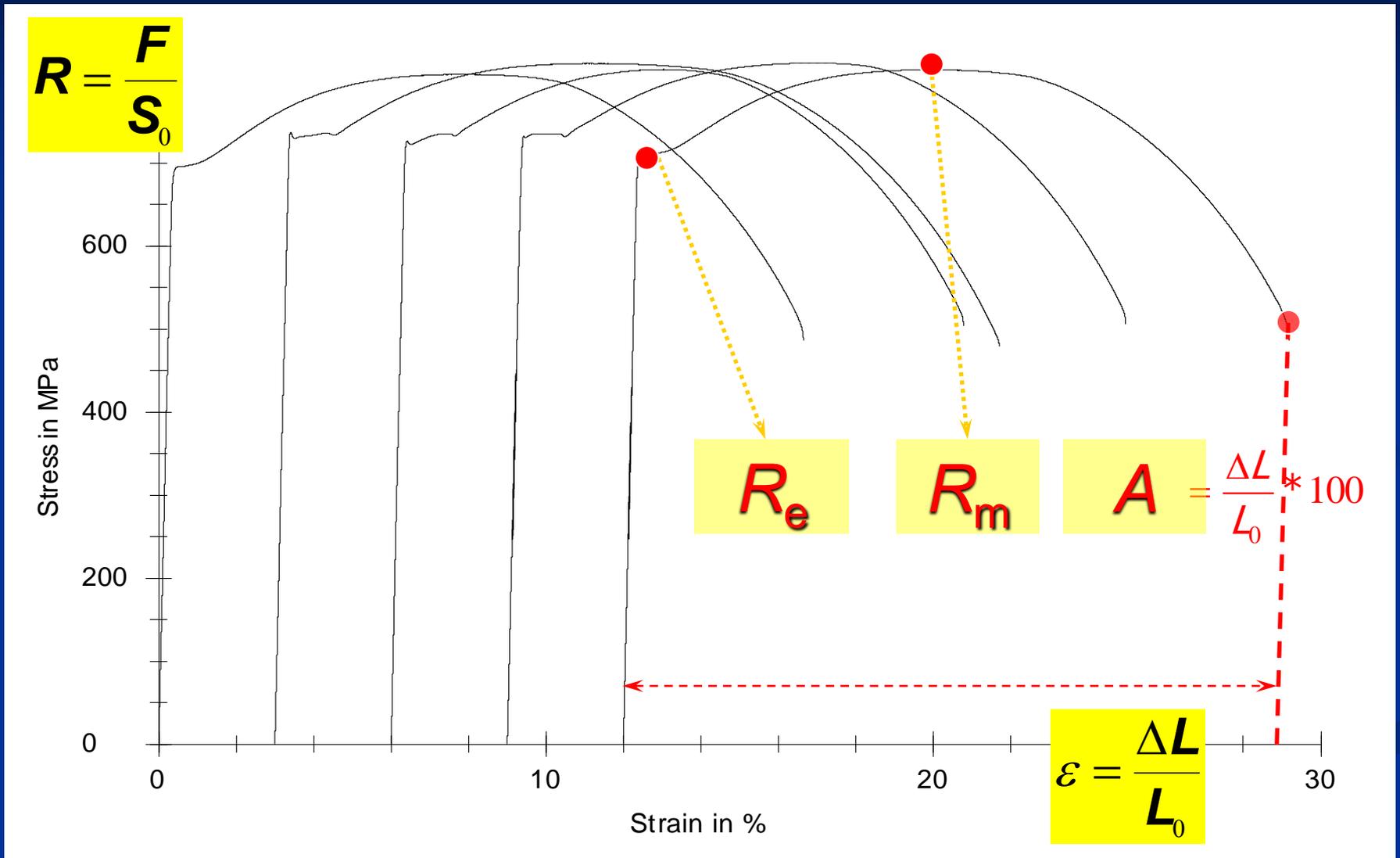


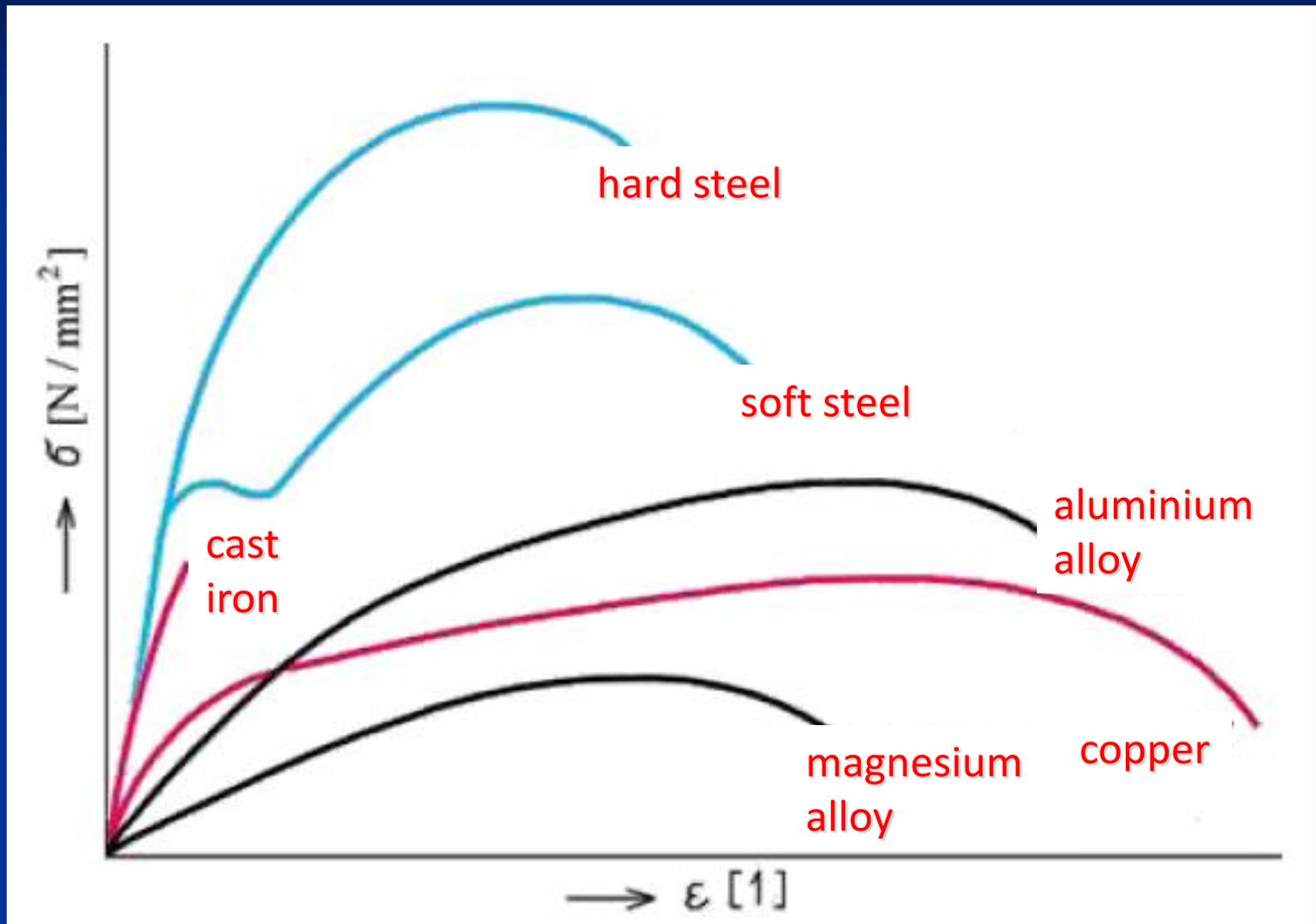
Tensile deformation and tensile test - II

- ❖ **Tensile test**
- ❖ **Tensile loading of monocrystal**
- ❖ **Plastic deformation**
- ❖ **True stress – true strain curve**

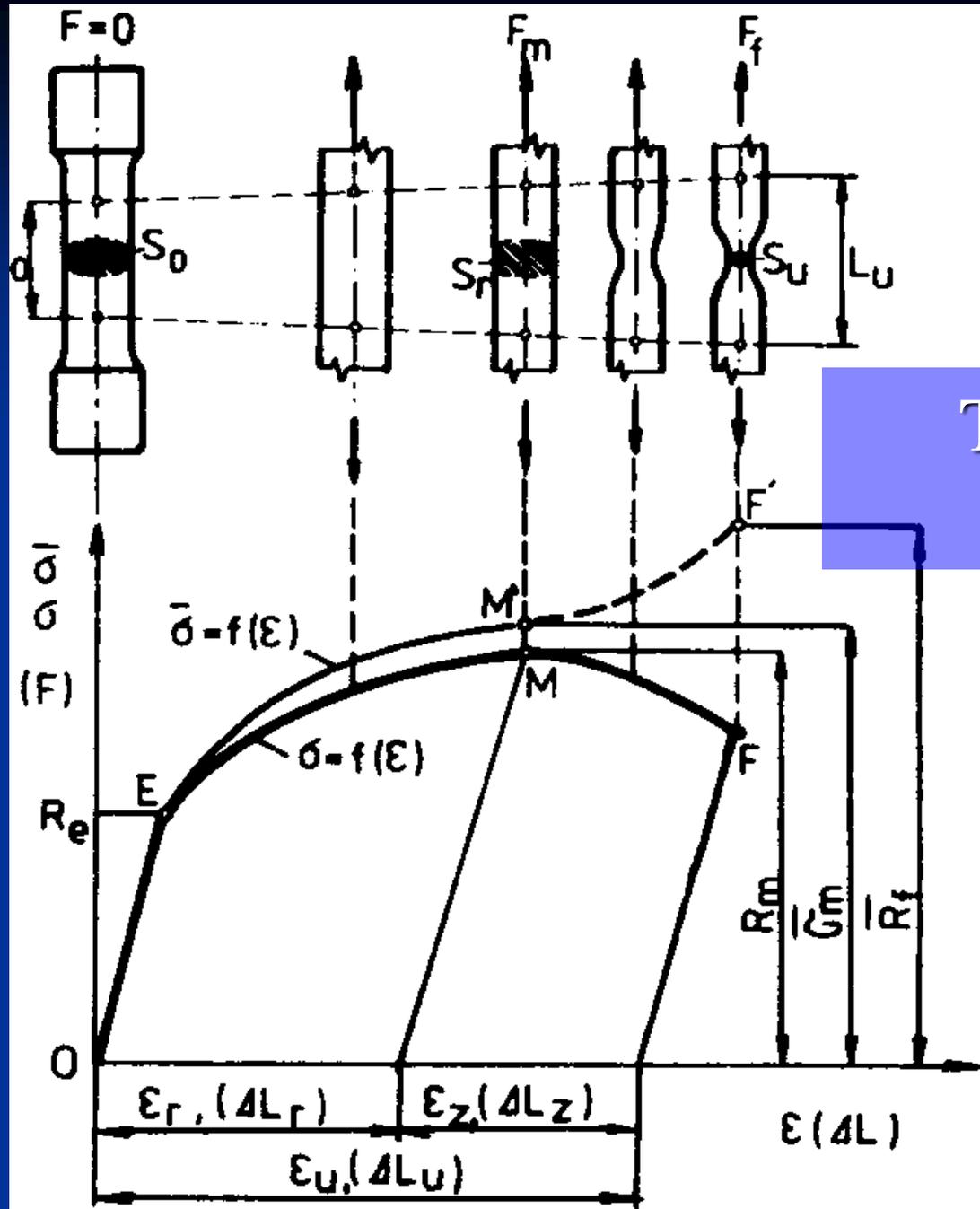
Tensile test



Tensile test

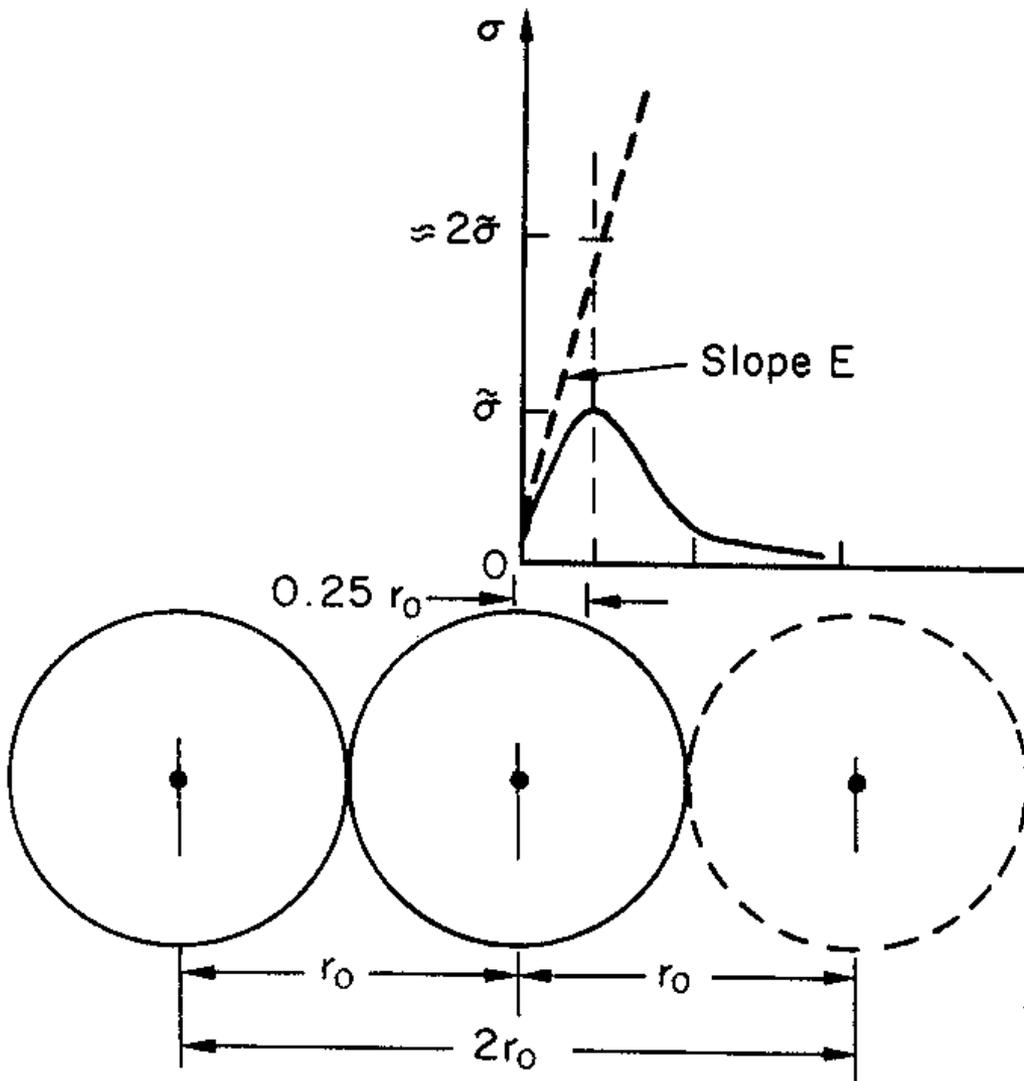


Tensile test



True stress – true strain
diagram

Ideal strength



$$\sigma = E\varepsilon$$

$$2\tilde{\sigma} \approx E \frac{0,25r_0}{r_0} = \frac{E}{4}$$

$$\tilde{\sigma} \approx \frac{E}{8}$$

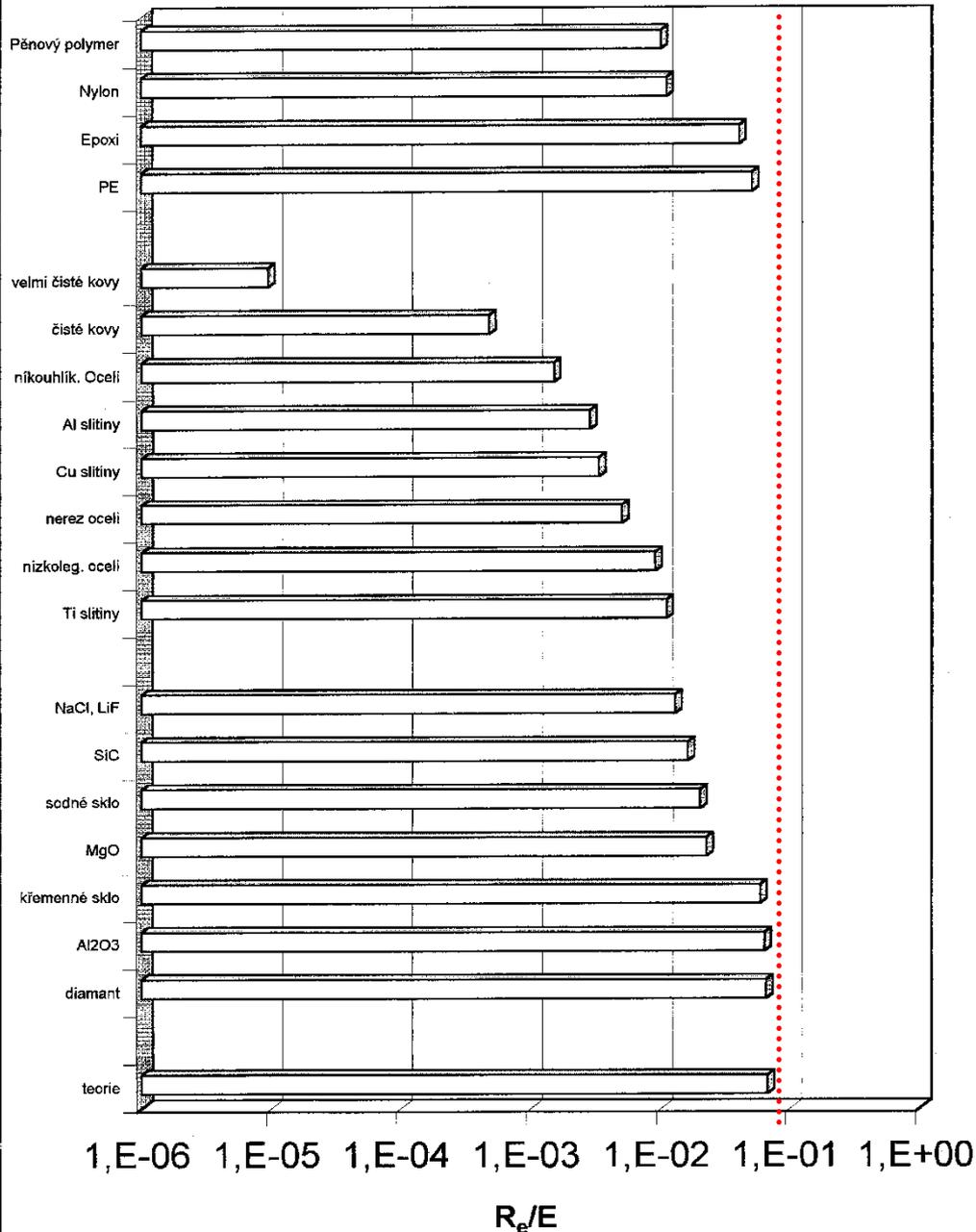
Ideal strength

Why is there a difference between ideal and real strength ?

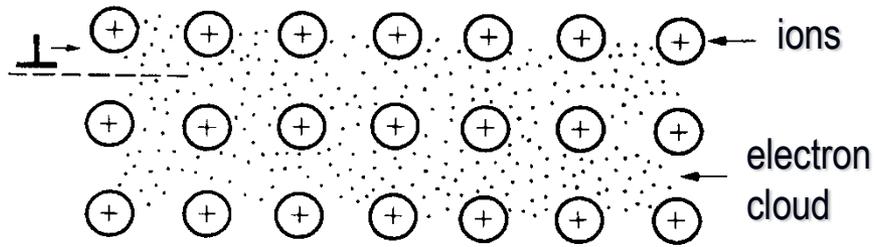
point defects – vacancy, divakancy, foreign atoms

line defects – dislocations
- screw, edg, mixed

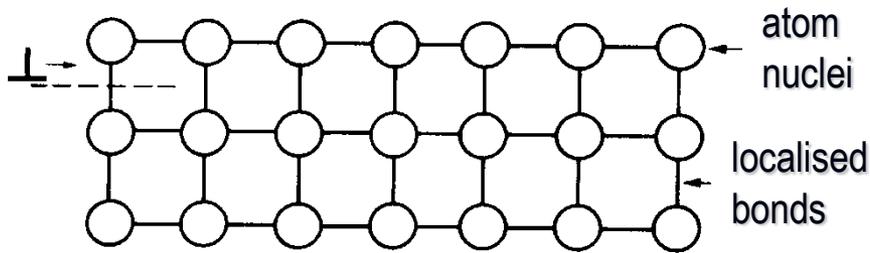
Stacking faults – grain boundaries and their mutual interaction



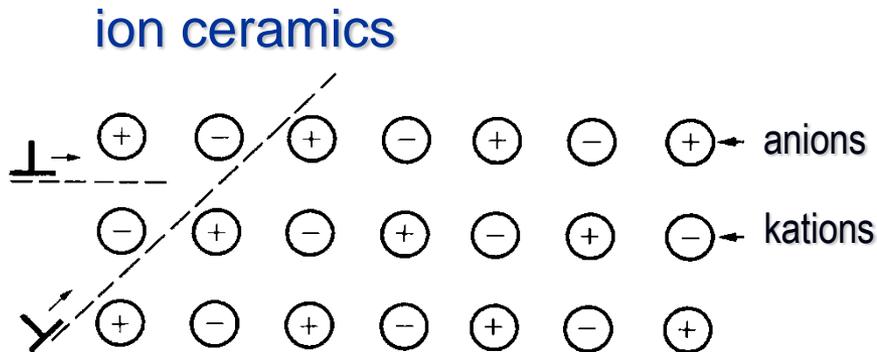
Ideal strength vs defects



metal



covalent ceramics



ion ceramics

metals – inherently brittle, ductile depends upon the type of crystalline lattice

covalent ceramics (r.t.) – there are no moving dislocation – the materials are brittle

glass – there are no moving dislocations – material is brittle

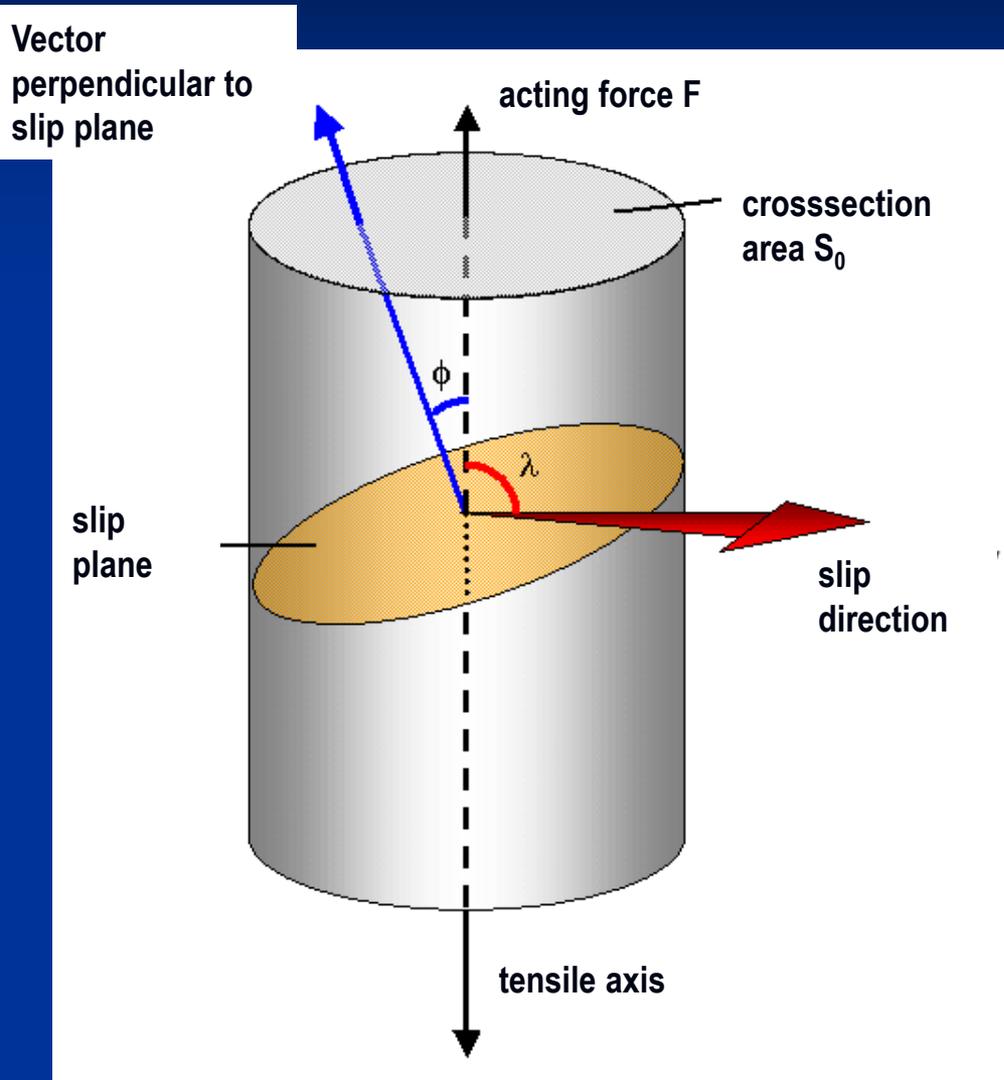
covalent plastics

ion ceramics

- *mono-crystals* plastically deformable (e.g. NaCl)

- *poly-crystal brittle* (small number of slip planes)

Tensile test of monocrystal (metal)



$$\tau_{slip} = \sigma (\cos \Phi \cos \lambda)$$

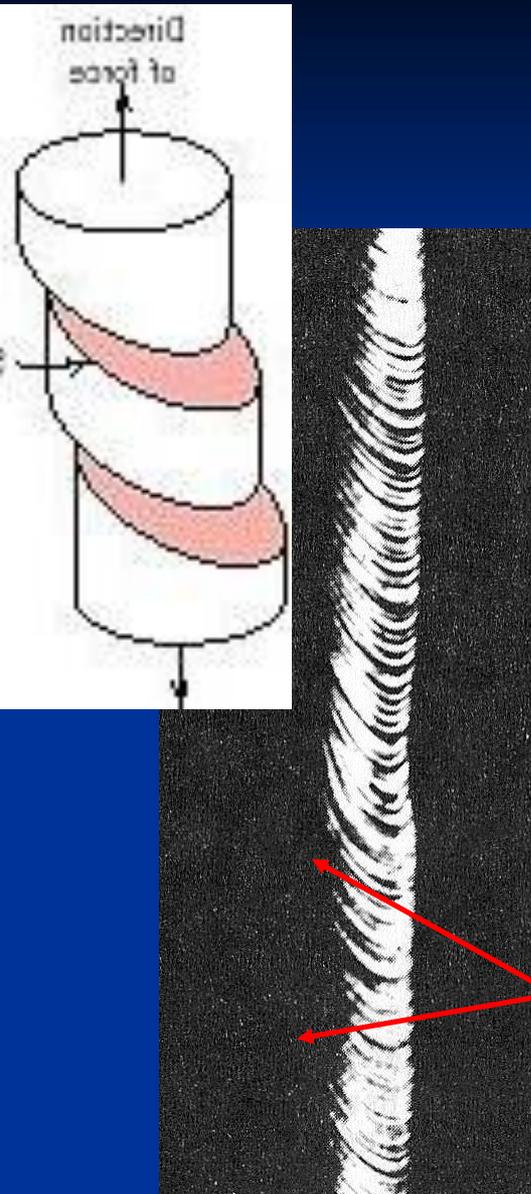
Schmid's rule

- slip occurs in the system where the following equation is valid

$$m\sigma = \tau_{slip}$$

Tensile diagram of monocrystal

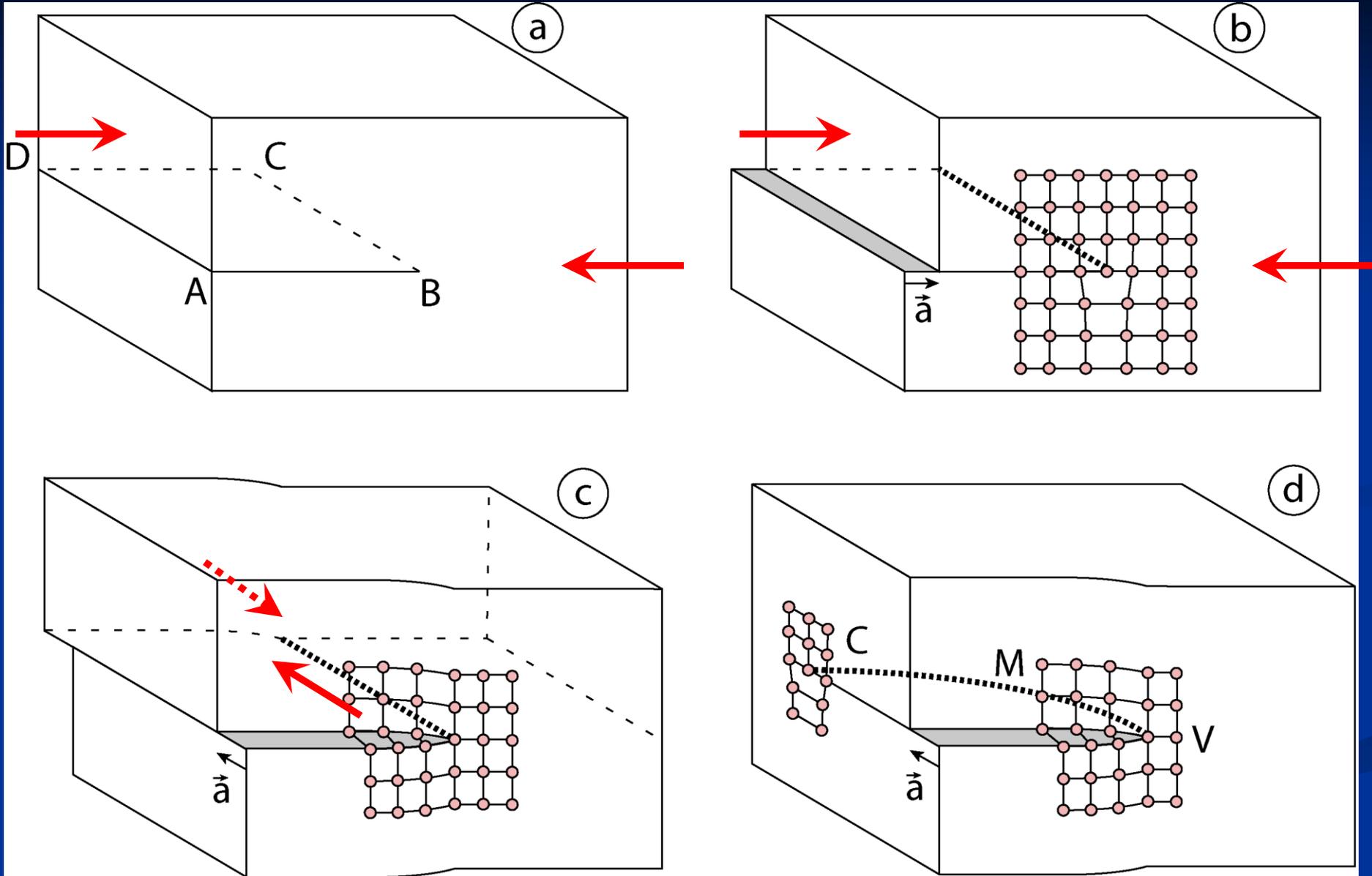
moving dislocations



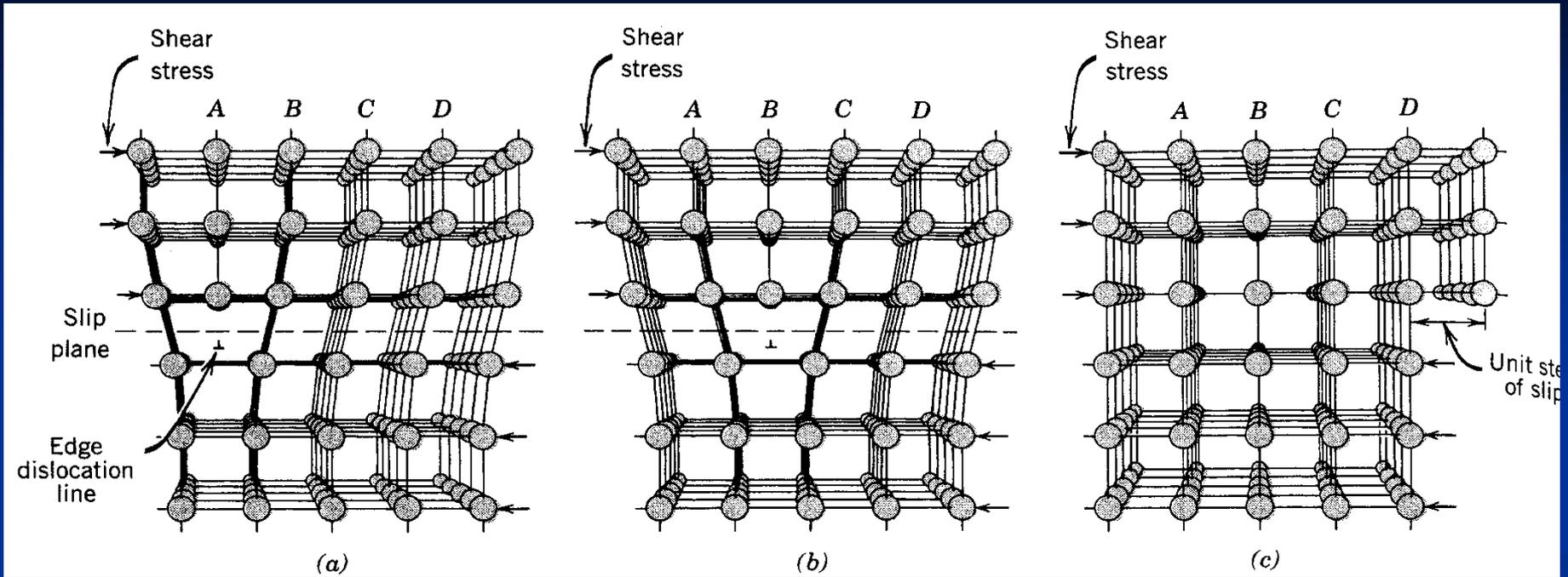
- slip direction the same as close packed direction (the most densely arranged atoms)
- slip plane is the same as the close packed plane
- dislocation slip is running in slip plane, in which the highest shear stress is acting

active slip planes

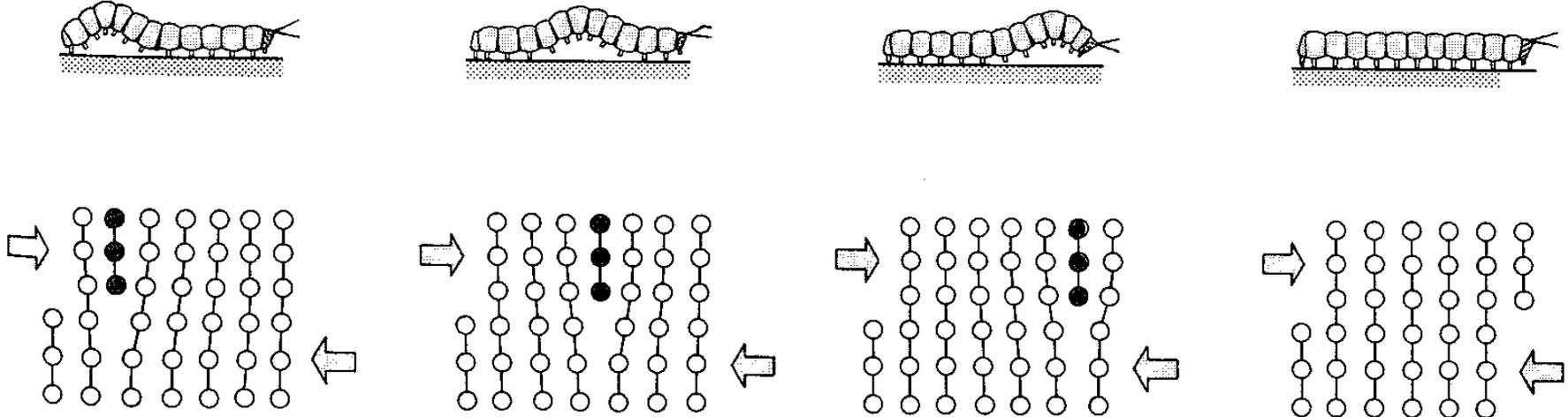
Active / mobile dislocation



Active / mobile dislocation

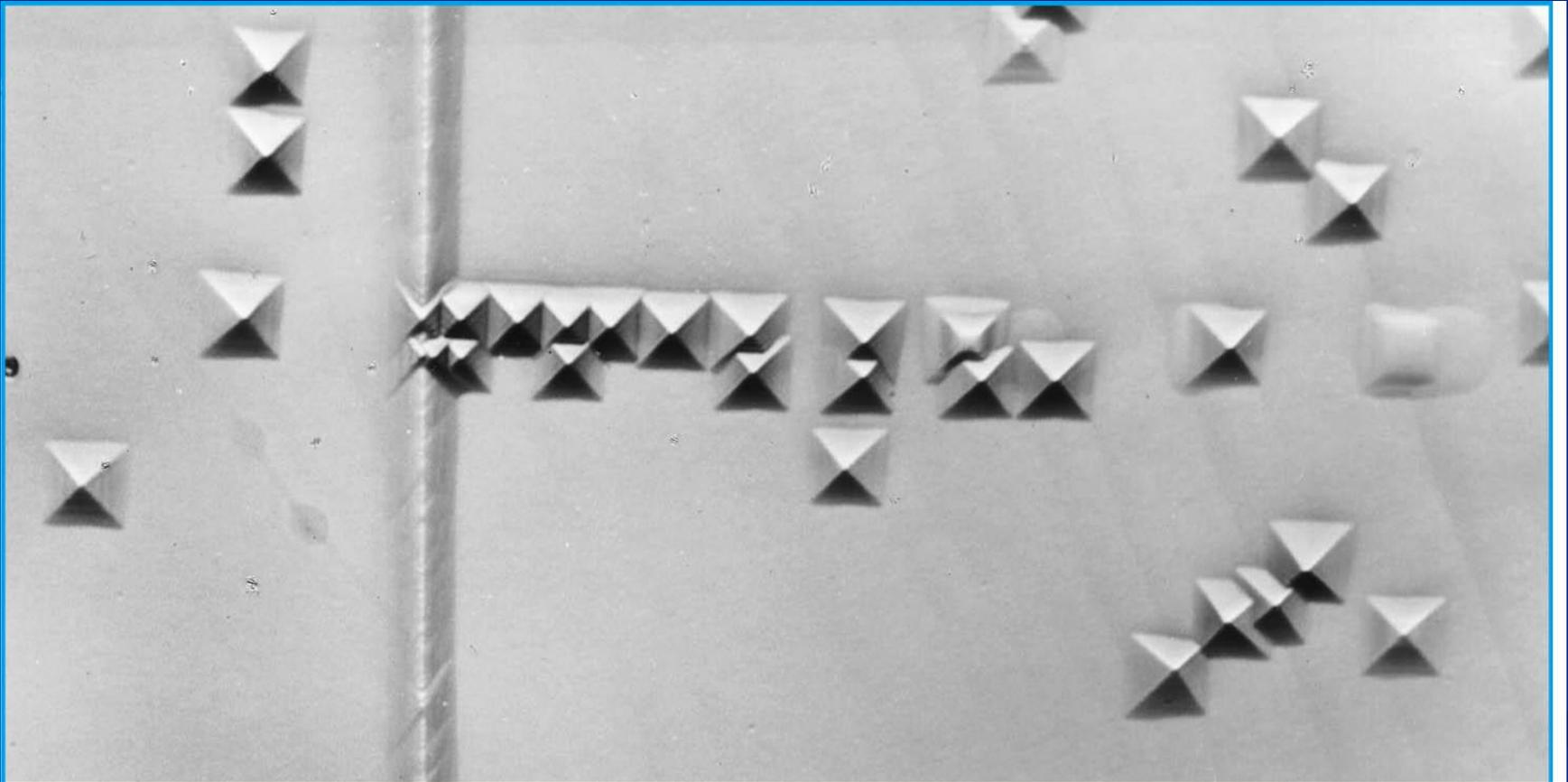


arthropod

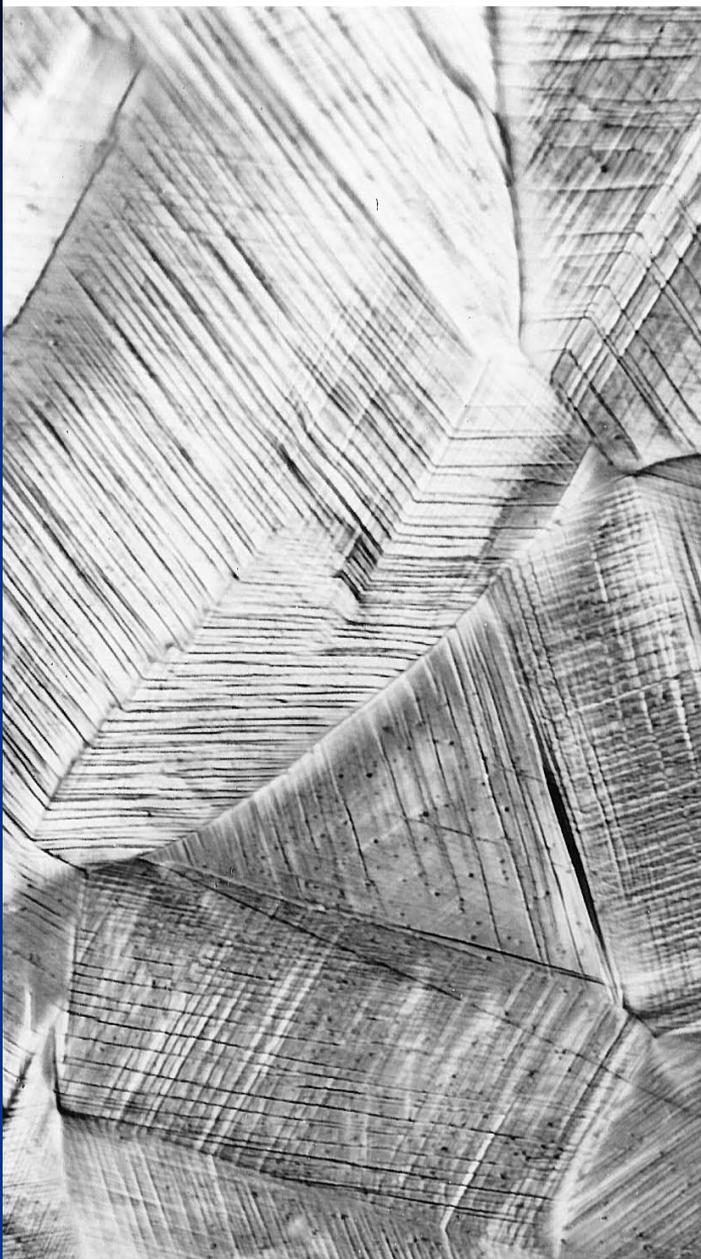


Active / mobile dislocation

Experimental evidences for the presence of dislocations
etch pits

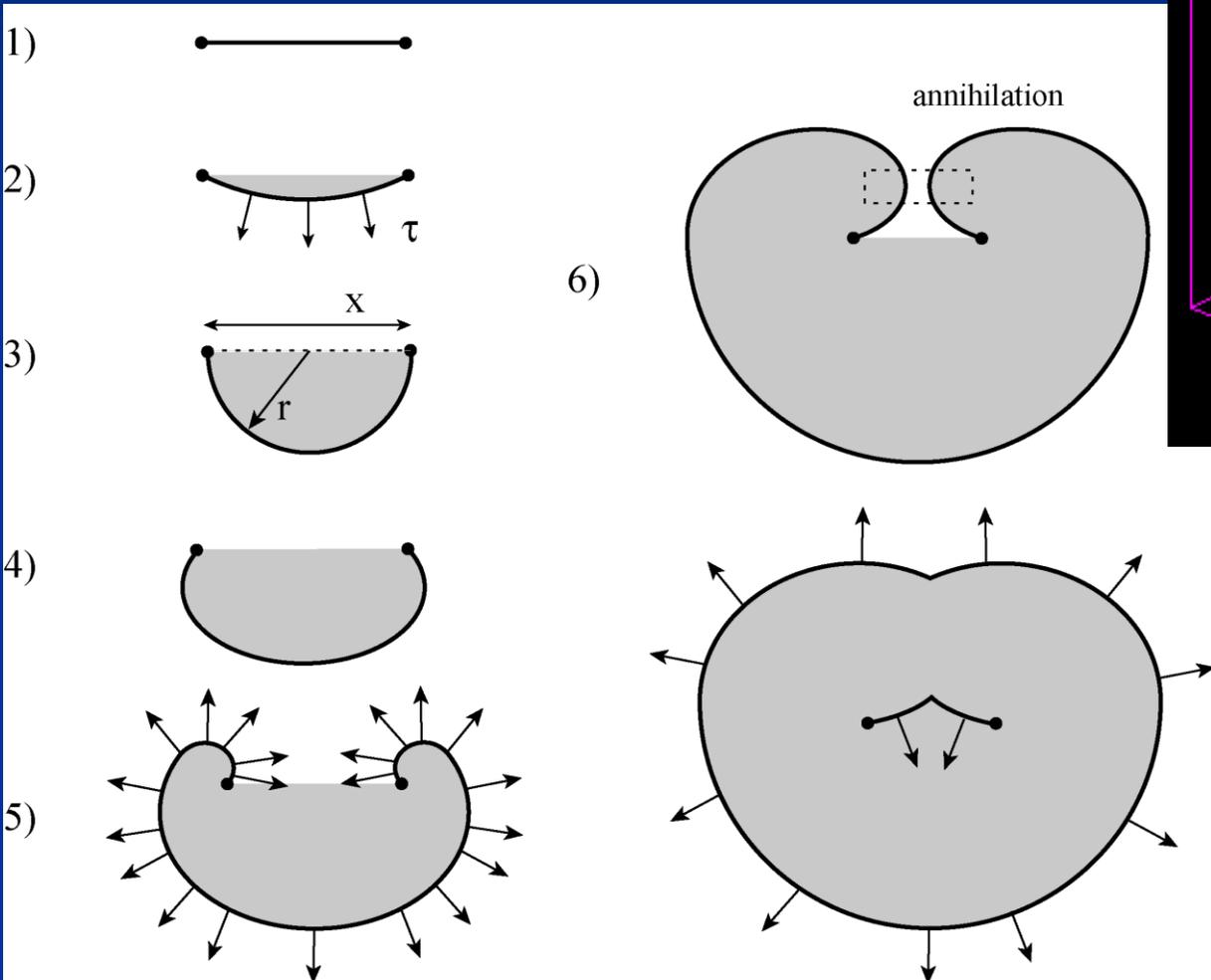
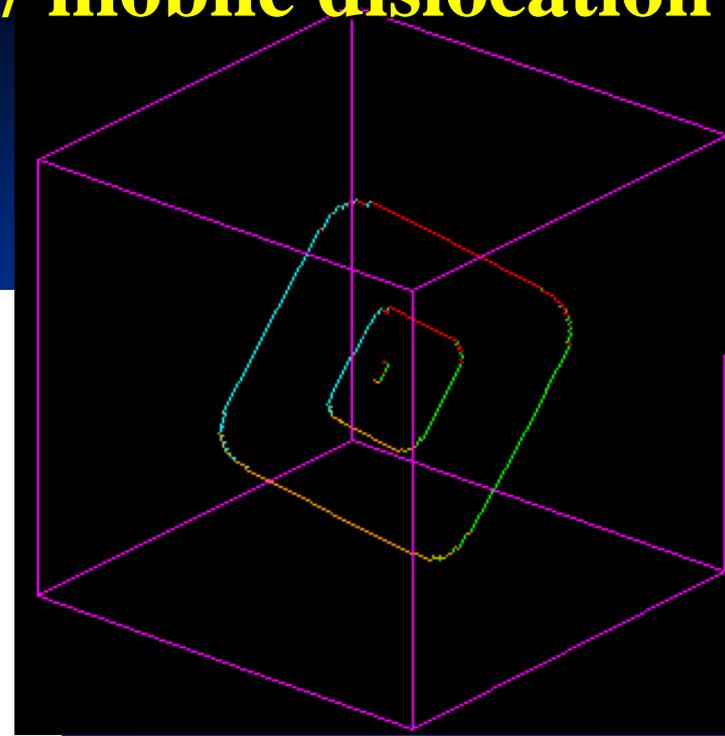


Active / mobile dislocation

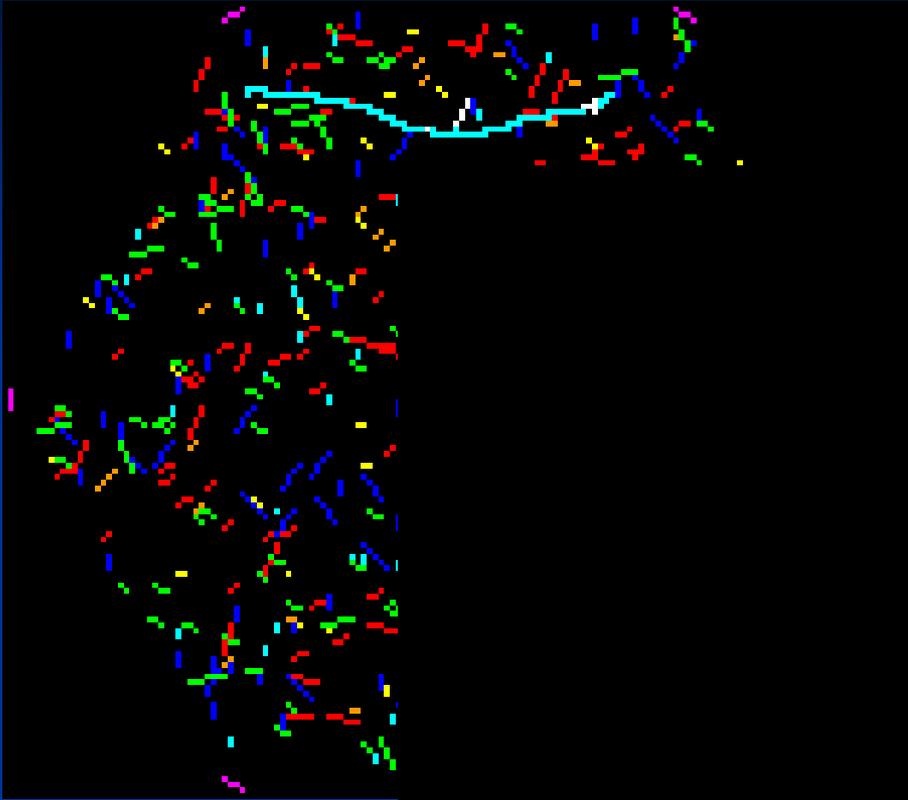


Active / mobile dislocation

Frank - Read source
(anchored dislocation segment + shear stress acting in slip plane)

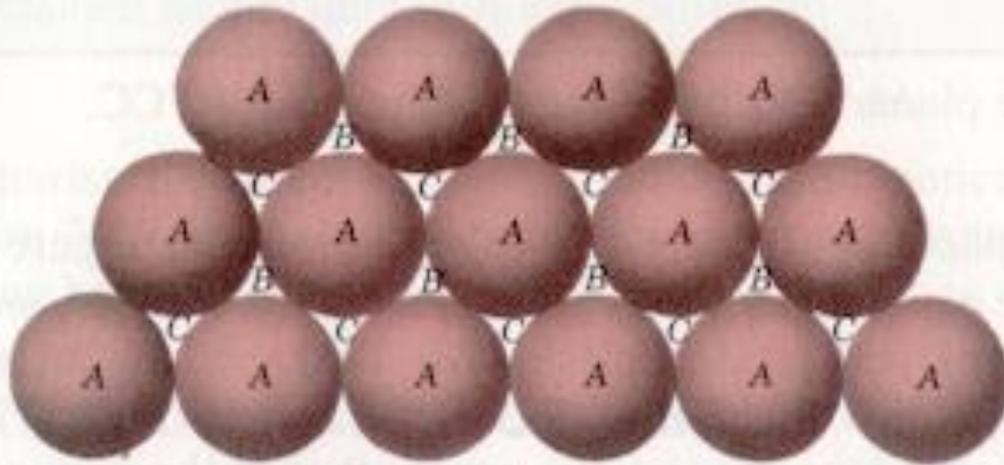


Anchored dislocations vs mobile dislocations





Tensile diagram of monocrystal



(a)



(b)

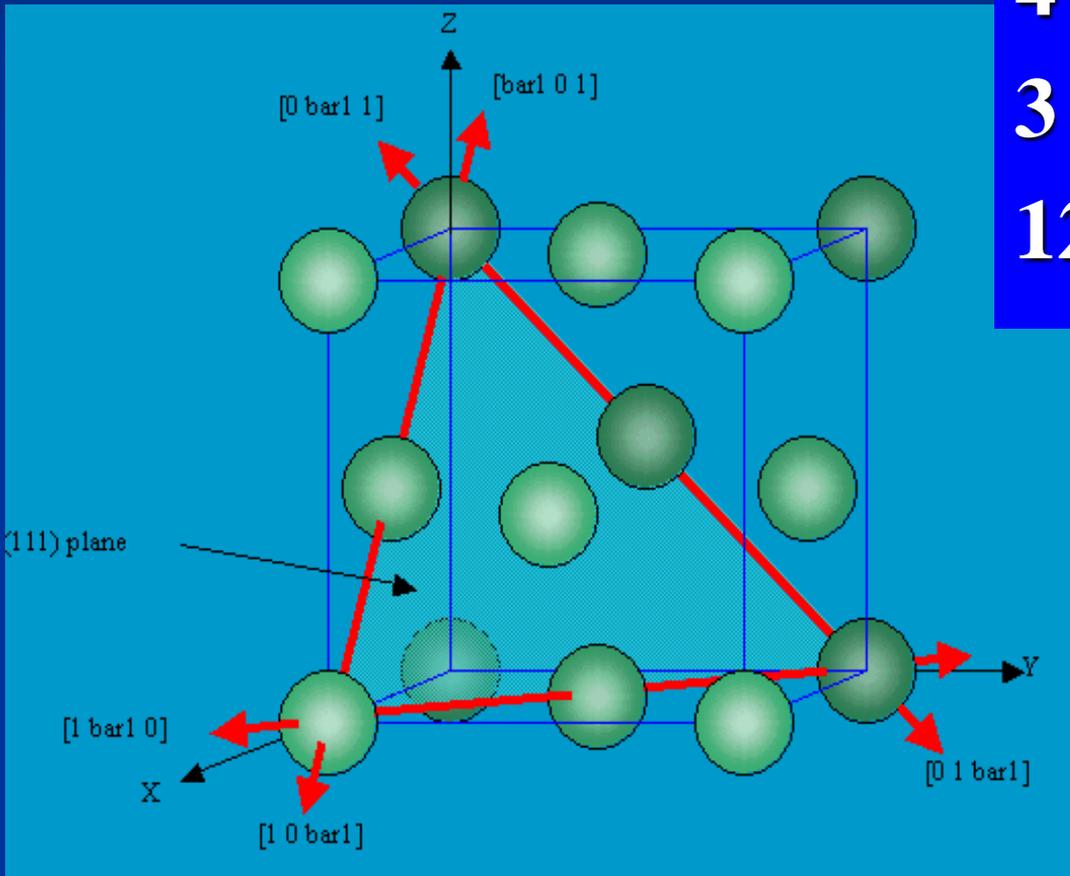
Tensile diagram of monocrystal

fcc metals – Al, Cu, γ -Fe, Ag, Au, Pt

4 planes $\{111\}$

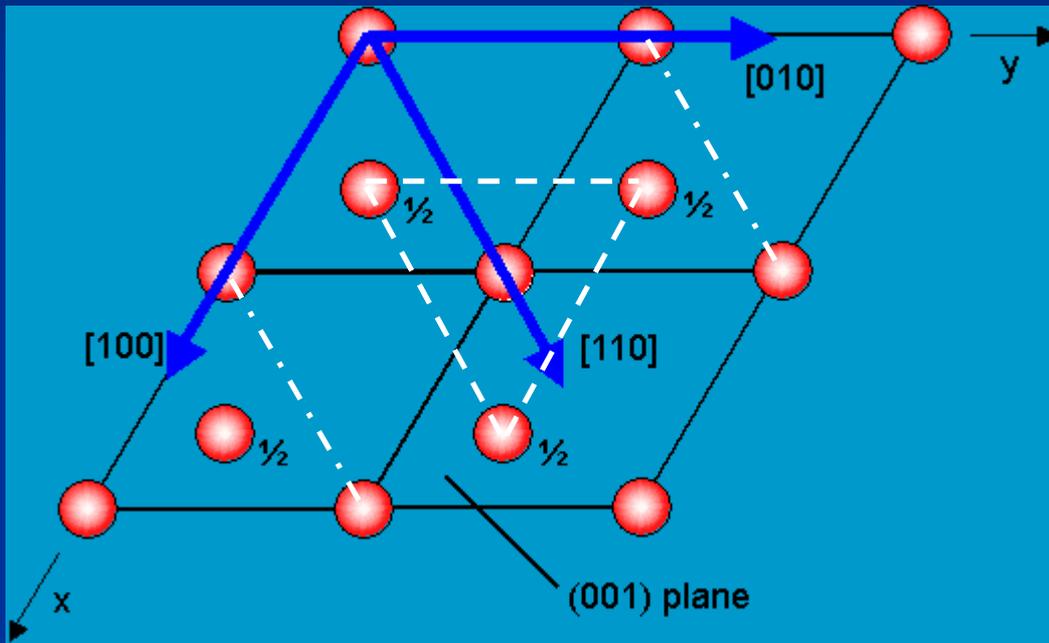
3 directions $\langle 110 \rangle$

12 slip systems



Tensile diagram of monocrystal

hcp metals – Mg, Zn, Cd, Be, Ti



base plane

$\{0001\}$1x

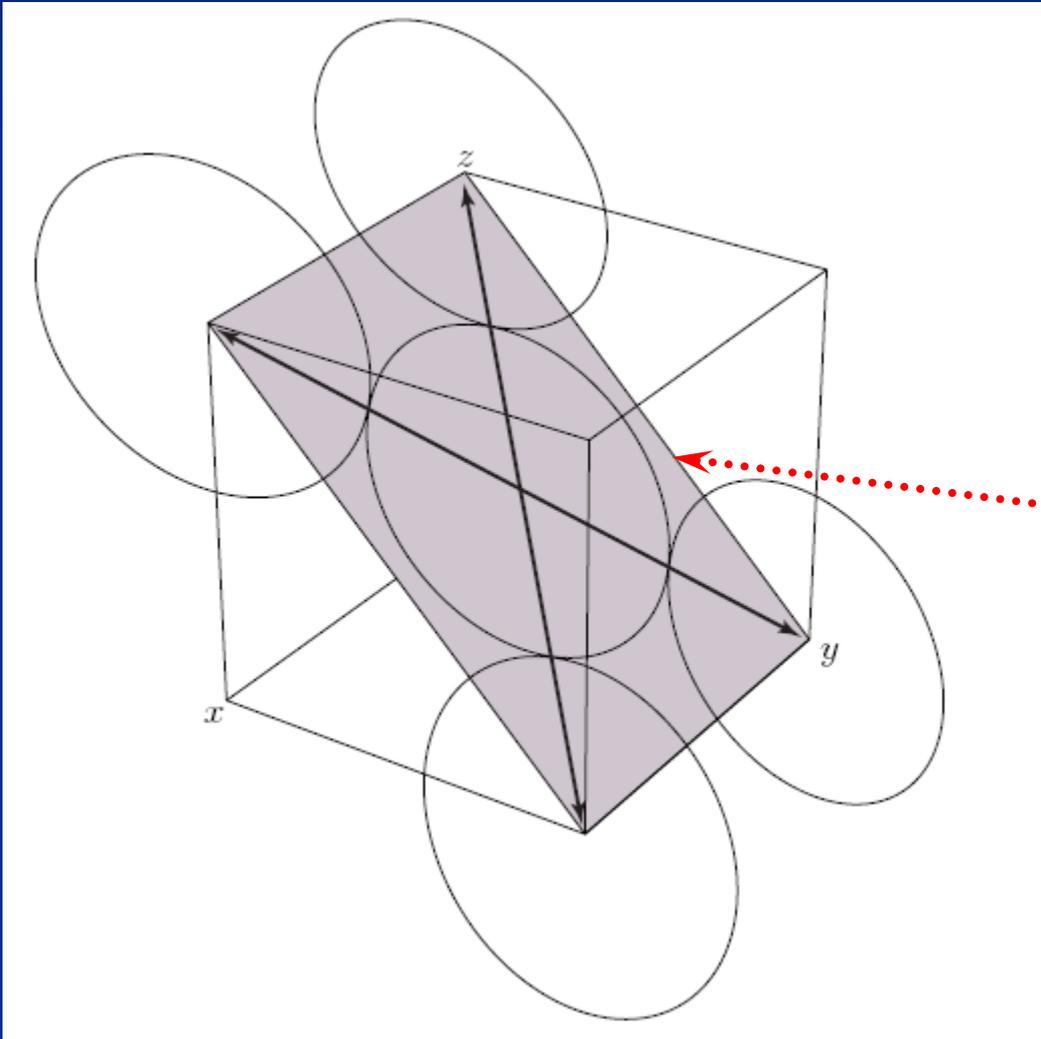
direction

$\langle 1120 \rangle$3x

3 slip systems

Tensile diagram of monocrystal

bcc metals - α Fe, Mo, W



direction

$\langle 111 \rangle$ 3

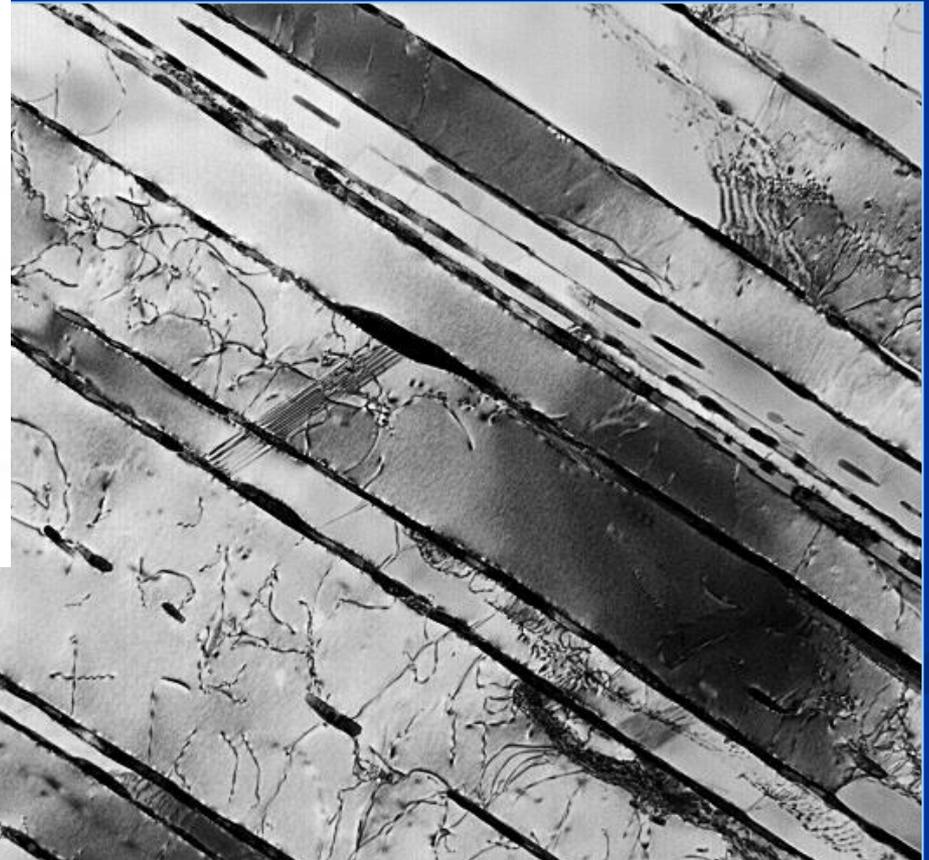
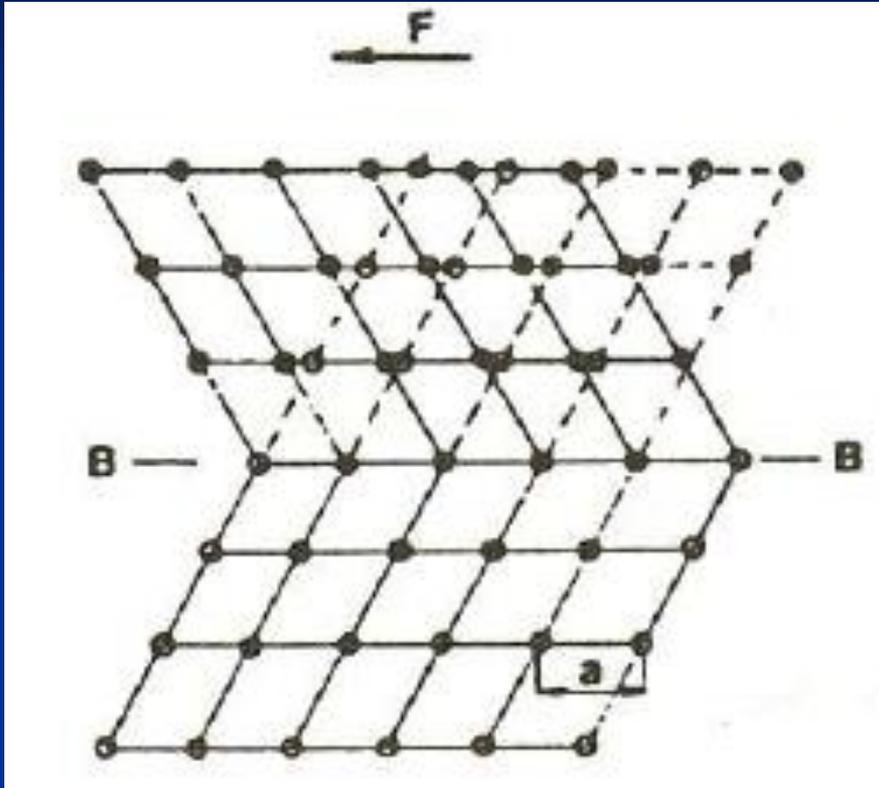
planes

$\{110\}$ 4

$\{211\}$ 4

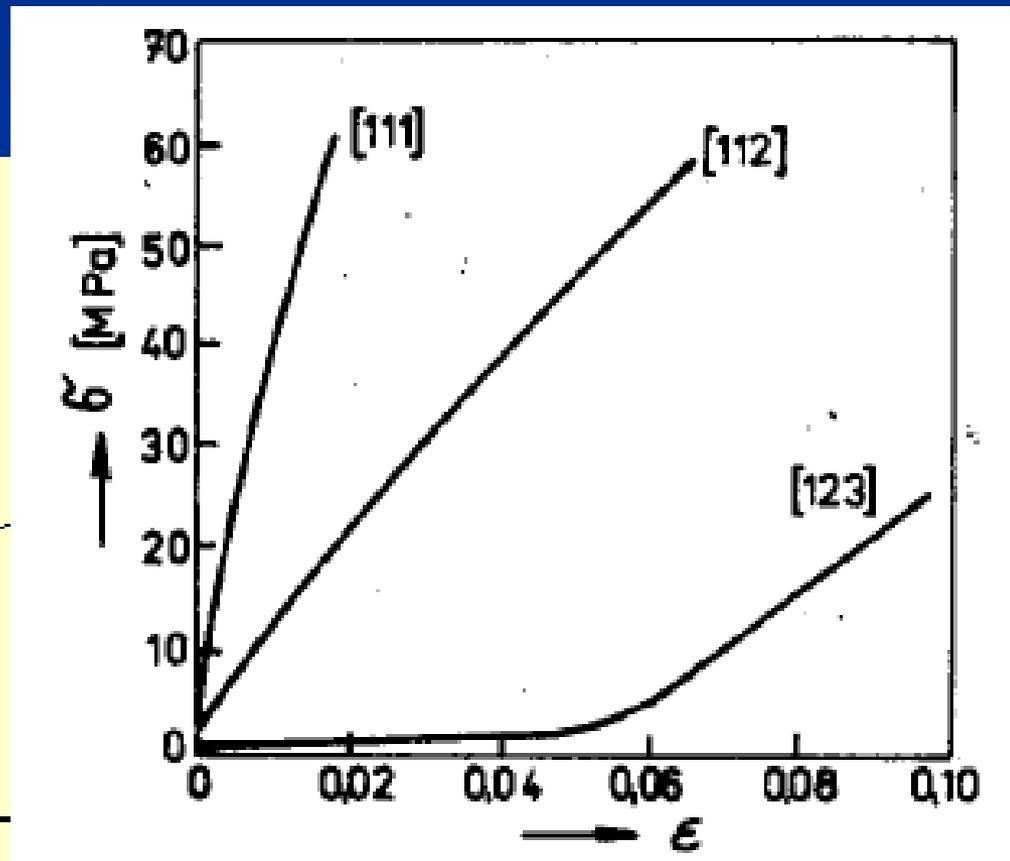
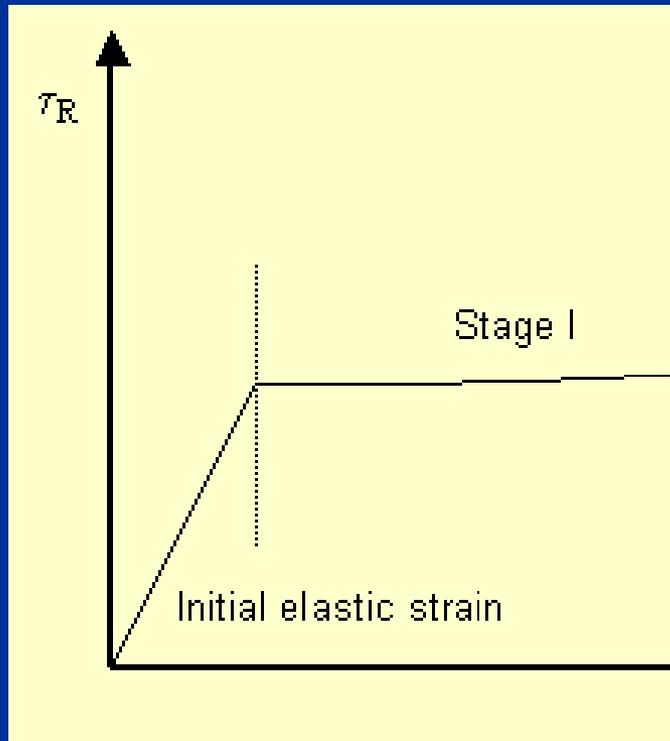
$\{321\}$ 8

Tensile diagram of monocrystal twinning



Tensile diagram of monocrystal

- I. stage of easy slip
- II. stage of linear hardening
- III. stage of softening



Tensile diagram of monocrystal

What is typical for separate lattices ??

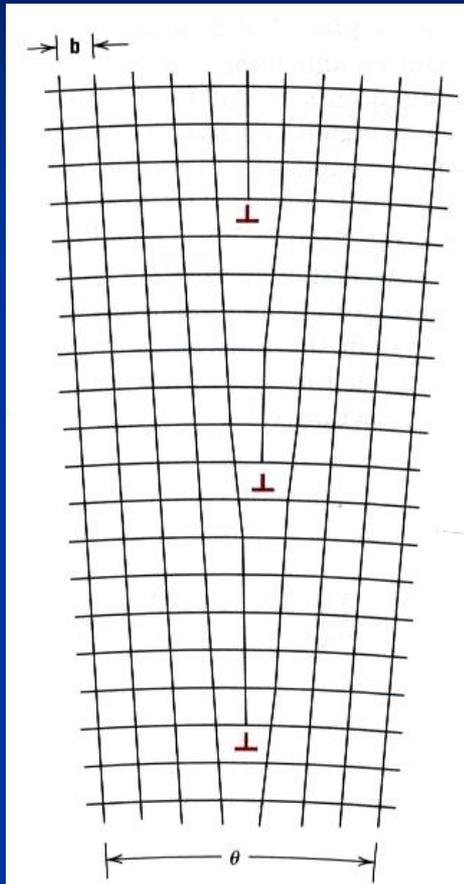
fcc: $\tau_{\text{krit}} = (0,3-0,8)\text{MPa}$; I. stage is 30%;
II. a III. stage depends on temperature

hcp: $\tau_{\text{krit}} = (0,3-0,8)\text{MPa}$; I. stage 200%;
II. a III. stage depends on temperature

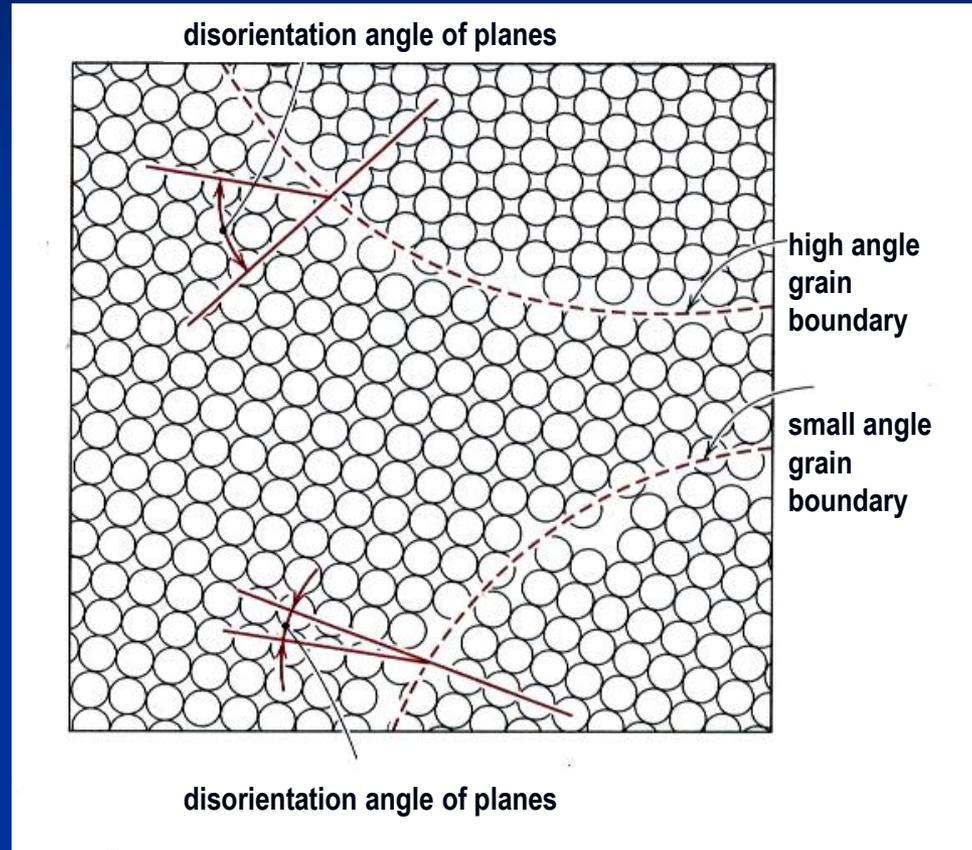
bcc: $\tau_{\text{krit}} = (30-80)\text{MPa}$ a is depending on
temperature; I stage too short

Tensile diagram of polycrystal

small angle boundary

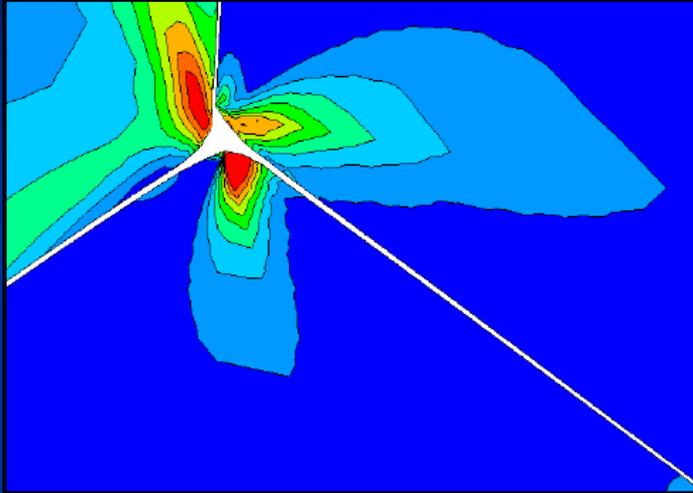


high angle boundary

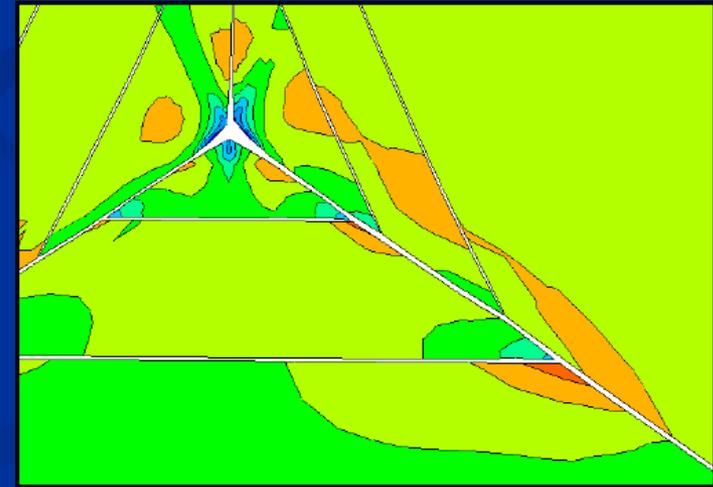
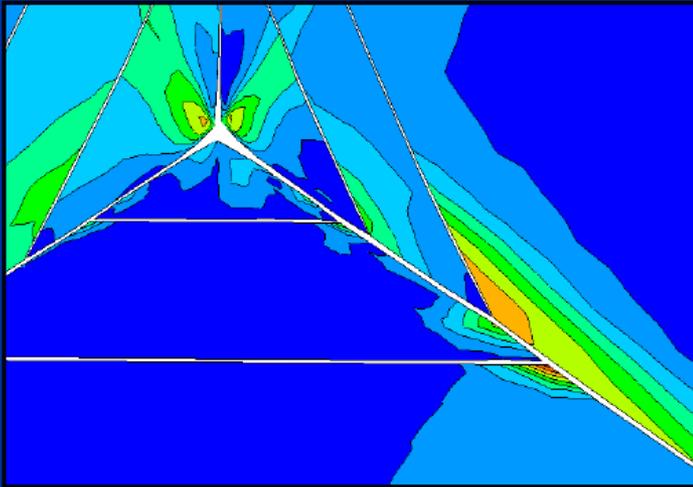
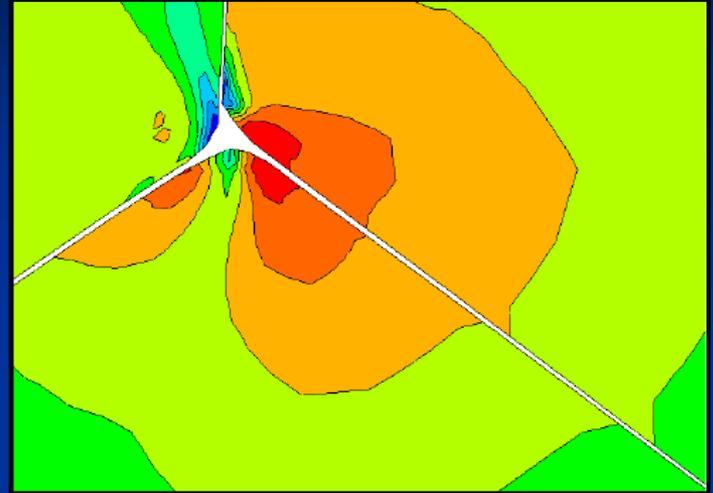


Tensile diagram of polycrystal

equivalent plastic deformation



hydrostatic stress



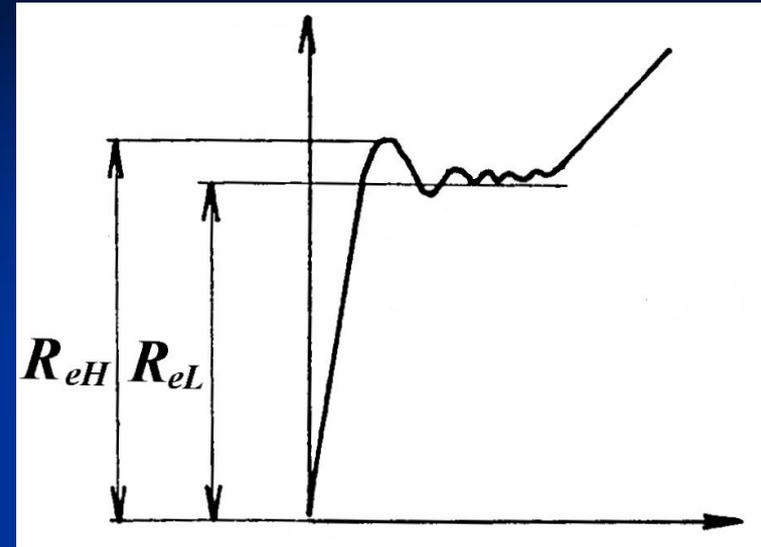
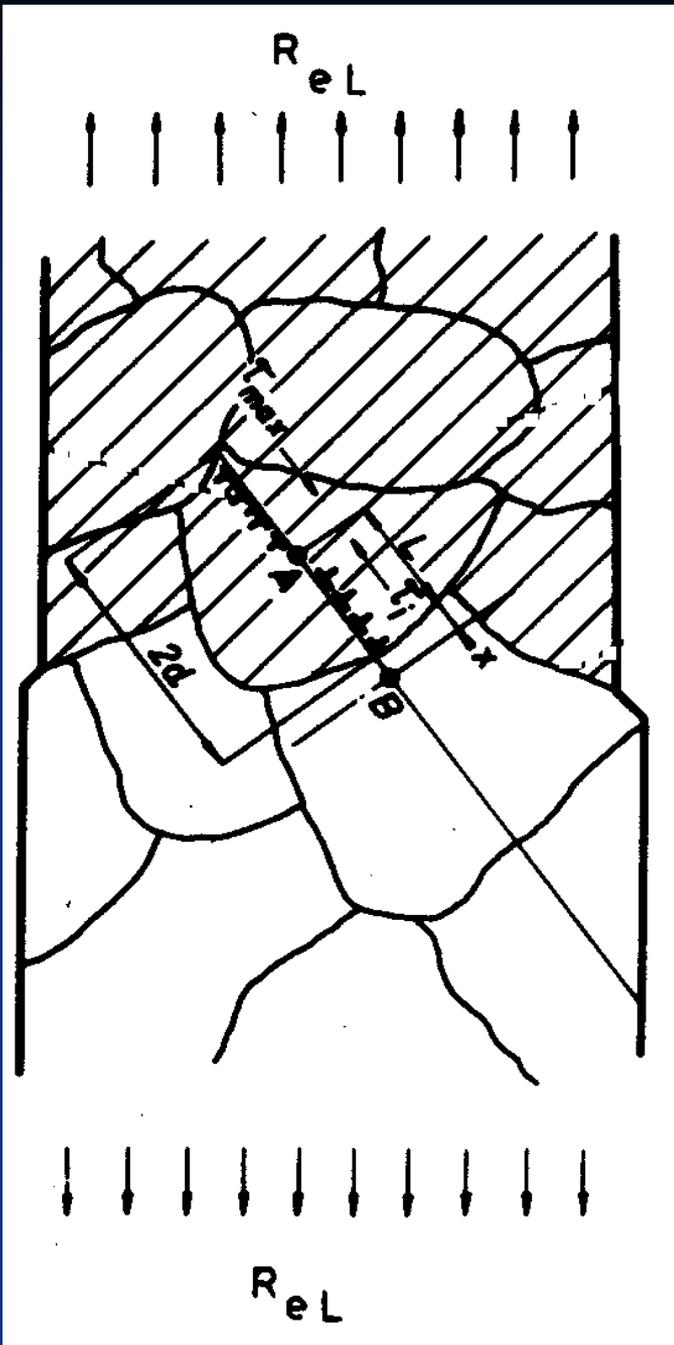
Tensile diagram of polycrystal

in 3d mobile dislocations

at least 5 independent slip systems

- ❖ **fcc lattice** (small τ_{krit} + 12 independent slip planes)
>>> **ductile material**
- ❖ **hcp lattice** (small τ_{krit} + sometimes only 3 independent slip planes) >>> as a rule **brittle**
- ❖ **bcc lattice** (high τ_{krit} + plenty of independent slip planes) >>> **strong and ductile**

Tensile diagram of polycrystal



$$R_{eL} = \sigma_i + k \cdot d^{-1/2}$$

Hall - Petch relation

Tensile diagram of polycrystal

Hall – Petch relation



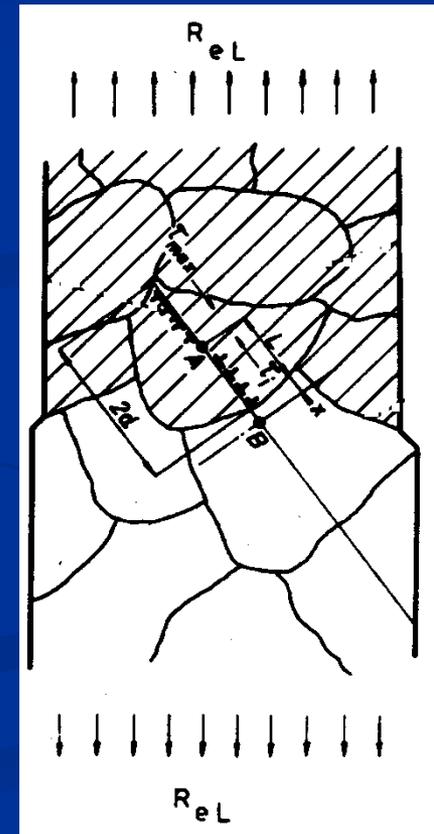
Tensile diagram of monocrystal

Hall - Petch relation

- τ_{\max} - slip stress acting in slip plane being caused by **applied load**
- τ_i - stress acting **against dislocation** movement (slip)
- τ_D - stress needed for **creation/unblocking** of dislocations

stress concentration in point B

$$(\tau_{\max} - \tau_i) \cdot \sqrt{\frac{L}{x}},$$



Tensile diagram of monocrystal

Hall - Petch relation

Condition for plastic deformation transfer at grain boundary

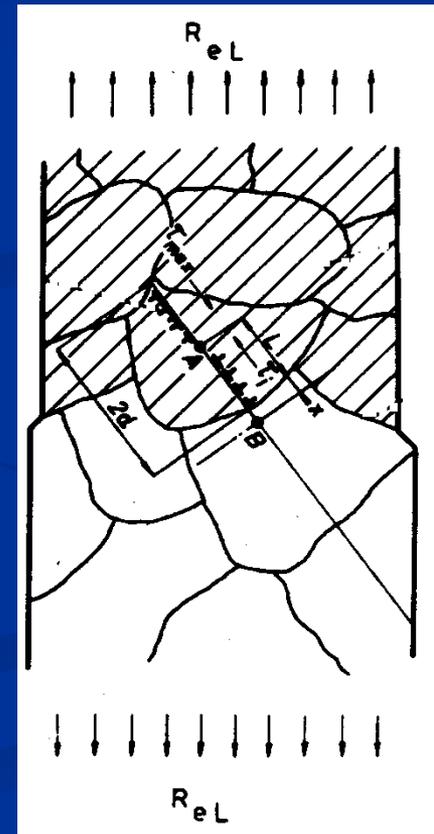
$$\tau_D = \tau_{\max} + (\tau_{\max} - \tau_i) \sqrt{\frac{L}{x}}$$

$$\tau_{\max} = \frac{\tau_i + \tau_D \sqrt{\frac{x}{L}}}{1 + \frac{x}{L}}$$

$$\tau_{\max} = \tau_i + k'_y d^{-1/2},$$

$$\sigma_i = 2\tau_i, k_y = 2^{3/2} k'_y$$

$$R_e = \sigma_i + k_y d^{-1/2}$$



Hall - Petch relation

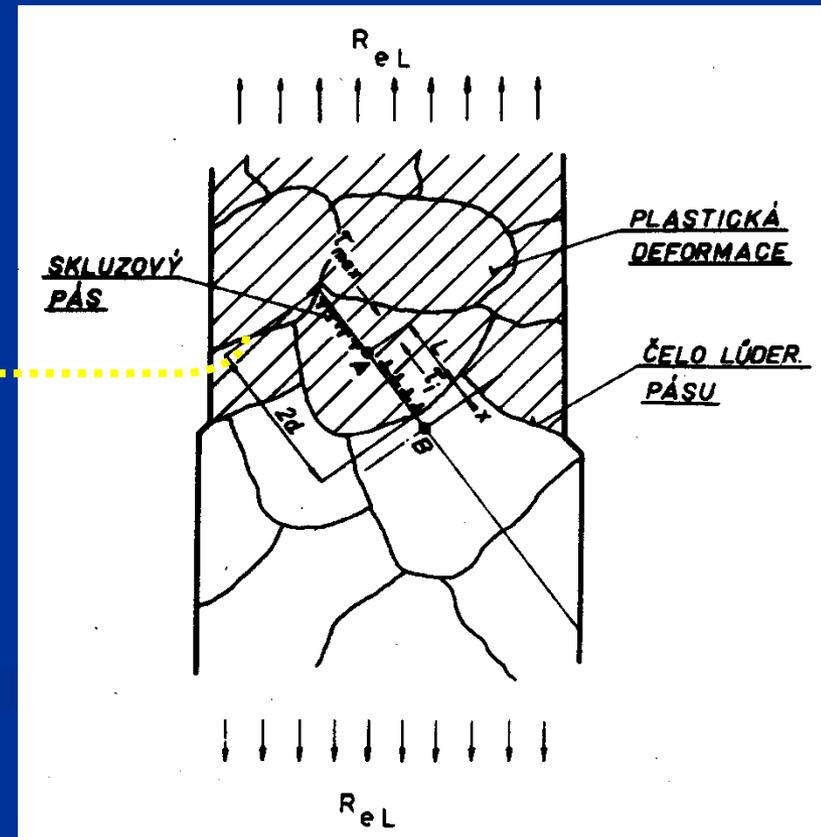
$$R_{eL} = \sigma_i + k \cdot d^{-1/2}$$

grain size effect

stress acting against
dislocation
movement



control of deformation
behaviour and strength
properties



σ_i friction stress - resistance of the real lattice against dislocation movement

$$\sigma_i = \sigma_0 + \sigma_\mu + \sigma_{t.r.} + \sigma_{p.r.}$$

σ_0 - Peiers - Nabarro stress

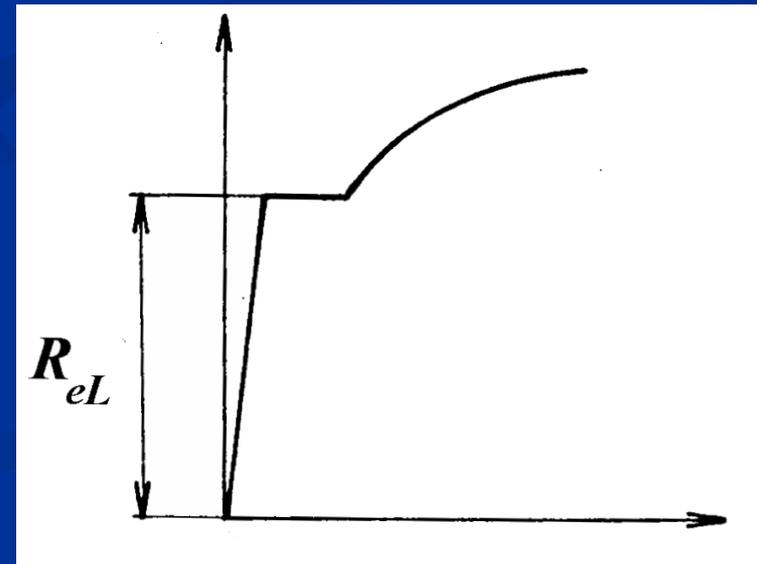
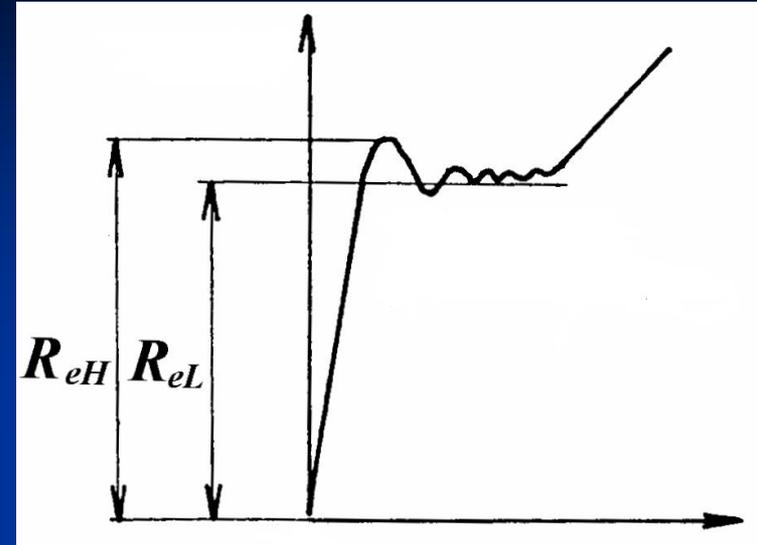
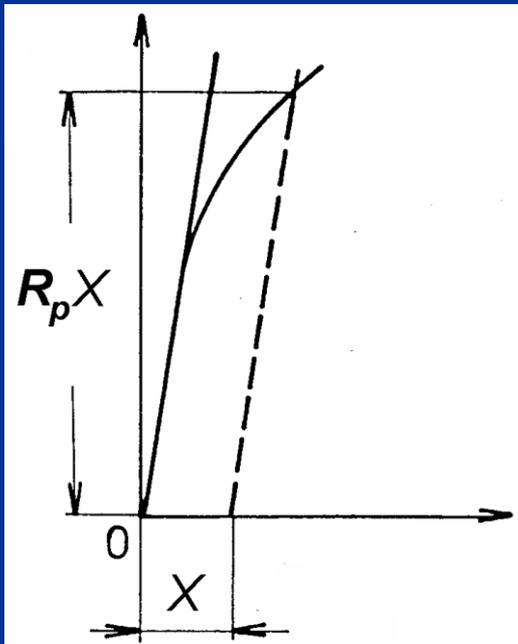
σ_μ - friction/resistance by other dislocations

$\sigma_{t.r.}$ - solid solution strengthening

$\sigma_{p.r.}$ - precipitation hardening
- effect of interstitial atoms
- cold deformation hardening

- ❖ strengthening effect (σ_i)
- ❖ temperature effect
- ❖ loading rate effect

Hidden yield strength



True stress – true strain curve

True stress

$$\sigma = \frac{F}{S} \quad \sigma = R \frac{S_0}{S}$$

$$\frac{S_0}{S} = \frac{L}{L_0} = \frac{\Delta L + L_0}{L_0} = (\varepsilon + 1)$$

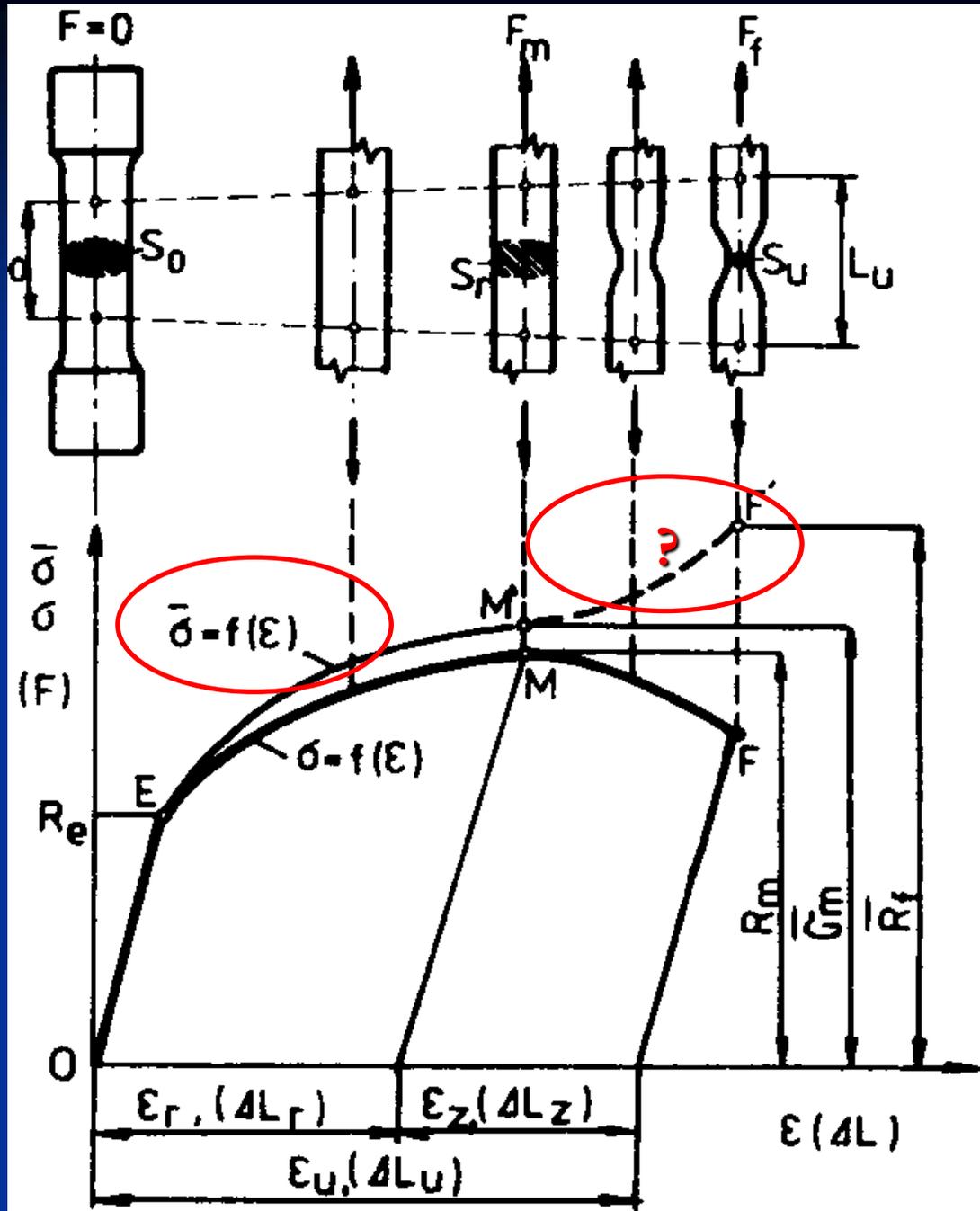
$$\sigma = R(1 + \varepsilon)$$

True strain

$$\bar{\varepsilon} = \int_{L_0}^{L_1} \frac{dL}{L} = \ln L_1 - \ln L_0 = \ln\left(\frac{L_1}{L_0}\right) = \ln\left(\frac{\Delta L}{L_0} + 1\right) = \ln(\varepsilon + 1)$$

$$\bar{\varepsilon} = \ln\left(\frac{S_0}{S}\right)$$

True stress – true strain curve



True stress – true strain curve

Holomon equation

$$\sigma = k\bar{\varepsilon}_p^n,$$

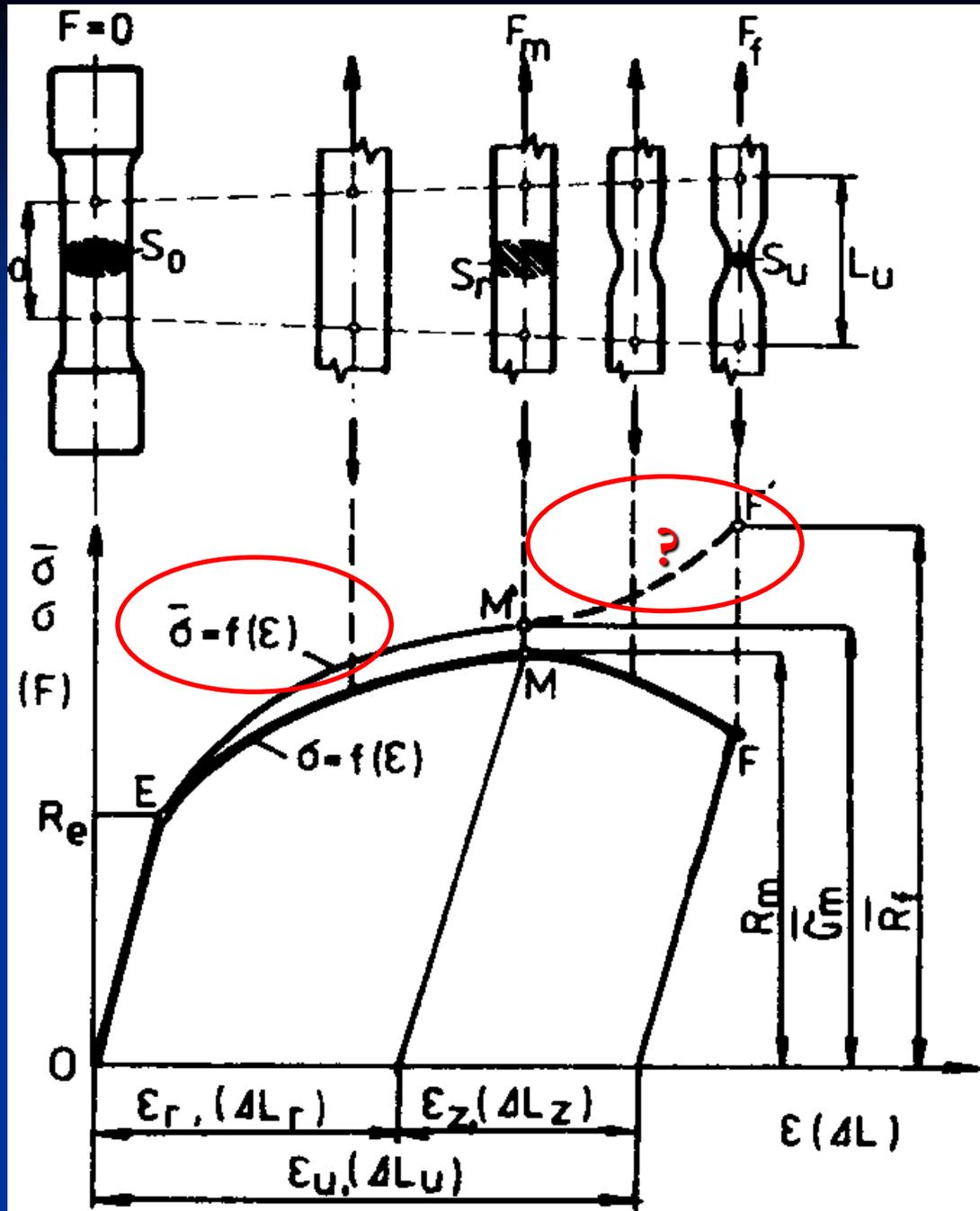
k - coefficient of strain hardening

n - strain hardening exponent

Ramberg - Osgood equation

$$\bar{\varepsilon} = \varepsilon_{el} + \bar{\varepsilon}_p = \frac{\sigma}{E} + \left(\frac{\sigma}{k} \right)^{\frac{1}{n}}$$

True stress – true strain curve



True stress – true strain curve

necking – stress triaxiality !

for quantification of localised deformation
correction is needed

$$\sigma_n = \frac{F}{S_a}$$

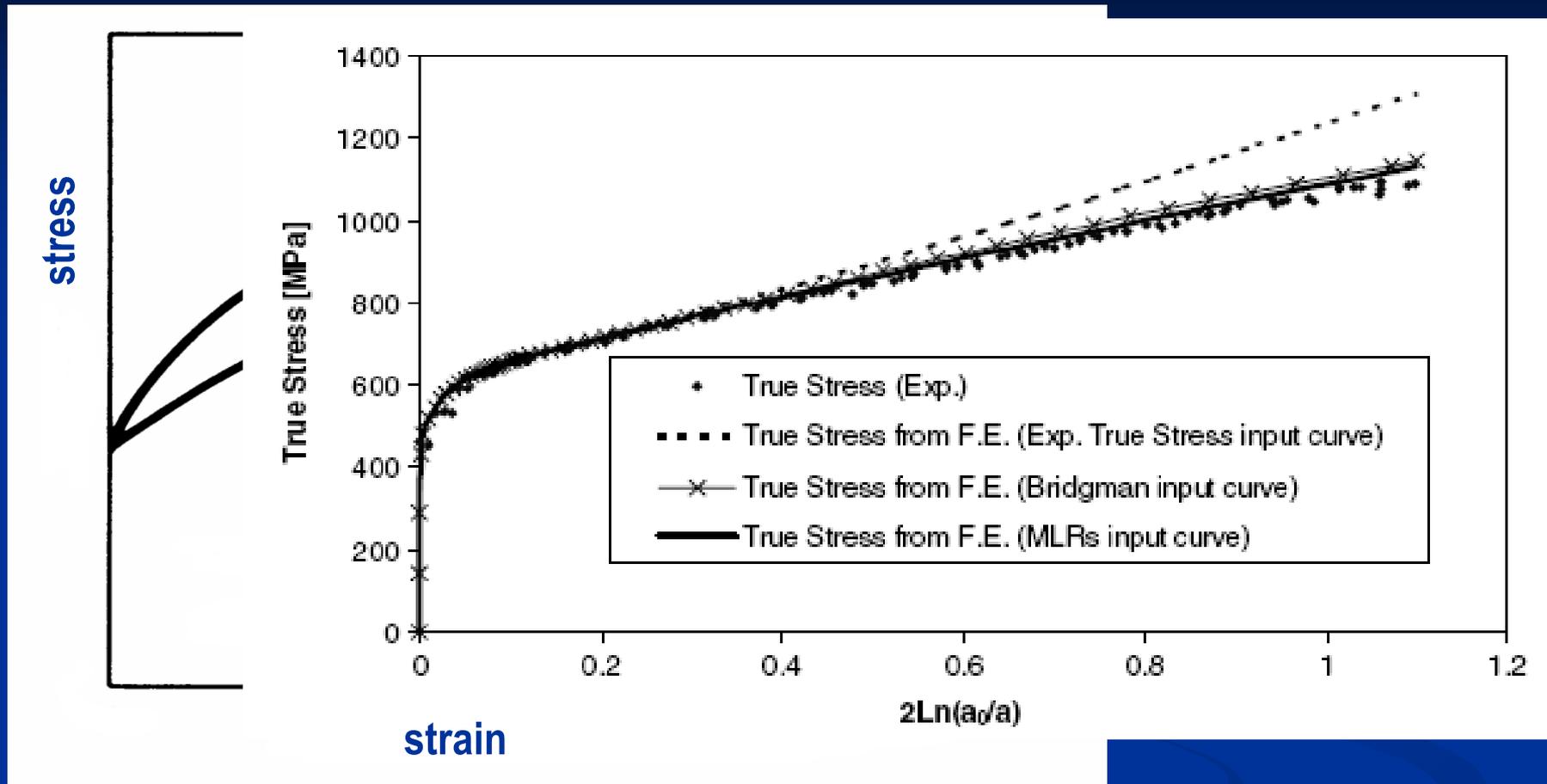
Equivalent stress corresponding to the same
deformation but caused by uniaxial tensile stress -
correction of nominal stress to uniaxial stress:

$$\sigma_B \rightarrow (2\tau_{\max}) = \sigma_n \cdot B$$

$$B = 0,83 - 0,1786 \cdot \log \bar{\epsilon}$$

Correction for necking presence according to Bridgman

True stress – true strain curve



Correction for the necking presence according to Mirone

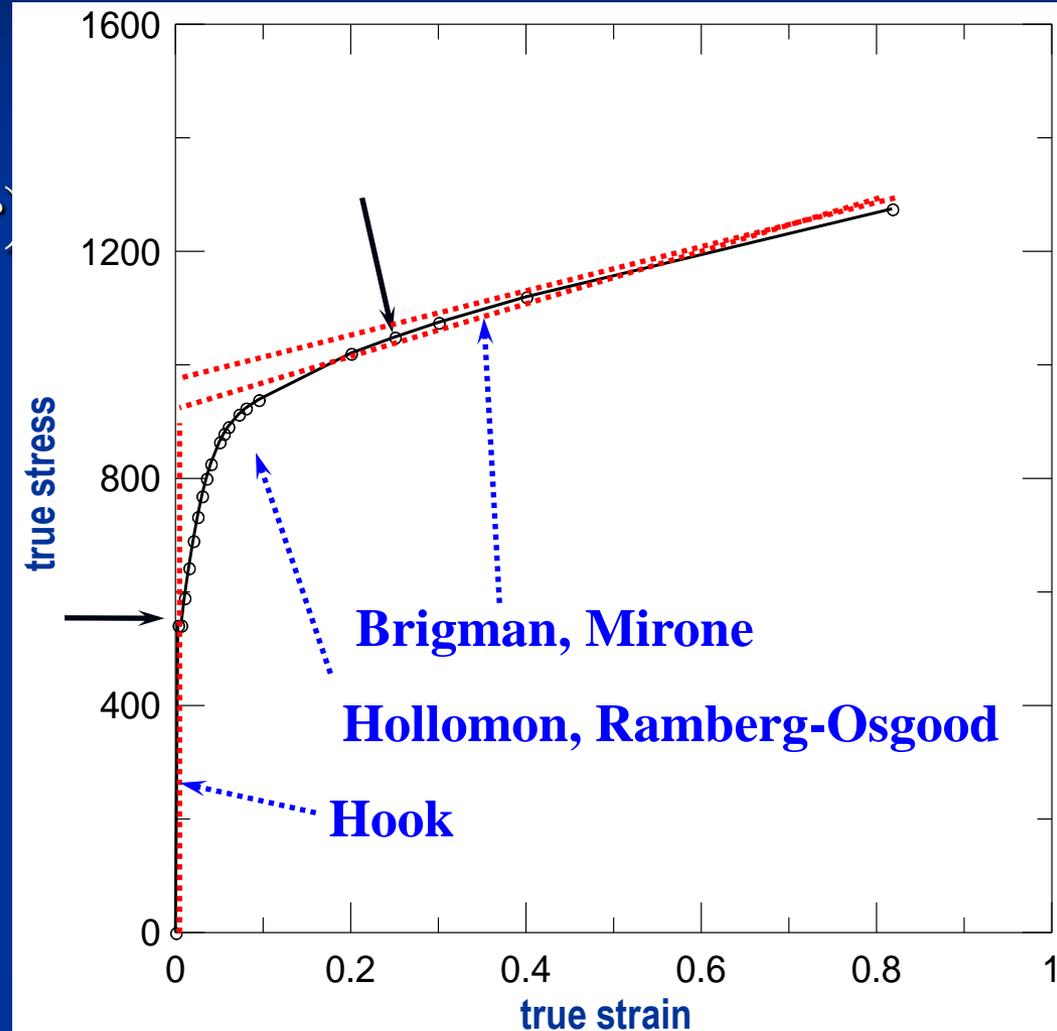
(simple multinominal)

$$\sigma(\bar{\varepsilon}) = 1 - 0,6058(\bar{\varepsilon} - \bar{\varepsilon}_{pn})^2 + 0,6317(\bar{\varepsilon} - \bar{\varepsilon}_{pn})^3 - 0,2107(\bar{\varepsilon} - \bar{\varepsilon}_{pn})^4$$

True stress – true strain curve

FEM calculations tensile (material)
curve implementation:

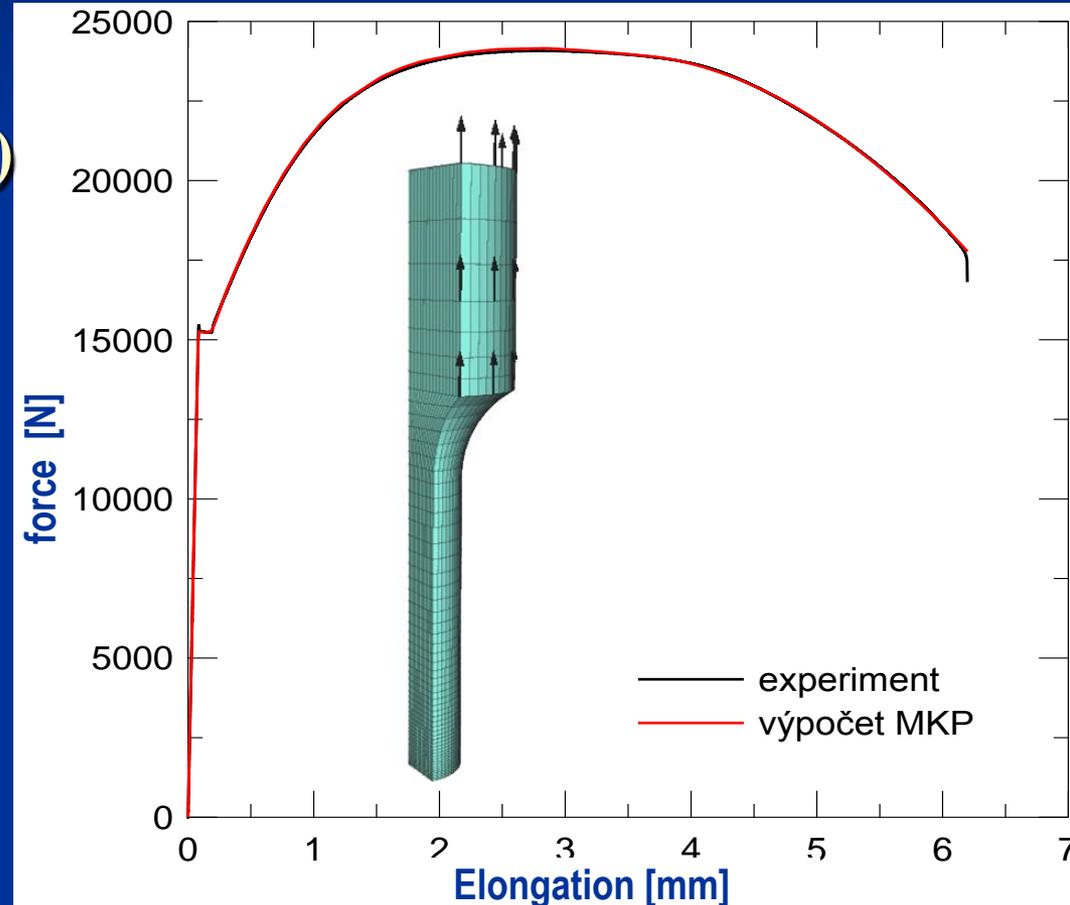
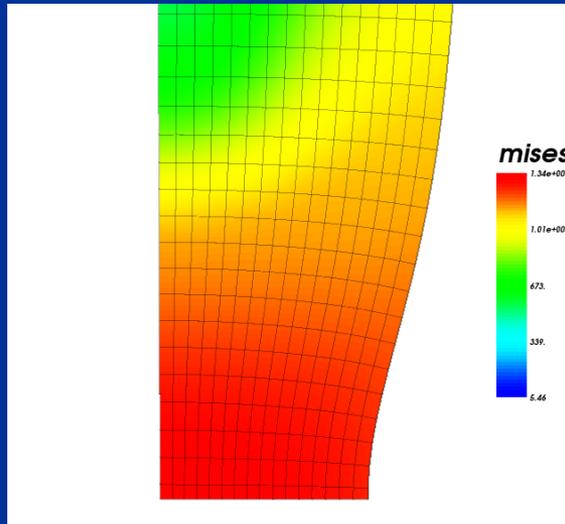
- ❖ bilinear
- ❖ multilinear
(step by step linear)
- ❖ $E, n (N)$
- ❖ true stress - true strain curve



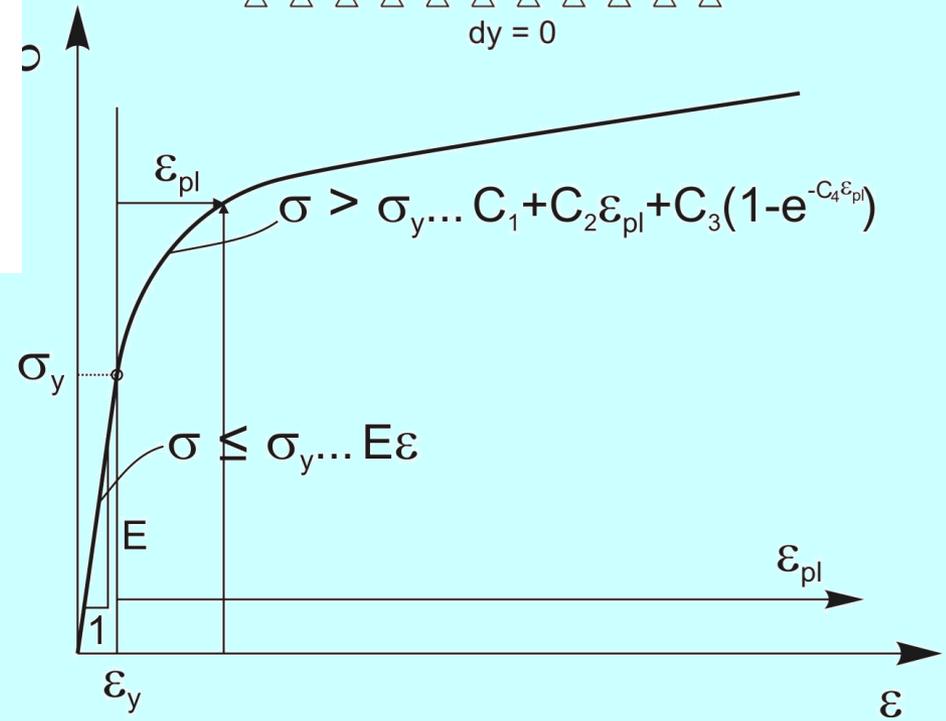
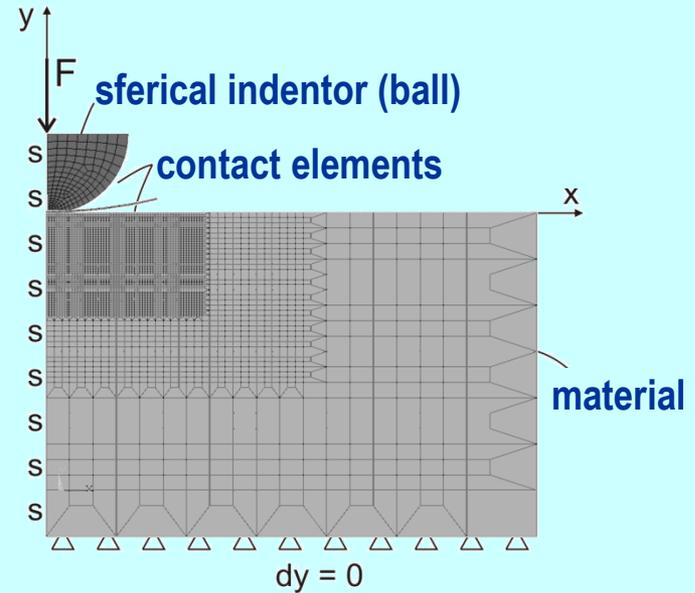
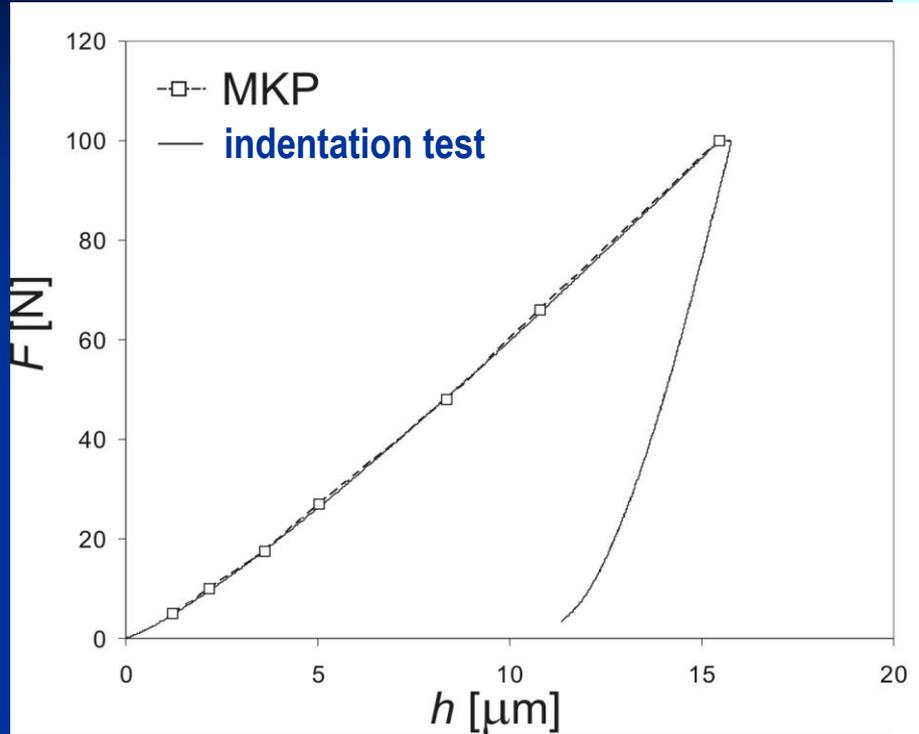
True stress – true strain curve

FEM calculations tensile (material) curve implementation:

- ❖ bilinear
- ❖ multilinear
(step by step linear)
- ❖ E , n (N)
- ❖ true stress - true strain curve



Tensile curve from indentation



Tensile curve from indentation

$$\sigma = \sigma_y + R_0 \varepsilon_{pl} + R_0 (1 - e^{-b \varepsilon_{pl}})$$

C1	C2	C3	C4
551,5	345,7	419,4	27,8

