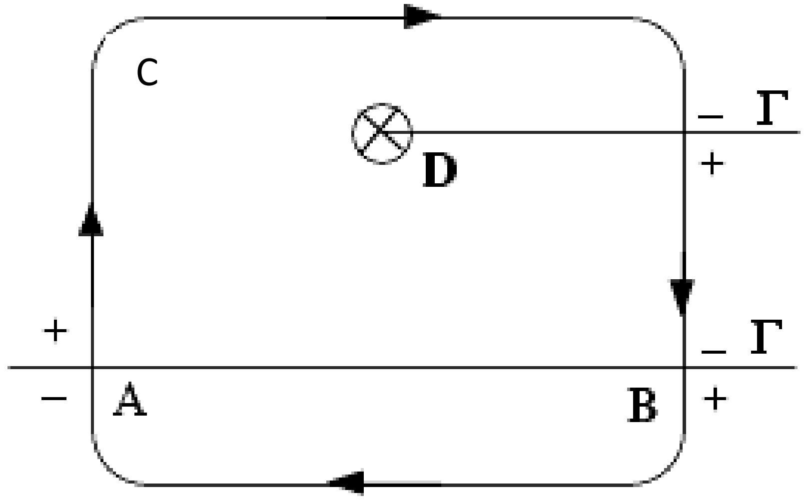


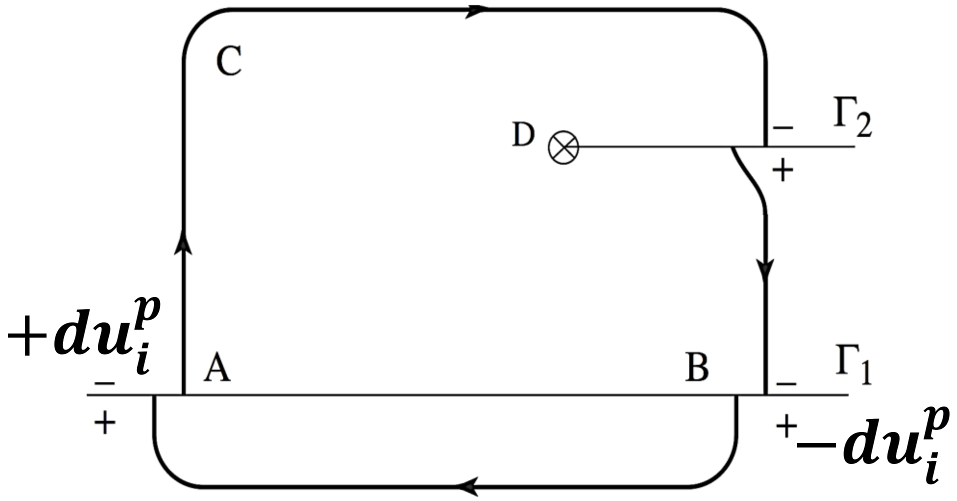
Burgers vector

$$\boxed{\vec{b} = \oint d\overrightarrow{u^e} = -\oint d\overrightarrow{u^p} = \iint \overline{\overline{\alpha}}\, d\vec{S}}$$

$$\alpha_{ij} = \frac{\Delta b_i}{\Delta S_j}$$







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Analogy with electromagnetism

$$\vec{b} = \oint_C \overline{\overline{\beta}}^e \, d\vec{x} \qquad i = \oint_C \vec{H} \, d\vec{l}$$

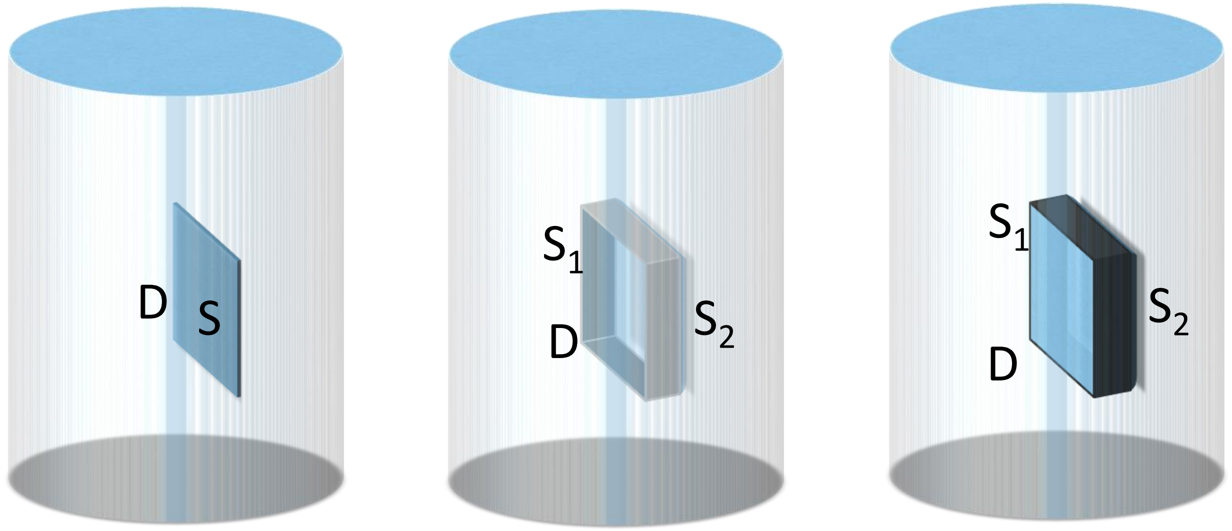
$$\vec{b} \leftrightarrow i \qquad \overline{\overline{\beta}}^e \leftrightarrow \vec{H}$$

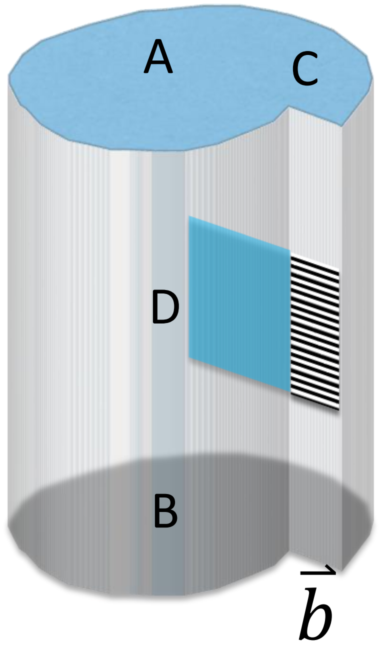
$$\overline{\overline{\alpha}} = rot \ \beta^e \qquad \vec{j} = rot \ \vec{H}$$

$$div \ \overline{\overline{\alpha}} = 0 \qquad div \ \vec{j} = 0$$

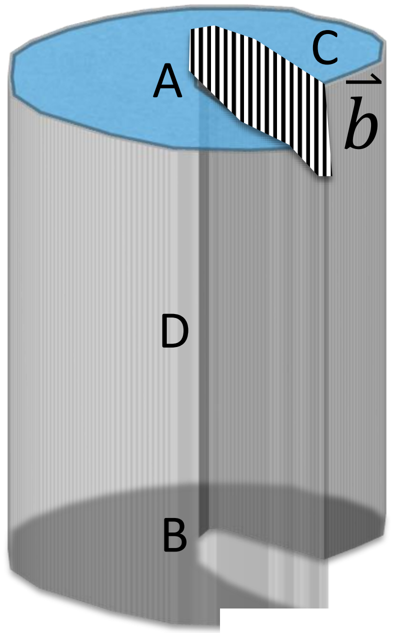
Dislocations induce internal stress fields like current flowing in wire induces magnetic fields

Continuum: Volterra dislocations (1860-1940)

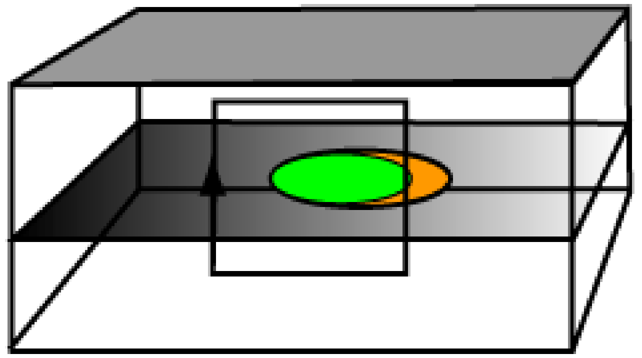




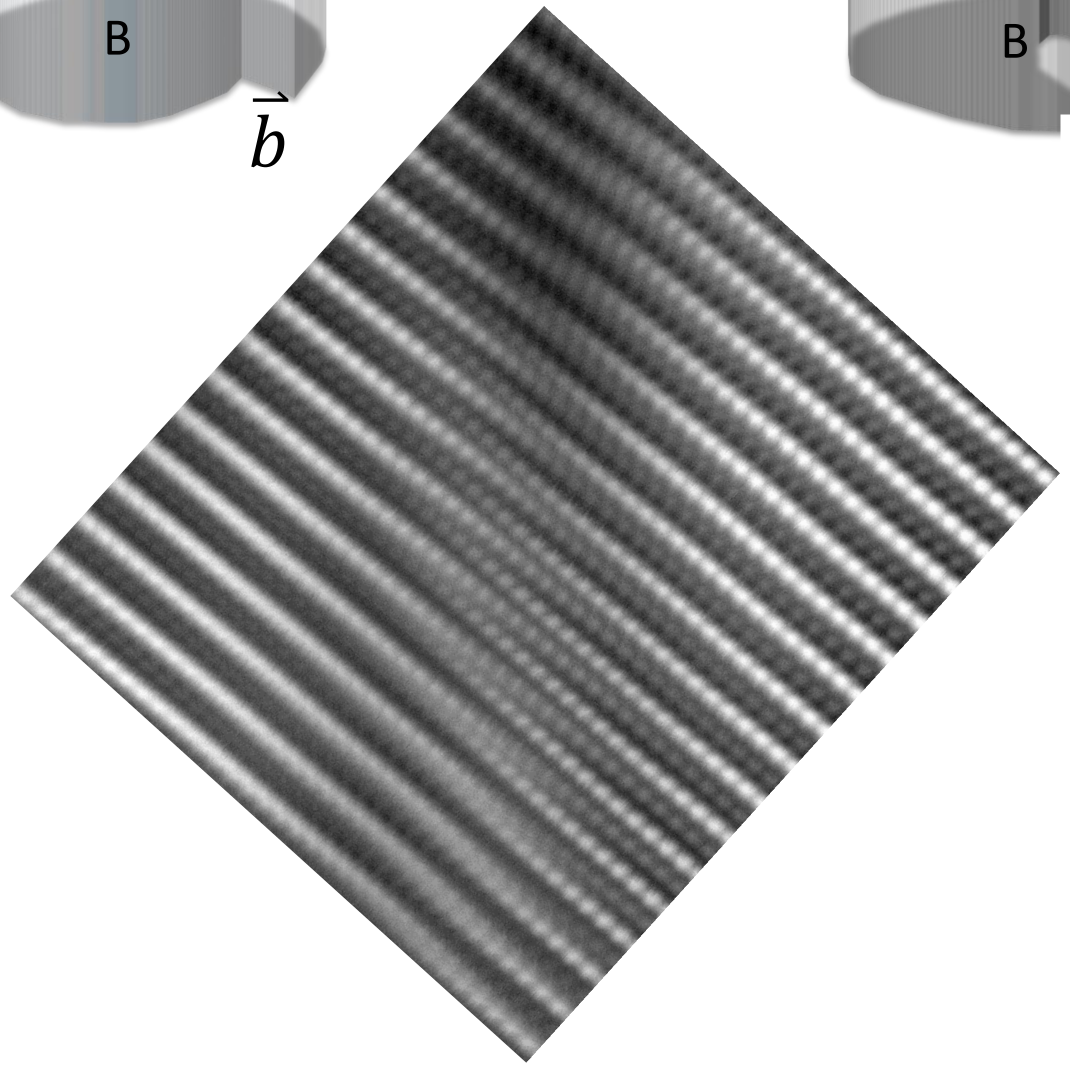
Edge dislocation

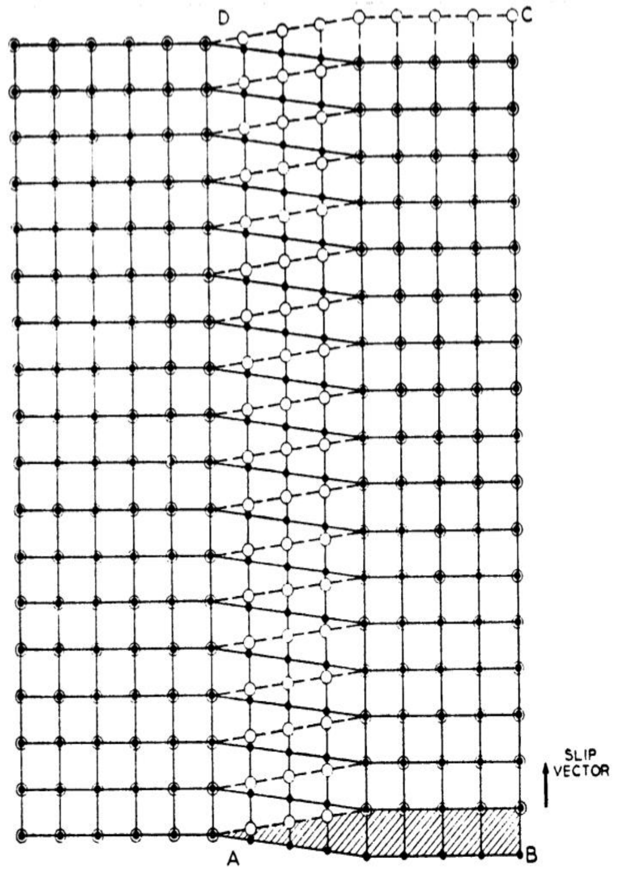


Screw dislocation



cut, shear, paste





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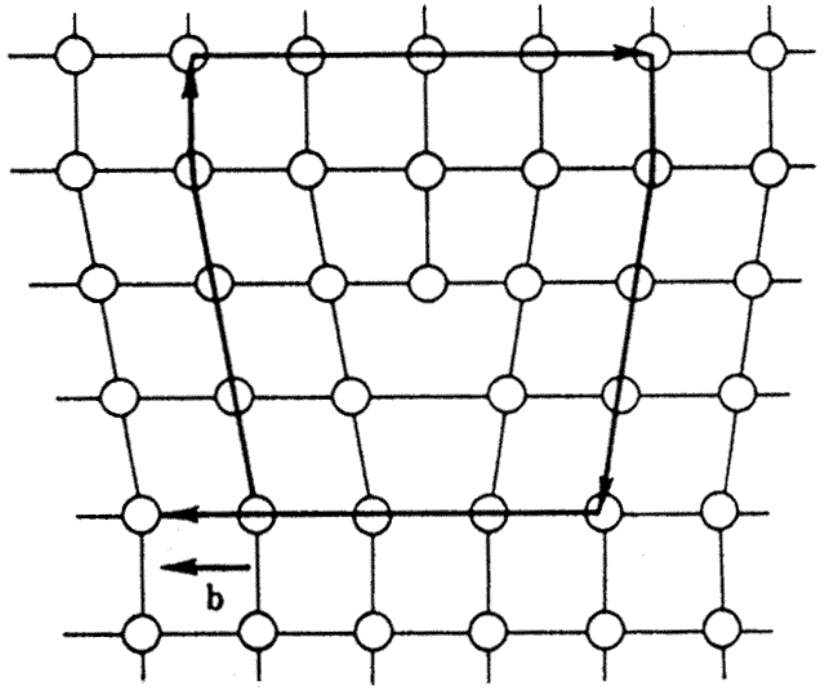
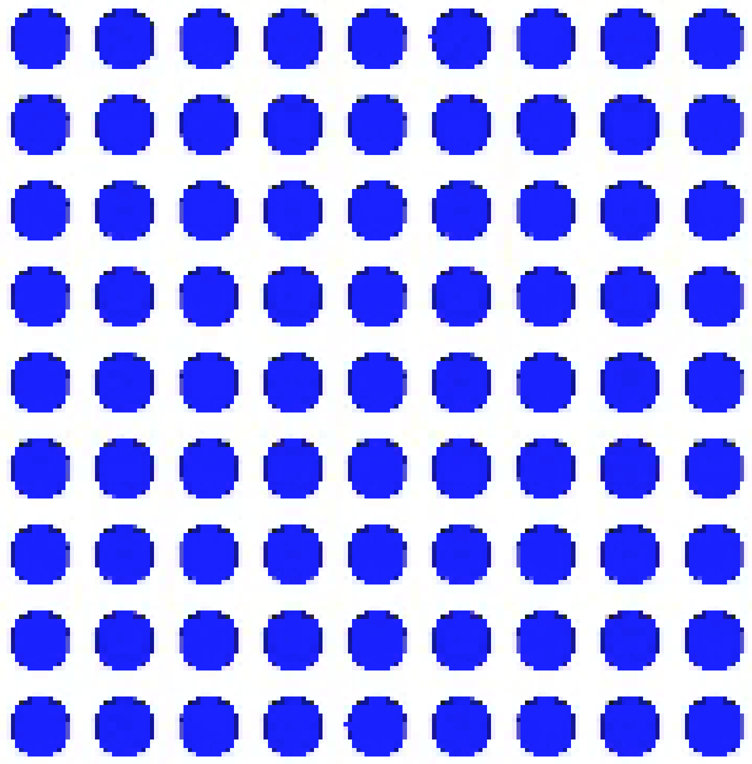
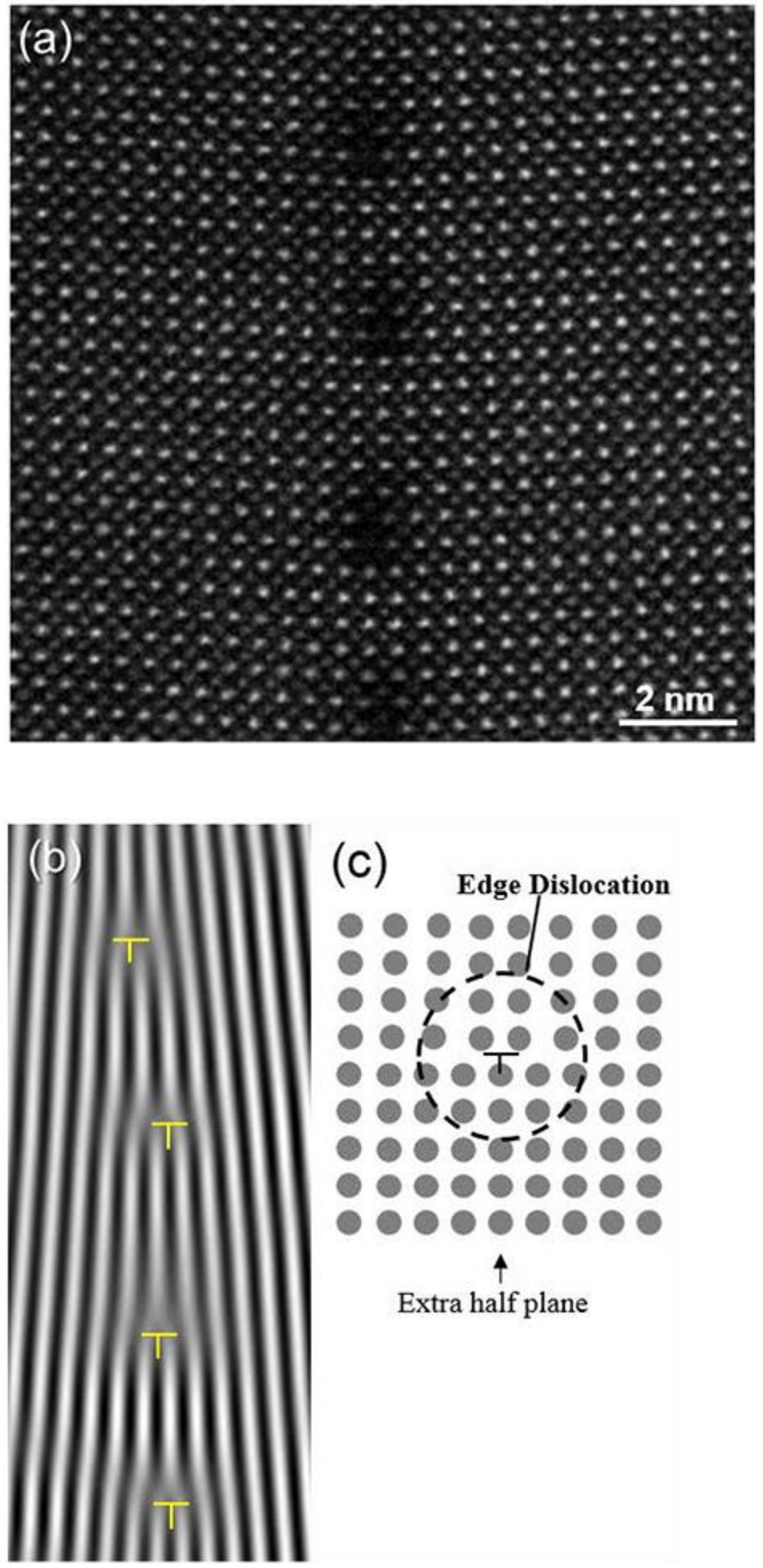
Transposition to the crystalline lattice: Burgers vectors







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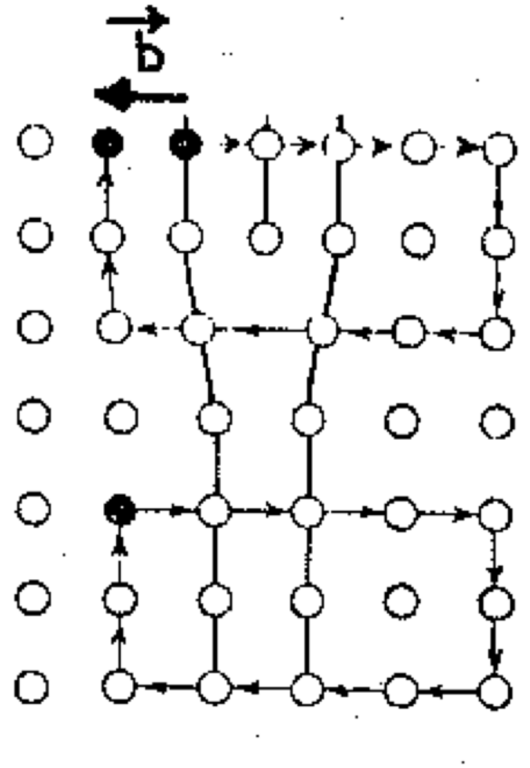
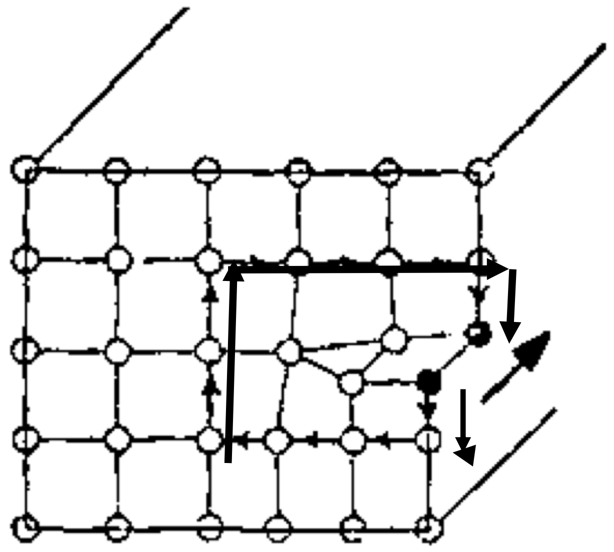
Slip plane



$\vec{b}$ and $\vec{\xi}$ are perpendicular

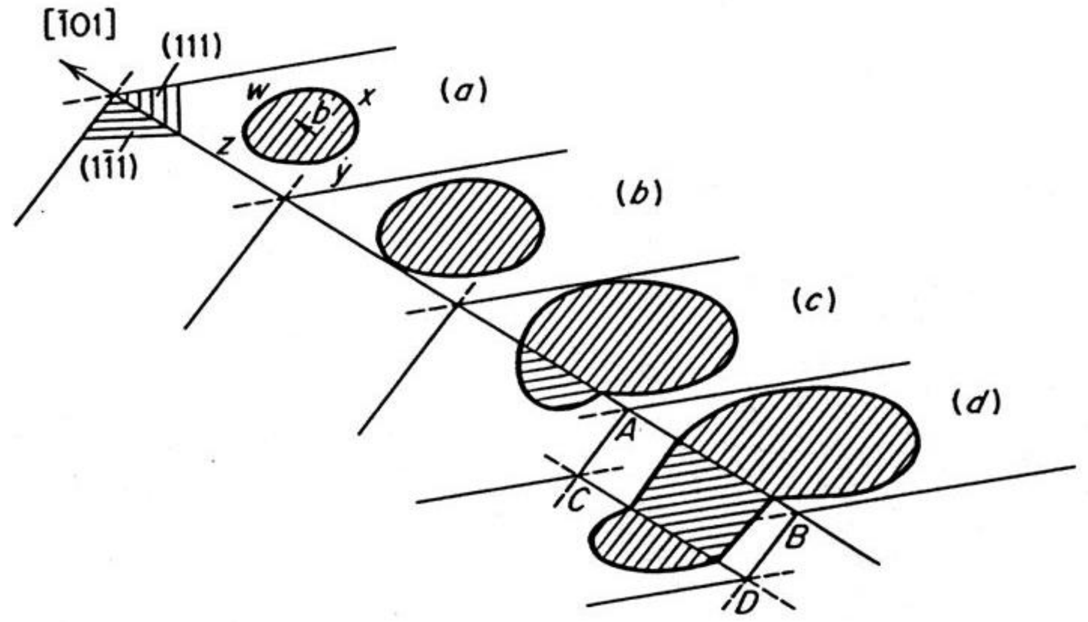
Edge



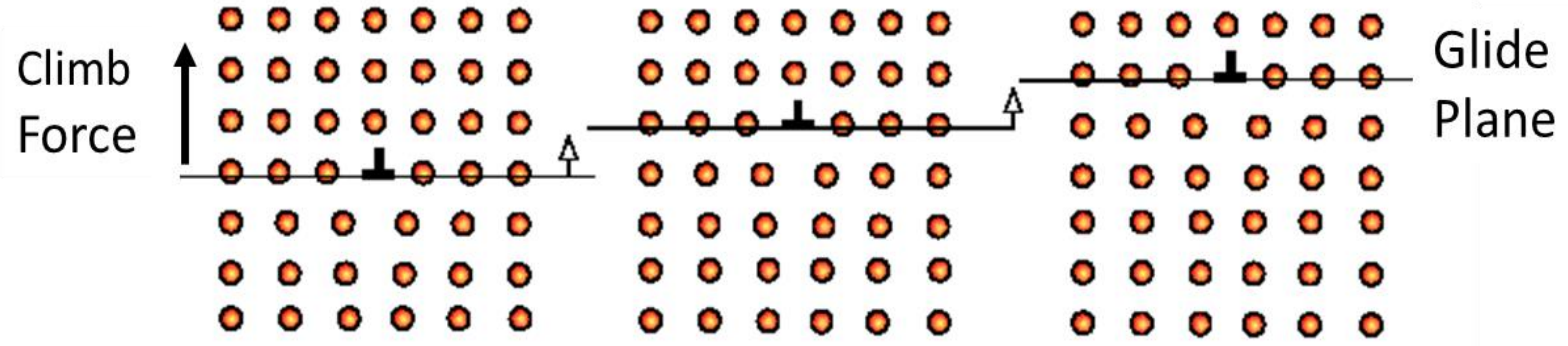
$\vec{b}$ and $\vec{\xi}$ are parallel

Screw

Cross slip



Climb



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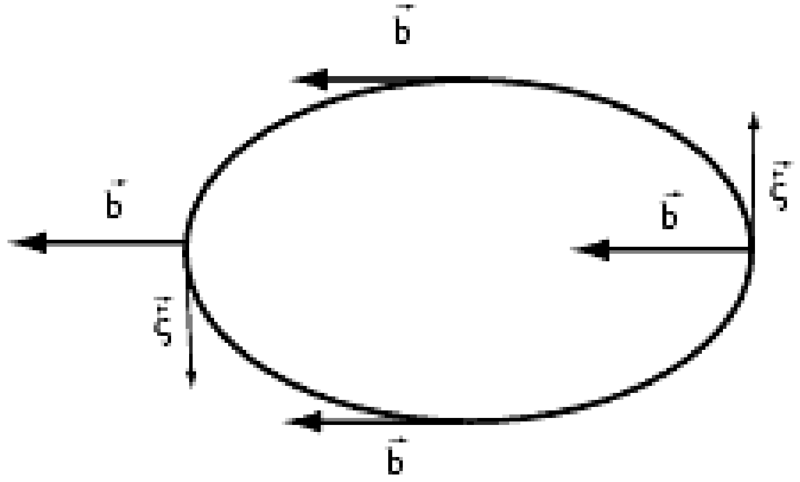
Properties of the Burgers vector

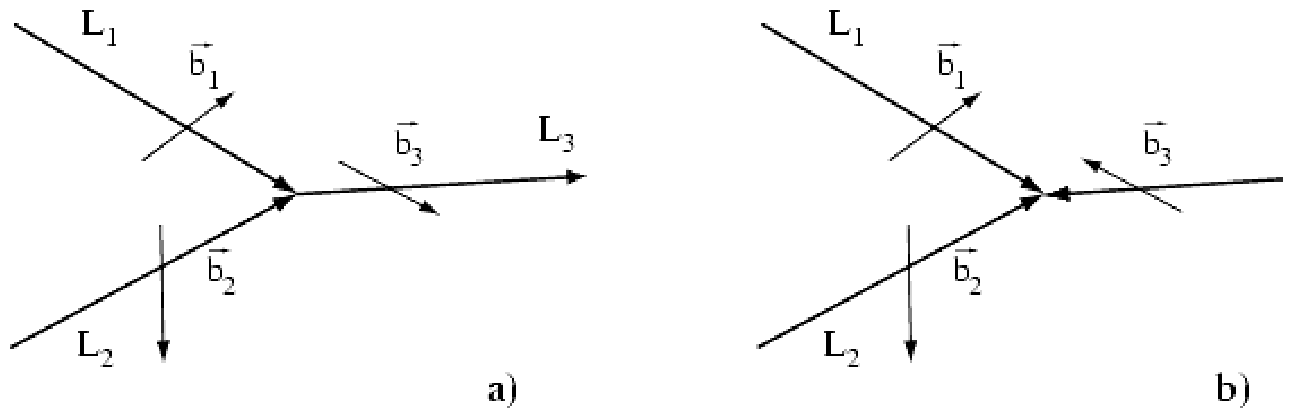
Equivalent of the Kirchoff laws

Conservation (mesh rule)



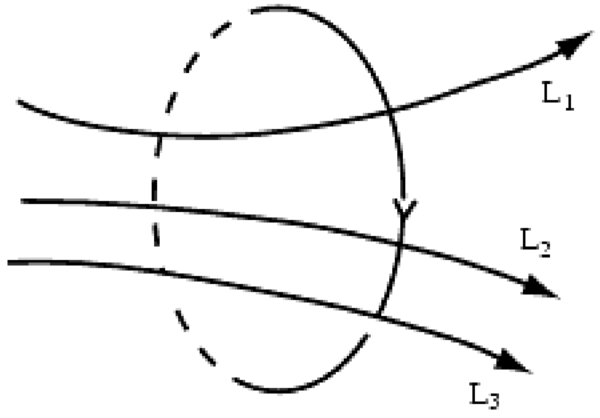
$\vec{b}$ is constant

Sum at a node



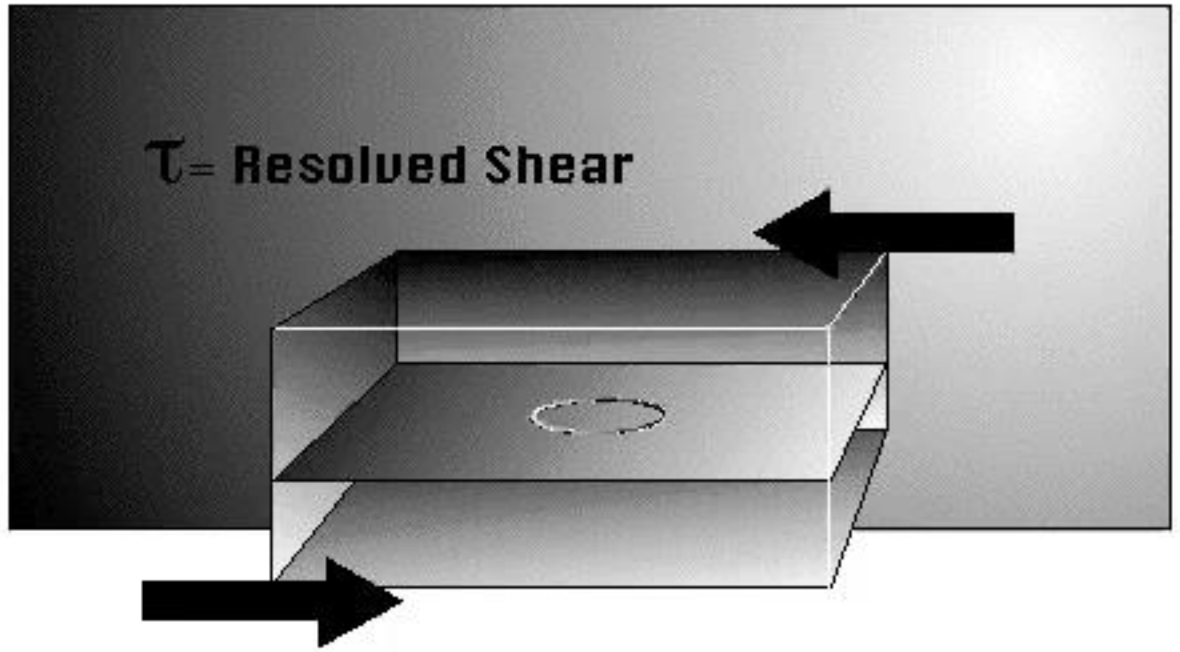
$$\vec{b}_3 = \vec{b}_1 + \vec{b}_2$$

additivity

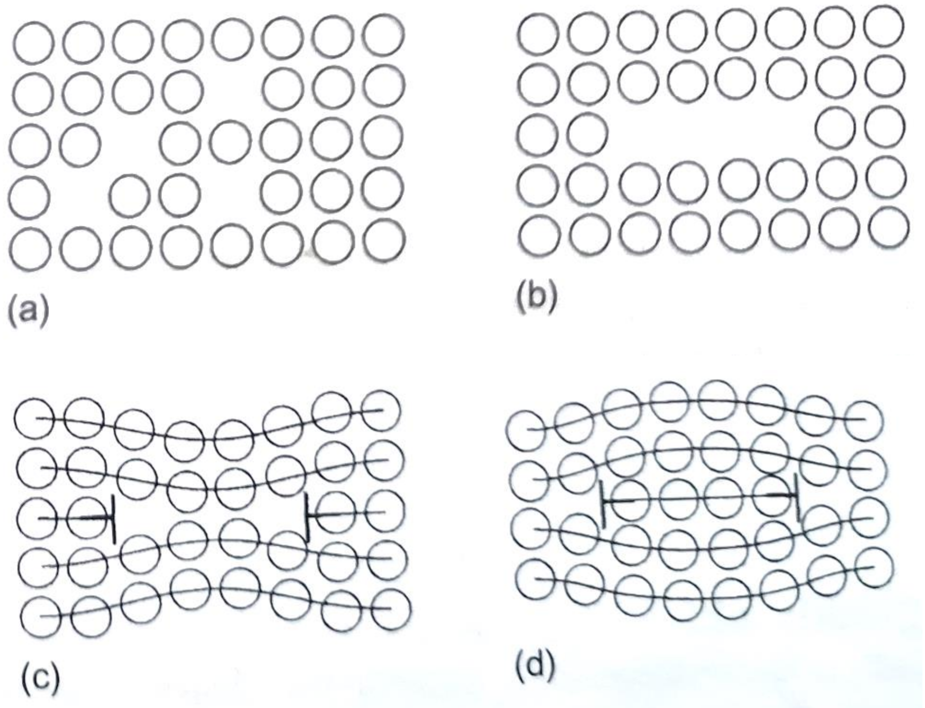


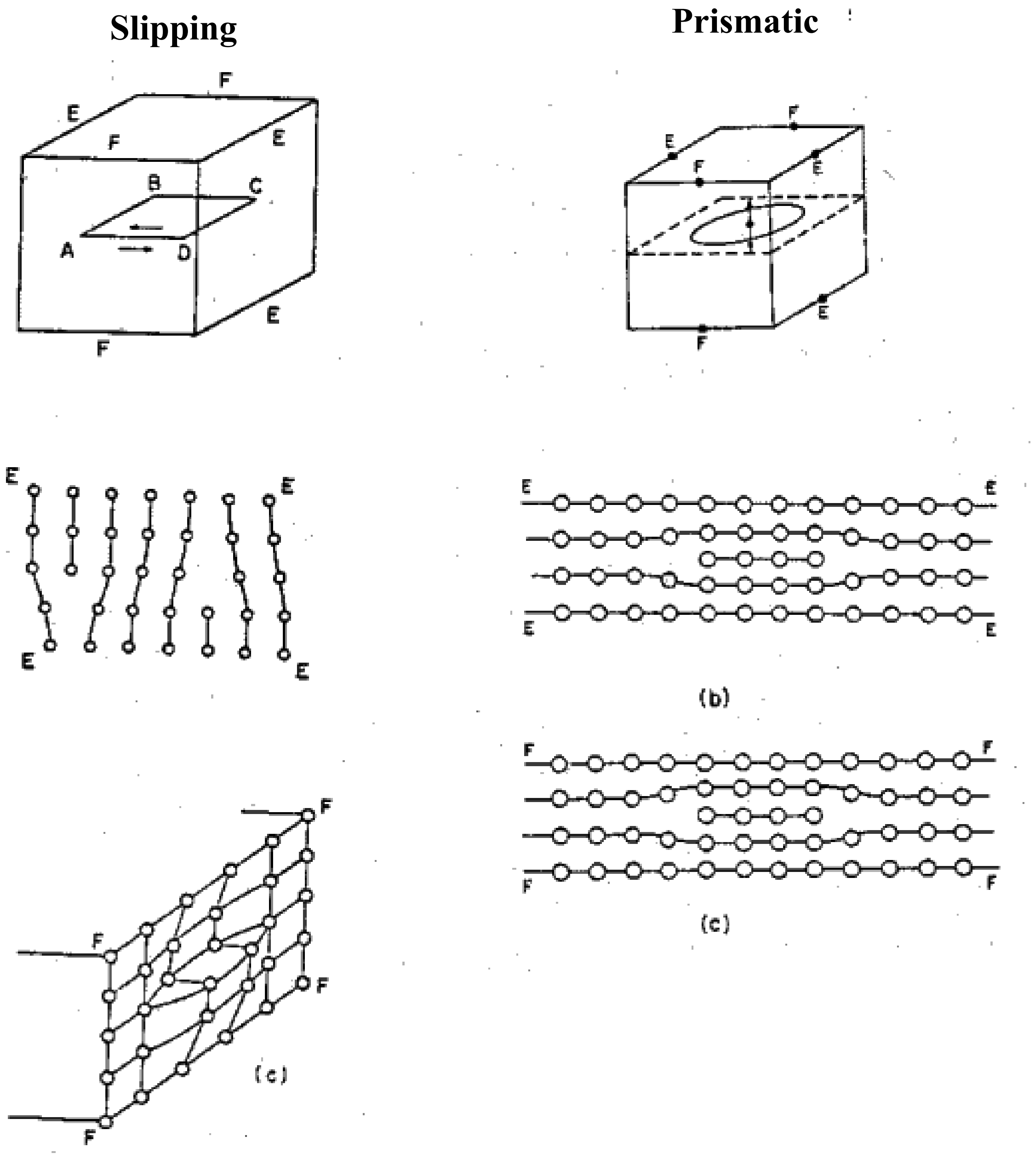
$$\vec{b} = \vec{b}_1 + \vec{b}_2 + \vec{b}_3$$

Dislocation loops



Formation of dislocation loops
in irradiation





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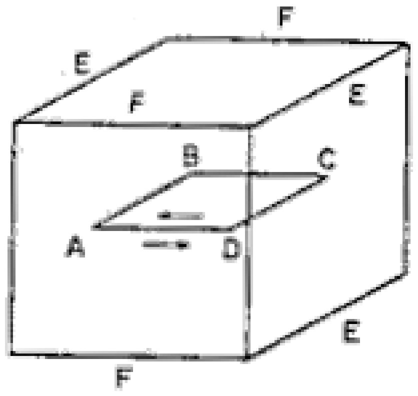
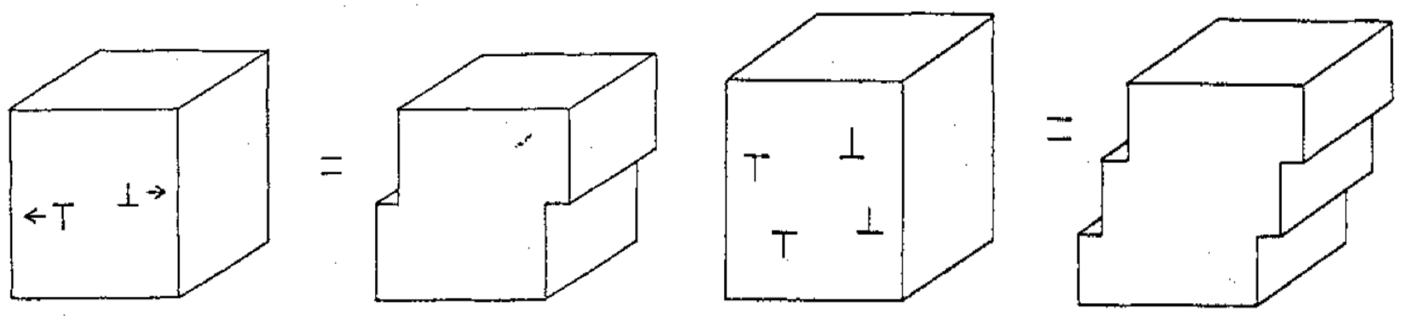
Dislocation loops

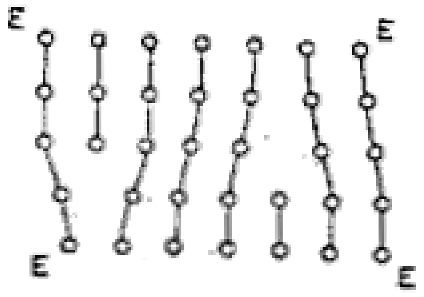
Slip

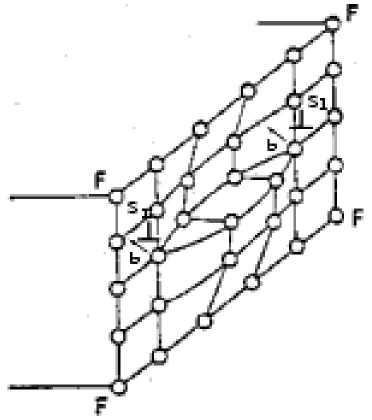


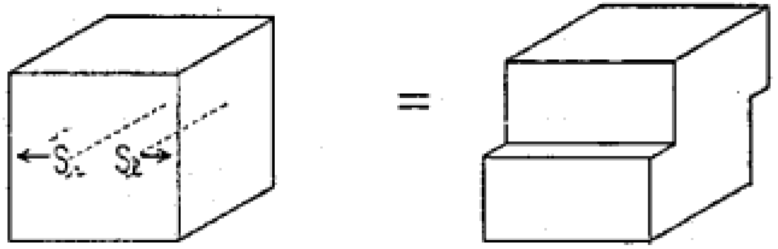
Edge components

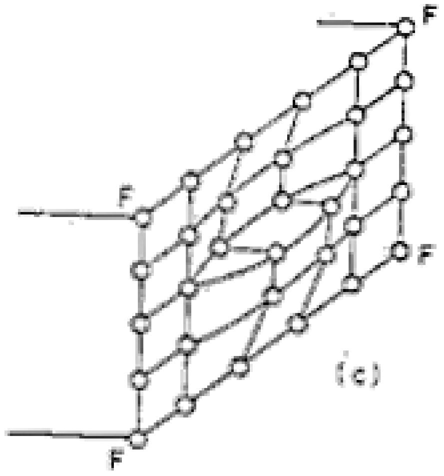


Screw components







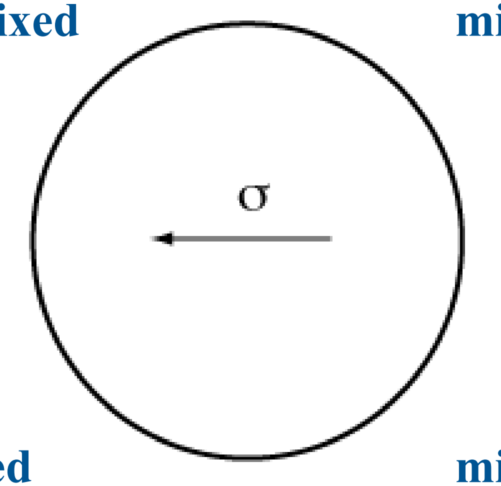


screw

mixed

mixed

edge

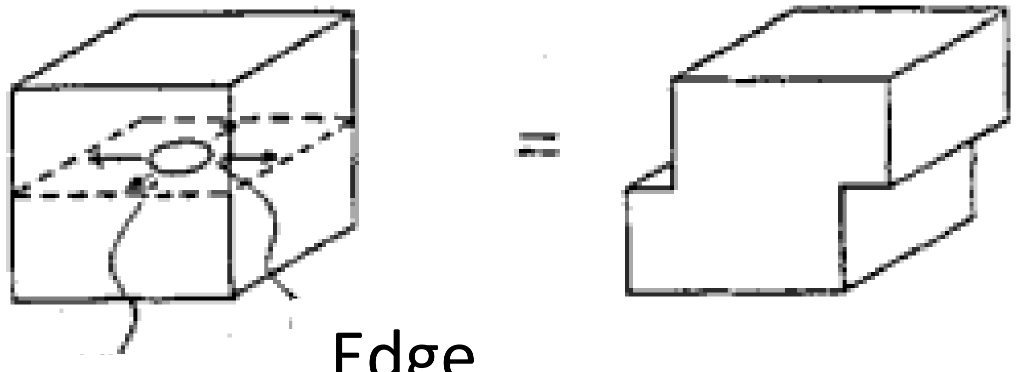


edge

mixed

mixed

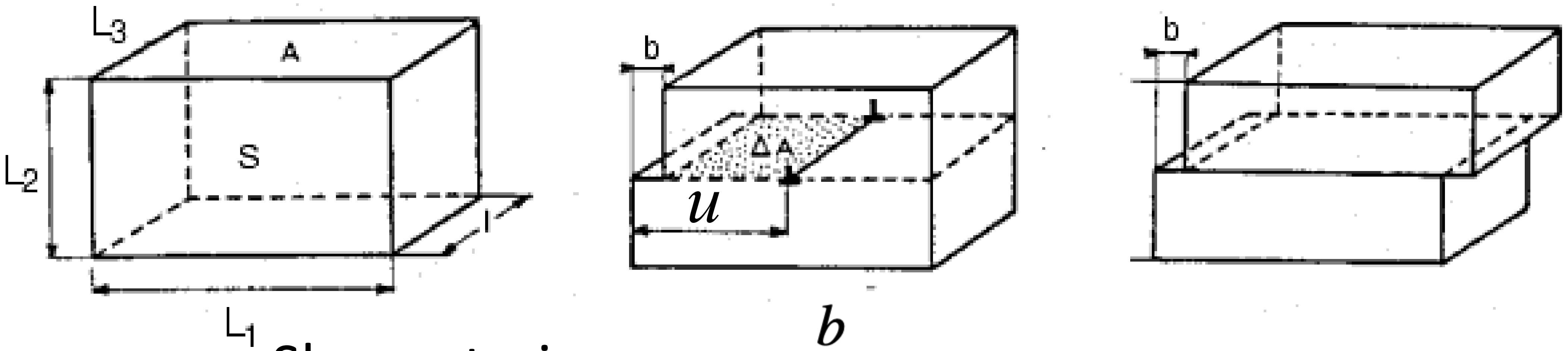
screw



Edge

Screw

Orowan equation

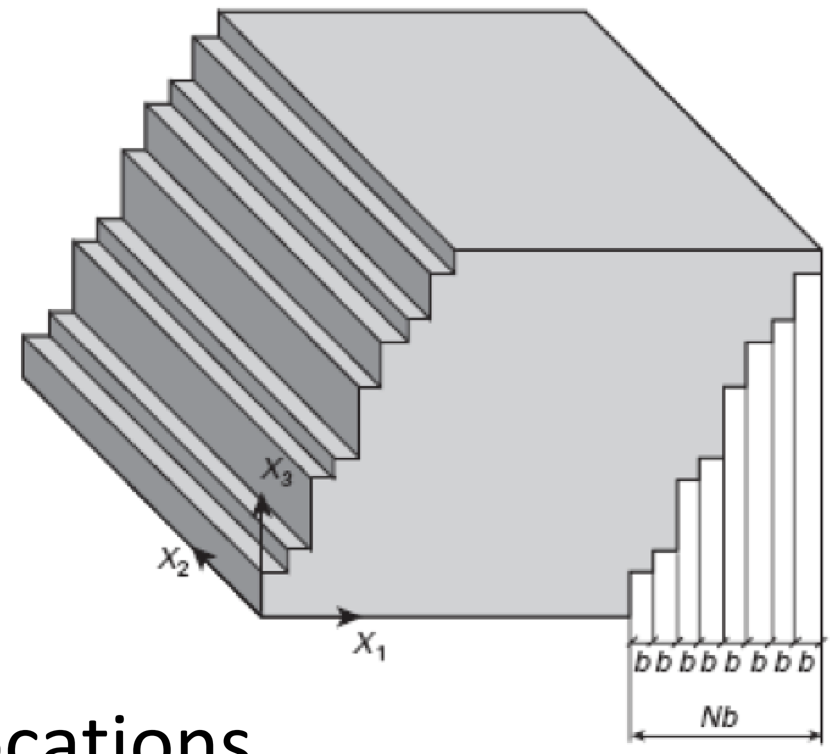


Shear-strain: $\varepsilon = \dfrac{b}{L_2}$

Partial displacement

$$\varepsilon = \frac{b}{L_2}\frac{u}{L_1} = \frac{b}{S}u$$

$$\varepsilon = \frac{b}{L_2}\frac{u}{L_1}\frac{L_3}{L_3} = \frac{b}{V}\Delta A$$



Many dislocations: density of dislocations

$$\varepsilon = \frac{N}{V} b \cdot \Delta A \qquad \varepsilon = \frac{N}{S} b \cdot u \qquad \Lambda = \frac{N}{S} = \frac{N \cdot L_3}{V} \qquad \boxed{\dot{\varepsilon} = \Lambda b \dot{u} = \Lambda b v}$$

<u>Orowan's equation</u>

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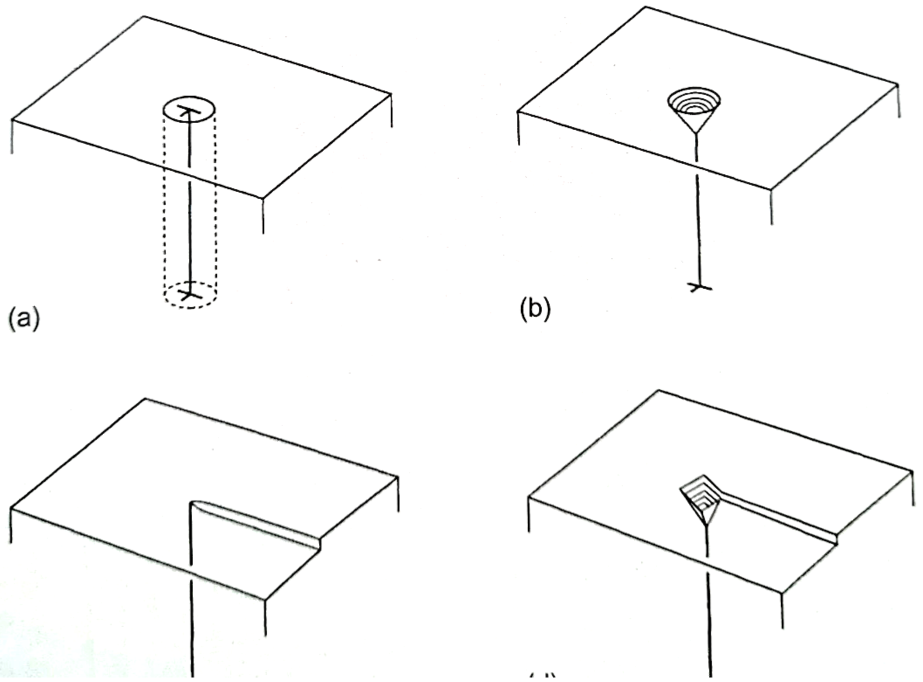
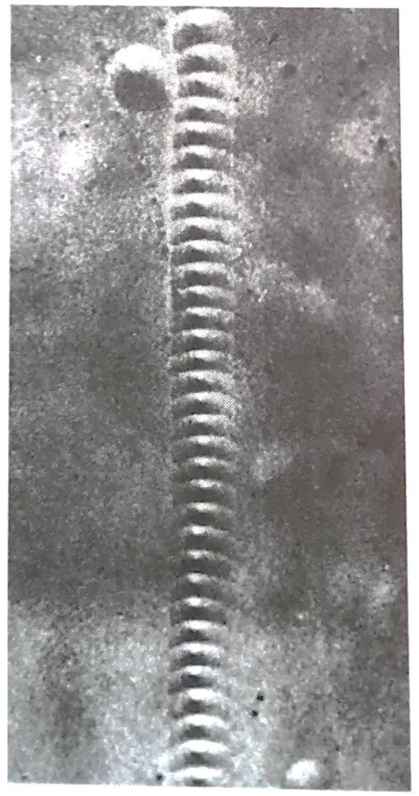
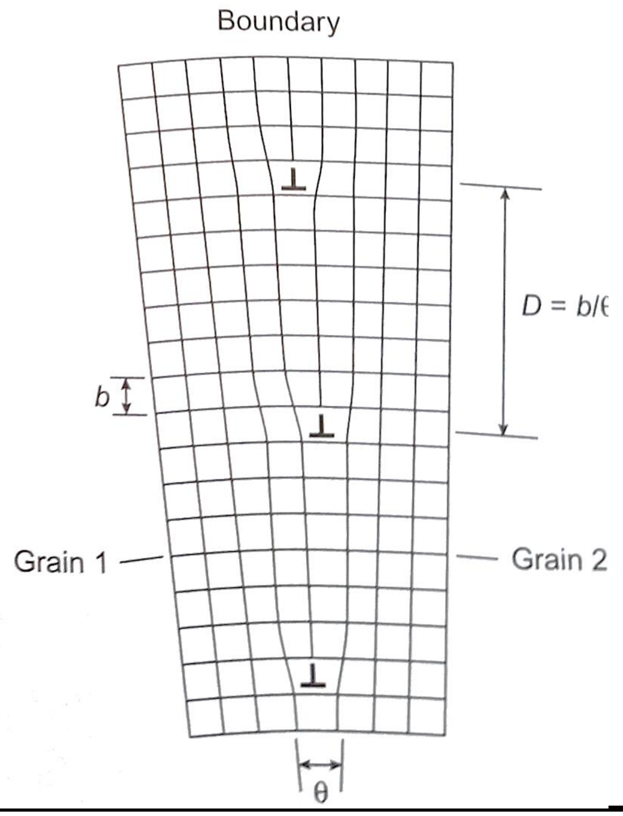
Etch pits

Edge

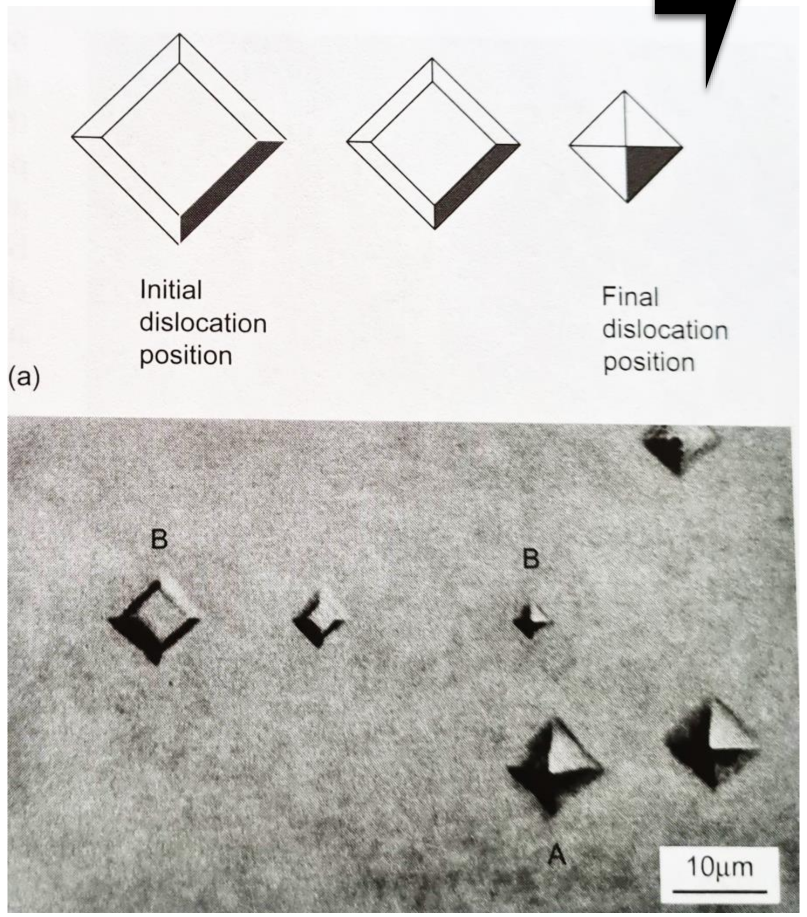
Screw







Dislocation motion



Etch pits along the grain boundaries having a dislocation network

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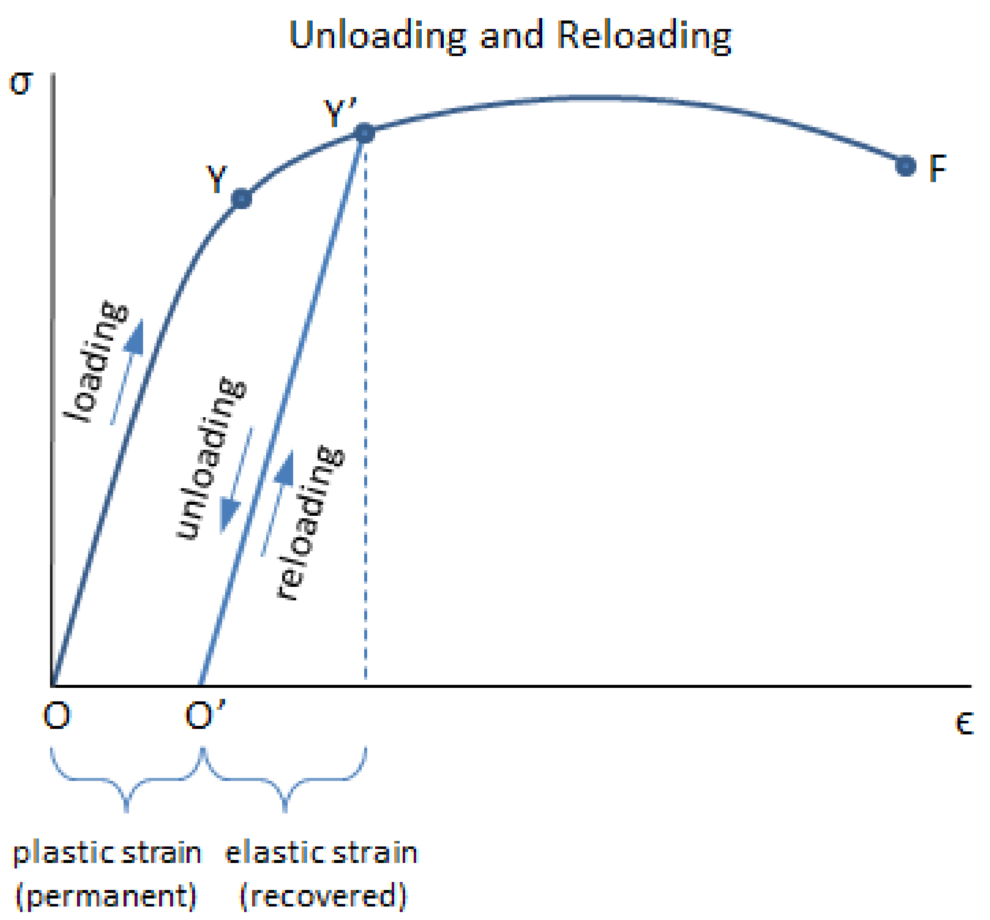
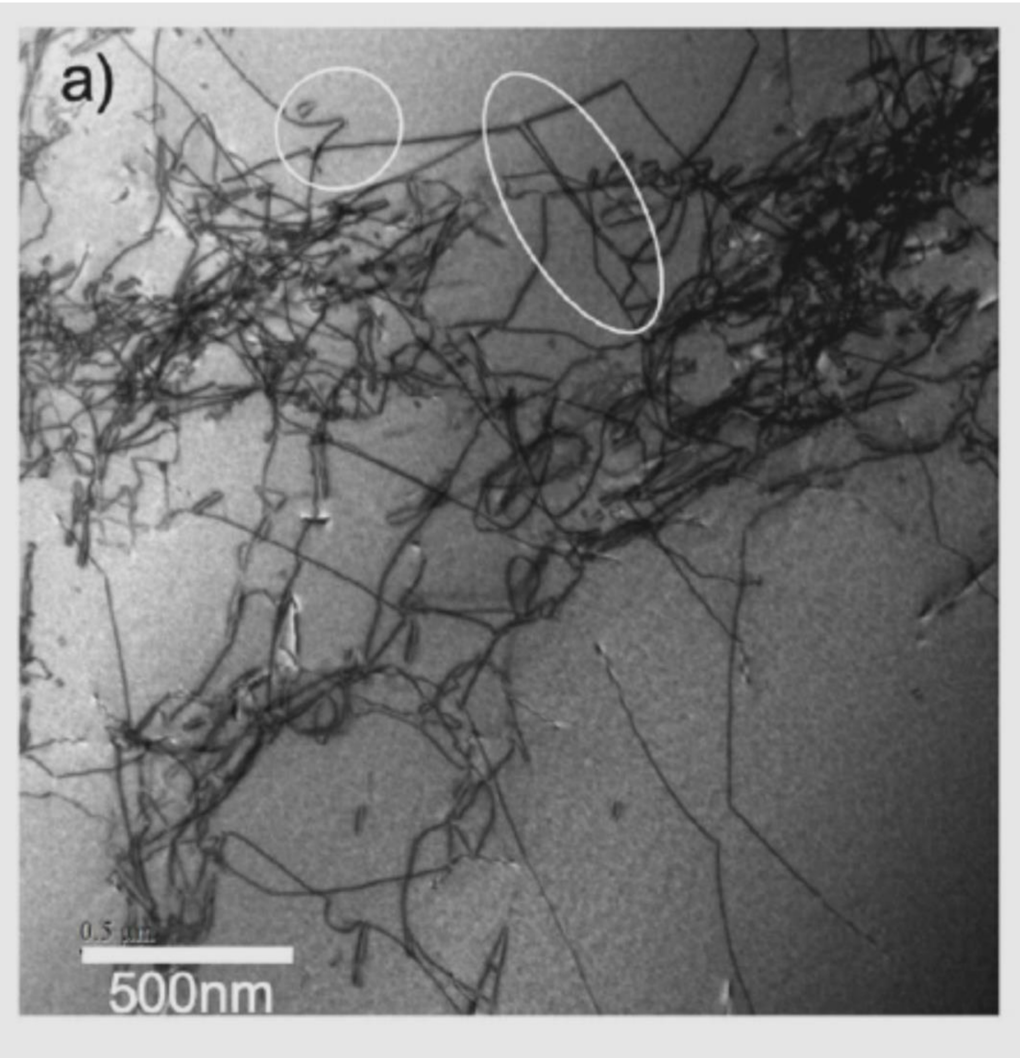
Strain hardening: multiplying dislocations



Tensile curve:
increase of the elastic limit



Dislocations in 10% deformed iron

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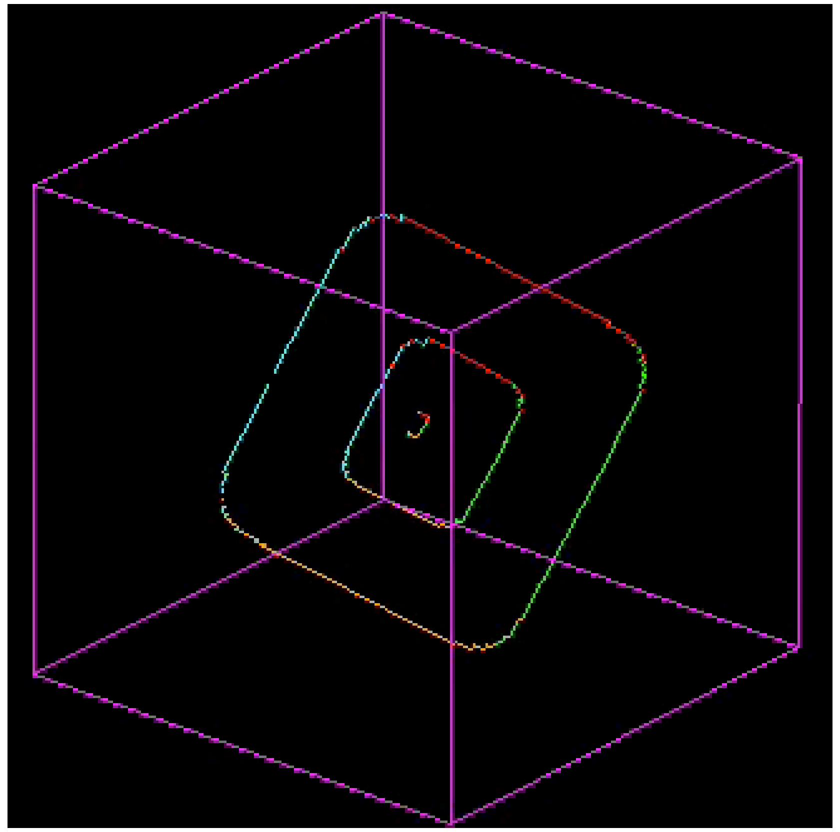
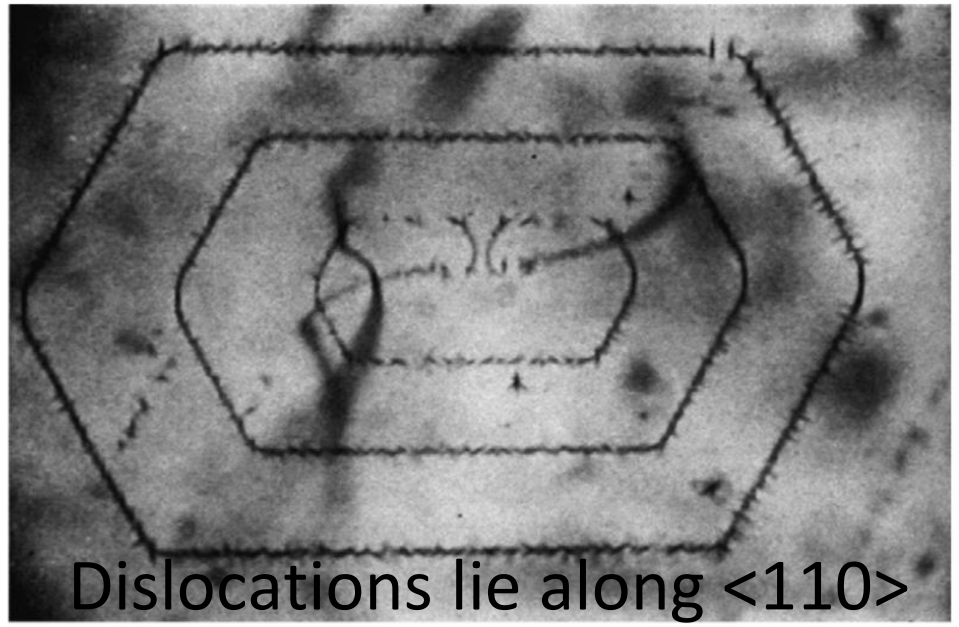
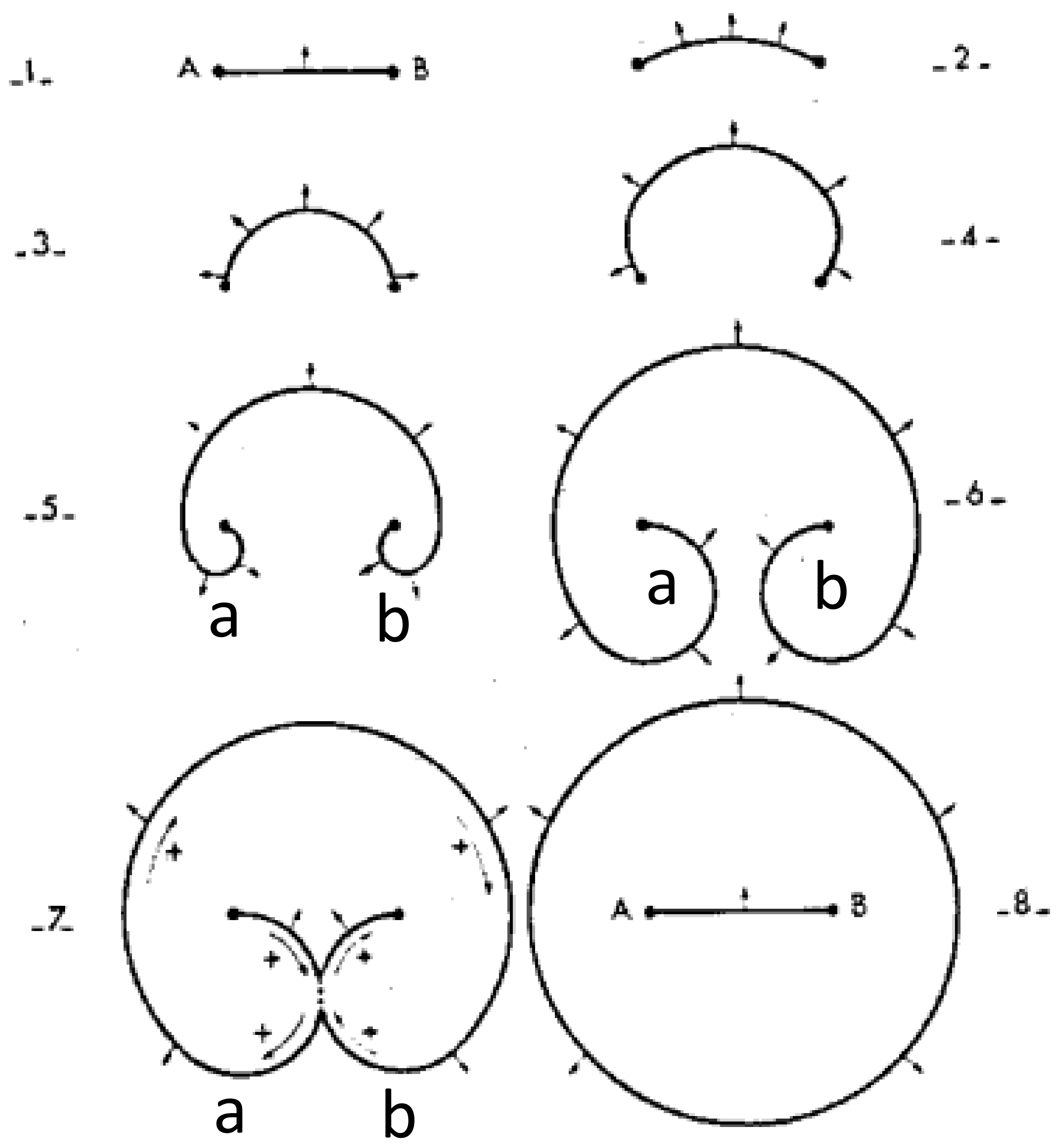
Multiplying dislocations: Frank-Read



F-R source in Si



$$\tau_{max} = \mu b / L$$



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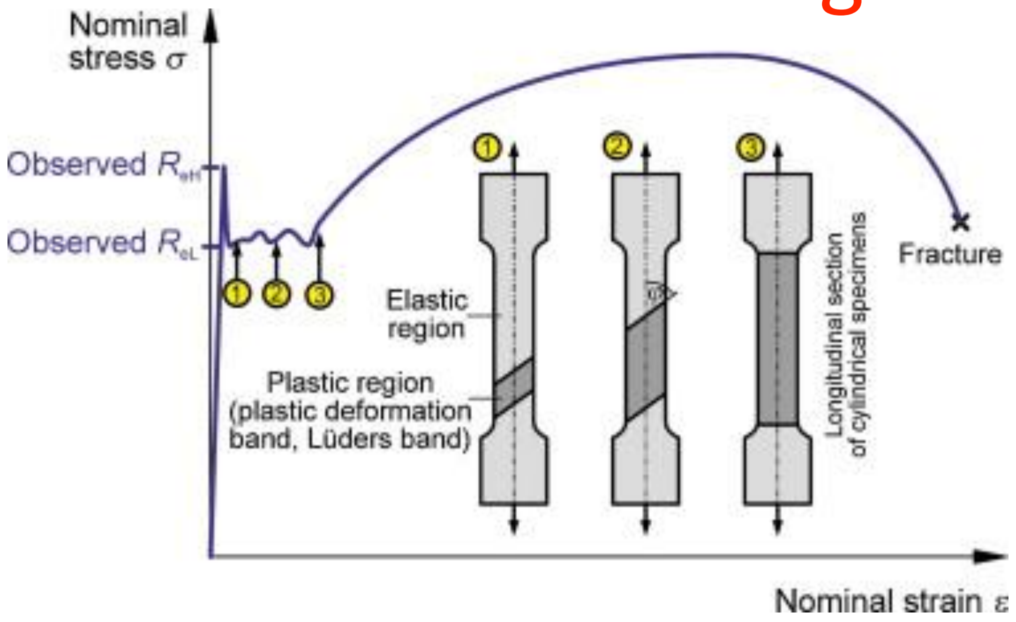
Other hardening modes

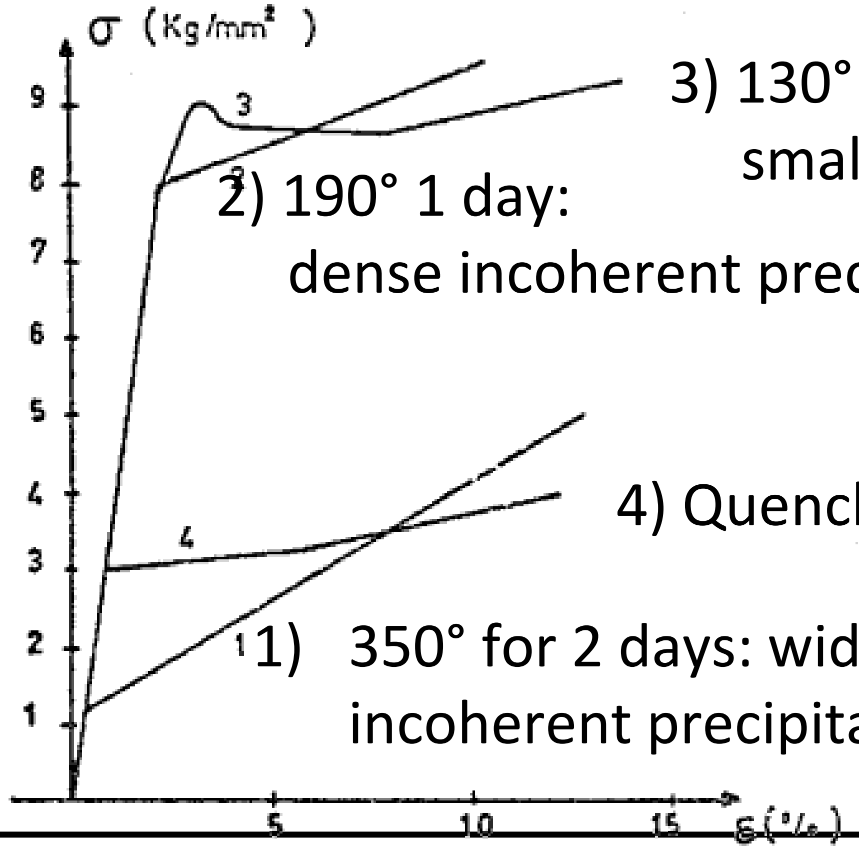
Pinning



Mild Steel to carbon

Structural hardening: precipitates

Al-2%Cu



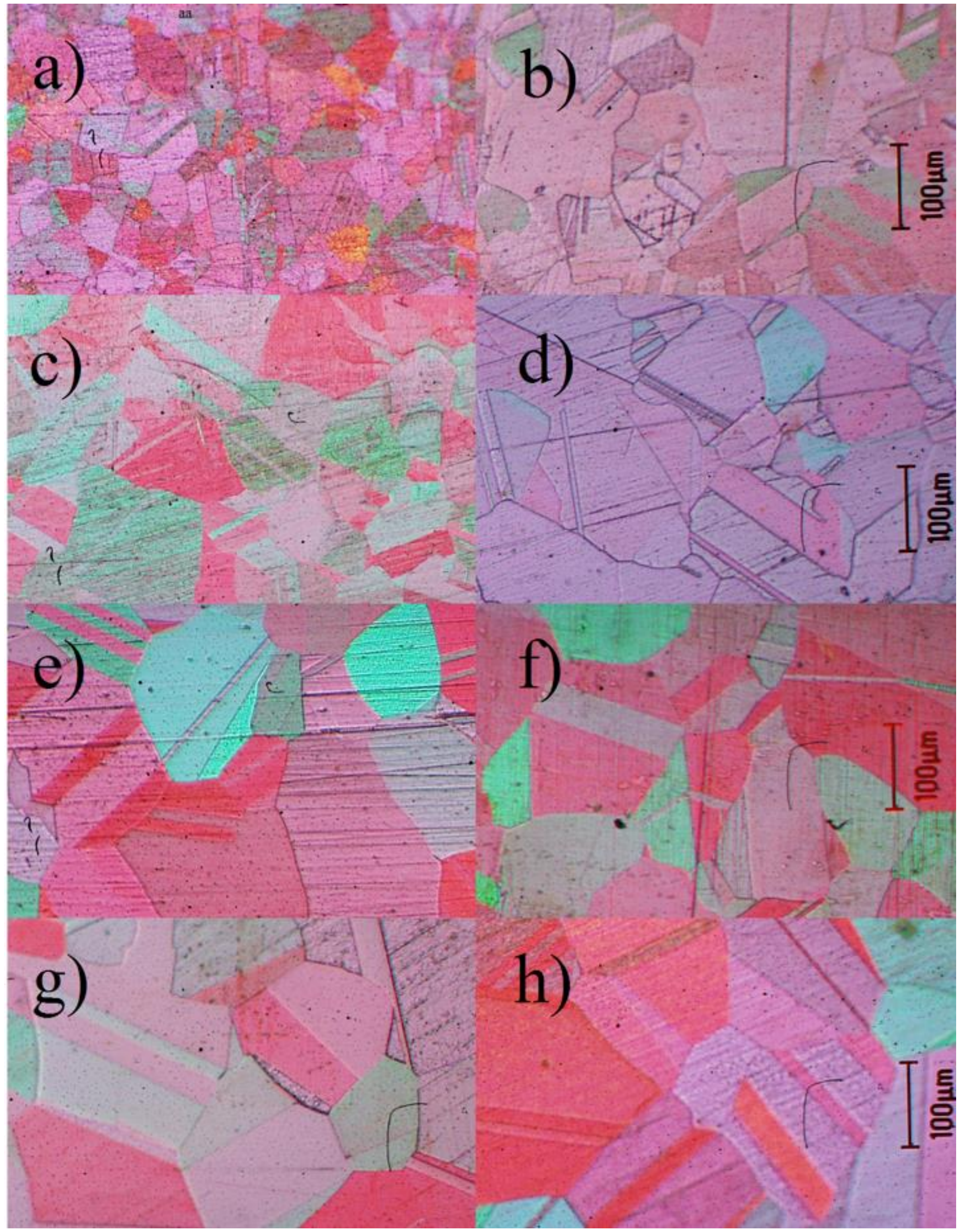
3) 130° 2 days: dense small coherent precipitates

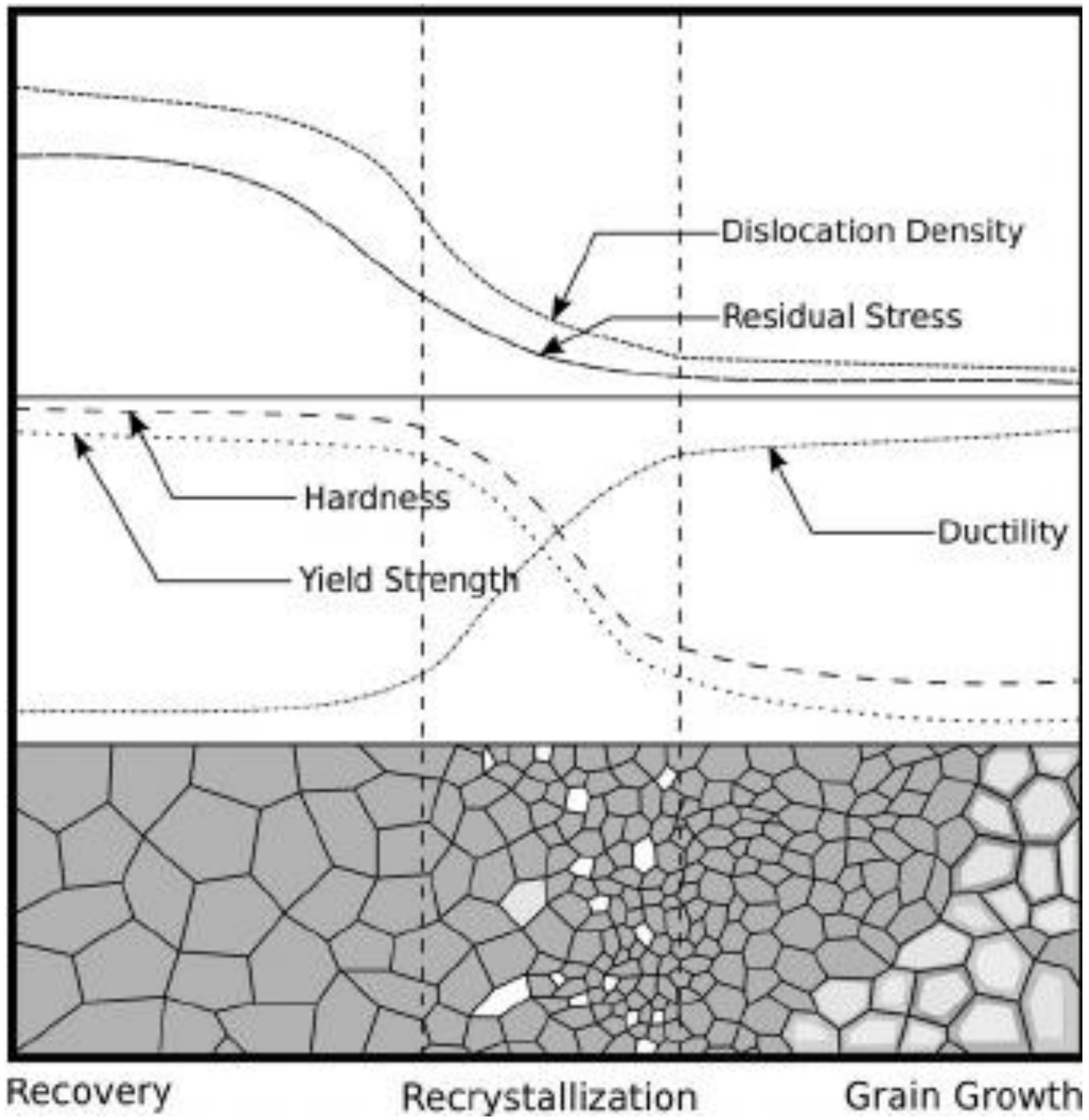
2) 190° 1 day: dense incoherent precipitates

4) Quenched: solid solution

1) 350° for 2 days: widely spaced incoherent precipitates

Recrystallization





Increase of the grain size in gold

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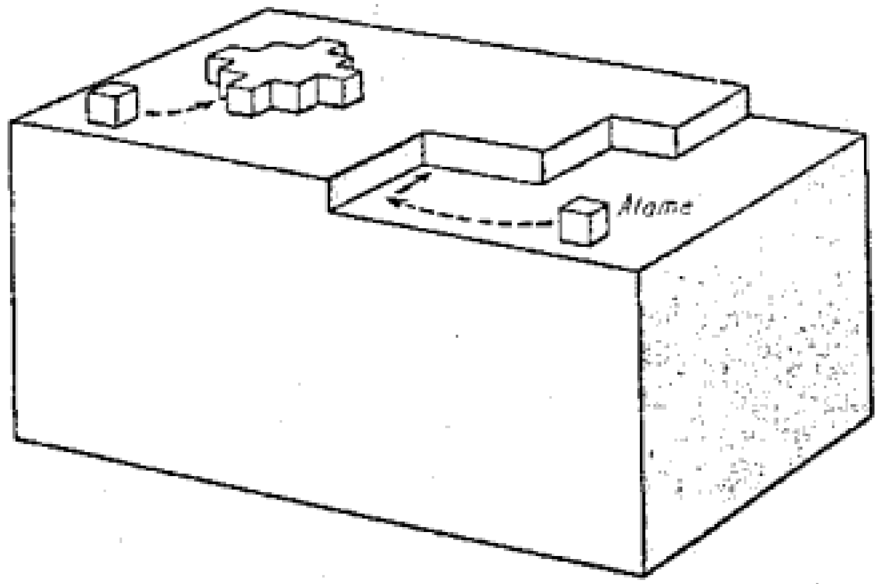
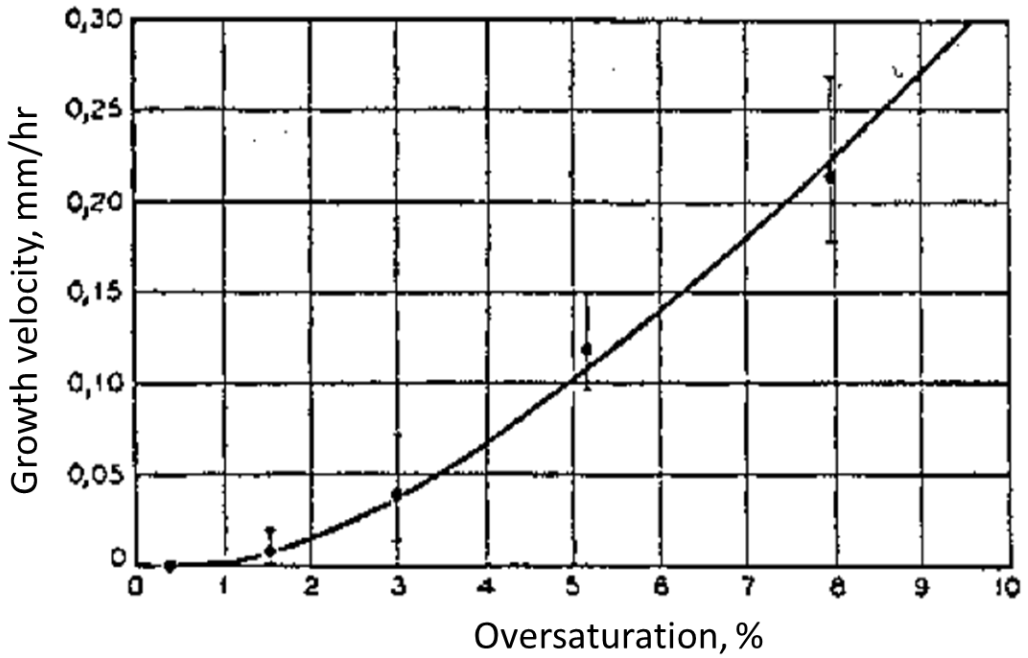
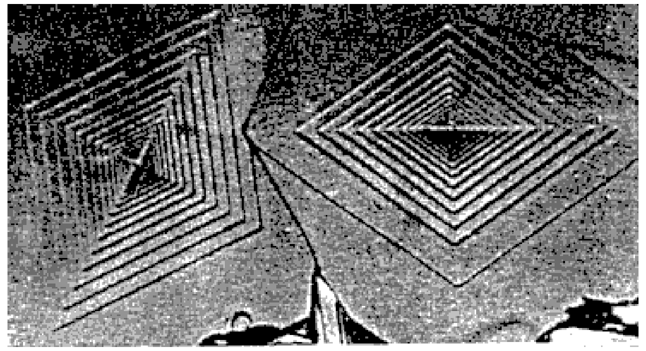
Growth of crystals



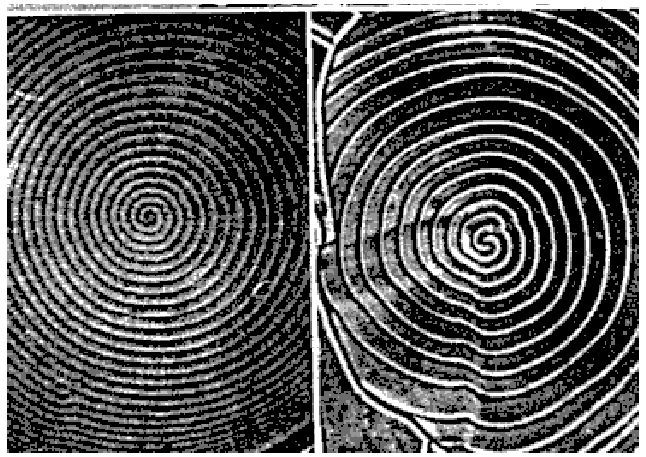


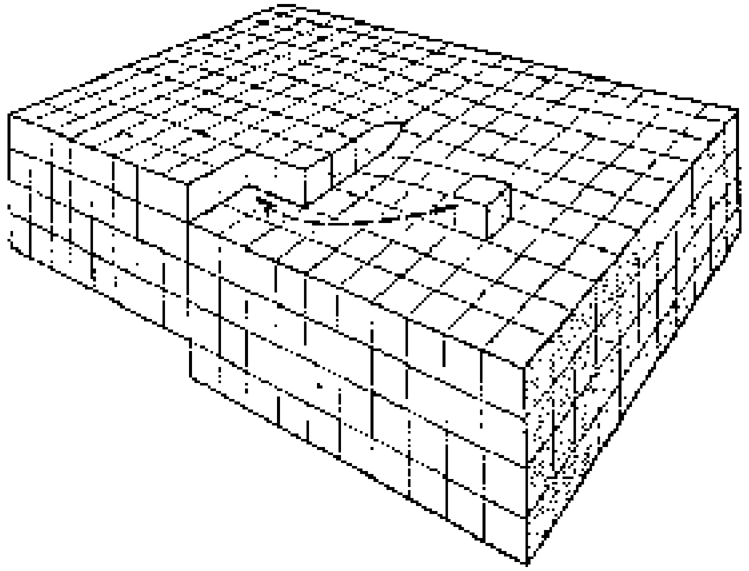
Growth of crystals depending on supersaturation

Polyethylene crystal



SiC





$$\rho = 2\rho_c\theta$$

$$\omega = \frac{d}{dt}\left(\frac{\rho_\infty}{2\rho_c}\right) = \frac{v_\infty}{2\rho_c}$$