# AML 883 Properties and selection of engineering materials

**LECTURE 11. Strengthening mechanisms**

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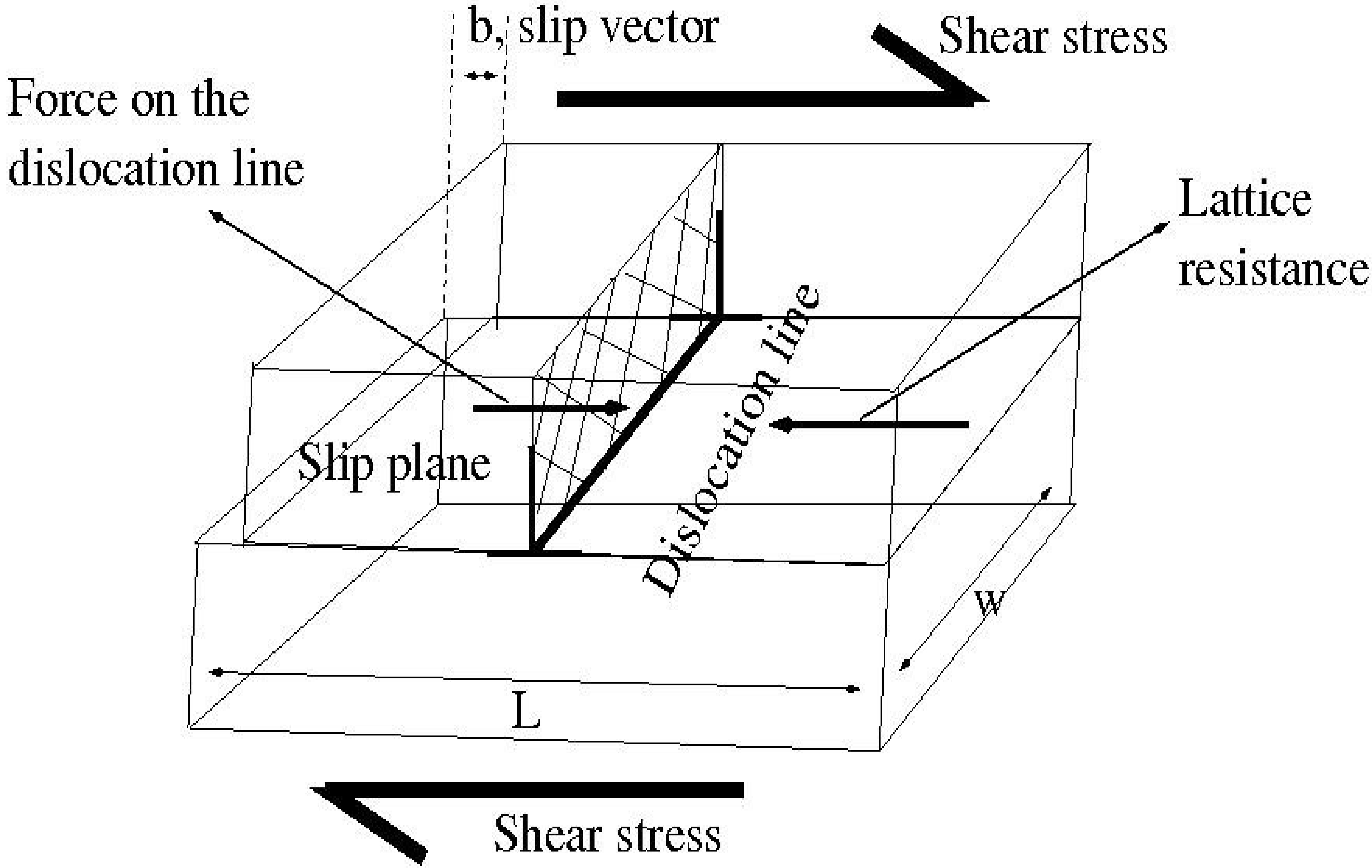
# Lattice resistance

- Why pure metals are soft and ceramics are hard?

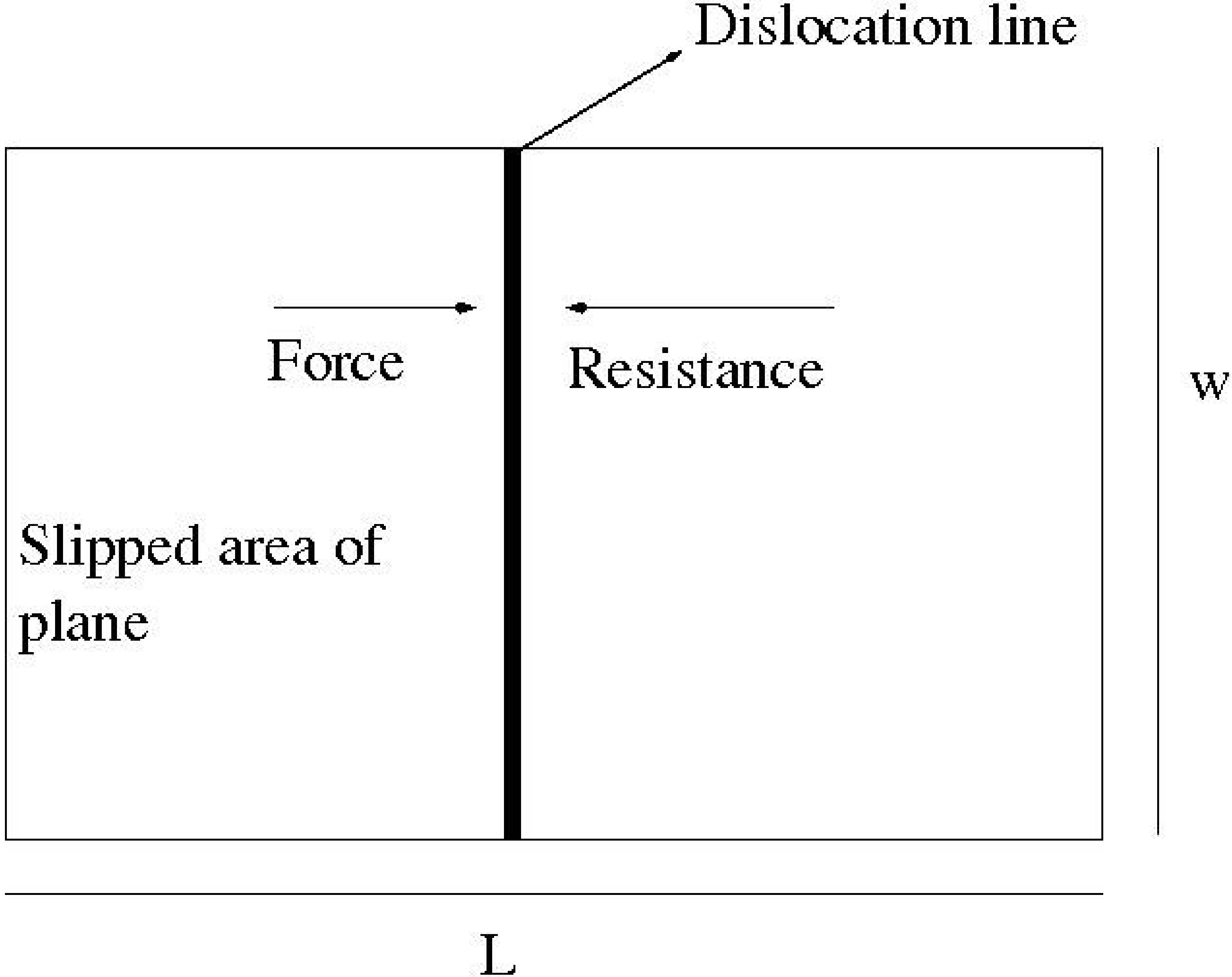
# Lattice resistance

- Why pure metals are soft and ceramics are hard?
- Bonding – non-localised (allow free flow of dislocations) and localised (lock dislocations in place)

# Lattice resistance



# Lattice resistance



# Lattice resistance

- Consider a dislocation moving in a slip plane
- Let the line be of width “w” and traverse a distance “L” under the influence of the applied shear stress “ $\tau$ ” to shift the upper crystal with respect to the lower crystal by “b”
- Then, shear force F = Lw$\tau$
- Work done, W = Lwb$\tau$
- Since this work is done against the lattice resistance per unit length, “f”, it equals fLw.

# Lattice resistance

- Equating the work done by the shear force and the work done by the lattice resitance, we obtain $\tau$ b = f
- This result holds for screw and mixed dislocations too!
- Provided shear stress exceeds f/b, the dislocations in the lattice will move

# Strengthening mechanisms

- Lattice resistance – intrinsic property – much like modulus and can hardly be manipulated
- However, we can make the dislocation do more work while slipping by putting impediments on its way
- Different types of impediments lead to different strengthening mechanisms
- How to calculate the contribution of impediments?

# Strengthening mechanisms

- Spacing between obstacles – say at a distance L
- Number of obstacles that perunit length of dislocation faces: 1/L
- Each obstacle exerts a pinning force – say p
- Contribution of obstacles to resistance is thus p/L
- Addition to shear stress: p/(bL)

# Pinning force

- Pinning – an elastic effect
- “p” -- goes as $Gb^2$
- Thus, the shear stress needed to push a dislocation through obstacles is $\tau = \alpha Gb / L$
- $\alpha$ -- Dimensionless constant that characterises the obstacle strength

# Solid solution strengthening

- Random substitutional solid solution: say zinc in copper to produce brass
- Cast copper – Yield strength of 62 M Pa (E=115 G Pa)
- High tensile bronze – Yield strength 193 M Pa (E = 105 G Pa)
- Zinc – bigger than copper
- Consider concentration of the solute, c

# Solid solution strengthening

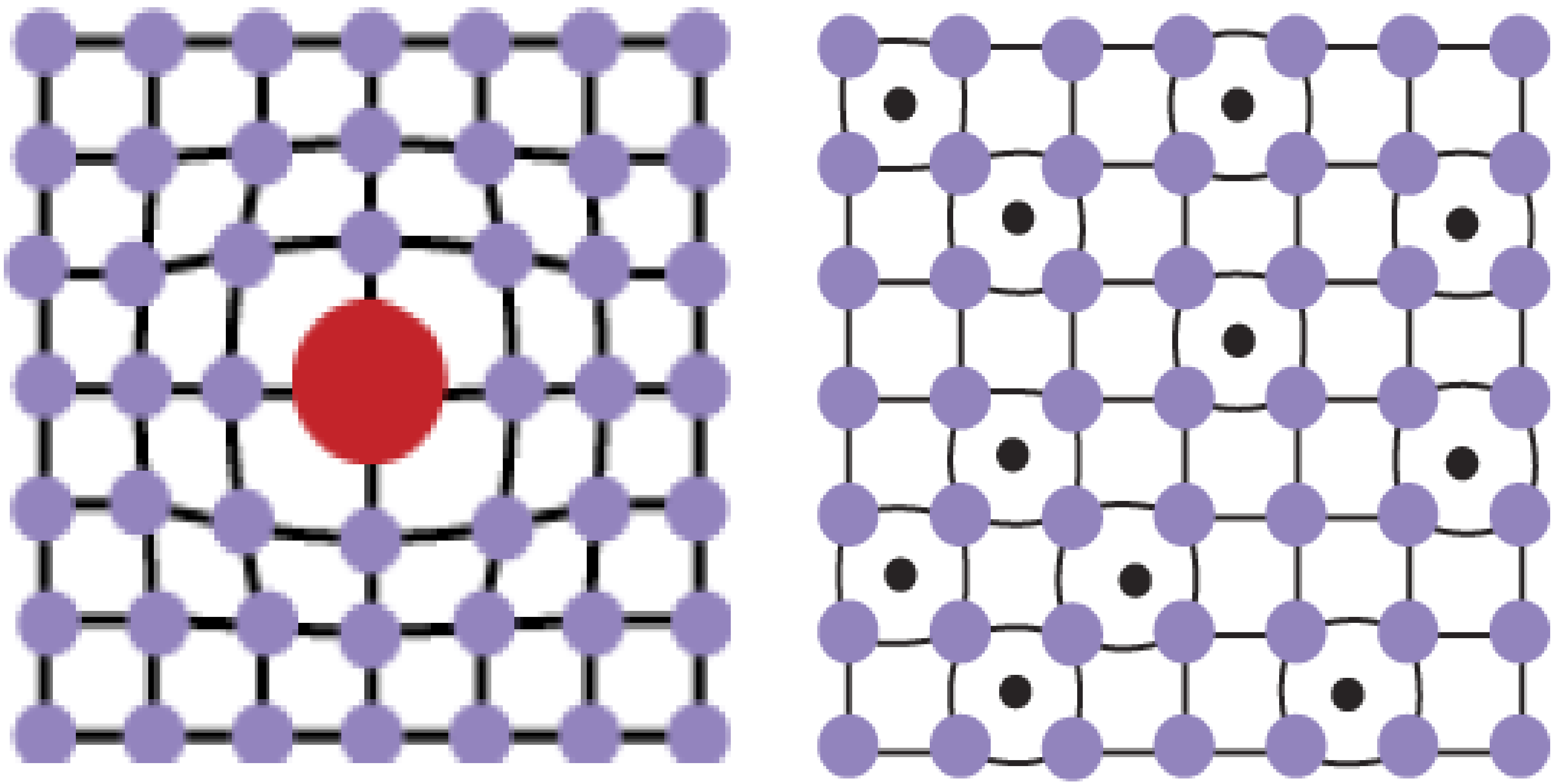
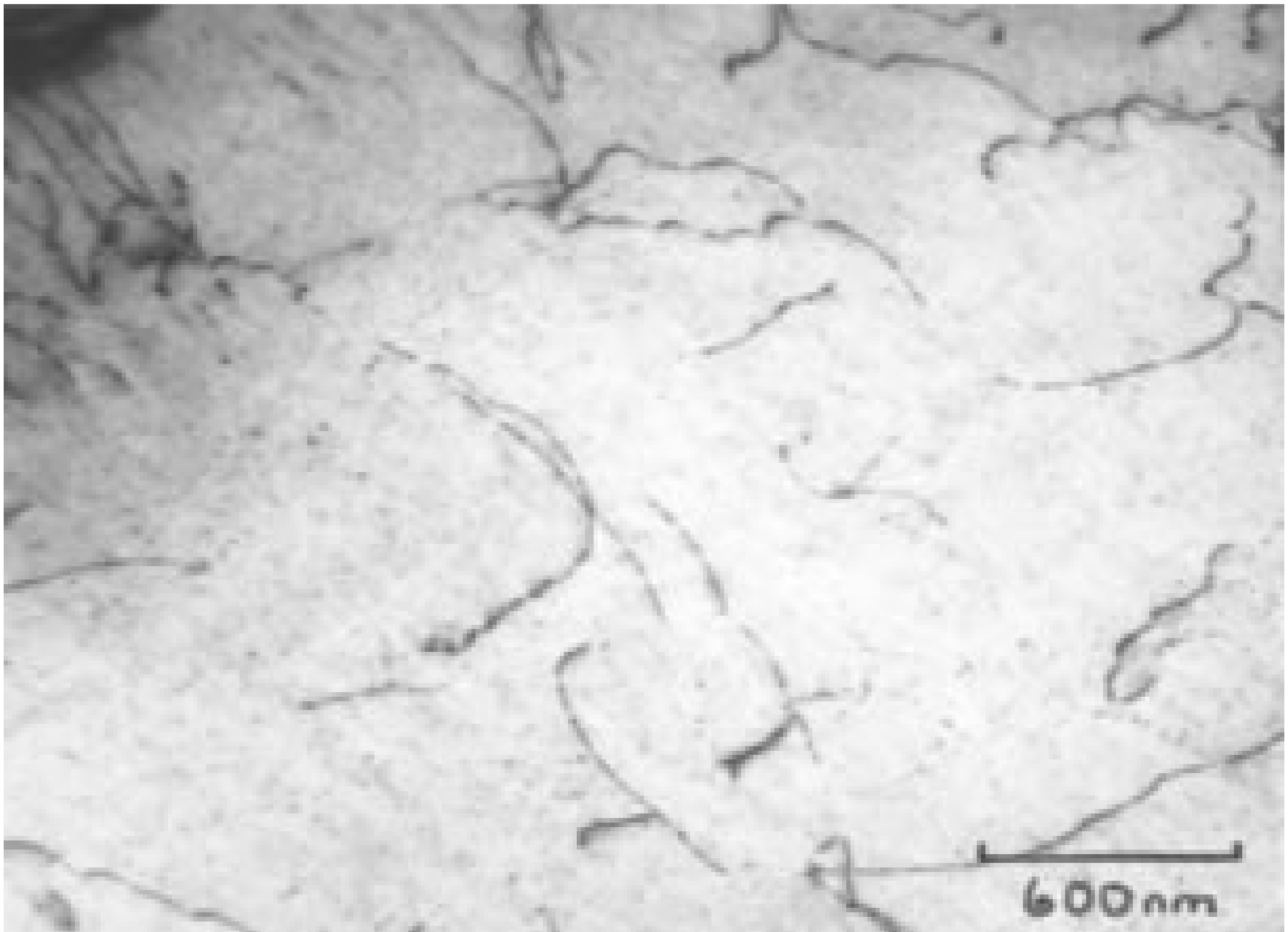


Image courtesy: wiki

# Solid solution strengthening

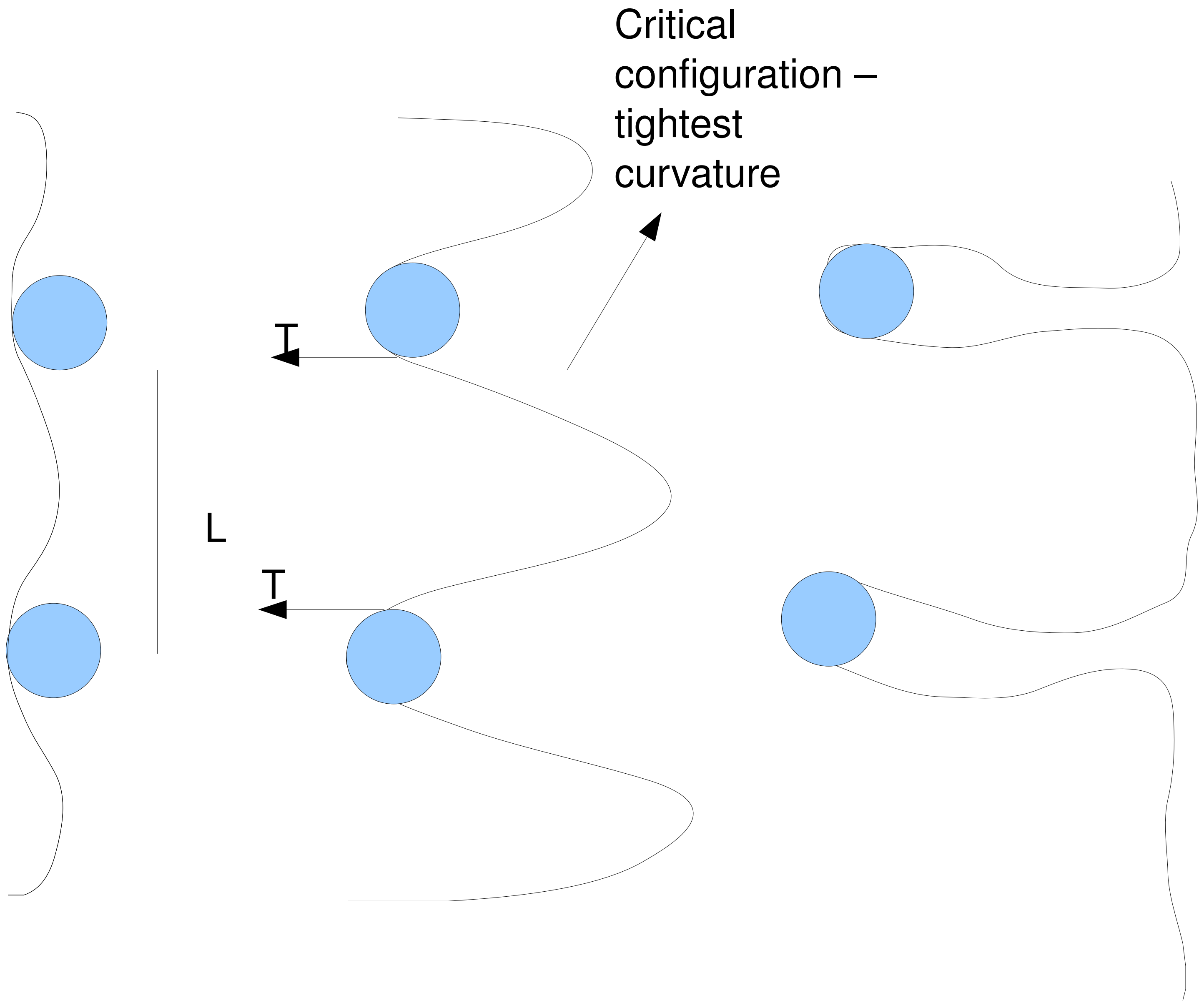
- Consider concentration of the solute, c
- If "a" is the size of the zinc atoms, $c = a^2 / L^2$
- Or, $L = a c^{-(1/2)}$
- Thus, solid solution hardening goes as the square root of concentration (with the non-dimensional constant $\alpha$ representing the distortion in the crystal due to the solutes)

# Precipitate (dispersion) strengthening




Steel University.Org Homepage – Dislocation bowing at precipitates

# Precipitate strengthening




Slipped region – to the left of the dislocations

# Precipitate strengthening

- Critical configuration – radius of the bowed dislocation is half the inter-particle spacing
- On one segment of length L, a force of $\tau b L$ is acting which is balanced by twice the line tension $2T = G b^2$
- $\tau = Gb/L$
- Precipitation hardened aluminium alloys – 15 times stronger than pure aluminium

# Precipitate strengthening

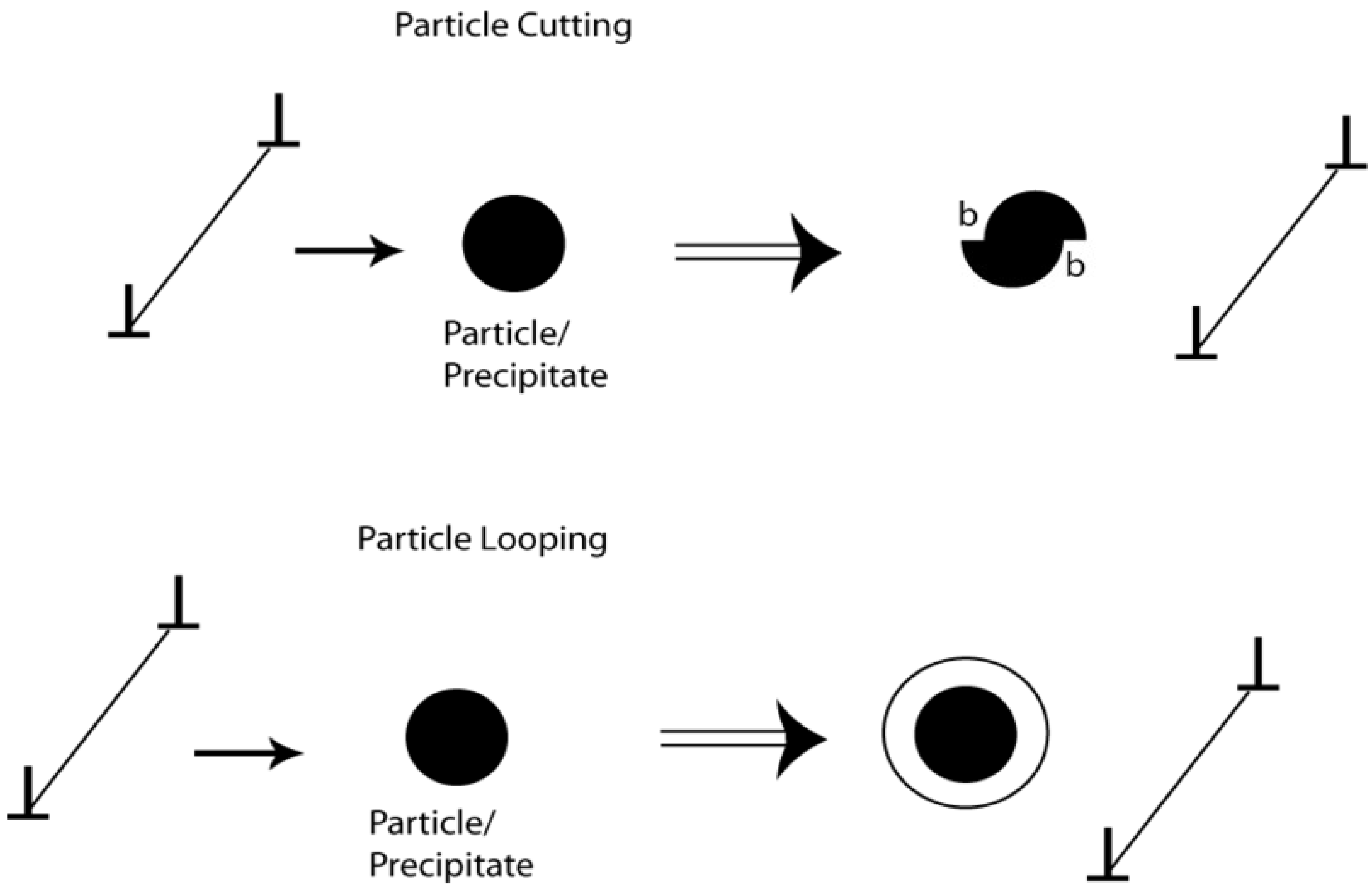
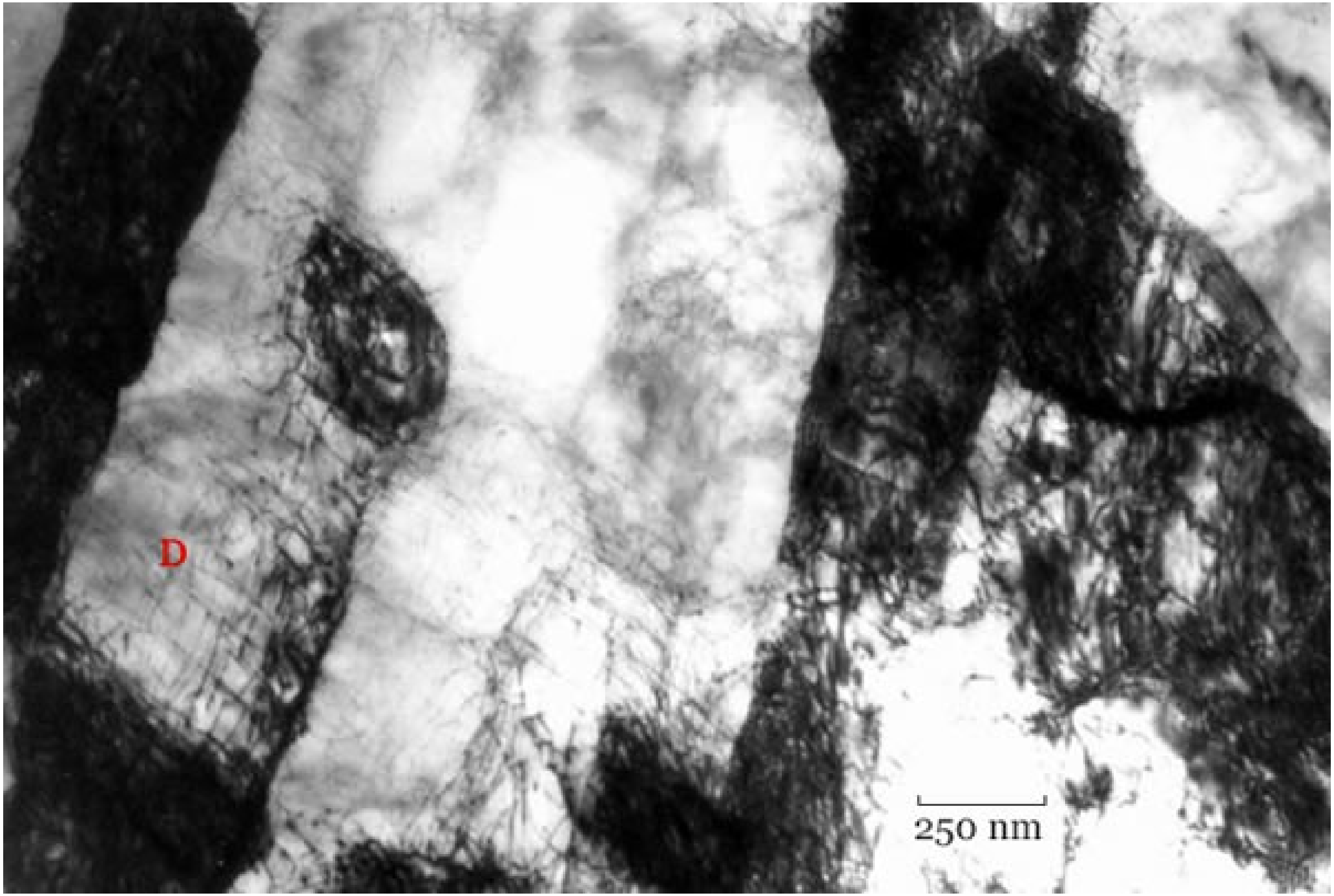


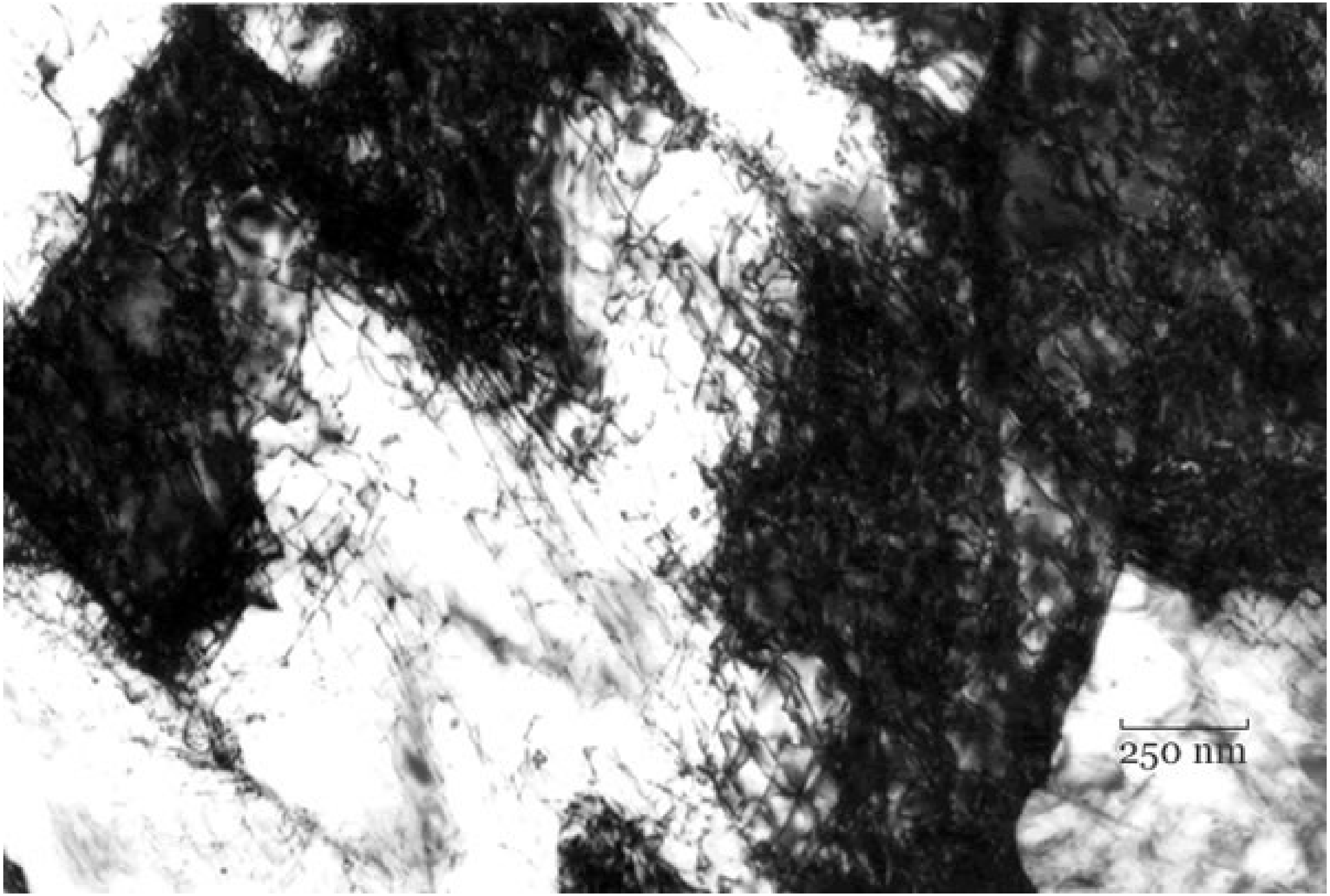

Image courtesy: wiki

# Work hardening




Steel University.Org Homepage – Forest of dislocations

# Work hardening

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# Work hardening

- Dislocation faces a forest of dislocations
- Average spacing between dislocations is the inverse square root of the dislocation density
- Moving dislocation cutting through a forest of dislocations produces jogs
- Jogs exert a pinning force of $Gb^2/2$
- Thus, work hardening goes as

$$(1/2)Gb(\rho_d)^{0.5}$$

# Grain-size hardening

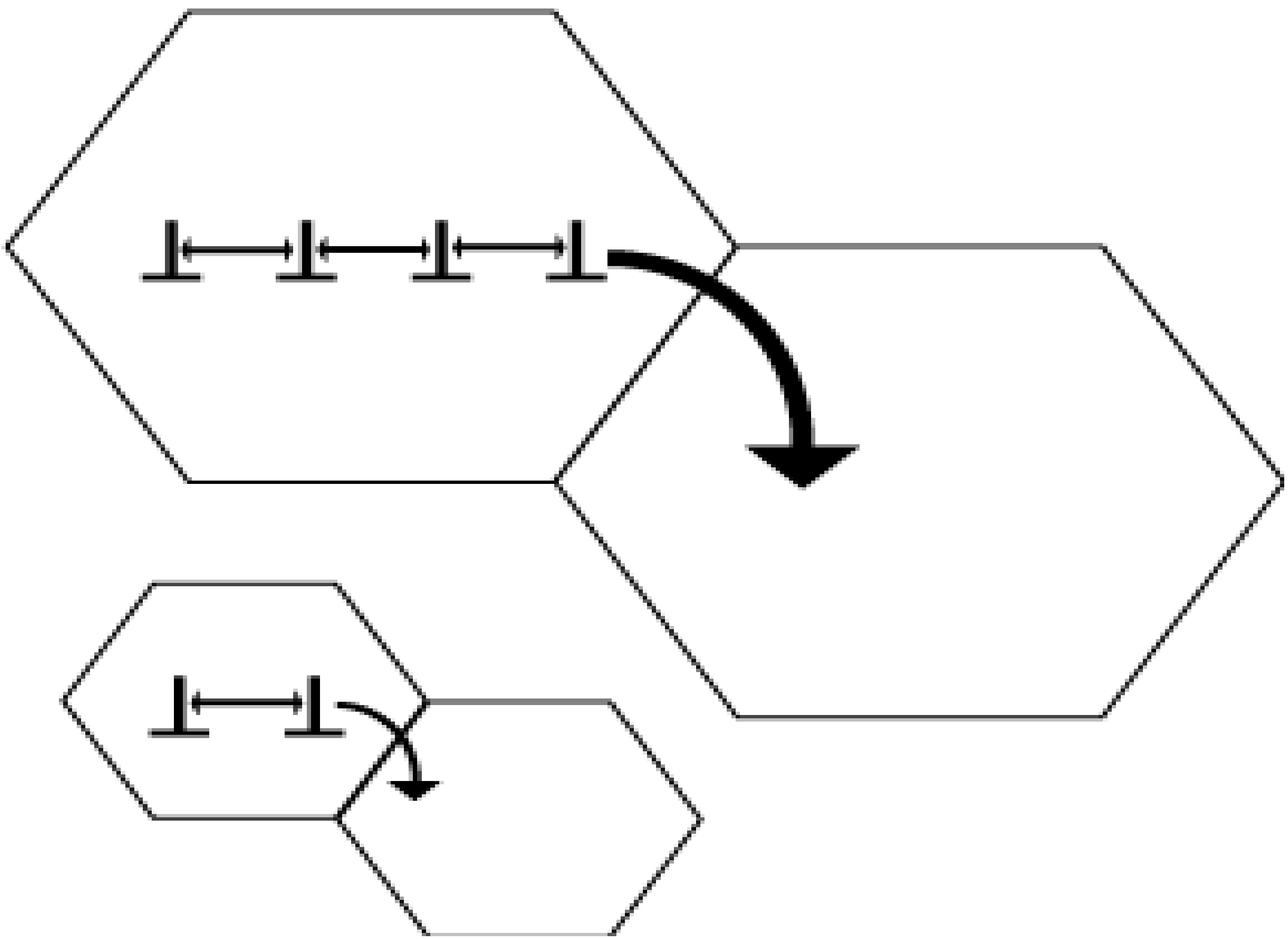


Image courtesy: wiki

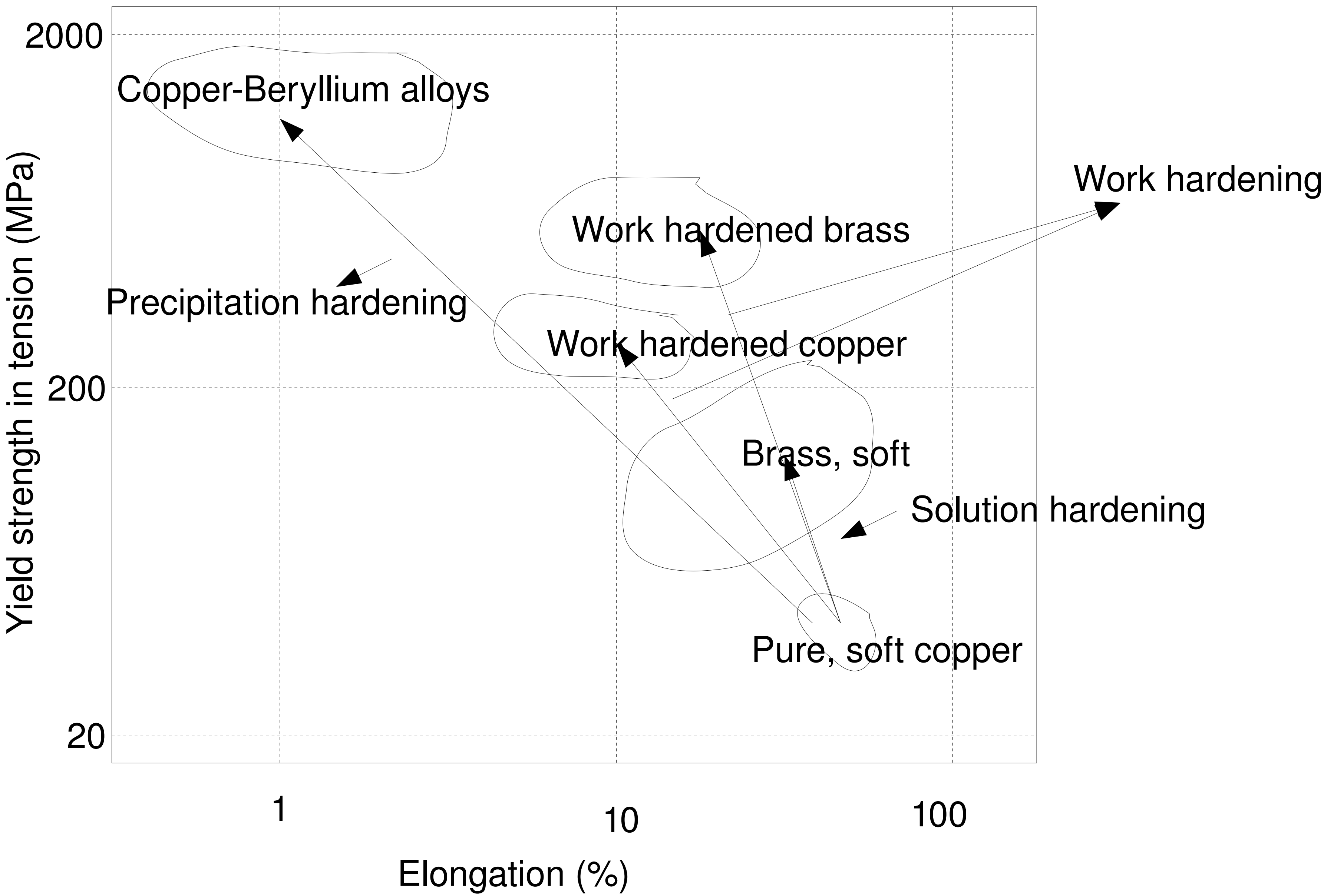
# Grain-size hardening

- $\tau_{gb} = k_p / \sqrt(D)$
- $k_p$ -- Petch constant
- Hall-Petch relationship

# Additivity of strengthening mechanisms

- To first approximation, the strengthening mechanisms are additive;
- Polycrystalline materials in tension – use the strengthening mechanisms, calculate the shear stresses, and use Taylor factor

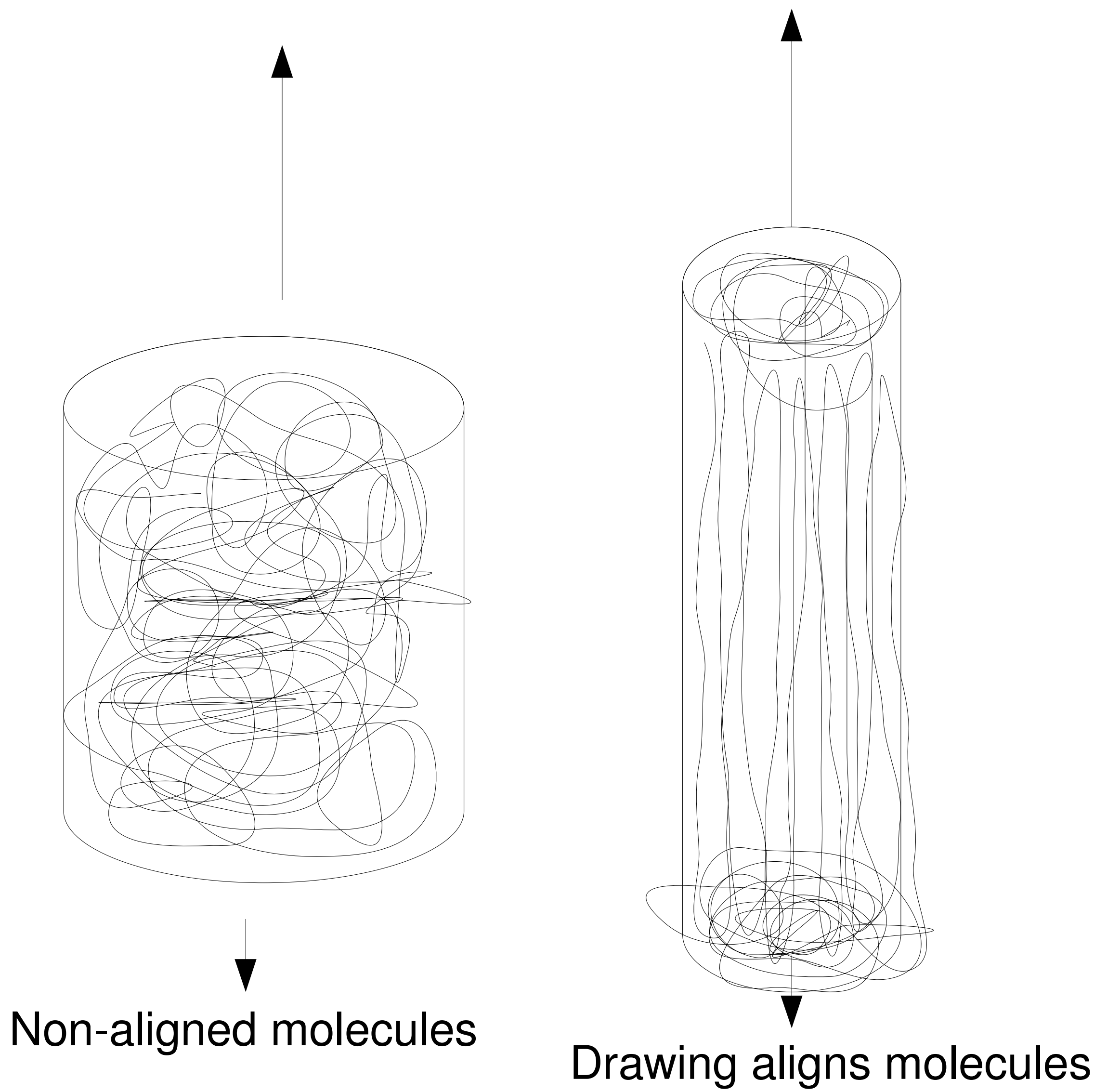
# Strength versus ductility



# Strength versus ductility

- Increasing strengths leads to decreasing ductility
- Are there ways of having both – ductility and strength?
- Yes! We'll discuss two methods – cryo-rolling and ECAP later while discussing the processes

# Plastic flow in polymers



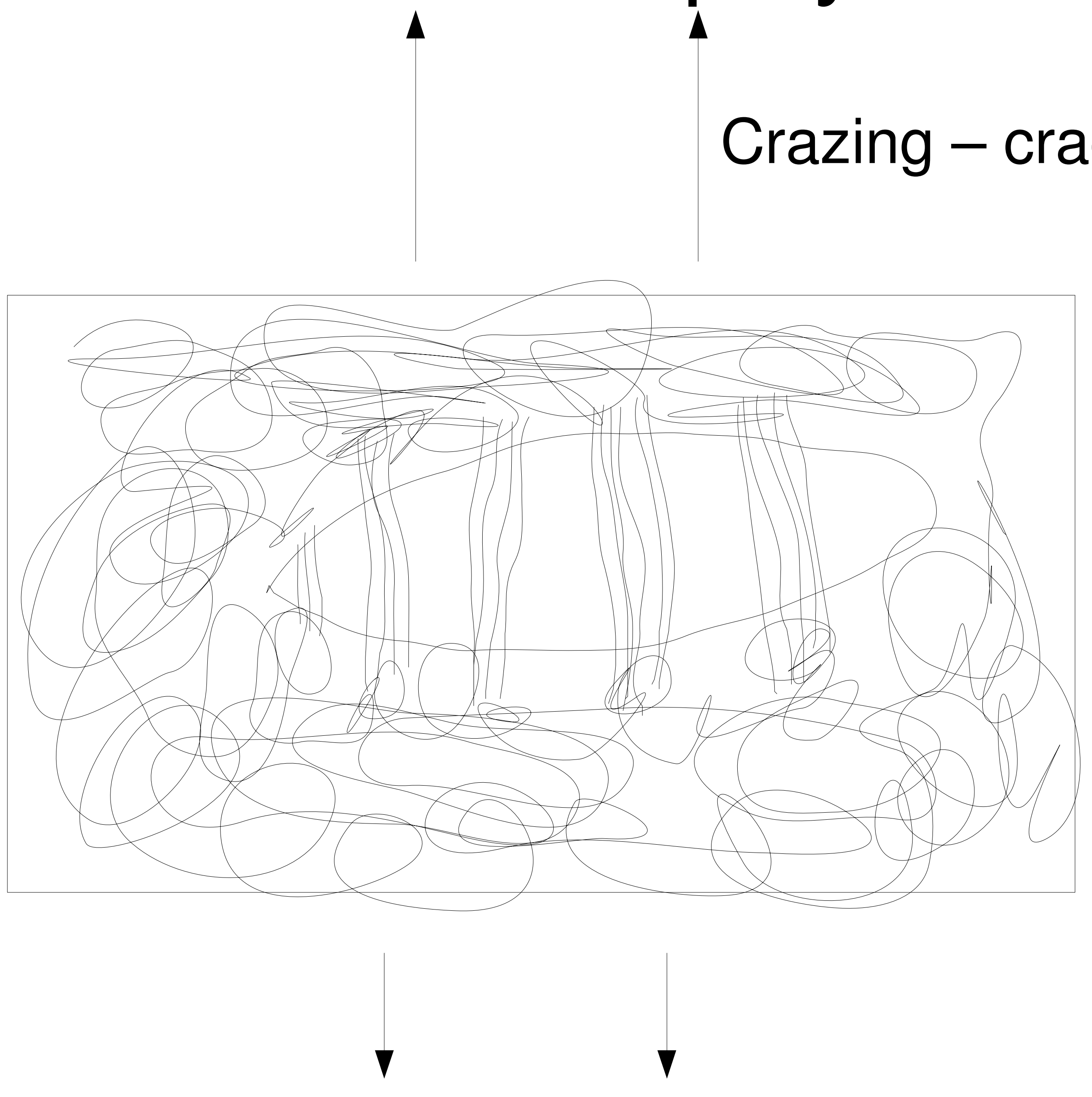

Drawing

# Drawing

- Low temperatures – polymers are brittle
- Above 0.75 Tg, when pulled in tension, polymers are cold drawn
- Drawn polymer – stiffer by a factor of about 8
- Limited geometry
- Polymers with higher Tg, at room temperature, craze

# Plastic flow in polymers

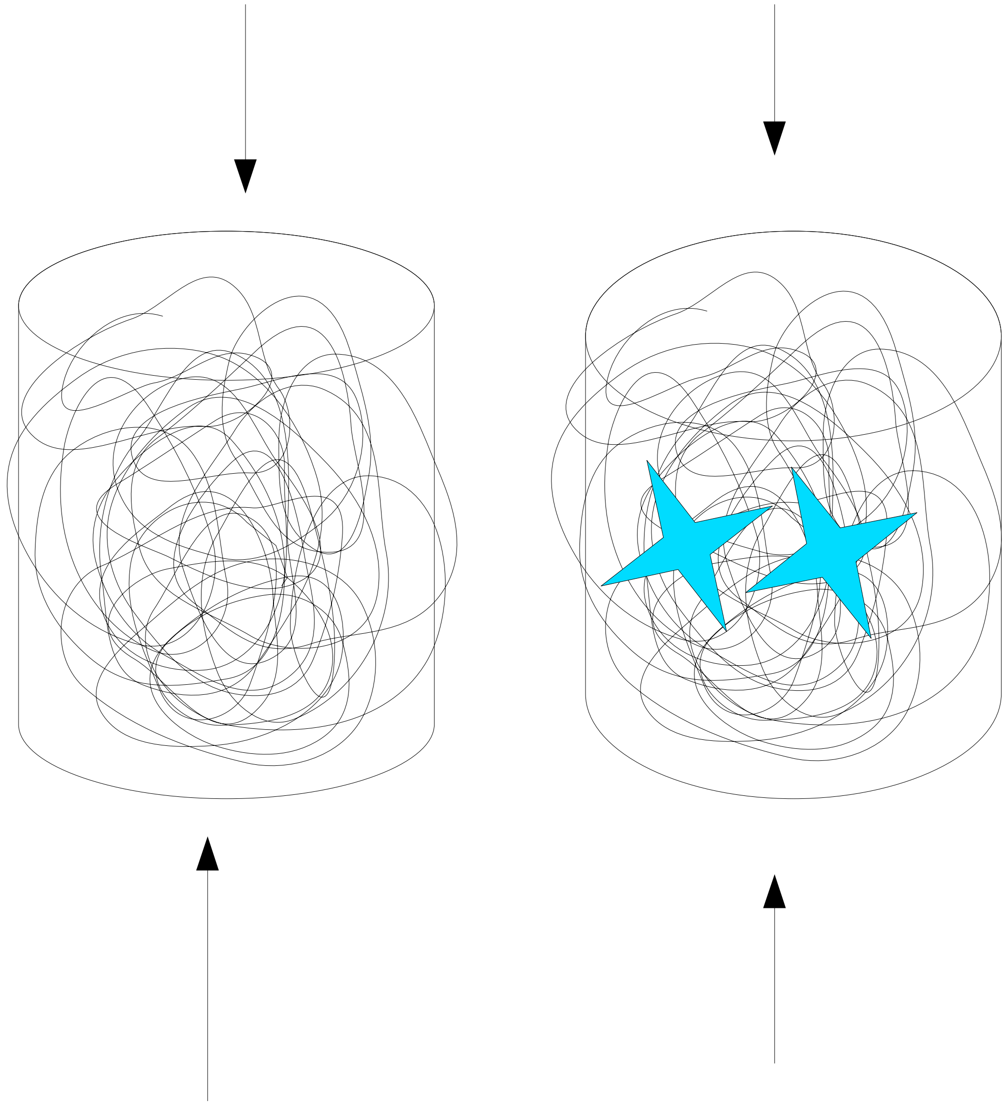
Crazing – crack + drawing



# Crazing

- Crazes scatter light
- Hence, when present, they cause whitening
- Continuous loading – leads to crazes becoming cracks and fracture of sample

# Plastic flow in polymers



Shear-banding

# Shear banding

- Large plastic strain in compression

# Strengthening polymers

- Non-crystalline solids – Dislocation is not a useful concept
- Think of some unit step of the flow process
  -- the relative slippage of two segments of a polymer chain
  -- shear of a small molecular cluster in a glass
- Lattice resistance – of the same origin; breaking strong bonds are difficult: ceramics are strong; breaking weak bonds are easy: polymers are weak

# Strengthening polymers

- Belnding – mixture of two polymers
- Drawing – deliberate use of molecular alignment during stretching to strengthen a polymer
- Cross-linking – creation of strong covalent bonds between long chain molecules
- Reinforcement – particles, fibres or fabrics

Stiffness, hardness, and strength; what next?

Stiffness, hardness, and strength; what next?
Toughness!

# Toughness

Image courtesy: Christopher Thomas – via the wiki site

# Broken glass – closer look

Image courtesy: Christopher Thomas – via the wiki site

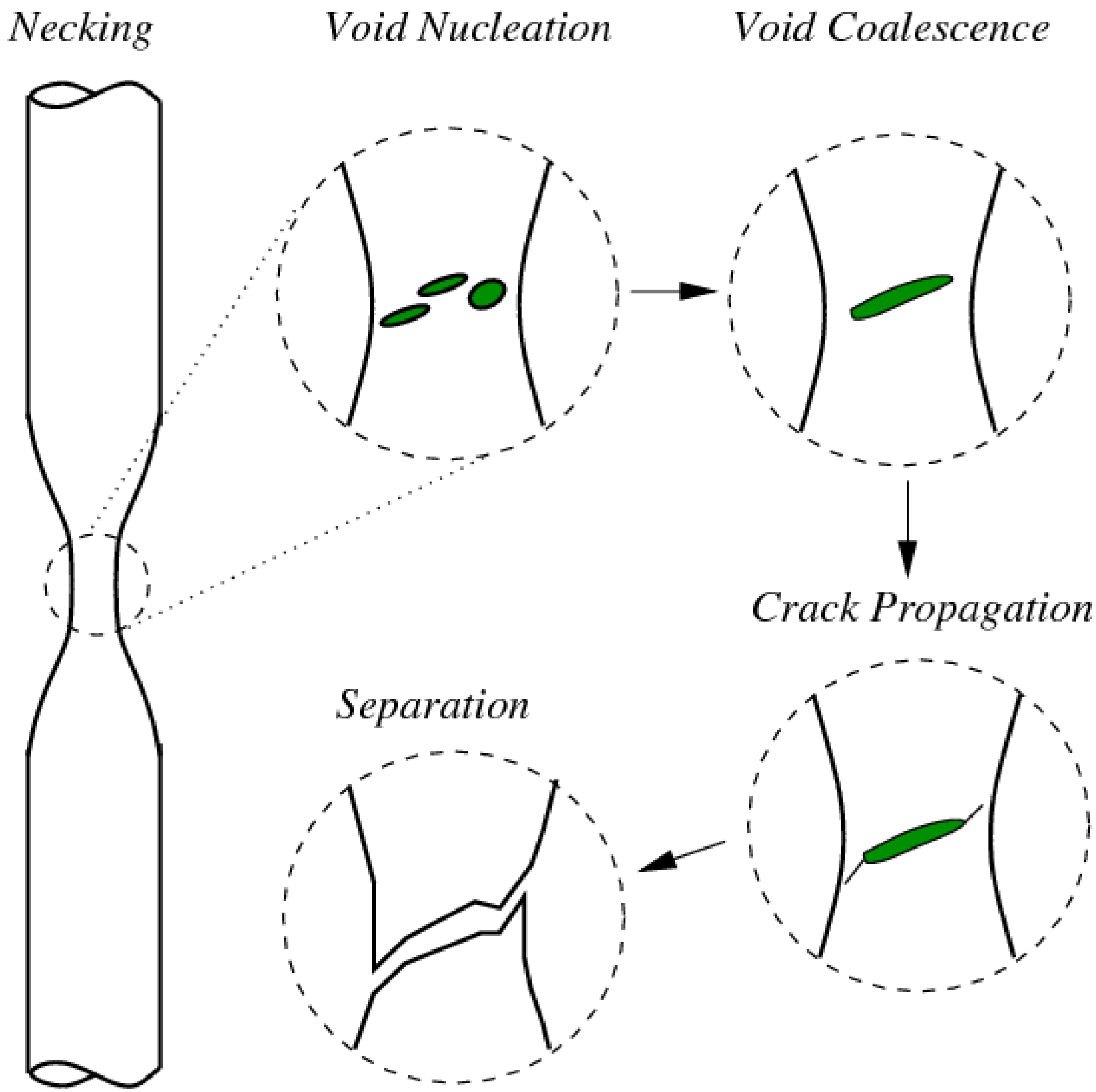
# Ductile fracture

Image courtesy: wiki

# Brittle and fatigue fracture

Image courtesy: wiki

# Ductile fracture

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# Fatigue on fanblades