Strengthening Mechanism

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Mechanism of strengthening of materials

Macroscopic plastic deformation → motion of large numbers of dislocations

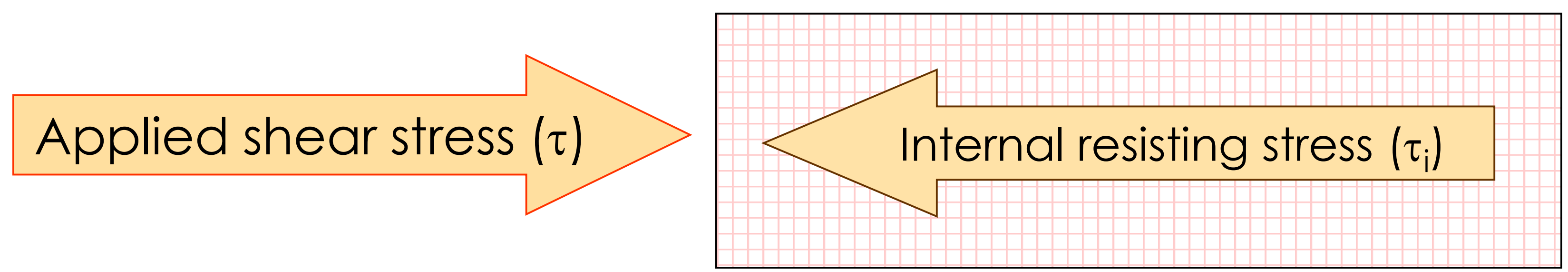
- Ability of a metal to plastically deform depends how easily dislocations move.
- Hardness and strength depends on how plastic deformation can be made to occur,
- If we Reduce mobility of dislocations → mechanical strength can be enhanced; as a result greater mechanical forces will be required to initiate plastic deformation.

Restricting dislocation motion makes a material stronger.

Called as strengthening of the material.

Mechanisms

1. Strain hardening
2. Grain size refinement
3. Solid-solution alloying
4. Precipitation hardening



Strain hardening

- Plastic deformation is caused by dislocations moving and leaving the crystal $\Rightarrow$ that dislocation density should decrease with plastic deformation.
- Further, if dislocations are the agent weakening the crystal $\Rightarrow$ then with increased dislocation density the material should get weaker! But, contrary there is an increase in strength!
- Strain hardening → multiplication of dislocations.
- The increase in flow stress with strain is called strain hardening (or work hardening).
- This implies some sources of dislocation multiplication / creation should exist &
- More dislocations is somehow cause a 'traffic jam' kind of scenario and leading to strengthening.

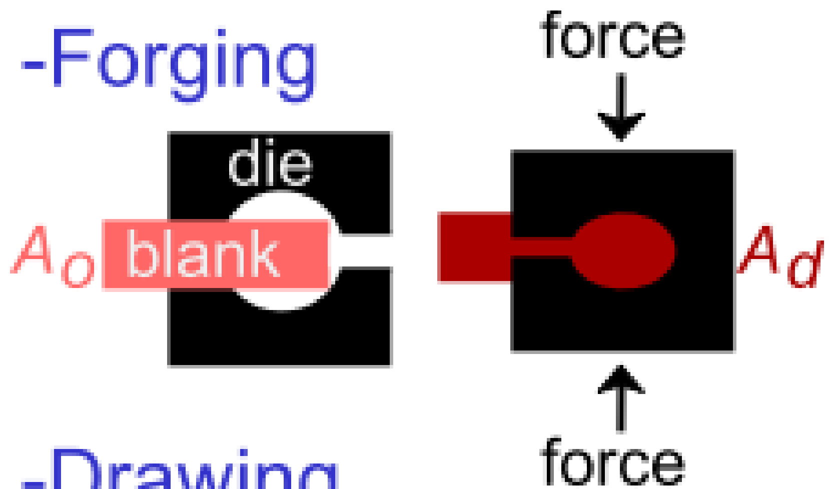
Strain hardening

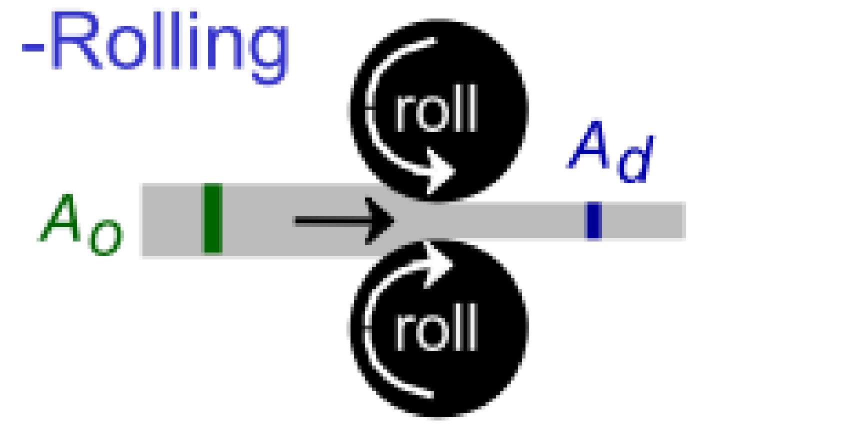
$$\begin{array}{ccc} \textit{Annealed material} & & \textit{Stronger material} \\ \rho_{\text{dislocation}} \sim (10^6 - 10^9) & \xrightarrow{\textit{Cold work}} & \rho_{\text{dislocation}} \sim (10^{12} - 10^{14}) \end{array}$$

Strain hardening

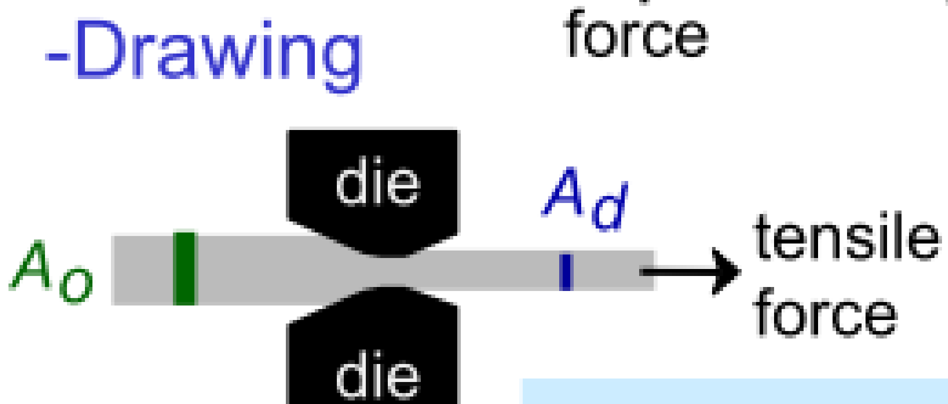
Cold working

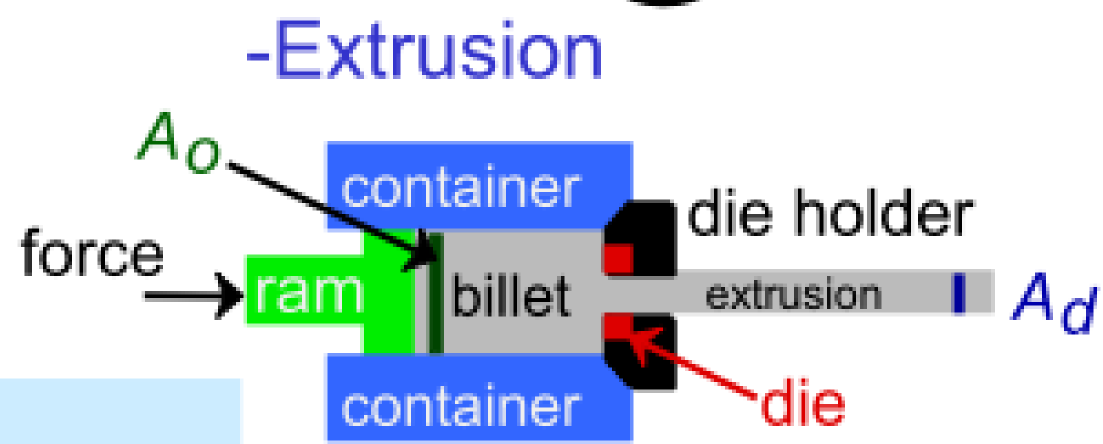
- Room temperature deformation
- Changes cross sectional area





Adapted from Fig. 14.2, *Callister & Rethwisch 3e.*





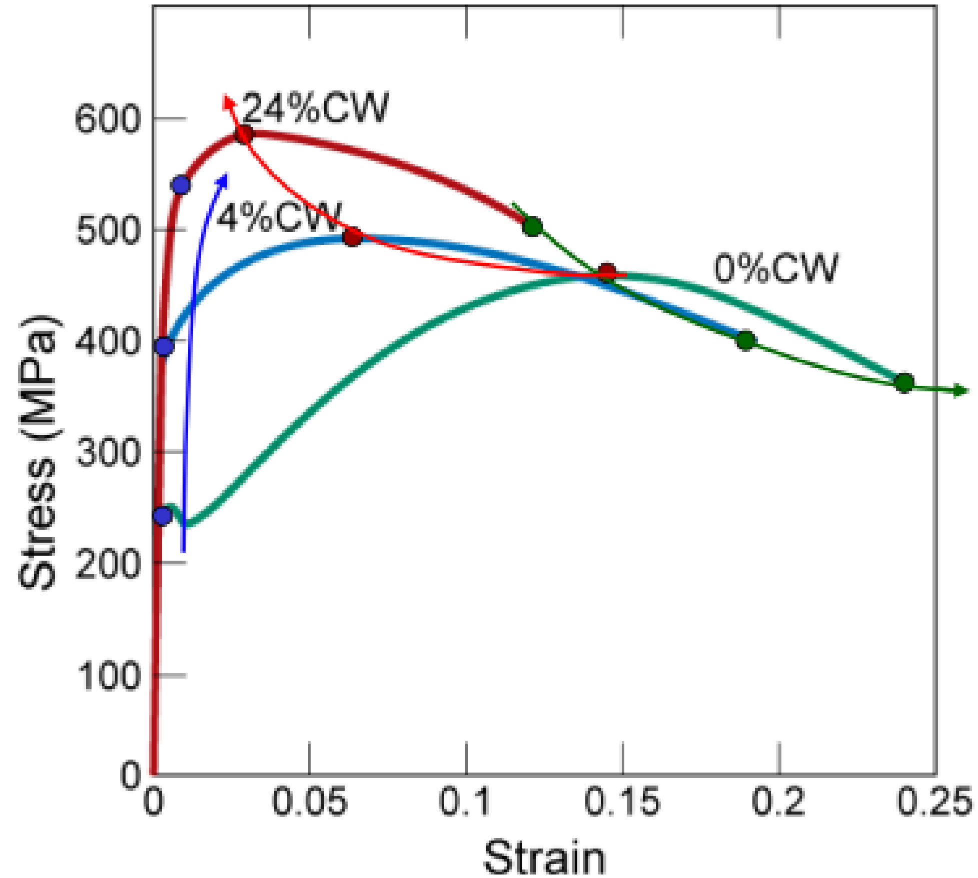
$$\%CW = \frac{A_o - A_d}{A_o} \times 100$$

Strain hardening

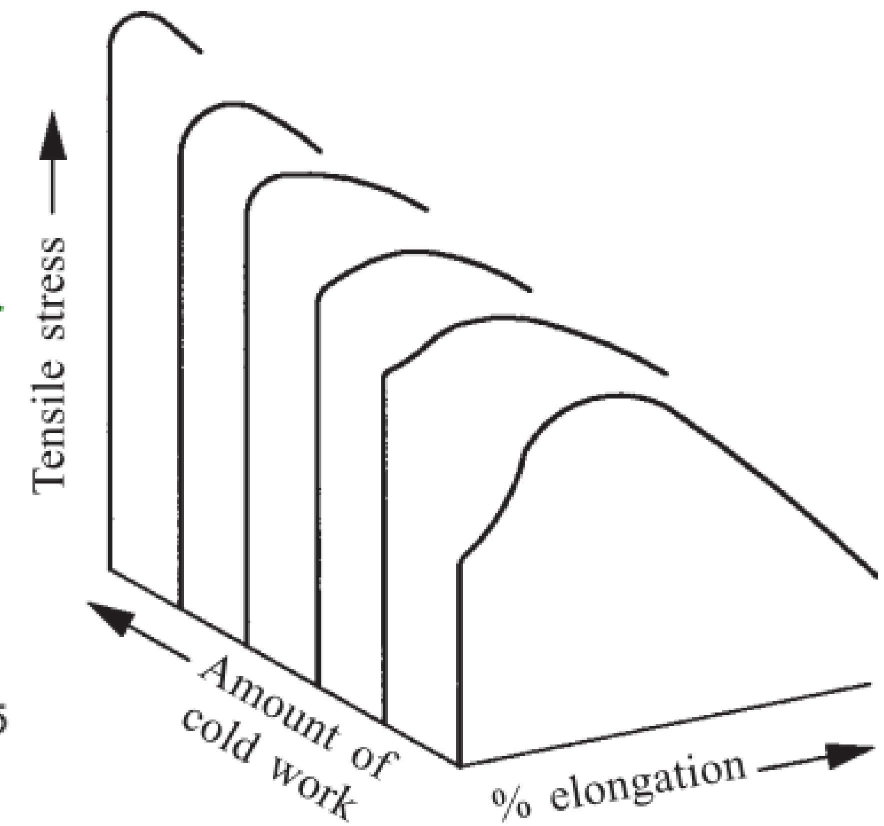
$$\tau = \tau_0 + A\sqrt{\rho}$$

stress to move a dislocation in a matrix of dislocation density ρ

Stress to move a dislocation in the absence of any dislocation



Mild steel cold worked to different degrees.



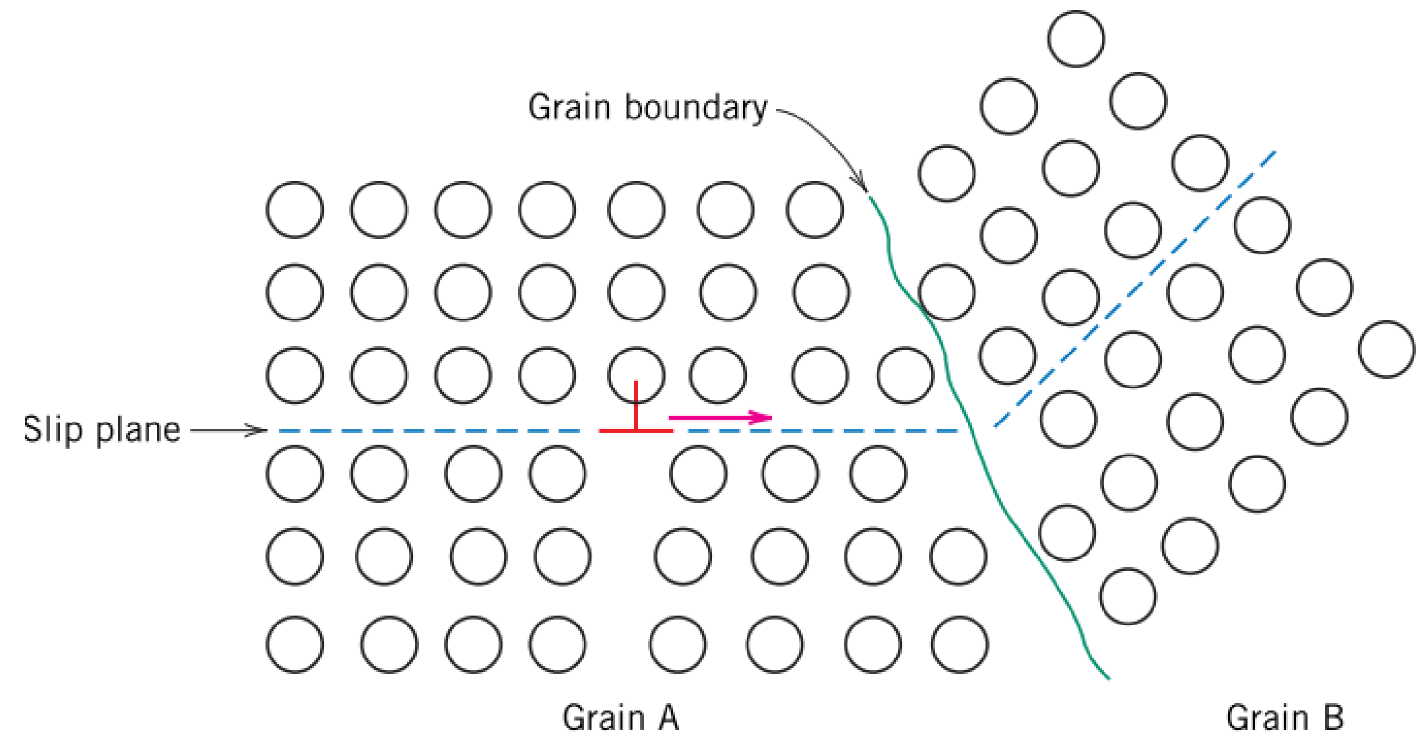
- Restricting the motion of dislocation transforms the material from ductile to hard.
- Strain hardening can be identified by increase in the yield strength.
- Metals "yield" when dislocations start to move (slip).
- "Yield" means permanently change shape.

Grain Refinement

The grain boundary acts as a barrier to dislocation motion.

Two grains are of different orientations:

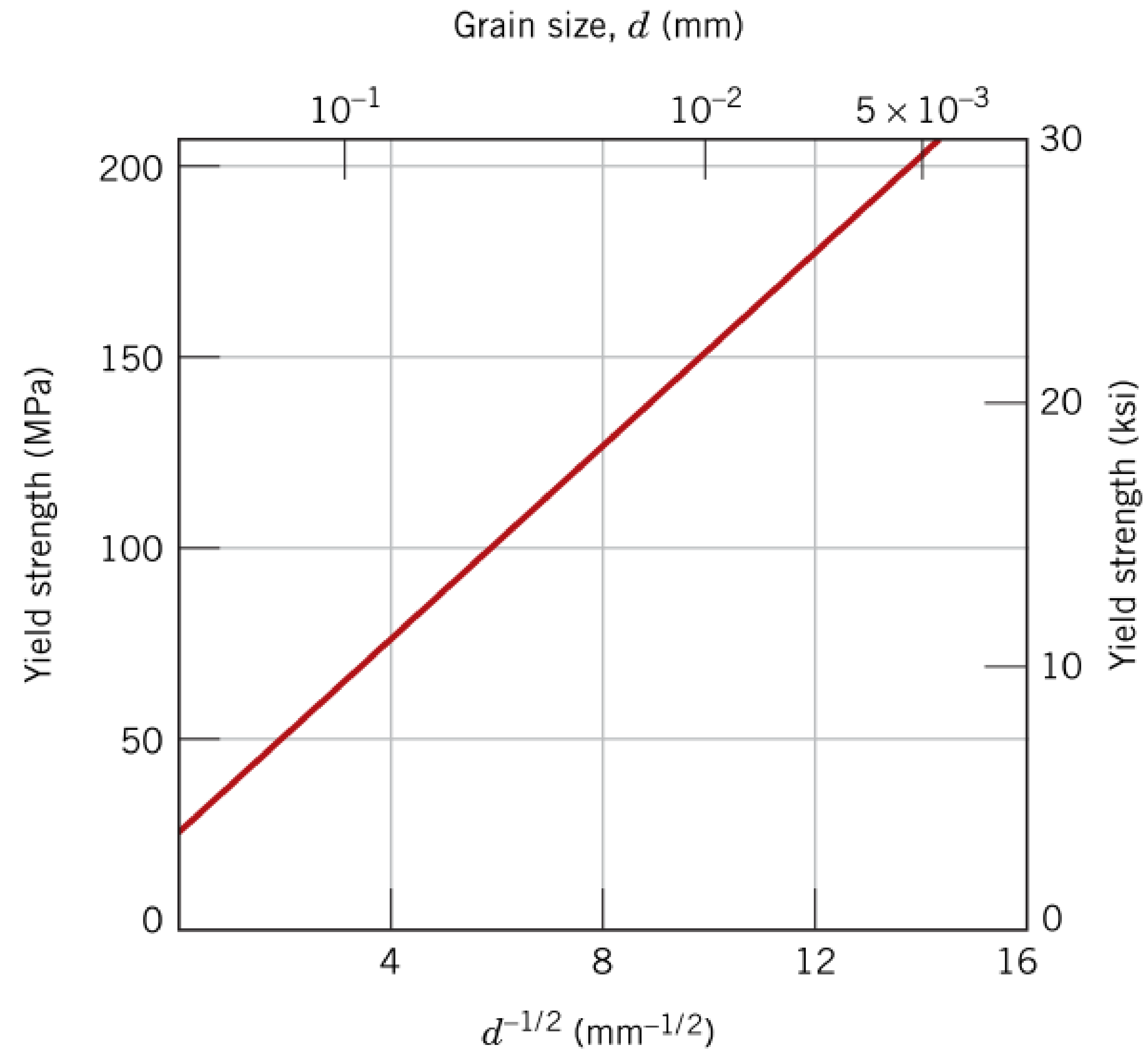
- Atomic disorder at grain boundary leads to discontinuity of slip planes from one grain into the other.
- A dislocation passing into grain B will have to change its direction of motion;
- This becomes more difficult as the crystallographic misorientation increases.



- For high-angle grain boundaries, dislocations tend to “pile up” at grain boundaries.
- These pile-ups introduce stress concentrations ahead of their slip planes, which generate new dislocations in adjacent grains.

Grain Refinement

A fine-grained material (small grains) is stronger than one that is coarse grained.



Yield strength for the same material in absence of any dislocations.

constant

$$\boldsymbol{\sigma_y = \sigma_0 + \frac{K}{\sqrt{d}}} \rightarrow \text{Hall - Petch equation}$$

Yield strength

average grain diameter

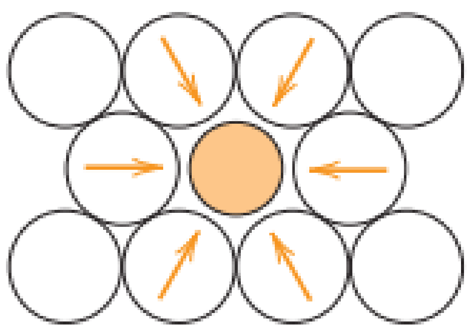
Solid solution alloying

Alloys are stronger than pure metals.

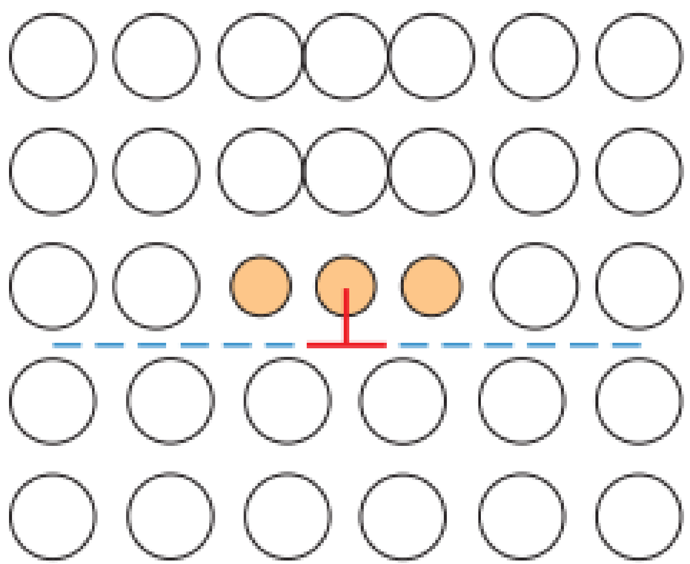
Impurity atoms impose lattice strains on the surrounding host atoms;
Larger the size difference larger is the strain field.

Results in lattice strain field interactions between dislocations and these impurity atoms;

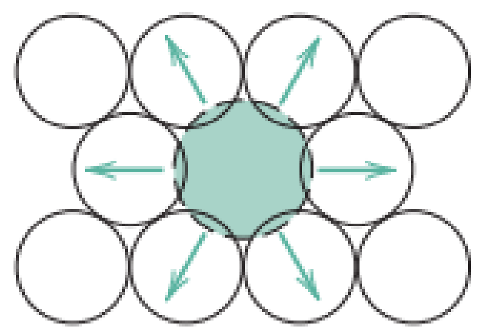
Dislocation movement is restricted.



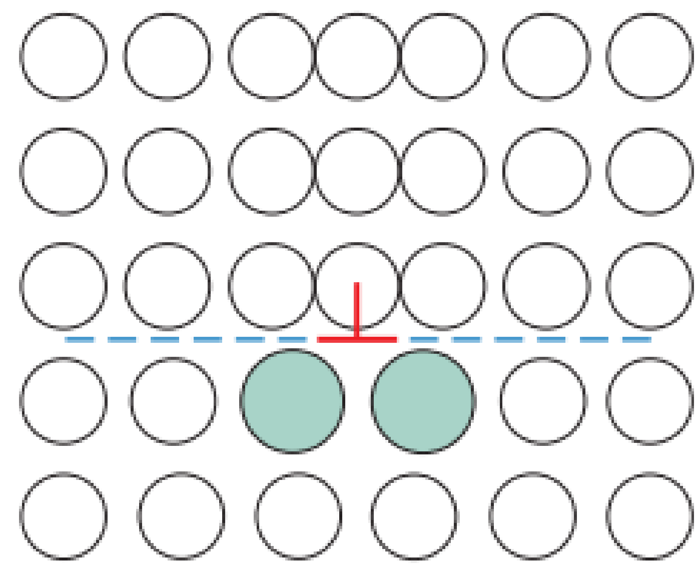
(a)



Compressive stress side



(a)



Tensile stress side

Solid solution alloying

Solute strengthening of Cu crystal by solutes of different sizes

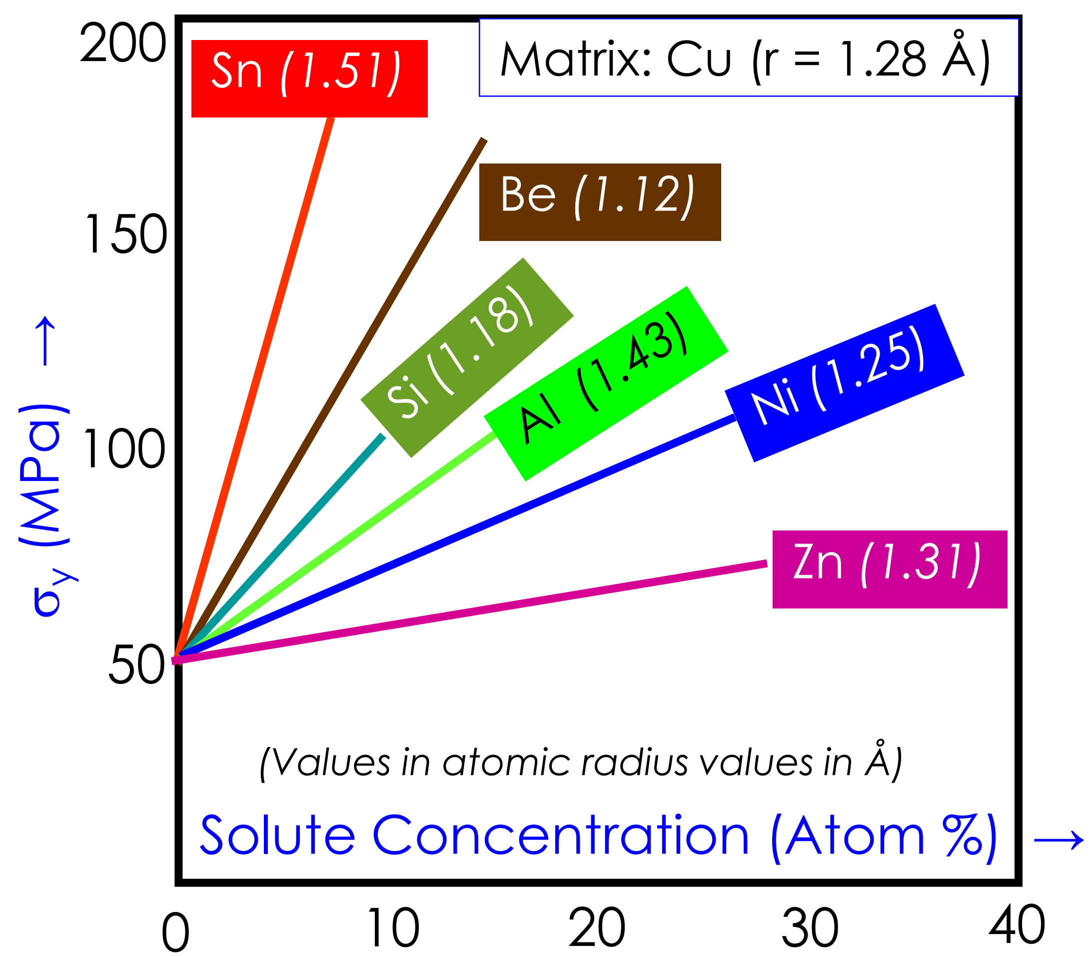
Size effect

Size effect depends on:

- Size difference
- Concentration of the solute *(c)*

For the same size difference the smaller atom gives a greater strengthening effect

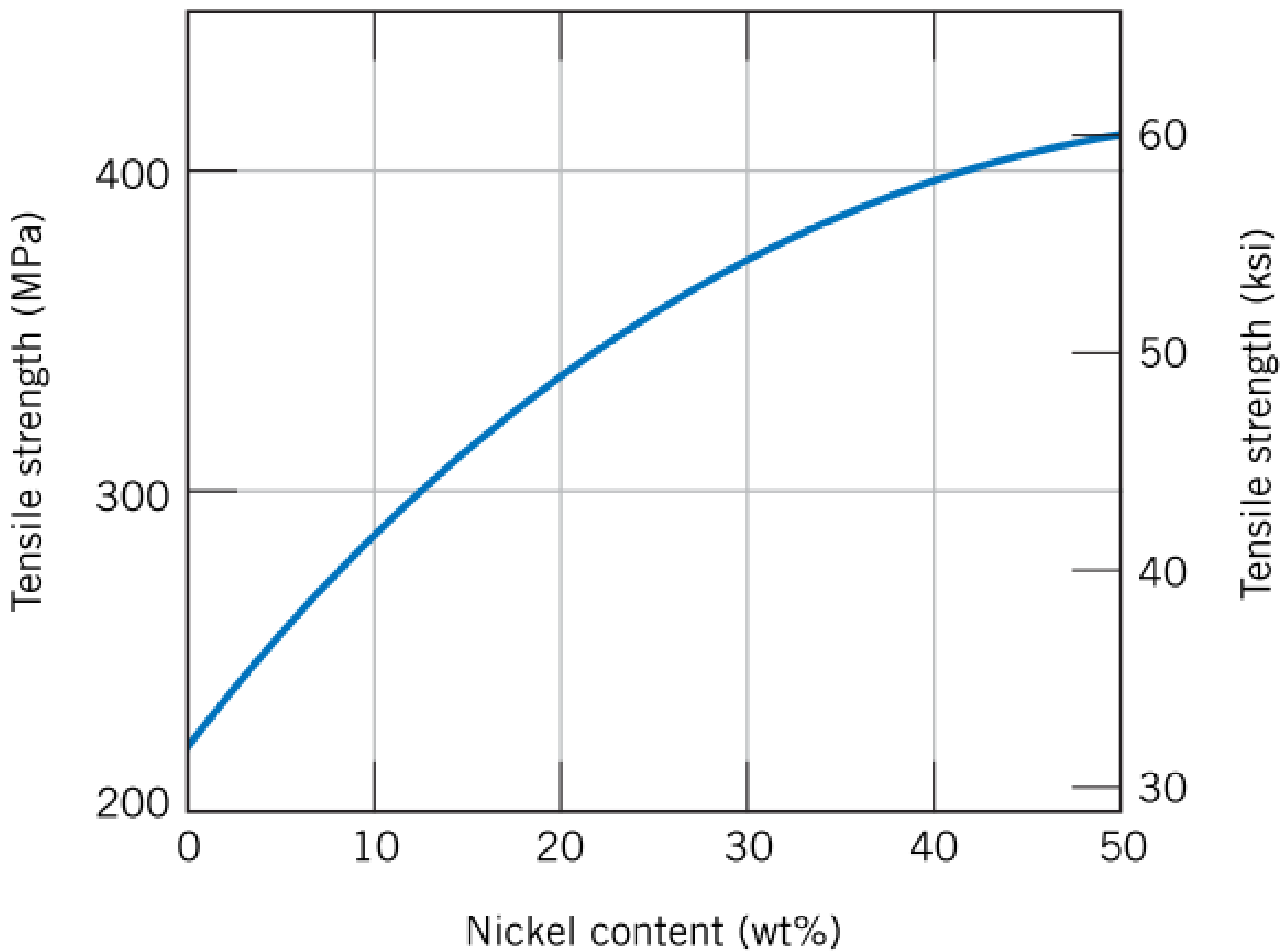
$$\sigma_y \tilde{\propto} c$$

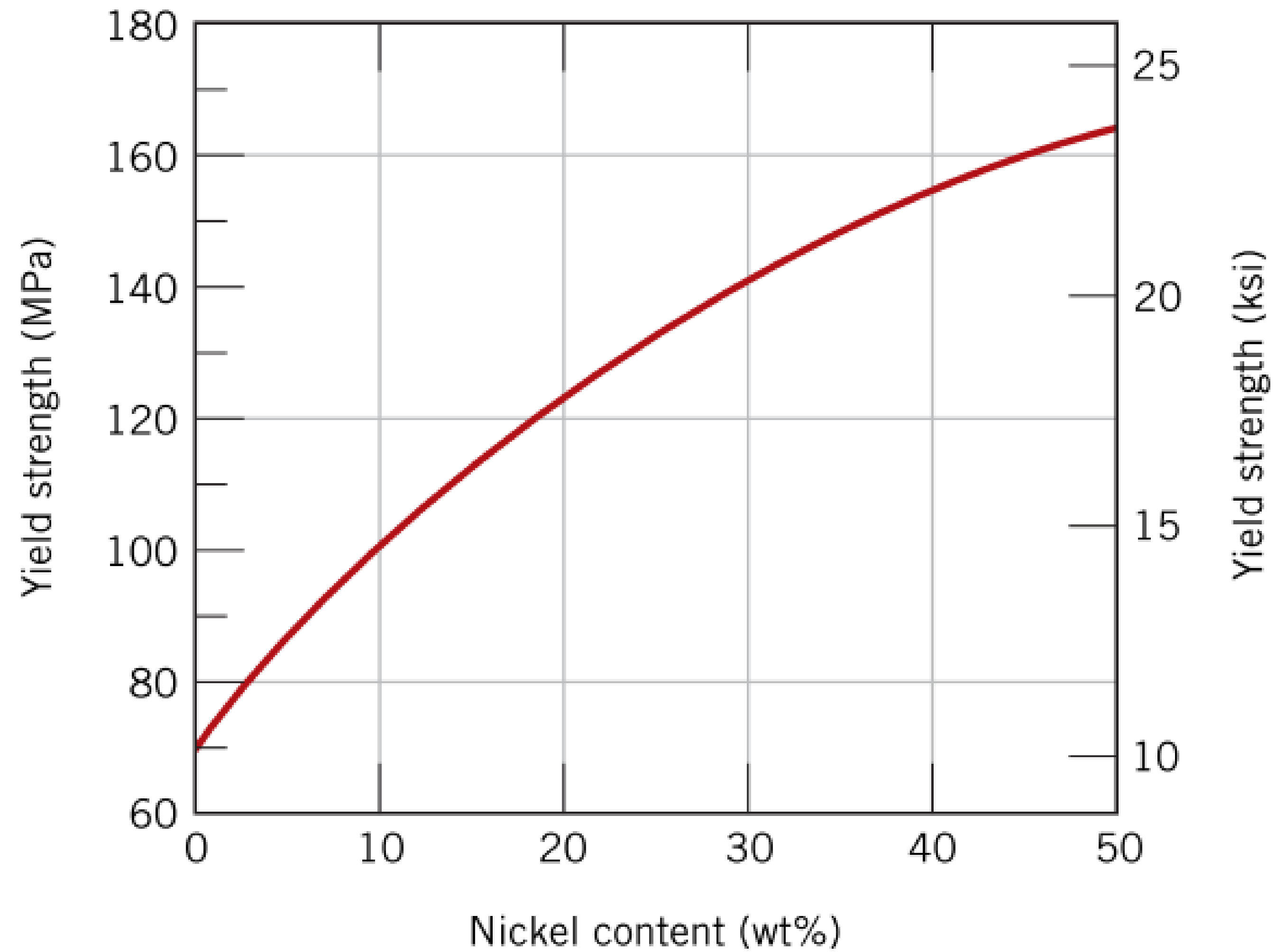


Solid solution alloying

Solid Solution Strengthening in Copper

Tensile strength & yield strength increase with wt% Ni.





Precipitation hardening

Strength and hardness of some metal alloys may be enhanced by the formation of extremely small uniformly dispersed particles of a second phase within the original phase matrix;

→Matrix + sub-microscopic distribution of precipitates.

Dislocations moving in the matrix are hindered by closely spaced precipitate particles;

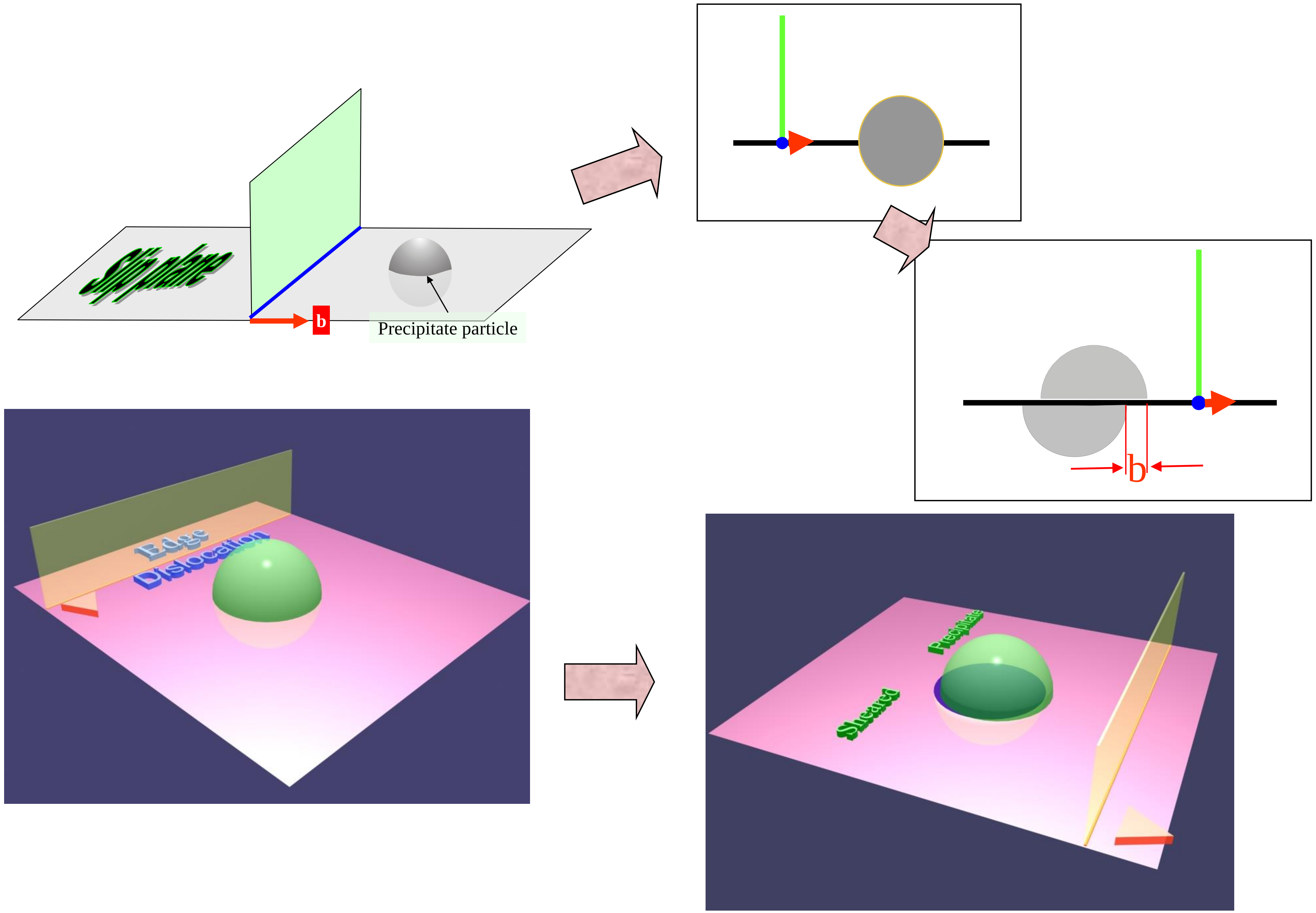
Strengthening effect is inversely proportional to the particle spacing.

A moving dislocation either

1. Cuts through the precipitate particles or
2. Bypasses them.

Process of Precipitation hardening

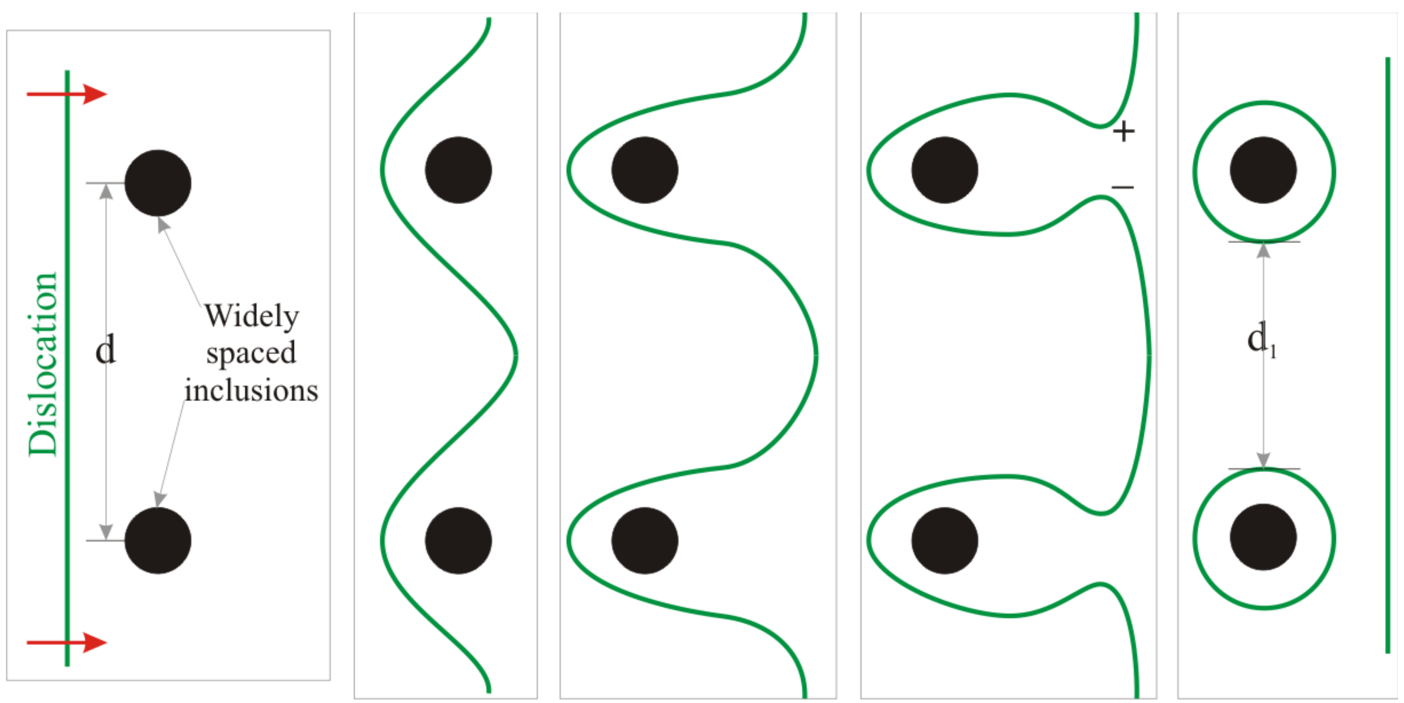
Schematic views of edge dislocation glide through a precipitate

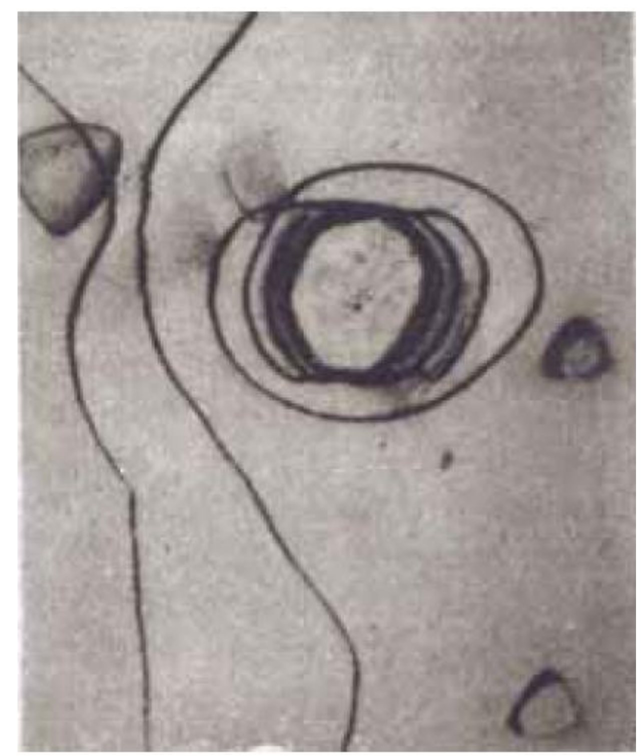


Process of Precipitation hardening

- Dislocations can bow around widely separated precipitates.
- In this process they leave dislocation loops around the inclusions, thus leading to an increase in dislocation density.
- The next dislocation arriving feels a repulsion from the dislocation loop and hence the stress required to drive further dislocations increases.
- Thus, the effective separation distance (through which the dislocation has to bow) reduces from ‘d’ to ‘d_1’.

Schematic views of edge dislocation bypass through a precipitate





Summary

1. Strengthening is a process to harden the material.
2. The restriction to the dislocation movement strengthen the material. As they interfere with their own field.
3. As the dislocation density increases, the stress to move dislocation increases.
4. Yield strength increases as the grain size decreases.
5. Larger the solute and solvent size difference, greater the hardening effect.
6. Precipitate strengthening is more when the particle spacing is small.