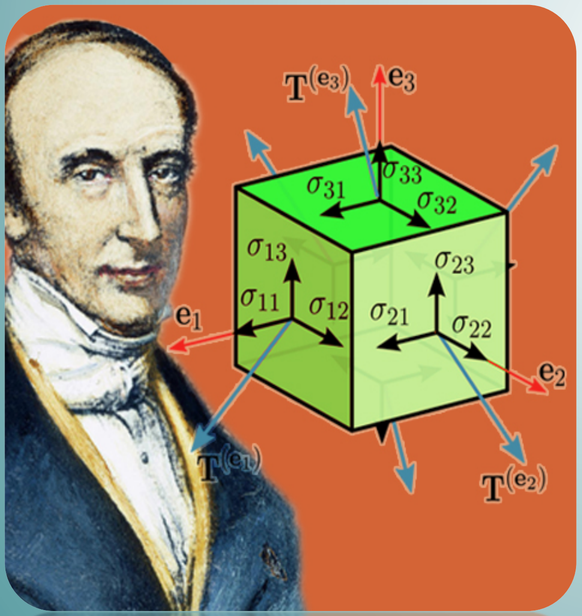
Mechanical Properties of Materials, Processing and Design

Topic 2. Plastic behaviour



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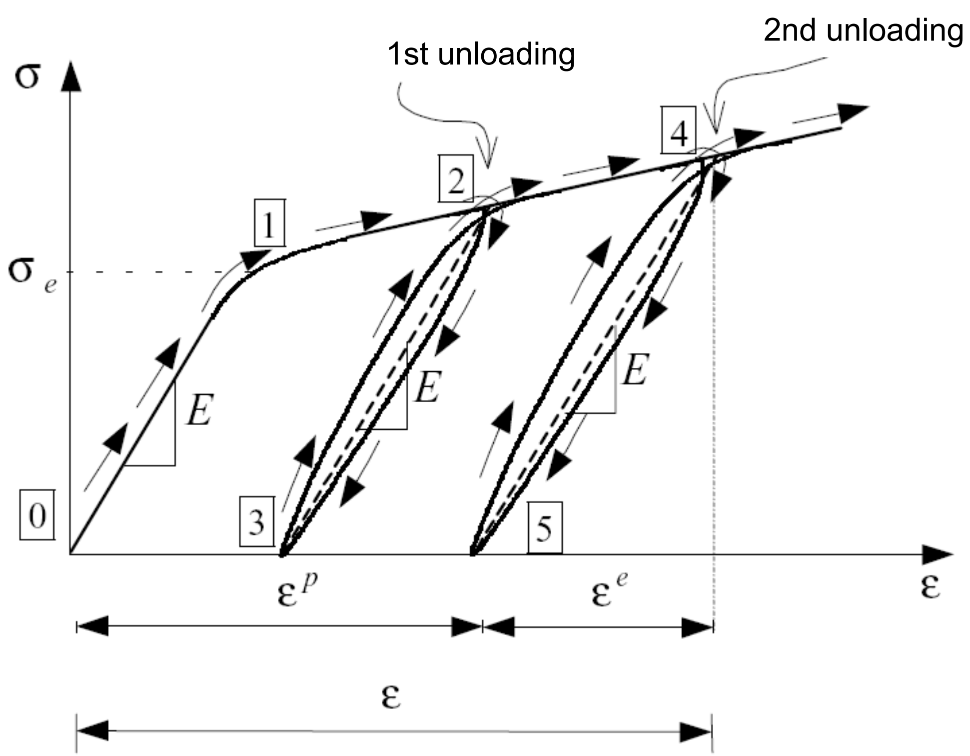
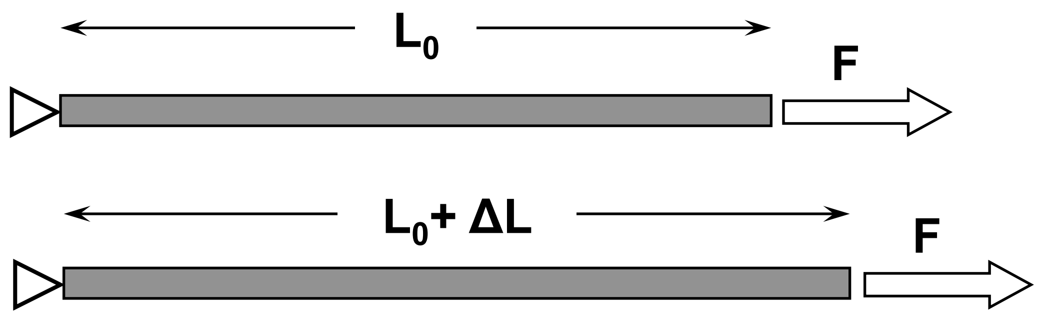
2.1. INTRODUCTION

PLASTICITY: implies **two changes** compared to elastic-linear behavior:

- **Loss on linearity** (stress is no longer proportional to strain).
- **Plastic / permanent deformations** occur.



2.2. TENSILE TEST



- Primary variables: Force (**F**) and elongation (**ΔL**).
- Derived variables: stress and strain.

Engineering variables → **True variables**

$$s = \frac{F}{A_0} \qquad e = \frac{\Delta L}{L_0}$$

$$\sigma = s(1+e)$$

$$\varepsilon = \ln(1+e)$$

$$\sigma > s$$

$$\varepsilon < e$$

$$\sigma = \frac{F}{A} \qquad d\varepsilon = \frac{dL}{L}$$

2.2. TENSILE TEST

Suggested exercises:

1) Demonstrate the expression relating the true strain with the engineering variables.

$$d\varepsilon = \frac{dL}{L} \quad \Rightarrow \quad \varepsilon = \int_0^{\varepsilon} d\varepsilon = \int_{L_0}^{L} \frac{dL}{L} = \ln\left(\frac{L}{L_0}\right) = \ln\left(\frac{L_0 + \Delta L}{L_0}\right) = \ln(1+e)$$

2) Demonstrate the expression relating the true stress with the engineering variables. Suppose that the volume of the specimen remains constant during the deformation process.

$$\left.\begin{aligned} &\sigma = \frac{F}{A} = \frac{F}{A_0}\frac{A_0}{A} = s\,\frac{A_0}{A} \\ &A_0 L_0 = A\,L \quad \Rightarrow \quad \frac{A_0}{A} = \frac{L}{L_0} = 1 + e \end{aligned}\right\} \quad \sigma = s\,(1+e)$$

2.2. TENSILE TEST

Suggested exercises:

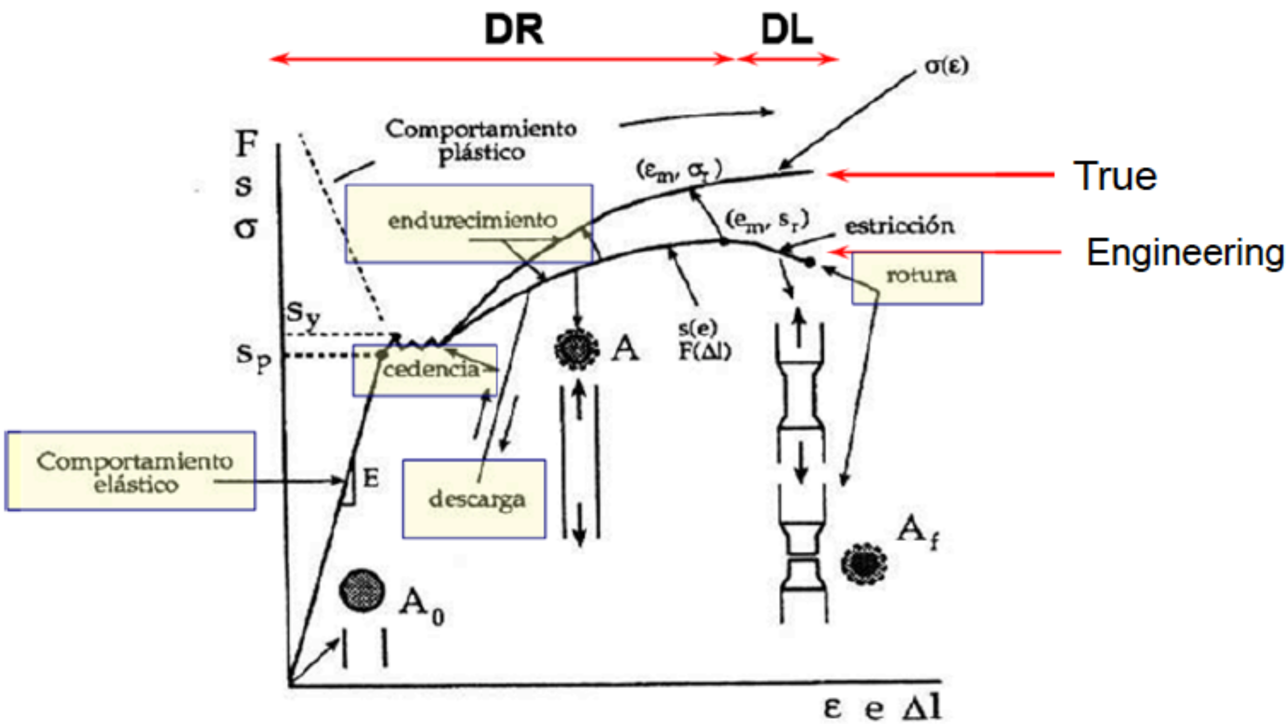
3) Demonstrate that true strains are smaller than engineering ones and that the opposite happens with stresses.

$$\left\{ \begin{array}{l} \sigma = \dfrac{F}{A} \\ A < A_0 \end{array} \right\} \Rightarrow \quad s = \frac{F}{A_0} < \sigma$$

$$\left\{ \begin{array}{l} d\varepsilon = \dfrac{dL}{L} \\ L > L_0 \end{array} \right\} \Rightarrow \quad e = \frac{\Delta L}{L_0} \quad de = \frac{dL}{L_0} > d\varepsilon$$

2.2. TENSILE TEST

- Typical tensile testing curve (with engineering and true variables) on a material with a yield plateau.



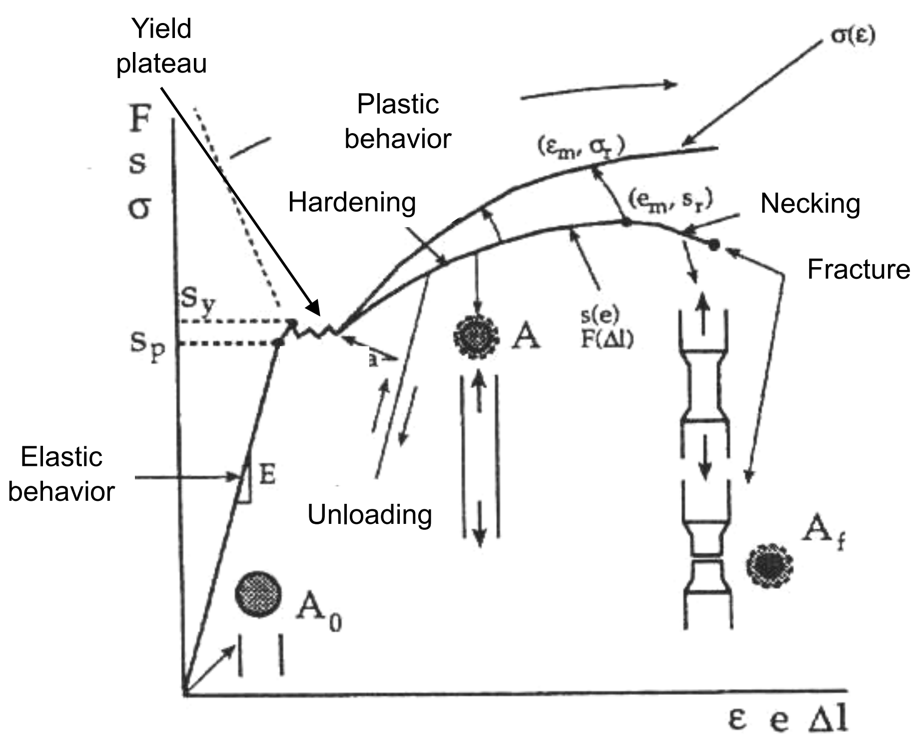
- **VÍDEOS**:

http://www.youtube.com/watch?v=I28m4FZzqro&feature=related

2.2. TENSILE TEST

Strength parameters:

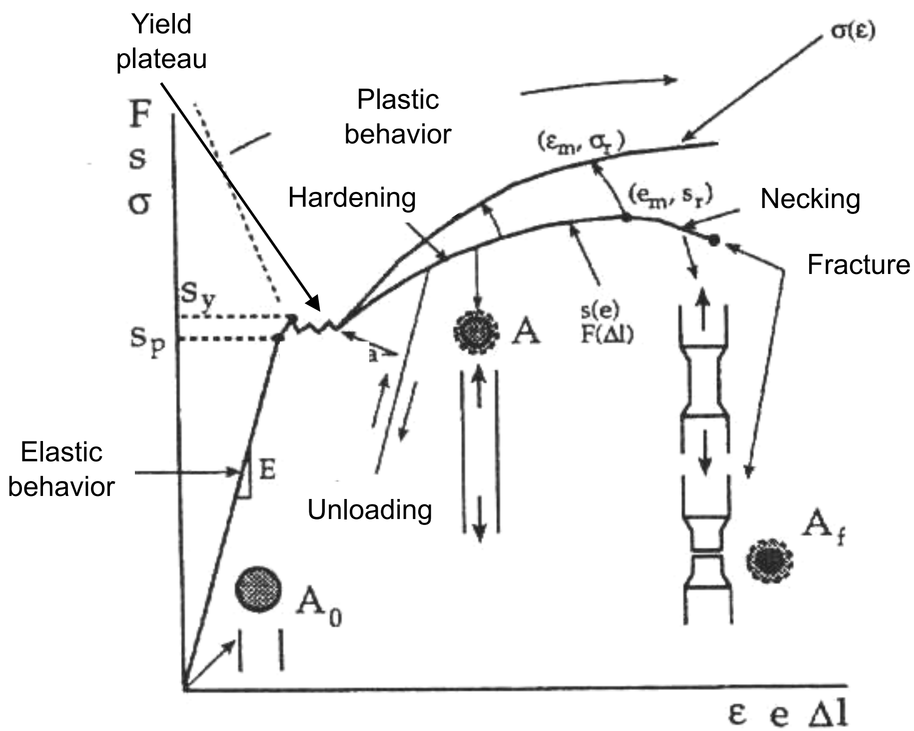
- Proportional limit stress: s_p
- Elastic limit stress / Yield stress: s_Y
- Tensile stregth: s_R



2.2. TENSILE TEST

Ductility parametres:

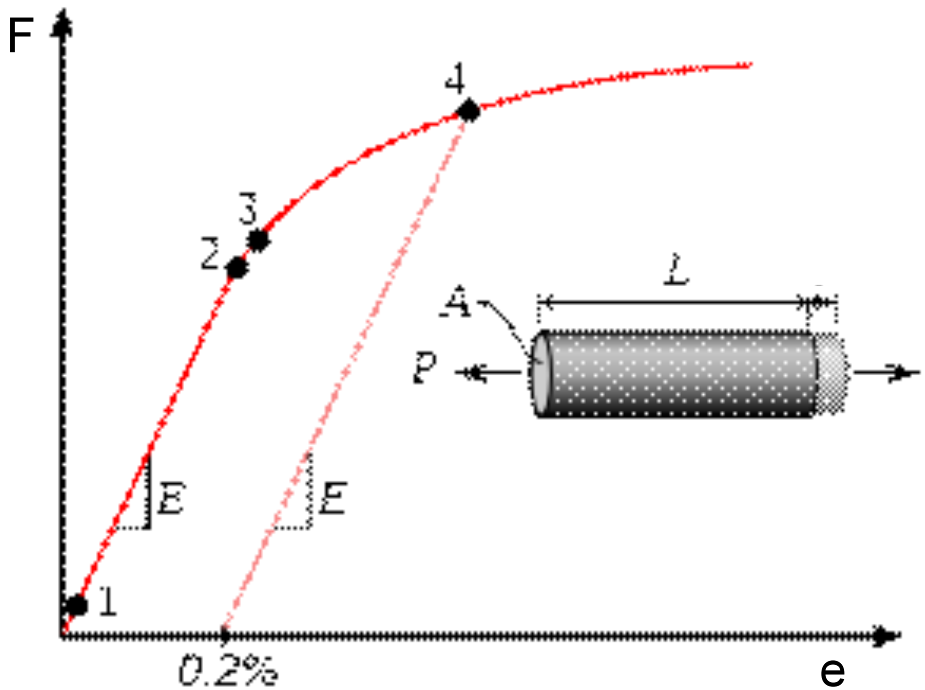
- Strain under maximum stress: e_m
- Elongation or lengthening at fracture: Δl_{frac}
- Area reduction: $RA = \dfrac{A_0 - A_f}{A_0}$



2.2. TENSILE TEST

Proof stress / engineering yield stress:

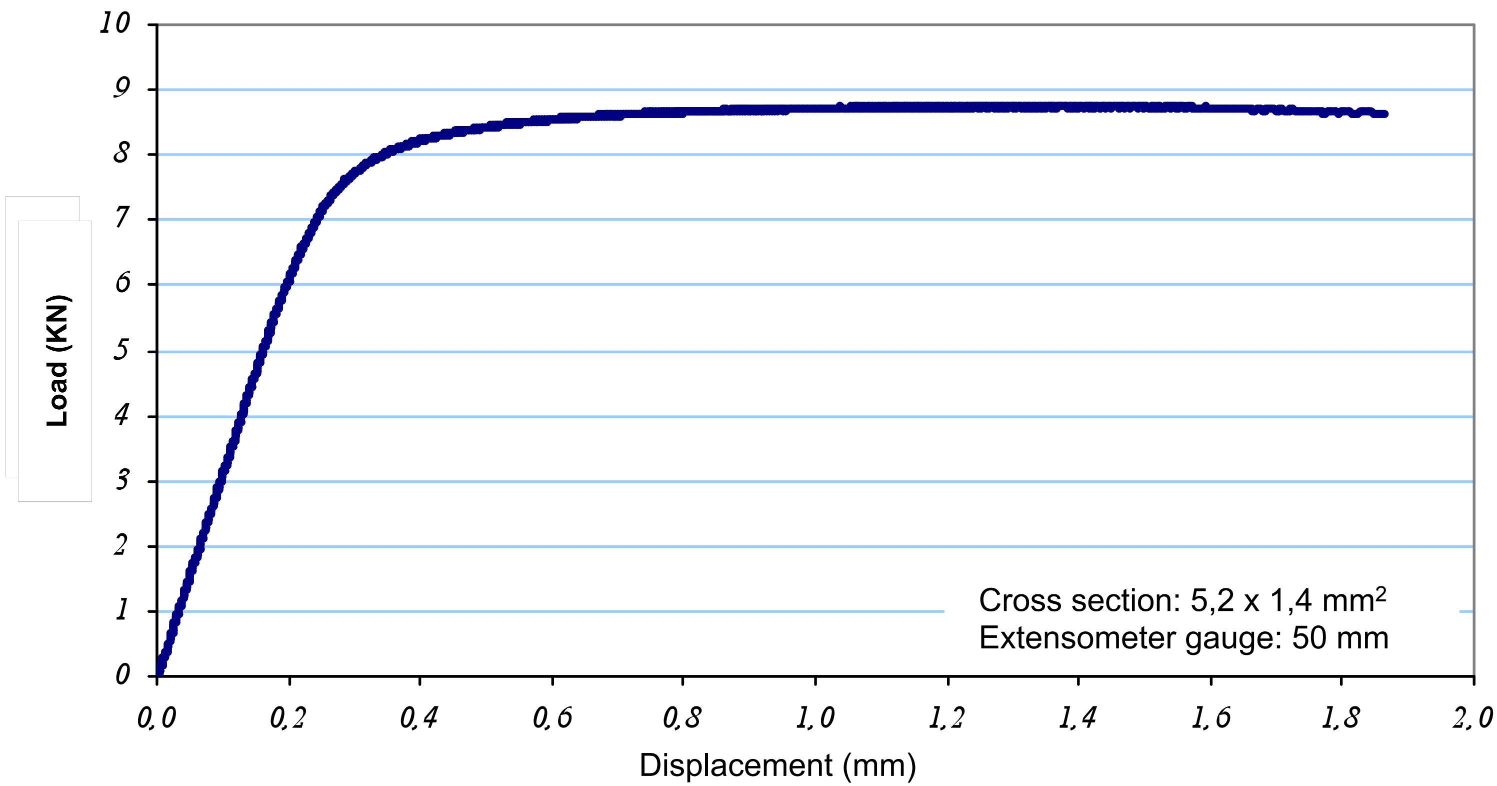
- Materials with continuous hardening.
- Definition: stress corresponding to a plastic strain of 0.2%.



2.2. TENSILE TEST

Suggested exercises:

In the following graph, the force-displacement data of a tensile test of a high-strength steel can be seen. As shown in the figure, it was measured with a 50 mm gauge extensometer, with a rectangular cross section of 5.2 x 1.4 mm^2.



2.2. TENSILE TEST

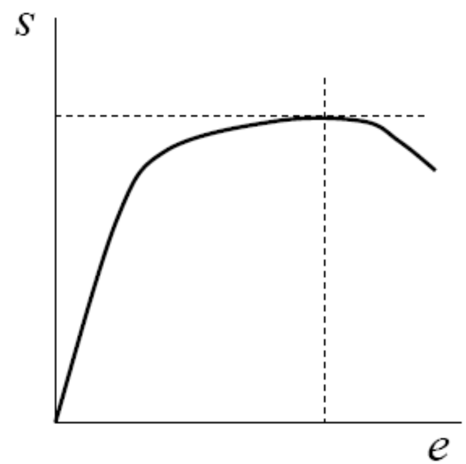
Suggested exercises:

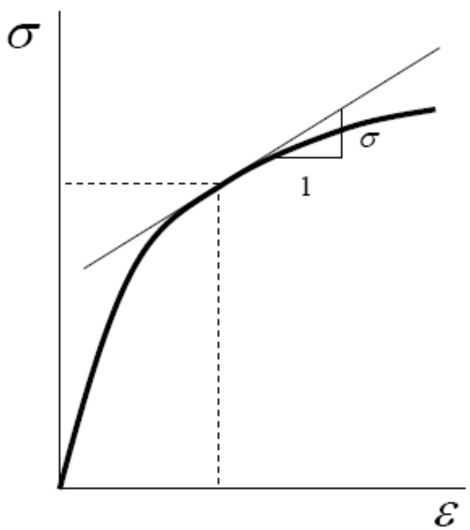
With the previously given information, answer to the following questions:

- Calculate the resistant parameters of the steel: Young's modulus, yield stress, tensile strength and strain for the ultimate tensile strength.
- Obtain the permanent elongation for the following forces: 6, 7, 8 y 8.5 kN.
- What is the force and the elongation for a load s = 1100 MPa?
- Determine the maximum load for a strip steel made out of the same steel but with a cross section of 10 x 2 mm^2.

2.2. TENSILE TEST

Ultimate tensile strength:





$$dF = 0 \quad \Rightarrow \quad d(\sigma A) = \sigma\, dA + d\sigma\, A = 0 \quad \Rightarrow$$

$$\Rightarrow \quad \frac{d\sigma}{\sigma} = -\frac{dA}{A}$$

- We will assume conservation of volume (this statement is approximately true in the plastic regime):

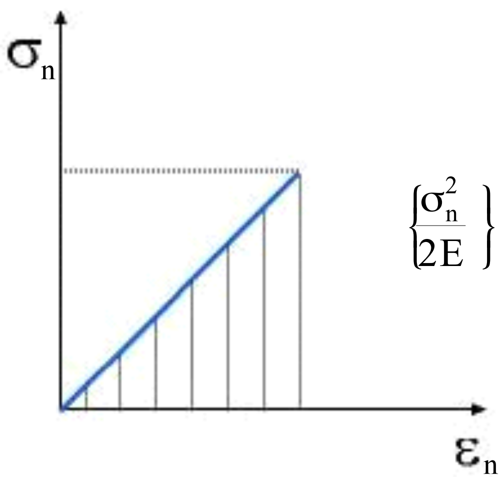
$$d(AL) = A\,dL + dA\,L = 0 \quad \Rightarrow \quad \frac{dL}{L} = -\frac{dA}{A}$$

$$\frac{dL}{L} = d\varepsilon = \frac{d\sigma}{\sigma} \quad \Rightarrow \quad \frac{d\sigma}{d\varepsilon} = \sigma$$

2.2. TENSILE TEST

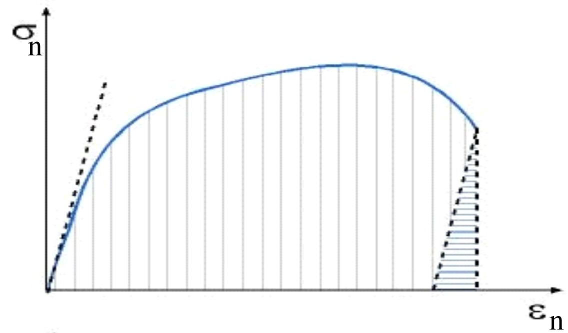
ENERGETIC ASPECTS:

Elastic regime



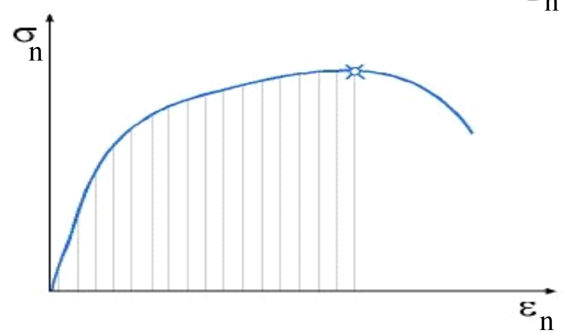
$$\left\{\frac{\sigma_n^2}{2E}\right\}$$

Plastic regime

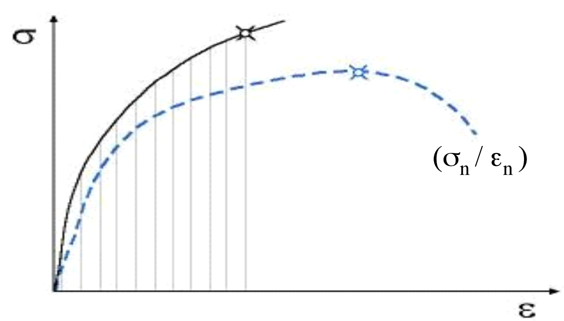


Required energy to generate a plastic deformation in the fracture point.

Elastic energy released at fracture point.



Total amount of energy (elastic and plastic) required to start the necking process.



Work done per unit volume:

$$U = U^{pl} + U^{e} =$$

$$= \int_0^{\varepsilon_n} \sigma_n d\varepsilon_n = \int_0^{\varepsilon} \sigma d\varepsilon$$

2.3. PLASTIC BEHAVIOR MODELS

BAUSCHINGER EFFECT / KINEMATIC HARDENING:

- Iso-resistent materials show the same response under compression or tension; therefore, the stress-strain curve is symmetric about the origin of the representation. Thus, the yield stress is the same for tension or compression.
- Suppose that a compression test is performed on a specimen previously subjected to a tensile test up to a stress σ_f beyond its yield stress σ_e. Therefore, σ_f is the new tensile yield stress.
- If the material response were symmetric, σ_f should be the new yield stress for compression. Nevertheless, in general, this is not the case.
- In many materials an increase in tensile yield strength occurs at the expense of compressive yield strength. The effect is named Bauschinger effect after German engineer Johann Bauschinger. It is known as well as kinematic hardening.
- Other materials show an iso-resistent response even when they were subjected to stress over their yield stress. They are said to show isotropic hardening.

2.3. PLASTIC BEHAVIOR MODELS

BAUSCHINGER EFFECT:

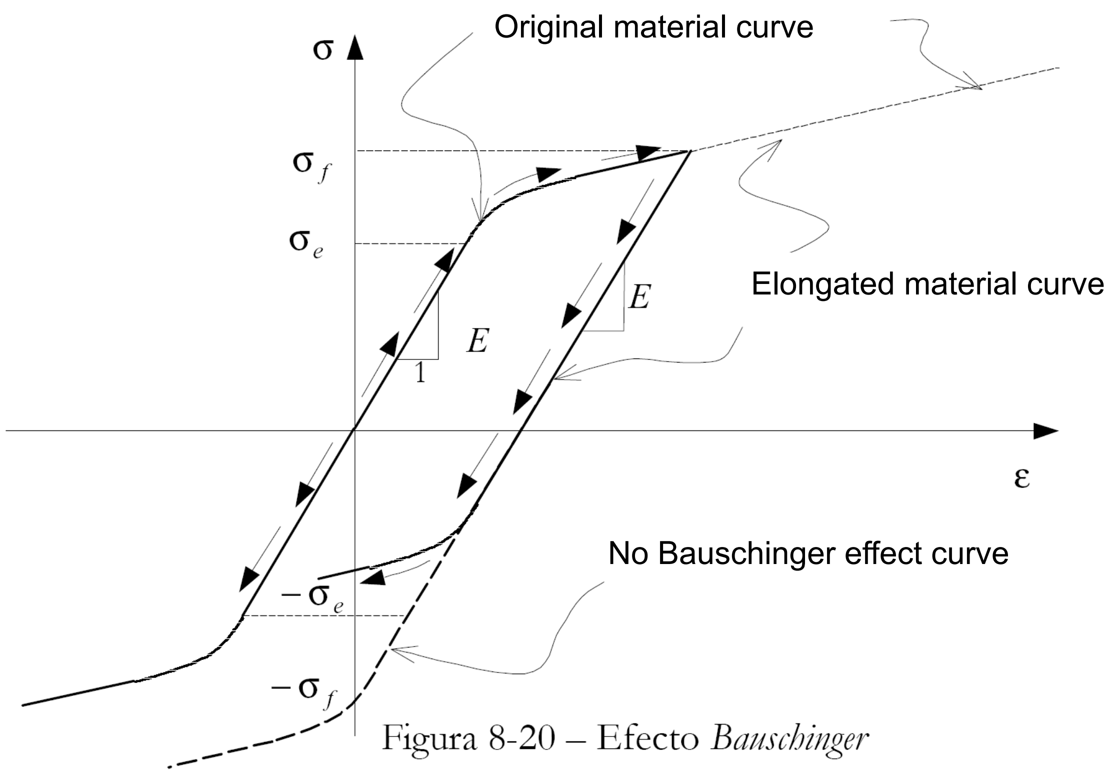
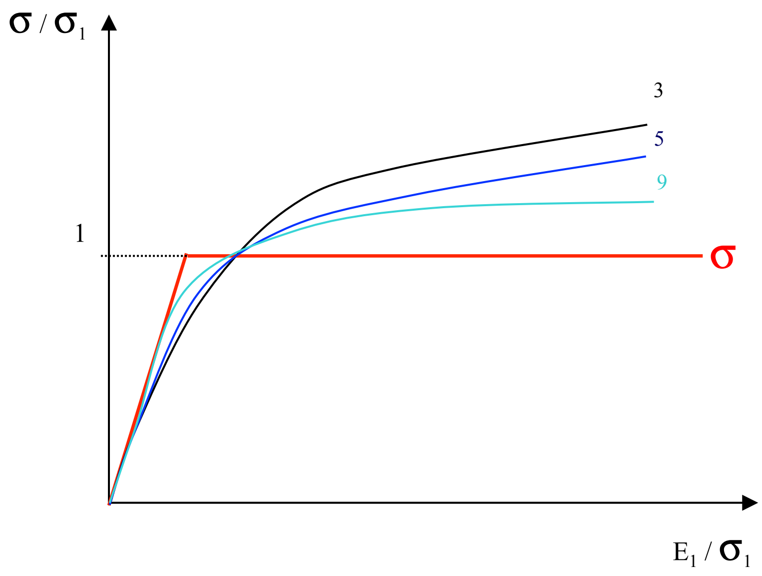


Figura 8-20 – Efecto *Bauschinger*

2.3. PLASTIC BEHAVIOR MODELS

NON-LINEAR HARDENING MODELS:



Ramberg – Osgood's equation

$$\varepsilon = \varepsilon^{e} + \varepsilon^{p} = \frac{\sigma}{E} + \left(\frac{\sigma}{C}\right)^{m}$$

Hollomon's equation

$$\sigma = K \cdot \varepsilon_{p}^{\ n}$$

2.3. PLASTIC BEHAVIOR MODELS

Suggested exercises:

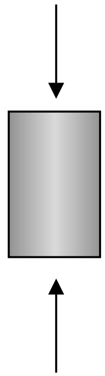
1) Demonstrate the mathematical equivalence between Ramberg-Osgood and Hollomon models, obtaining the relationship between their constituti-ve parameters.

2) By applying the maximum load condition on Hollomon's model, determine the physical meaning of the parameter 'n'.

2.4. OTHER CHARACTERIZATION TESTS

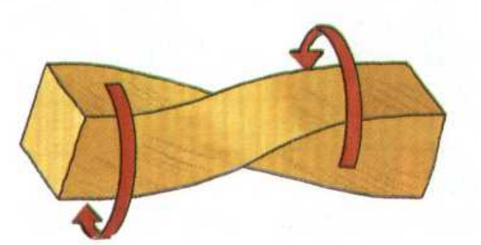
- Tensile test is, usually, the most important test for characterization of mechanical properties.
- There are other specific possibilities, such as:

Compression



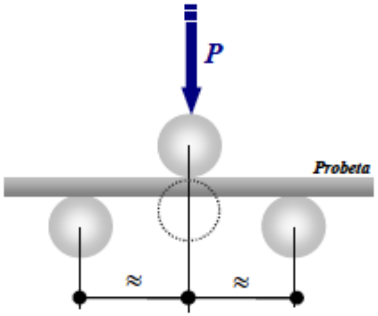
(Concrete)

Torsion

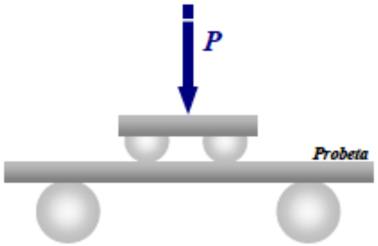


Bending tests

3 points



4 points



2.4. OTHER CHARACTERIZATION TESTS

- Compression test on concrete:

  http://www.youtube.com/watch?v=dtvm7YNsSU0

- 3 points bending test:

  http://www.youtube.com/watch?v=zeyqcPiUFPs&feature=related

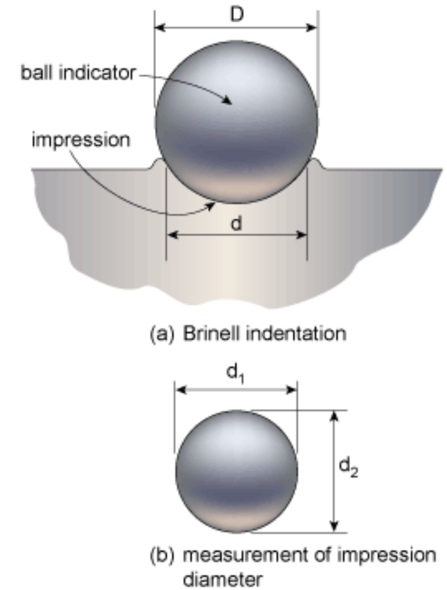
2.4. OTHER CHARACTERIZATION TESTS

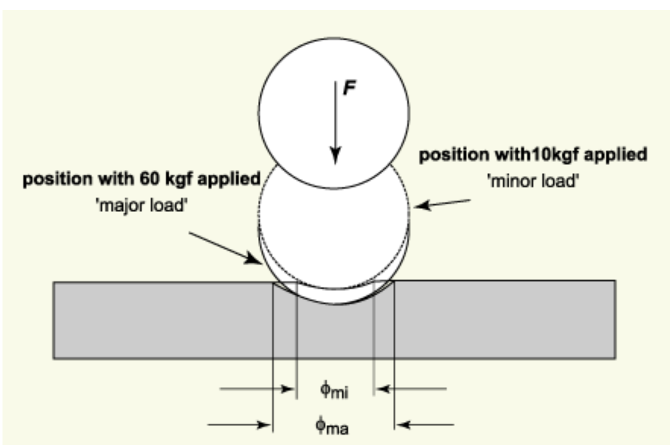
HARDNESS:

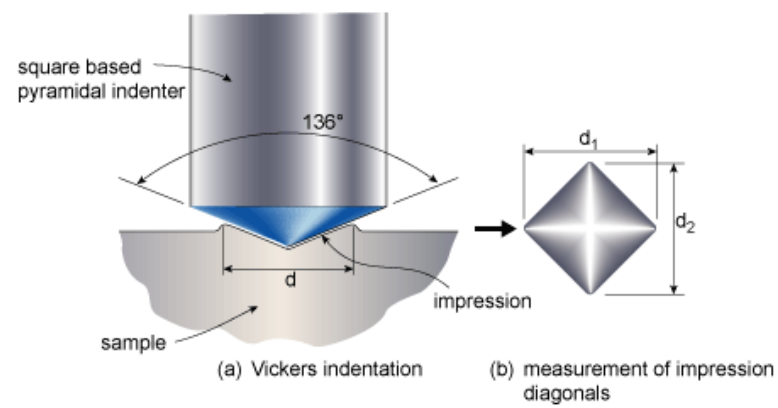
- **Hardness** is the opposition offered by materials to penetration, abrasion, scratching, cutting, permanent deformation, etc.
- In metallurgy hardness is measured using a durometer for the penetration test (**indentation hardness**). Depending on the kind of tip used and the range of loads applied, there are **different scales**, suitable for different ranges of hardness.
- The interest of the determination of the hardness in steels lies in:
  - It is a simple and inexpensive test.
  - It is a non-destructive technique (NDT).
  - Allows to correlate other properties, such as tensile strength.

2.4. OTHER CHARACTERIZATION TESTS

HARDNESS:

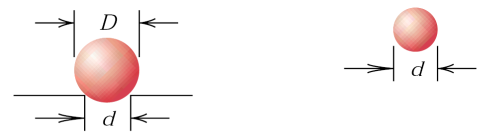
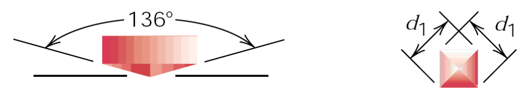
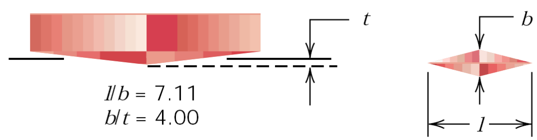
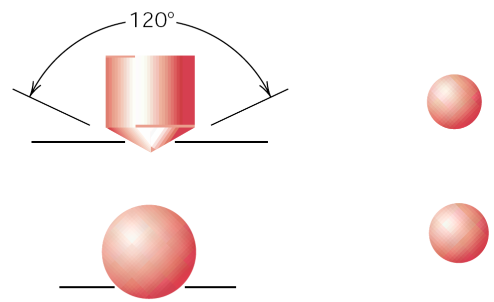






2.4. OTHER CHARACTERIZATION TESTS

HARDNESS:

Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$ in. diameter steel spheres			60 kg, 100 kg, 150 kg: Rockwell; 15 kg, 30 kg, 45 kg: Superficial Rockwell	

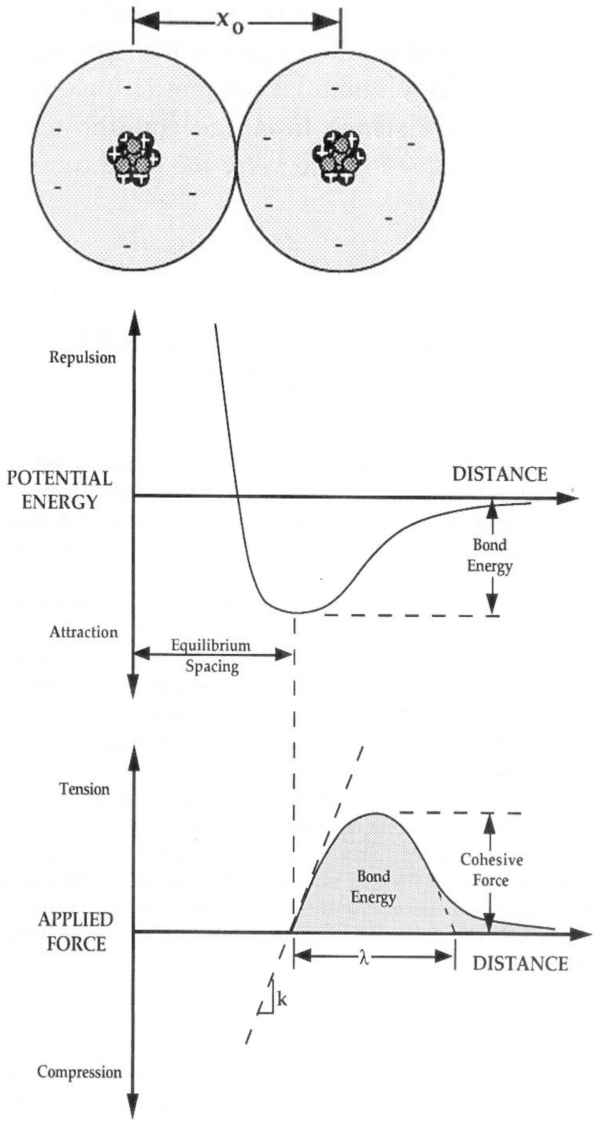
[a] For the hardness formulas given, P (the applied load) is in kg, while D, d, d_1, and l are all in mm.

Source: Adapted from H. W. Hayden, W. G. Moffatt, and J. Wulff, *The Structure and Properties of Materials,* Vol. III, *Mechanical Behavior.* Copyright © 1965 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

2.5. INFLUENCE OF DEFECTS

- The **elastic behavior** is a consequence (Lesson 1) of the microstructural nature of materials and the atomic bond stiffness.
- Is it possible to justify the plastic response of materials from these same principles?
- As will be seen afterwards, a naive estimate of the elastic limit from the same principles grossly overestimates its value. **It is necessary to have some additional ingredients.**
- **Real crystals have defects (dislocations)** that move easily within the crystal. The stress needed to activate the movement of dislocations is the elastic limit of the material. Aggregated strain, that comes from a large number of dislocations, lead to a macroscopic deformation of solids.
- **Dislocations are, therefore, carriers of the plastic deformation.**

2.5. INFLUENCE OF DEFECTS



Fracture implies breaking atomic bonds (monocrystal).

$$E = \frac{k}{x_0} = \frac{F_c \frac{\pi}{\lambda}}{x_0} = \frac{F_c}{x_0^2}\frac{\pi x_0}{\lambda} = \sigma_c \frac{\pi x_0}{\lambda}$$

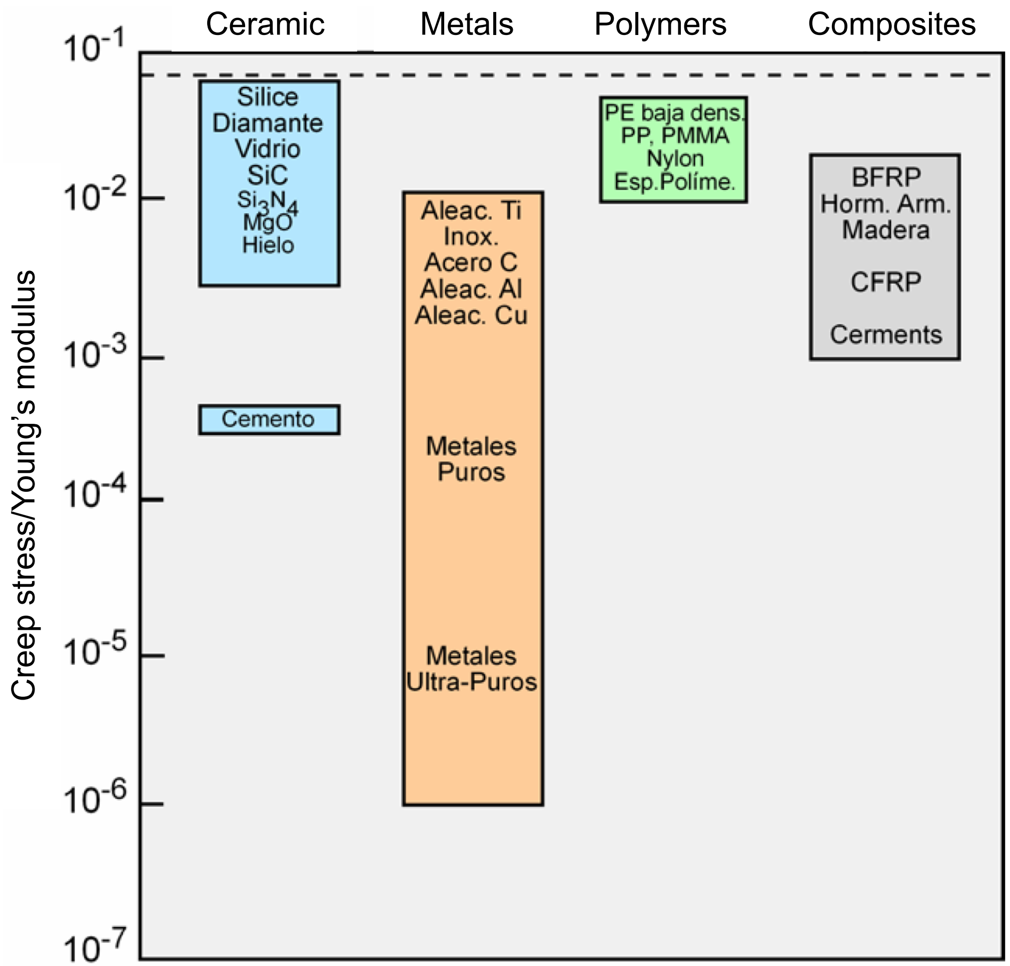
$$\sigma_c = \frac{E\lambda}{\pi x_0} \Rightarrow \left[\frac{\lambda}{x_0} \approx \frac{1}{5}\right] \Rightarrow \sigma_c \approx \frac{E}{15}$$

$$\sigma_c = \frac{E\lambda}{\pi x_0} \Rightarrow \left[\frac{\lambda}{x_0} \approx \frac{1}{5}\right] \Rightarrow \sigma_c \approx \frac{E}{15}$$

Is this result applicable to reality?

2.5. INFLUENCE OF DEFECTS

- The chart shows different values of s_Y/E by families of materials, along with the theoretical limit (1/15).
- Glass and ceramic materials are close to that theoretical limit, as well as polymers.
- All metals are far from that theoretical limit (up to 5 orders of magnitude).
- **What's the reason for that?**



2.5. INFLUENCE OF DEFECTS

CLASSIFICATION OF DEFECTS IN CRYSTALLINE MATERIALS:

IDEAL CRYSTAL:

Spatial arrangement of an object (subject) in accordance with a pattern (the network) that repeats indefinitely ordered in space.

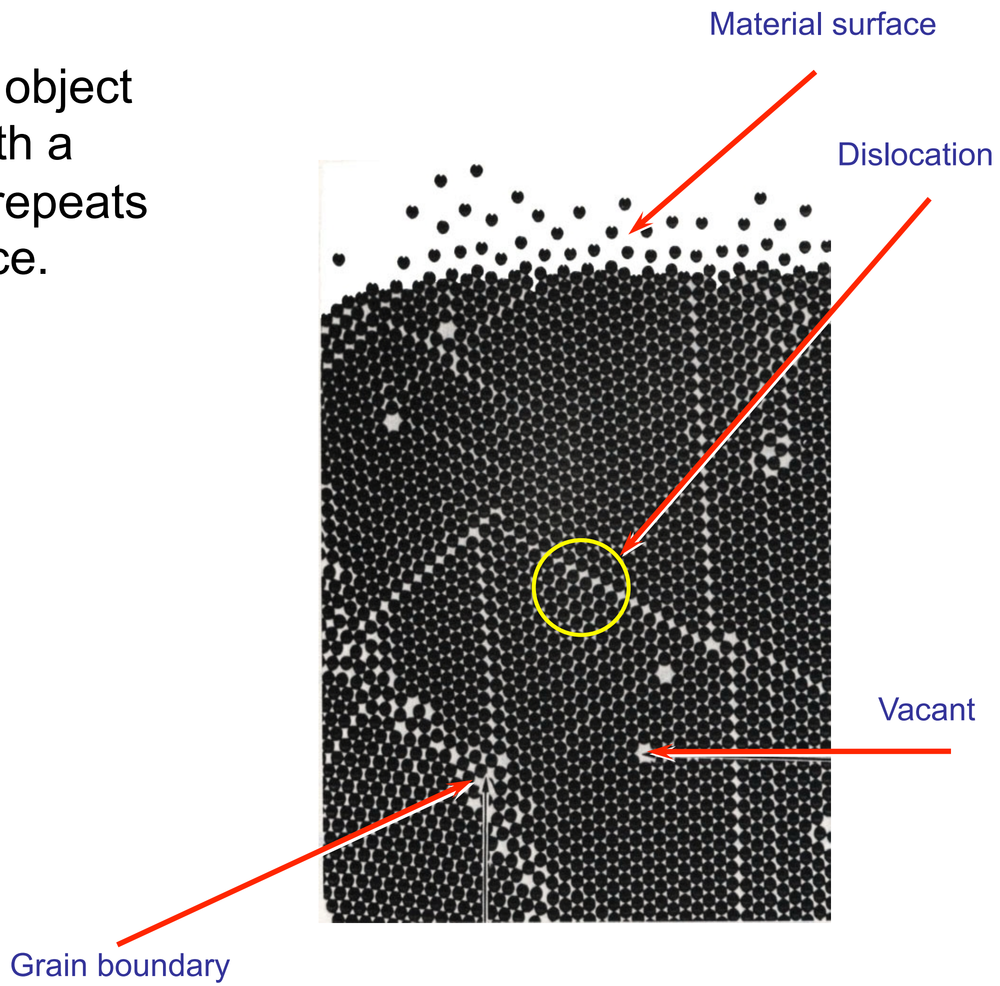
TYPES OF DEFECTS:

a) Point defects.

b) Linear defects.

c) Planar defects.

d) Bulk defects.



2.5. INFLUENCE OF DEFECTS

CLASSIFICATION OF DEFECTS IN CRYSTALLINE MATERIALS:

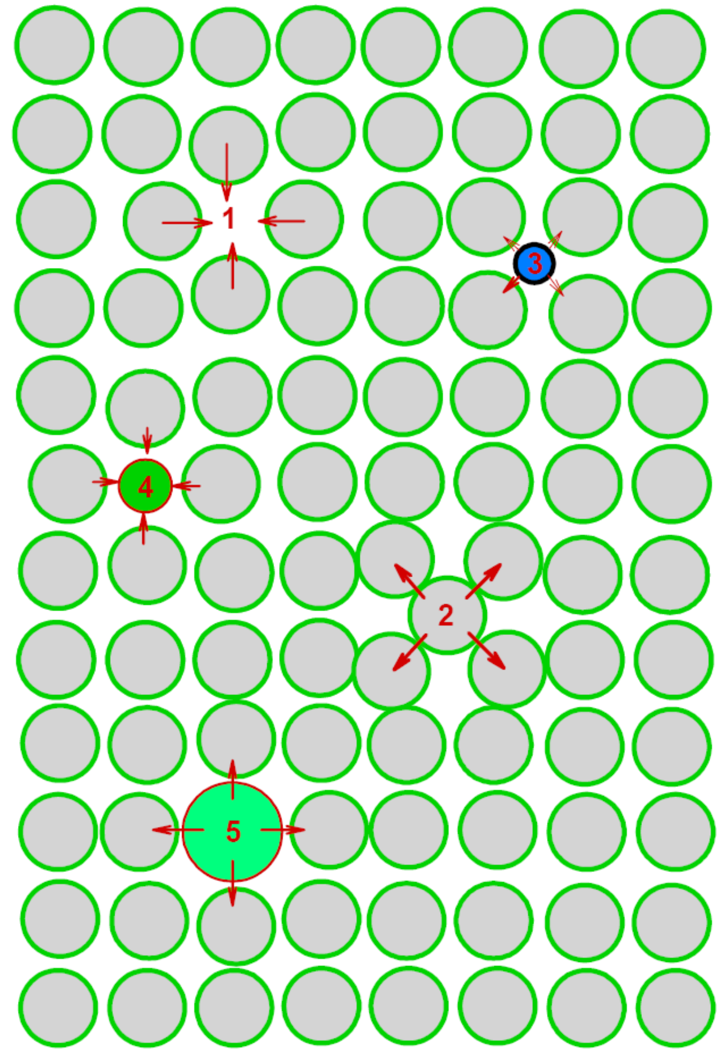
a) POINT DEFECTS:

a.1) Void.

a.2) Autointerstitial atom.

a.3) Interstitial impurity.

a.4 y a.5) Substitutional impurity.

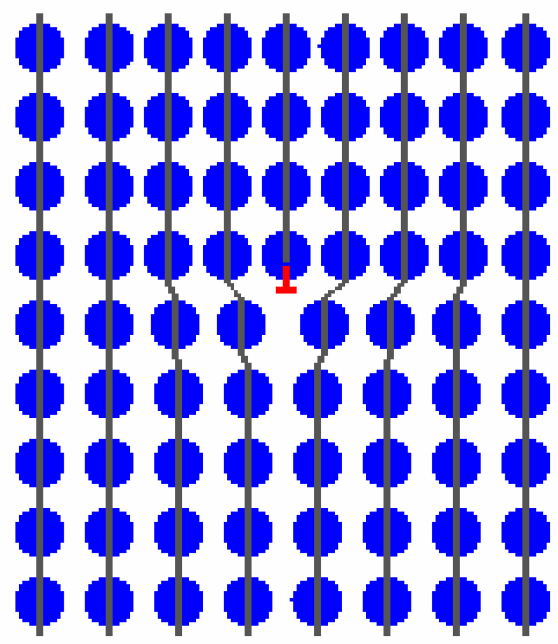


2.5. INFLUENCE OF DEFECTS

CLASSIFICATION OF DEFECTS IN CRYSTALLINE MATERIALS:

b) LINEAR DEFECTS:

- **Dislocation:** imperfection in a crystal lattice that is characterized by the existence of an additional atomic plane in the crystal network; it produces a displacement of the atoms that are in the area where the extra plane ends (while the rest of the crystal's atoms hardly experiment a change).

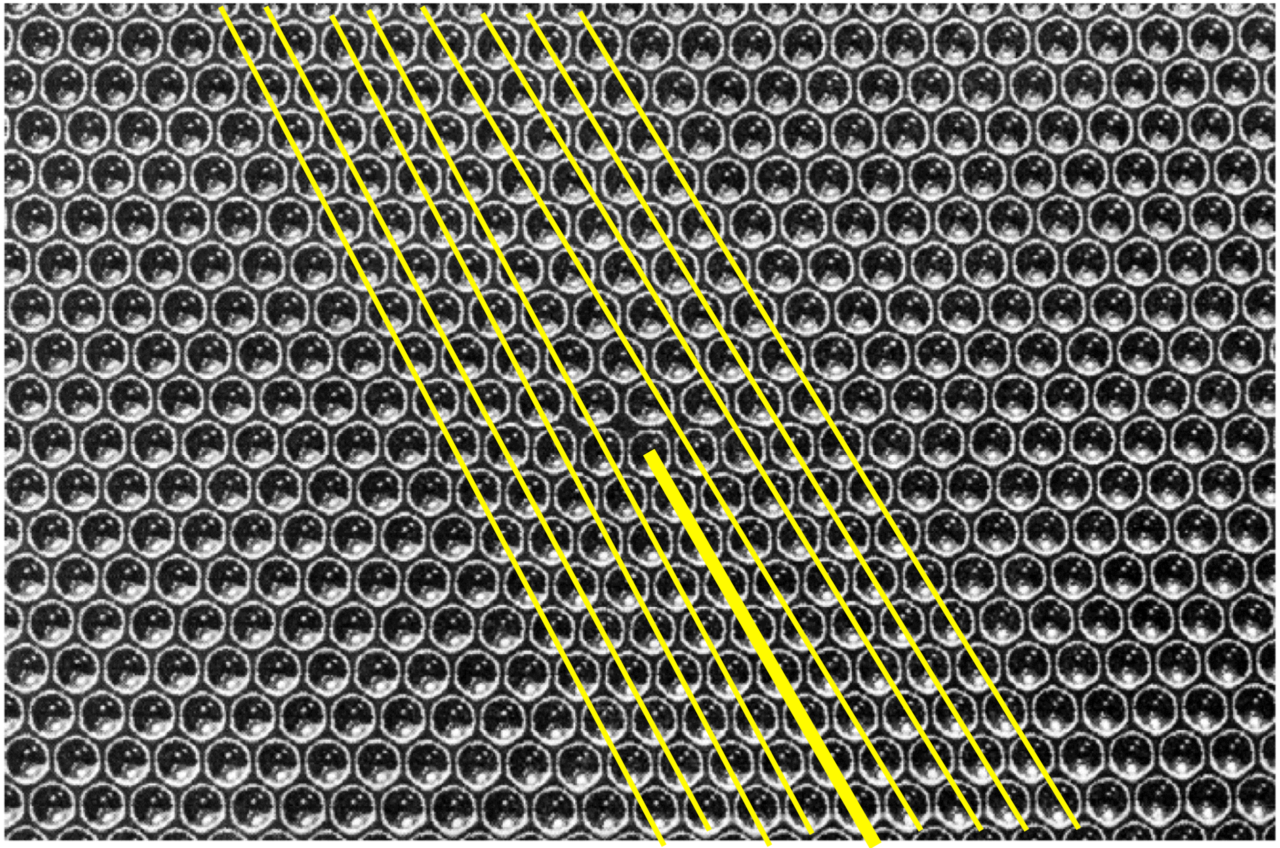


2.5. INFLUENCE OF DEFECTS

CLASSIFICATION OF DEFECTS IN CRYSTALLINE MATERIALS:

b) LINEAR DEFECTS:

Suggested exercise: locate the dislocation present in this 2D network.

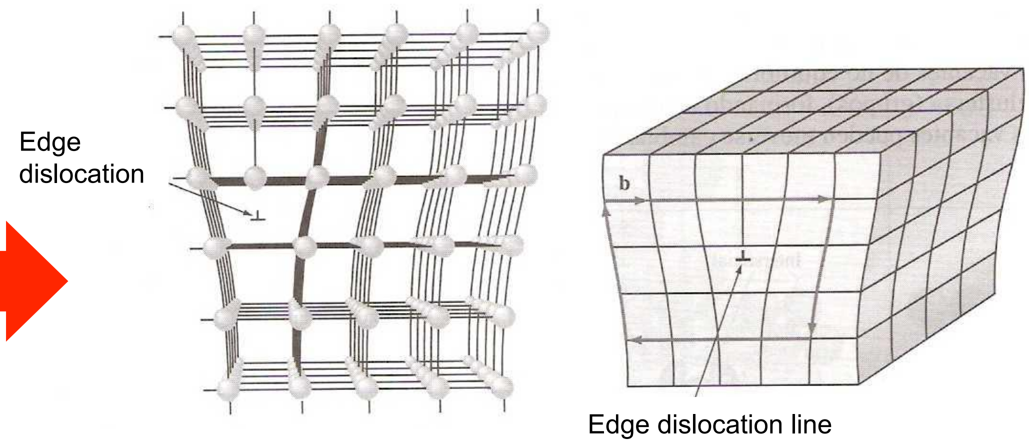


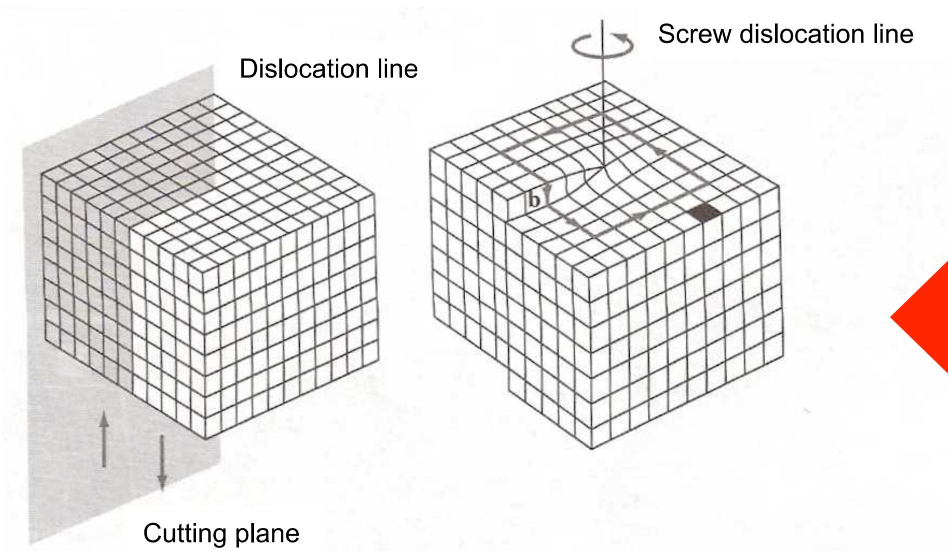
2.5. INFLUENCE OF DEFECTS

CLASSIFICATION OF DEFECTS IN CRYSTALLINE MATERIALS:

b) LINEAR DEFECTS:

Edge dislocation / wedge



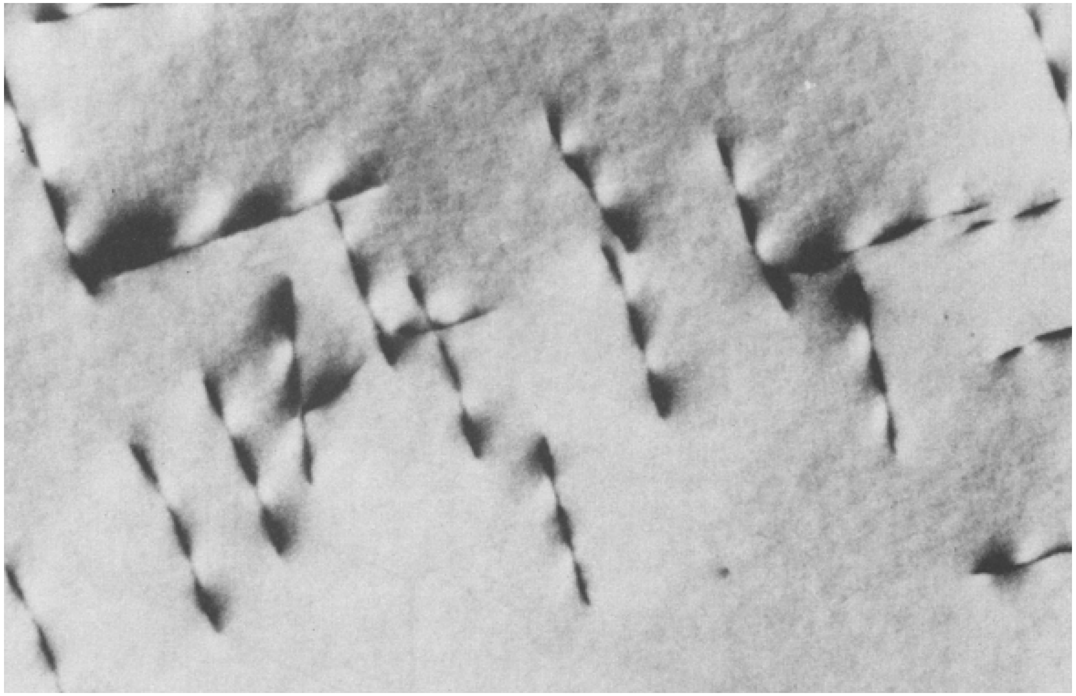


Helicoidal / screw dislocation

2.5. INFLUENCE OF DEFECTS

CLASSIFICATION OF DEFECTS IN CRYSTALLINE MATERIALS:

b) LINEAR DEFECTS:



- **TEM MICROSCOPY:** dislocations present in a stainless steel sheet of 100 nm thick. Dislocation lines present in the micrograph have an approximate length of 1000 atomic diameters. The picture size is approximately 1000 x 1500 nm.

2.5. INFLUENCE OF DEFECTS

CLASSIFICATION OF DEFECTS IN CRYSTALLINE MATERIALS:

c) PLANAR DEFECTS: GRAIN BOUNDARIES

- Separation boundaries between the different crystals constituting a polycrystalline material; each region has the same crystalline structure, but a different orientation.

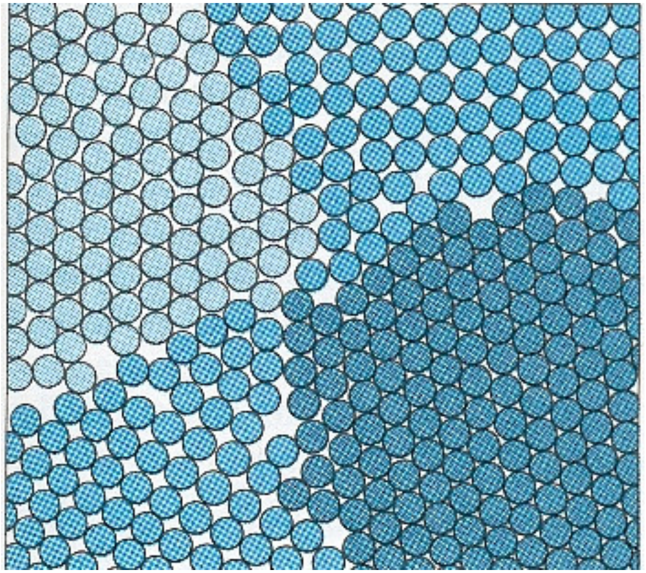
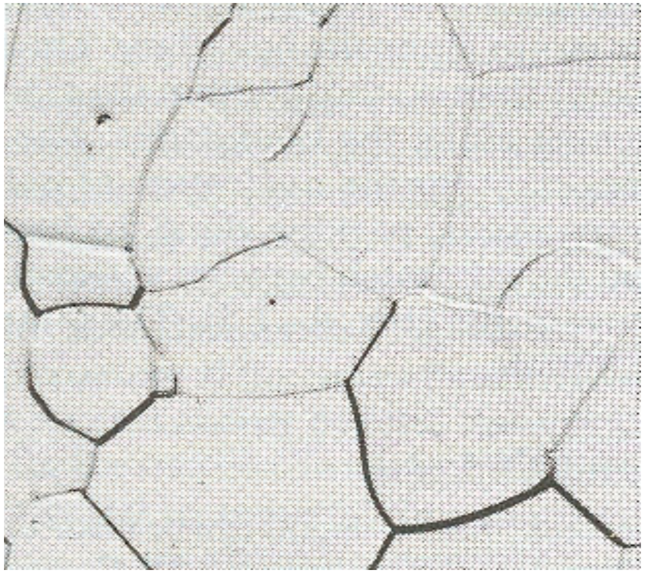


Diagram showing the arrangement of the atoms in the formation of grain boundaries.



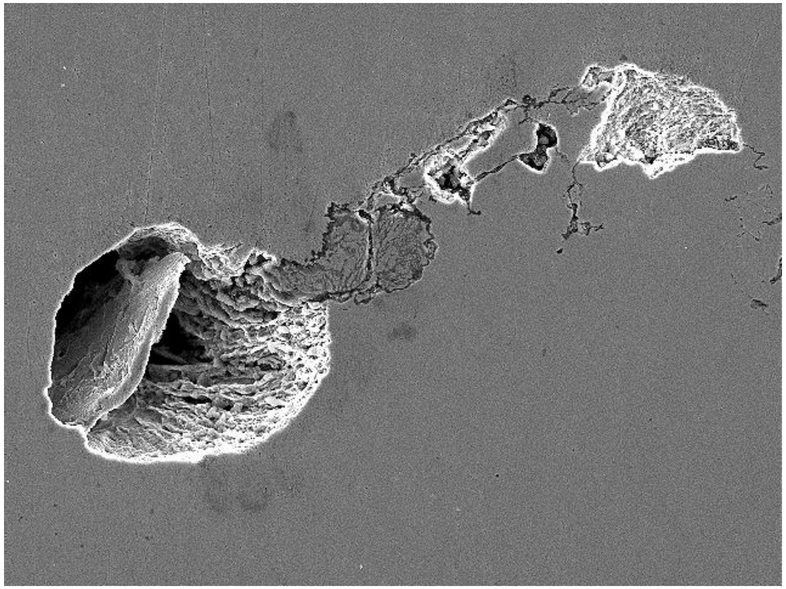
Grains and grain boundary in a sample of stainless steel.

2.5. INFLUENCE OF DEFECTS

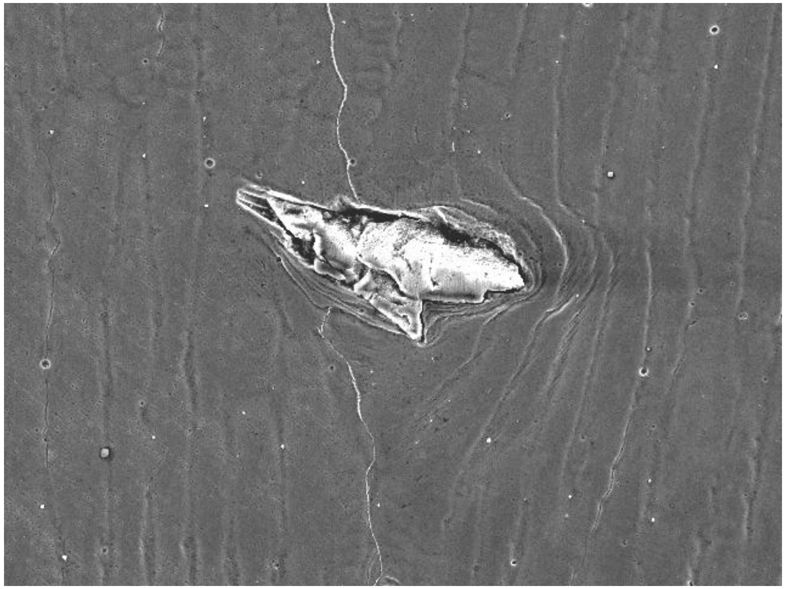
CLASSIFICATION OF DEFECTS IN CRYSTALLINE MATERIALS:

d) BULK DEFECTS:

¡THEY ARE NOT EXACTLY DEFECTS IN THE CRYSTAL LATTICE!



Porosity



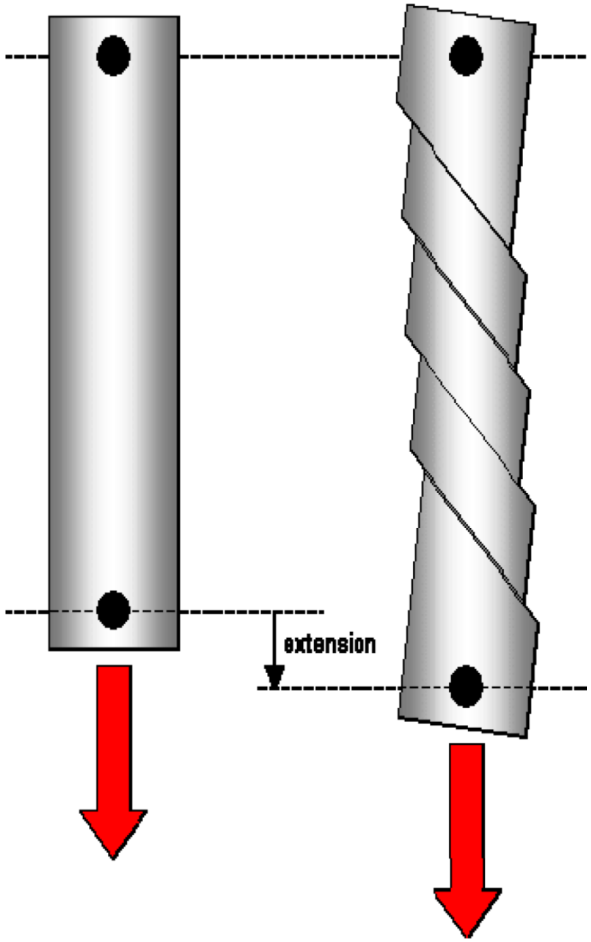
Inclusion

2.5. INFLUENCE OF DEFECTS

IMPORTANCE OF DISLOCATIONS:

- (Plastic) deformation is a consequence of glides in approximately parallel crystal planes.
- Generally, sliding/slip planes are compact planes (for example, {111} for a FCC crystal).
- For a particular sliding plane there are certain preferential gliding directions called "slip directions". Slip directions correspond to the most compact directions of the crystal (for example, directions <110> in a FCC crystal).

TENSILE TEST IN A MONOCRYSTAL

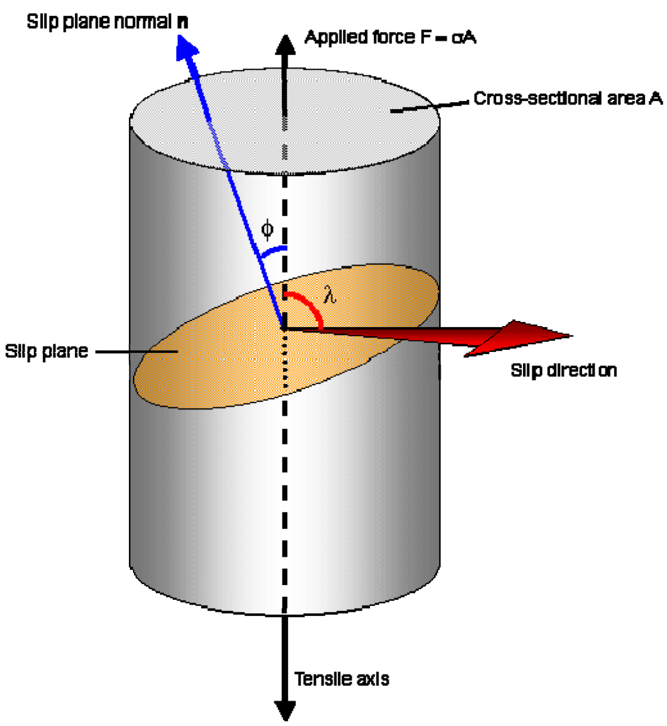


2.5. INFLUENCE OF DEFECTS

IMPORTANCE OF DISLOCATIONS:

SCHMID'S LAW:

- A force F is applied with an angle λ with respect to a certain slip direction.
- The effective shear stress along that given slip direction is only due to the F·cosλ component.
- The actual sample section in which F · cosλ is acting is A / cosφ.
- Shear stress along that given direction and sliding condition:



$$\tau_R = \frac{F}{A}\cos\phi \; \cos\lambda \quad \Rightarrow \quad \boxed{\tau_R = \sigma\cos\phi\cos\lambda \geq \tau_C}$$

2.5. INFLUENCE OF DEFECTS

IMPORTANCE OF DISLOCATIONS:

SCHMID'S LAW: SLIDING SYSTEMS

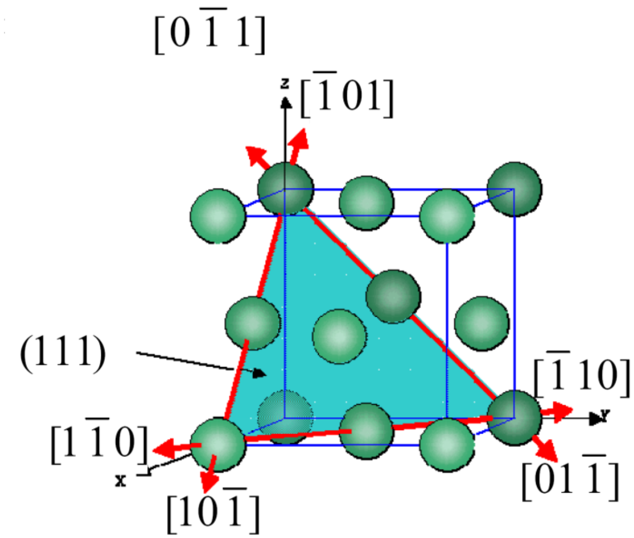
- A **sliding system** is defined by a slip plane and a slip direction.

Tabla 7.1 Sistemas de deslizamiento para los metales cúbicos centrados en las caras, cúbicos centrados en el cuerpo, y hexagonales compactos

Metales	*Plano de deslizamiento*	*Dirección de deslizamiento*	*Número de sistemas de deslizamiento*
	Cúbico centrado en las caras		
Cu, Al, Ni, Ag, Au	{111}	$\langle 1\bar{1}0\rangle$	12
	Cúbico centrado en el cuerpo		
Fe-α, W, Mo	{110}	$\langle \bar{1}11\rangle$	12
Fe-α, W	{211}	$\langle \bar{1}11\rangle$	12
Fe-α, K	{321}	$\langle \bar{1}11\rangle$	24
	Hexagonal compacto		
Cd, Zn, Mg, Ti, Be	{0001}	$\langle 11\bar{2}0\rangle$	3
Ti, Mg, Zr	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	3
Ti, Mg	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	6

Structure	Plane	Direction	τ_c (MPa)	Nº systems
Al (fcc)	{111}	<110>	0.49	12
W (bcc)	{110}	<111>	27.6	12
Ti (HCP)	{0001}	<1120>	0.64	3

- **Example:** FCC crystal:



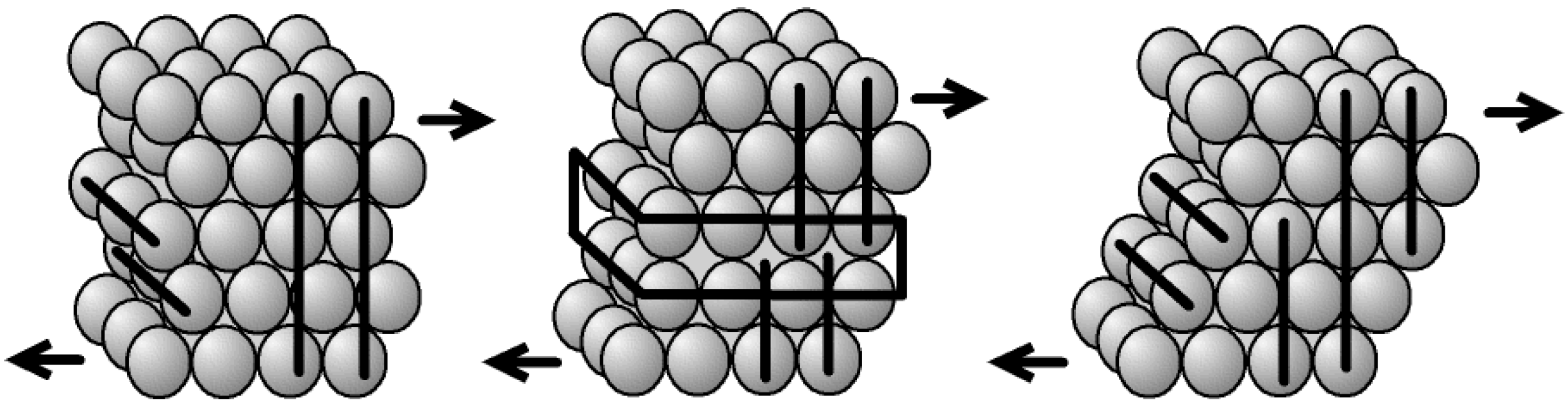
Planes (4): {111}

Directions (3): [1 0 -1] = [1 -1 0]
[0 1 -1] = [-1 1 0]
[0 -1 1] = [-1 0 1]

2.5. INFLUENCE OF DEFECTS

IMPORTANCE OF DISLOCATIONS:

- At first, the following sliding mechanism between crystal planes could be supposed:

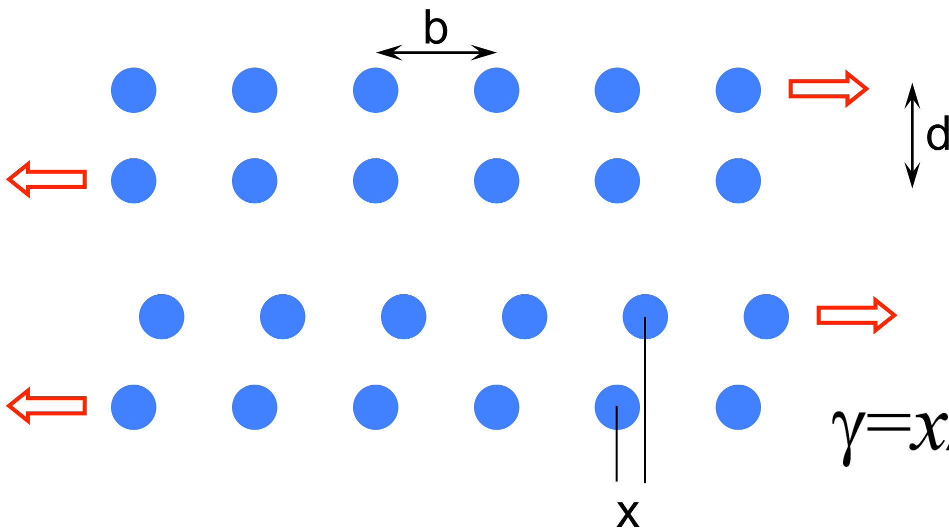


- The theoretical shear stress can be estimated using a simple model.

2.5. INFLUENCE OF DEFECTS

IMPORTANCE OF DISLOCATIONS:

CRITICAL SHEAR STRESS ASSESMENT:



$$\tau = \tau_{\max} \sin\left(\frac{2\pi x}{b}\right)$$

(Lattice periodicity)

$$\gamma = x/d$$

$$\left(\frac{d\tau}{dx}\right)_{x=0} = \frac{2\pi\tau_{\max}}{b}$$

$$\left(\frac{d\tau}{dx}\right)_{x=0} = \left(\frac{d\tau}{d\gamma}\right)_{x=0} \left(\frac{d\gamma}{dx}\right)_{x=0} = G \cdot \frac{1}{d}$$

$$\tau_{\max} = \frac{bG}{2\pi d} \approx \frac{G}{2\pi}$$

2.5. INFLUENCE OF DEFECTS

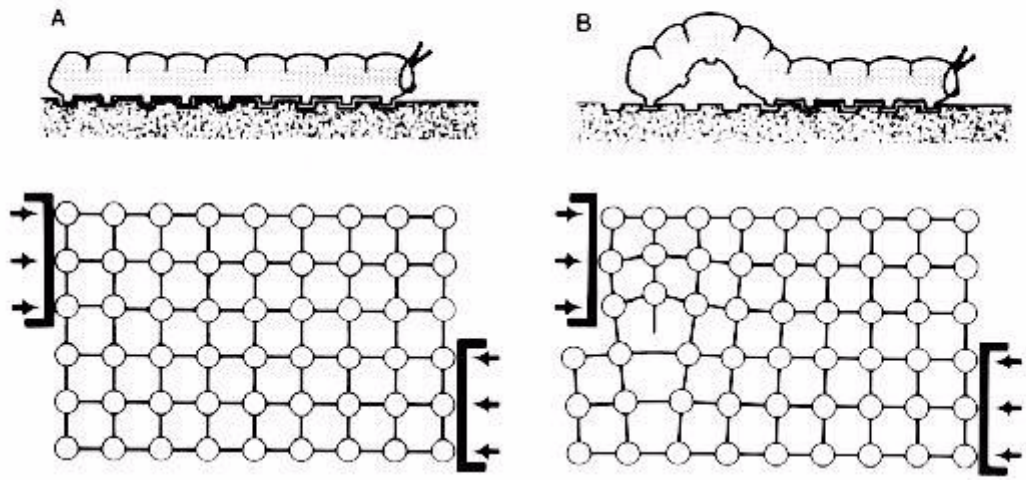
IMPORTANCE OF DISLOCATIONS:

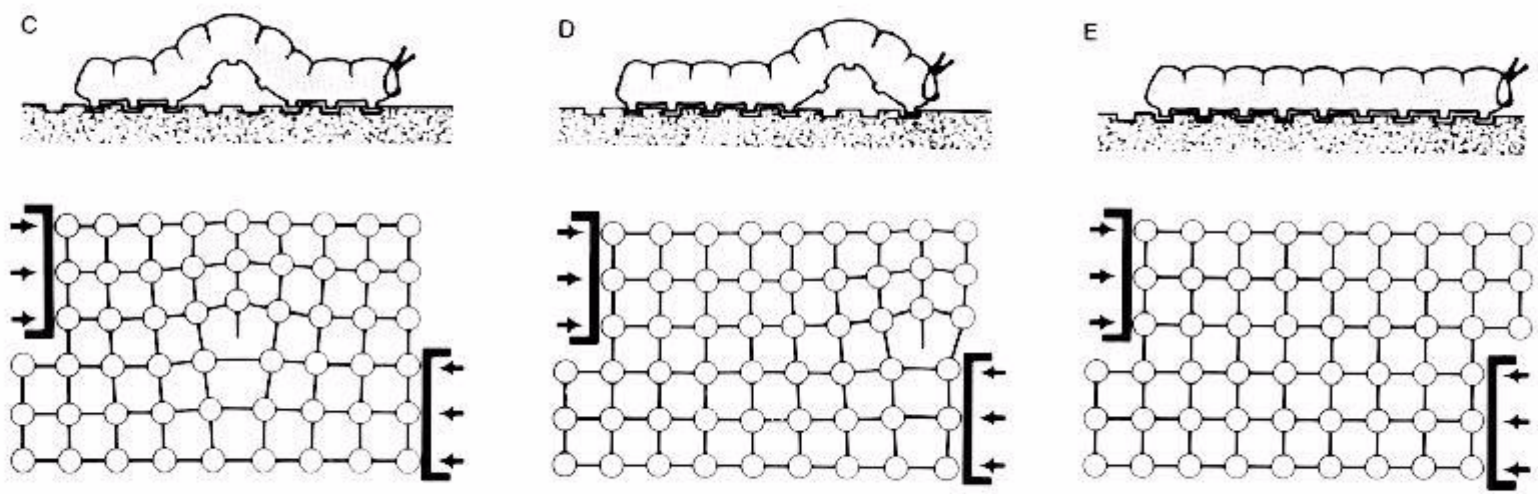
- According to this simple calculation, the shear stress needed to plastically deform a perfect crystal is in the order of G/6; more sophisticated calculations (using more precise interatomic potentials) offer as a result a critical stress in the order of G/30.
- Empirical evidence shows that the actual stress needed is several orders of magnitude lower.
- That is because crystals contain dislocations that reduce the stress needed to produce the sliding.
- **KEY IDEA:** it is much easier to move the crystal planes one by one (like a zipper) than all of them at the same time.

2.5. INFLUENCE OF DEFECTS

IMPORTANCE OF DISLOCATIONS:

The low stress level required to provoke dislocation motion is a consequence of the fact that the disturbance is spread out over many atomic diameters, the strain being appreciable only at the central region, known as the core. In a sort of reverse tug-of-war, the atoms ahead of the core oppose the motion while those behind promote it. The consecutive movement of the core, from site to site along the slip plane, is analogous to the crawling of a caterpillar, which eases the burden of movement by having only a few legs off the ground at any instant.

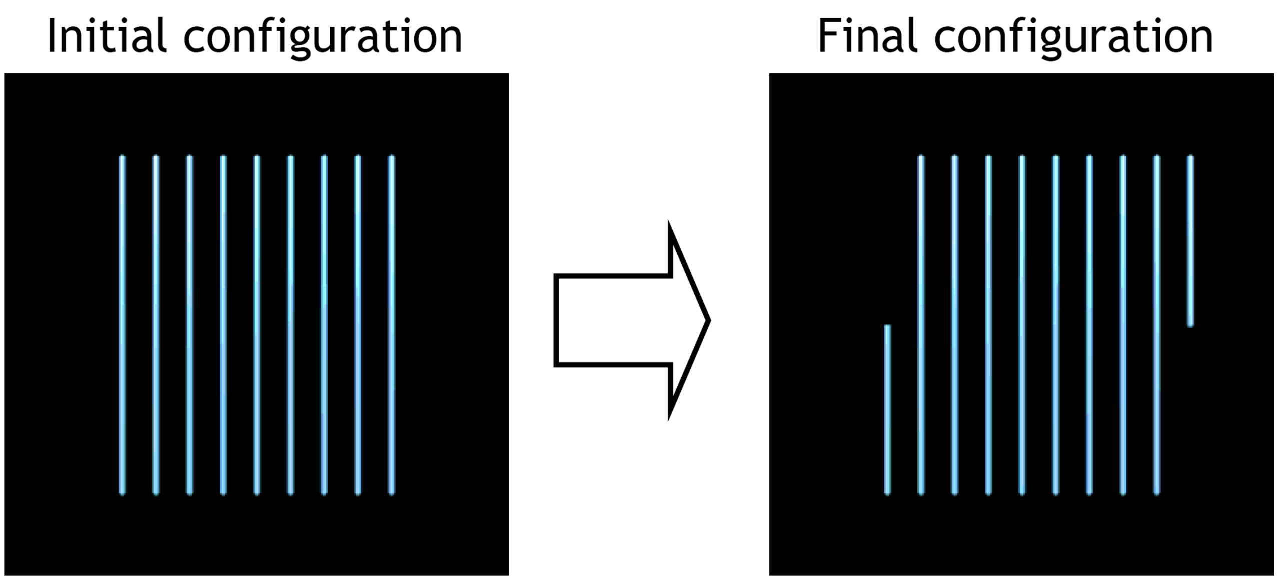




2.5. INFLUENCE OF DEFECTS

IMPORTANCE OF DISLOCATIONS:

- The movement of the dislocation along the crystal creates a plastic deformation.
- Dislocation motion: the bottom of the glass moves a distance *b* with respect to the top.



2.5. INFLUENCE OF DEFECTS

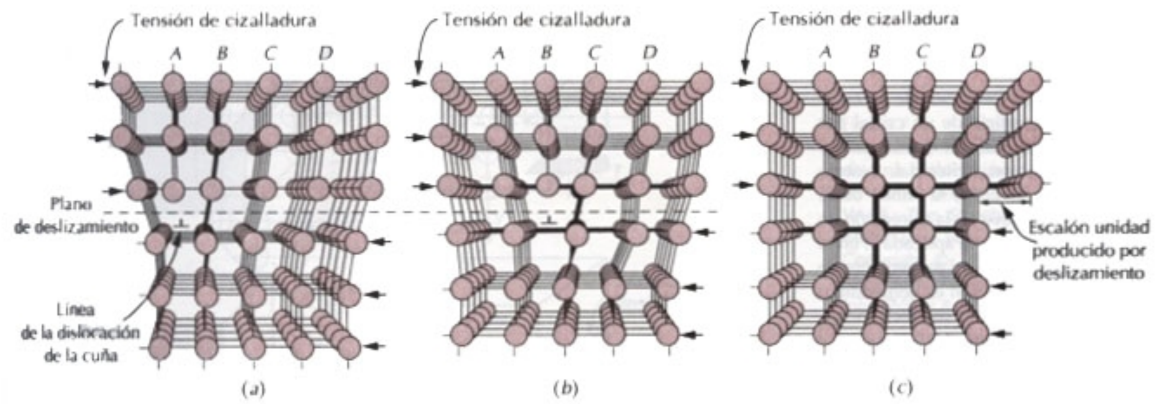
IMPORTANCE OF DISLOCATIONS:

- **Dislocations are always present** in the materials:
  - An annealed material (low dislocation density) may contain more than 1000 km of dislocations per cubic millimeter.
  - A heavily cold deformed material can reach up to 10 million km of dislocations per cubic millimeter.
- **Sliding provides ductility to metals**, otherwise, they would be brittle and could not be conformed (like ionic materials).
- **By interfering on the dislocations movement it is possible to alter the mechanical properties of a metal or an alloy** (an obstacle placed in the crystal prevents the movement of a dislocation, unless a greater stress is applied; therefore, this procedure increases the resistance).

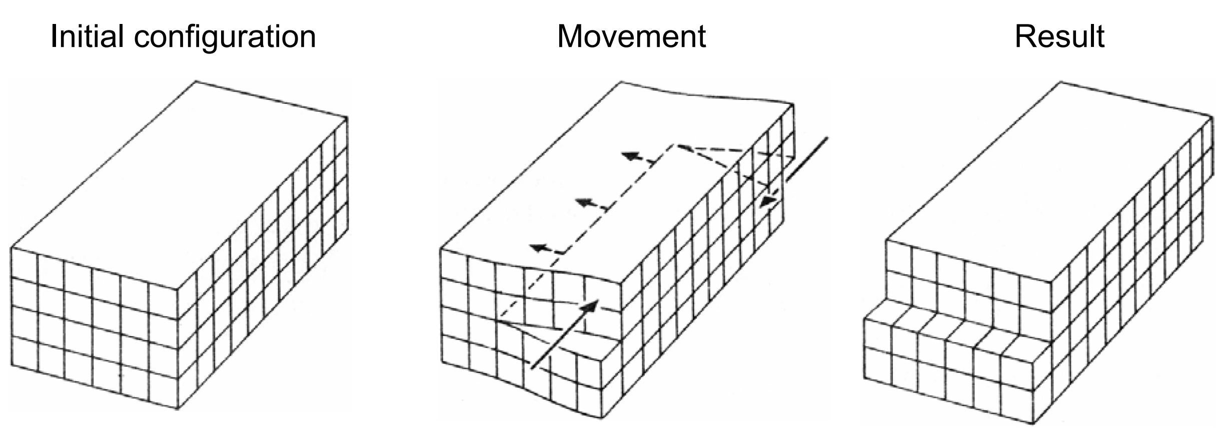
2.5. INFLUENCE OF DEFECTS

IMPORTANCE OF DISLOCATIONS:

EDGE / WEDGE DISLOCATIONS:



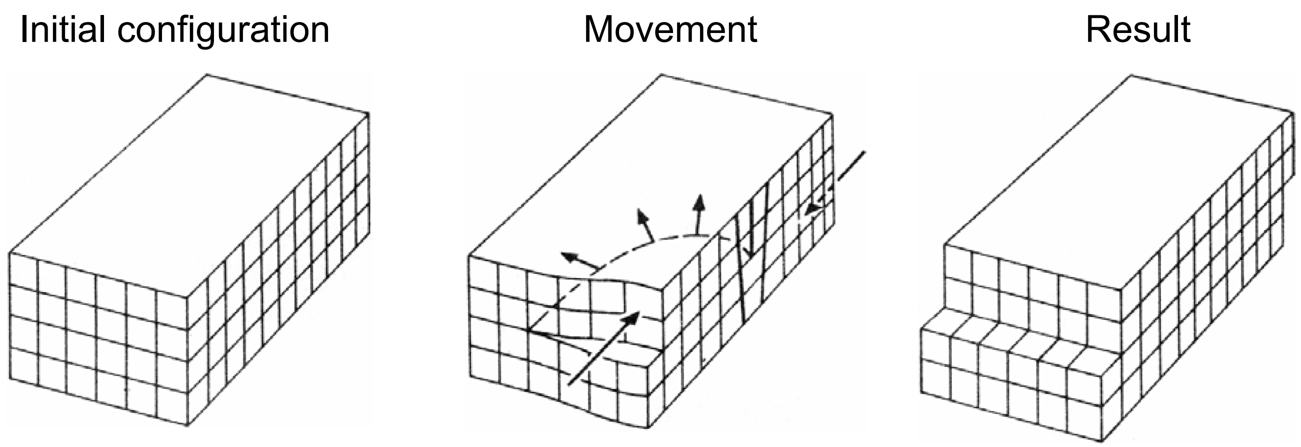
HELICOIDAL DISLOCATIONS:



2.5. INFLUENCE OF DEFECTS

IMPORTANCE OF DISLOCATIONS:

MIXED DISLOCATIONS:



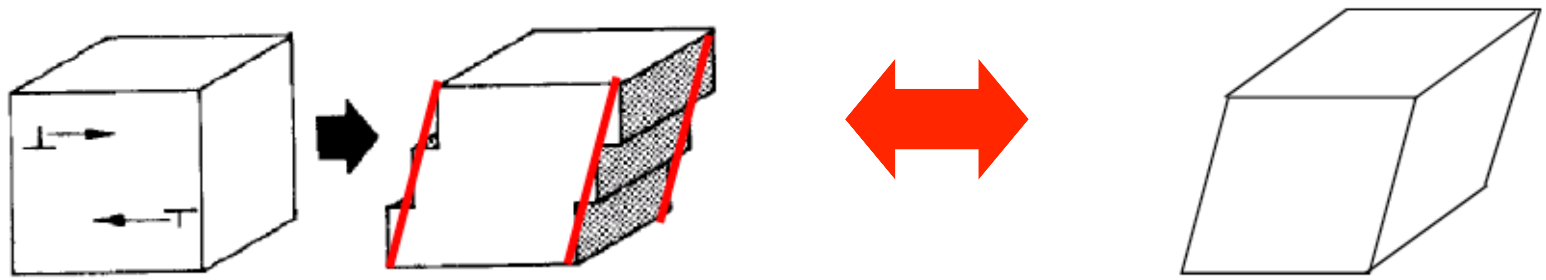
2.5. INFLUENCE OF DEFECTS

IMPORTANCE OF DISLOCATIONS:

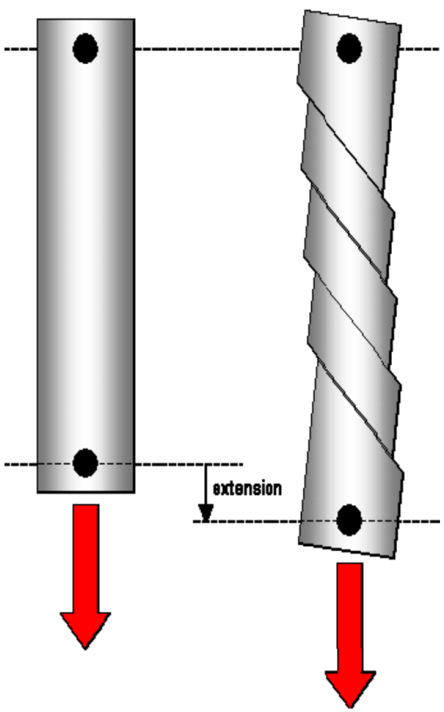
DISLOCATIONS MOVEMENT ILLUSTRATIVE VIDEOS:

- Explanation of wedge dislocations:
  http://www.youtube.com/watch?v=_oihyA23V2Q&feature=related
- Movement of a wedge dislocation:
  http://www.youtube.com/watch?v=iKKxTP6xp74&feature=endscreen&NR=1
- Movement of dislocations video:
  http://www.youtube.com/watch?v=BV1cxwxnhPs
  http://www.youtube.com/watch?v=9UeRrZFRe5k
- Annihilation of dislocations:
  http://www.youtube.com/watch?v=ry-iWBlmG64&feature=related
- Solid solution hardening:
  http://www.youtube.com/watch?v=RUuLusenhfA
- Frank Read:
  http://www.youtube.com/watch?v=5yID78ovcX8

2.5. INFLUENCE OF DEFECTS



Pure shear



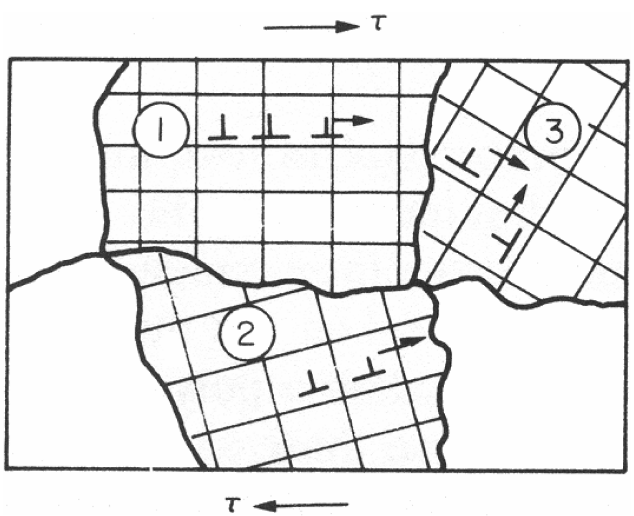
<u>CONSEQUENCE</u>:

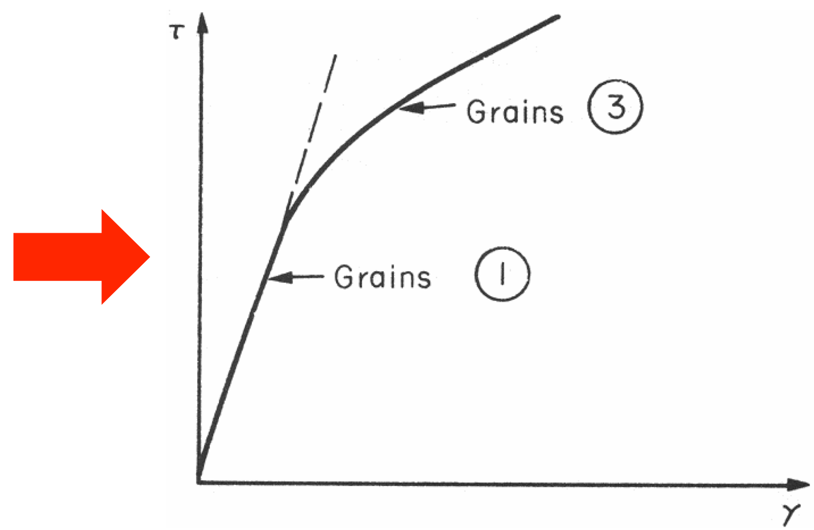
DURING THE PLASTIC DEFORMATION, VOLUME REMAINS CONSTANT

2.6. MONOCRYSTALS AND POLYCRISTALS

ELASTIC LIMIT INTERPRETATION:

- In general, monocrystals are anisotropic. In particular, they are anisotropic regarding to their yielding properties.
- Most engineering materials are polycrystalline, that is, they consist of an infinity of small monocrystals (grains), randomly oriented and bonded together.

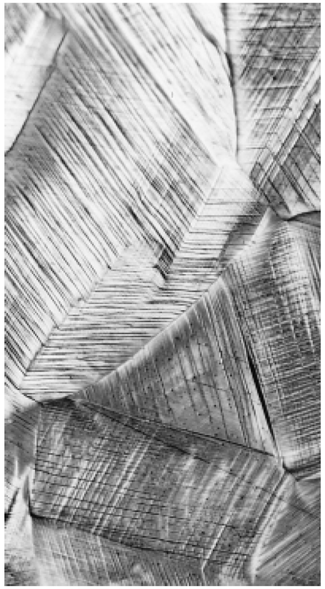




2.6. MONOCRYSTALS AND POLYCRISTALS

ELASTIC LIMIT INTERPRETATION:

- In polycrystalline metals the slip direction varies from grain to grain (in each grain, the more favorable system corresponds to the highest shear stress).
- **Example:** microphotograph of a copper sample; two sliding systems can be observed in most grains.



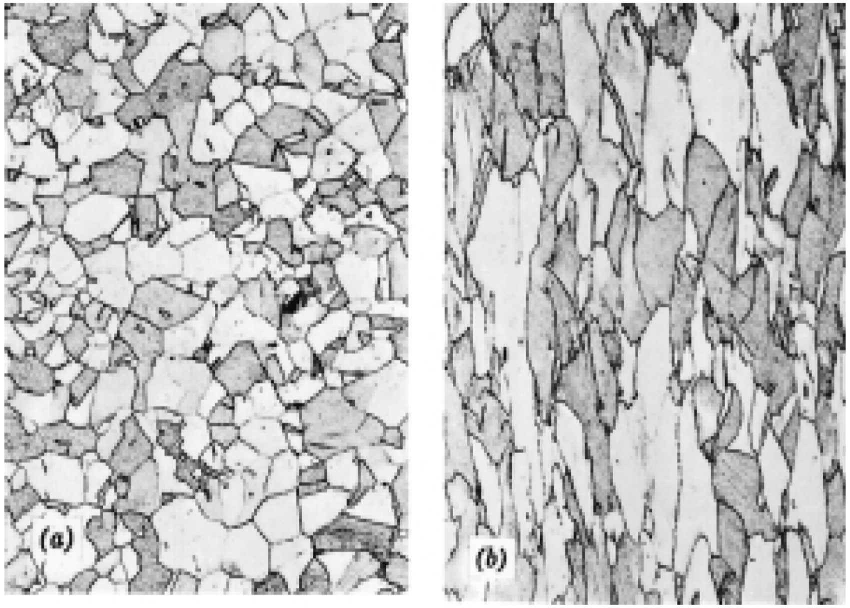


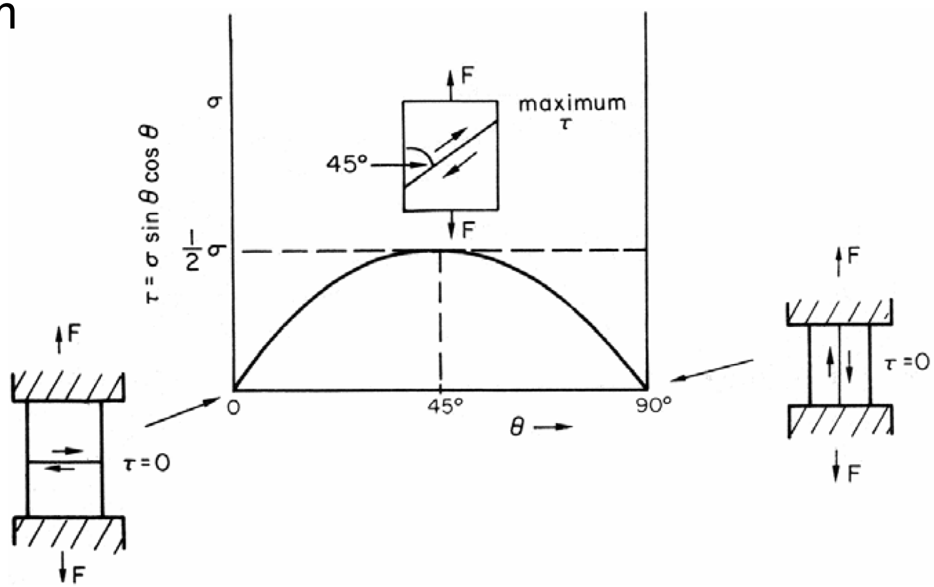
FIGURE 8.11 Alteration of the grain structure of a polycrystalline metal as a result of plastic deformation. (*a*) Before deformation the grains are equiaxed. (*b*) The deformation has produced elongated grains. 170×. (From W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials,* Vol. I, *Structure,* p. 140. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

2.6. MONOCRYSTALS AND POLYCRISTALS

ELASTIC LIMIT INTERPRETATION:

- Is theoretically demonstrated that the shear stress needed to yield a polycrystal is 1.5 τ_c.
- In a tensile test, the maximum shear stress occurs at 45º from the direction of the applied load:

$$\tau_{max} = \frac{\sigma}{2}$$



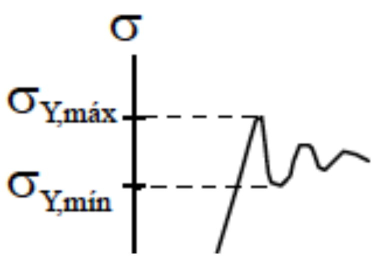
- Thus:

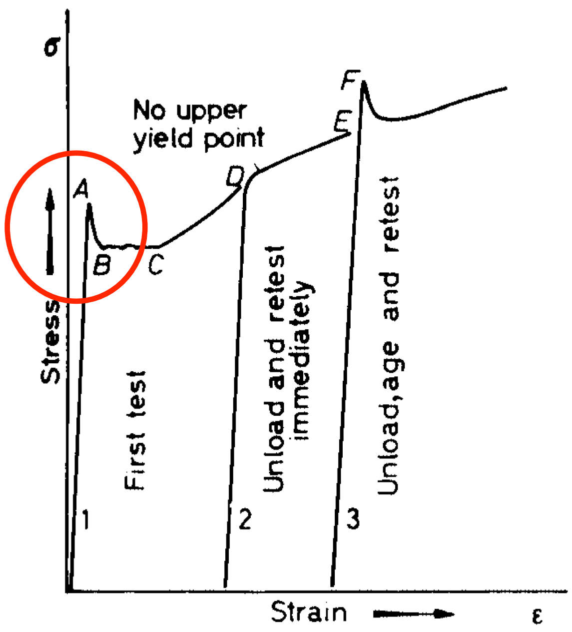
$$\tau_{max} = \tau_c \quad \Rightarrow \quad \sigma = \sigma_Y \qquad \sigma_y = 3\tau_c$$

2.6. MONOCRYSTALS AND POLYCRISTALS

REAL BEHAVIOR OF A POLYCRYSTAL:

- Some materials have an **upper elastic limit and a lower** one; that is typical of **steel with nitrogen or carbon impurities**.



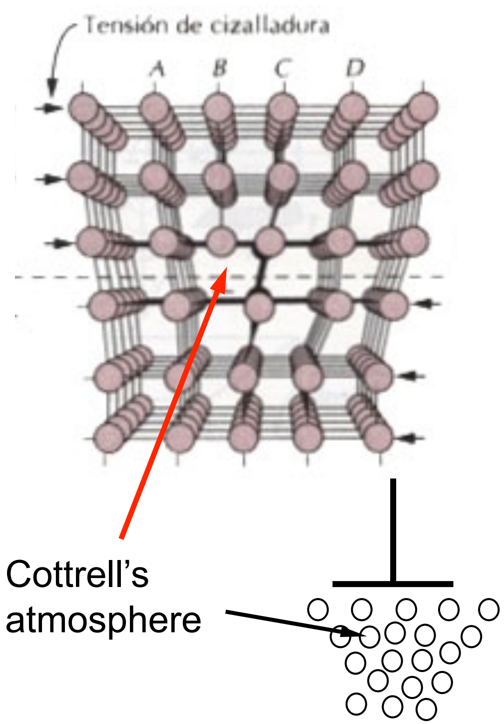


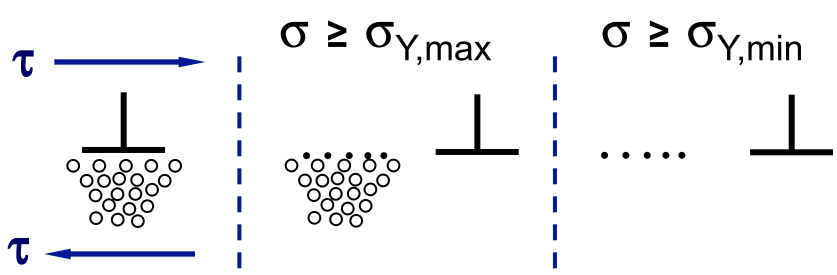
- Similarly, the **behavior when reloading after unloading** depends on the time elapsed since the unload.
- The phenomenon is pretty similar to that of the start of sliding due to friction (static and dynamic friction).
- It is associated with the formation of the so called **Cottrell atmosphere**, which hinders the start of dislocation sliding.

2.6. MONOCRYSTALS AND POLYCRISTALS

REAL BEHAVIOR OF A POLYCRYSTAL:

- Atoms of C, N are important because they interact with and immobilize the dislocations.
- If there is enough time-temperature an atmosphere of C,N will be formed below every dislocation (due to the distortion experienced by the lattice).
- The stress state that mobilizes free dislocations is not able do it in the presence of the atmosphere.
- This phenomena also justifies the differences in behavior after reloading.

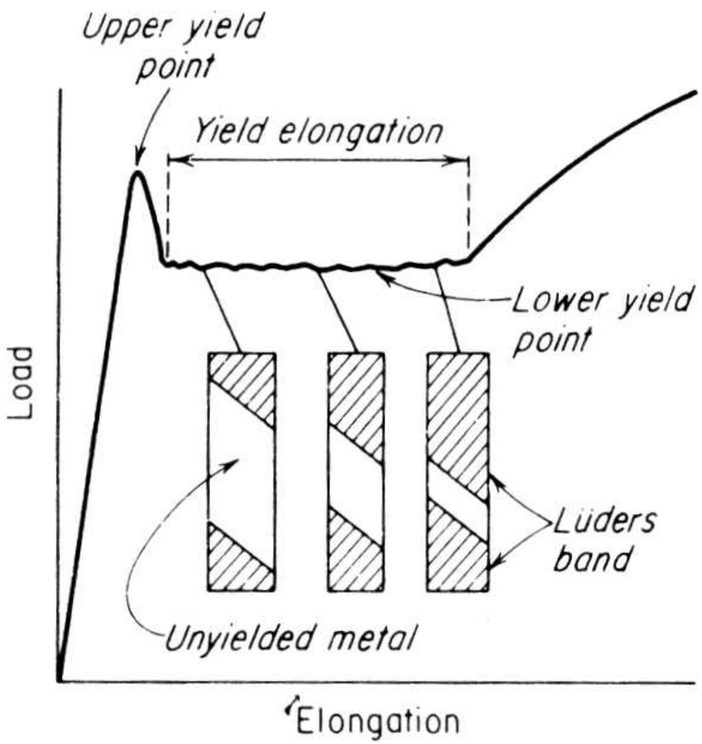


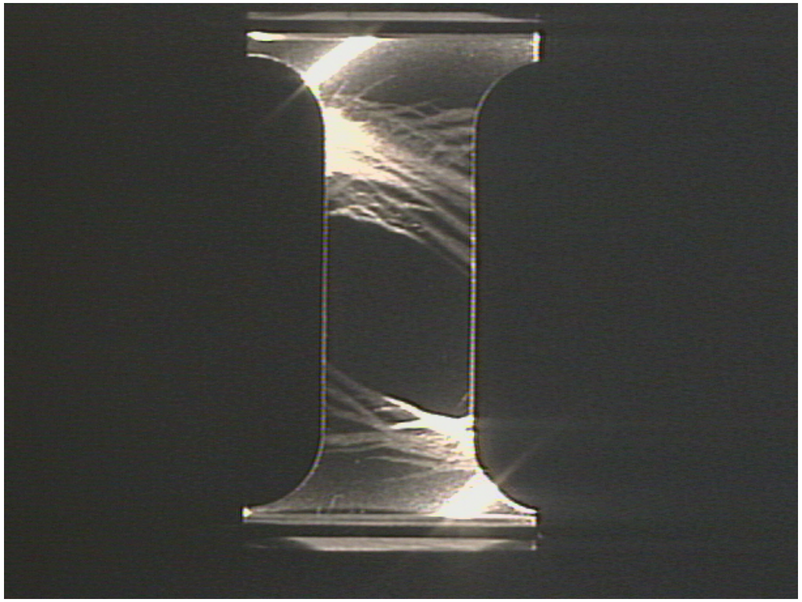


2.6. MONOCRYSTALS AND POLYCRISTALS

REAL BEHAVIOR OF A POLYCRYSTAL:

• A phenomenon associated with plasticity is the formation of **Lüders bands**.





2.7. HARDENING MECHANISMS

- In metallic materials, point, linear and planar defects hinder the dislocation sliding.
- Therefore, **it is possible to control the strength of a metallic material by controlling the amount and type of imperfections present in it**.
- There are **four possible hardening mechanisms**:
  - Solid solution hardening.
  - Precipitation hardening.
  - Strain hardening.
  - Grain refinement hardening.

2.7. HARDENING MECHANISMS

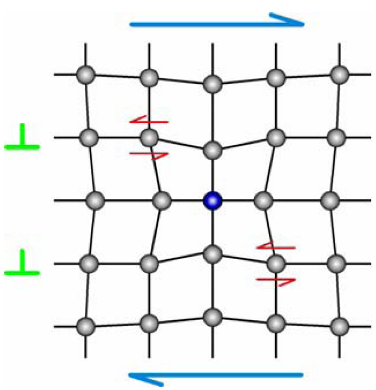
OVERVIEW:

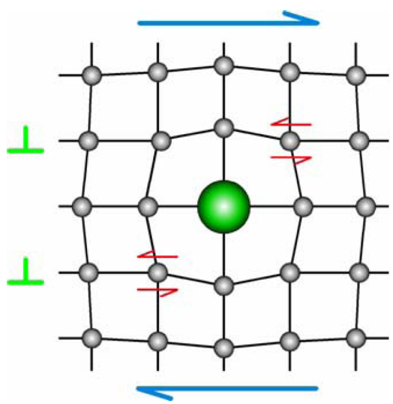
- Crystal is plastically deformed when the force acting on a dislocation overcomes the resistance to its movement.
- We can distinguish different **contributions to the resistance** that opposes to the dislocations development:
  - The **intrinsic resistance of the crystal**, caused by the need to break and create bonds successively with the appearance of the dislocation in each point; is generally really high for covalent bonds, but very low for metals (hence the diamond is so difficult to deform).
  - **Other defects** such as impurities, particles and other dislocations may also act as obstacles to the movement of dislocations.

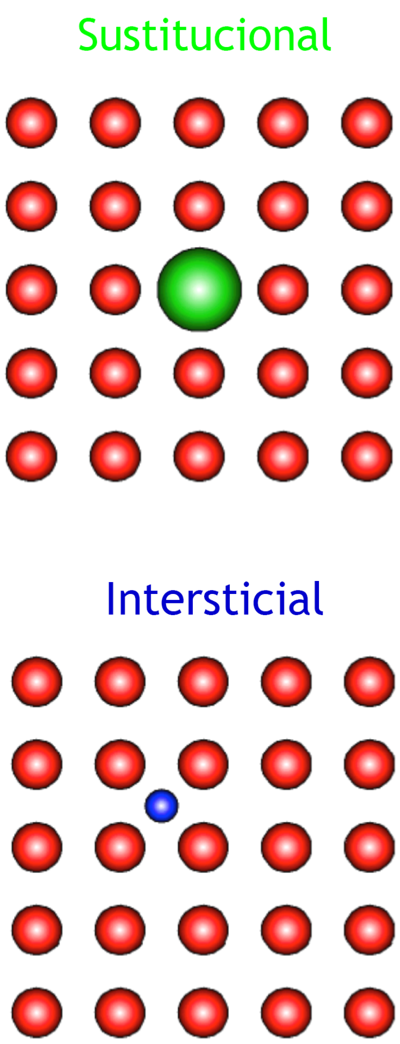
2.7. HARDENING MECHANISMS

SOLID SOLUTION HARDENING:

- Two different solid solutions can be distinguish: **SUSTITUTIONAL** and **INTERSTITIAL**.
- A strange atom in a crystal lattice introduces a major distortion in it.





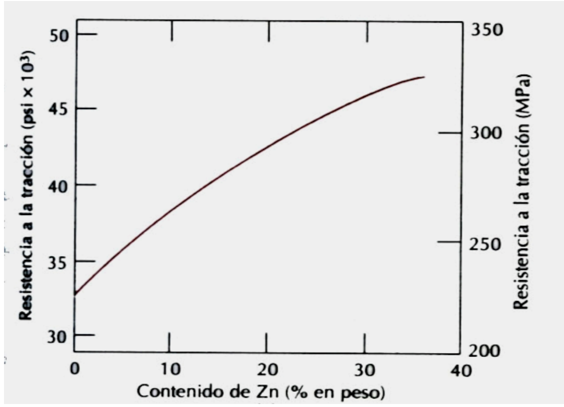


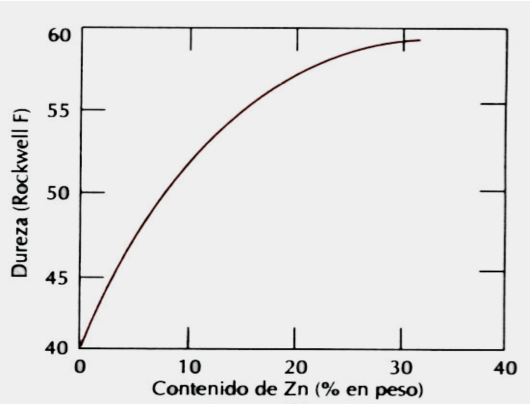
- **Those distortions hinder the movement of dislocations**, making it difficult, therefore, the onset of plasticity, and finally hardening the material.

2.7. HARDENING MECHANISMS

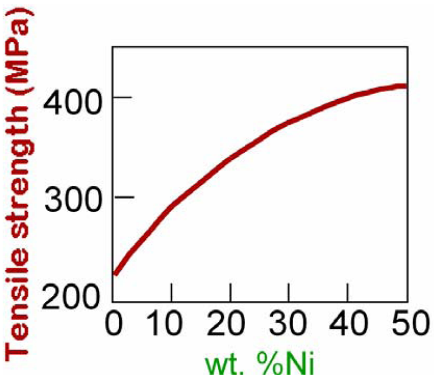
SOLID SOLUTION HARDENING: EXAMPLES:

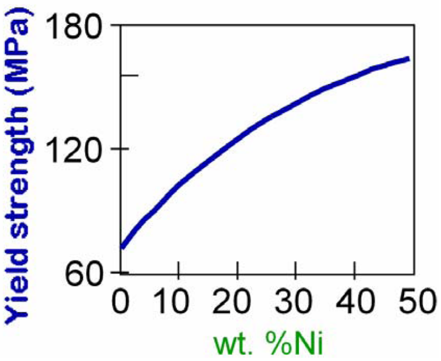
- Cu-Zn alloy (brass):





- Cu-Ni alloy:





2.7. HARDENING MECHANISMS

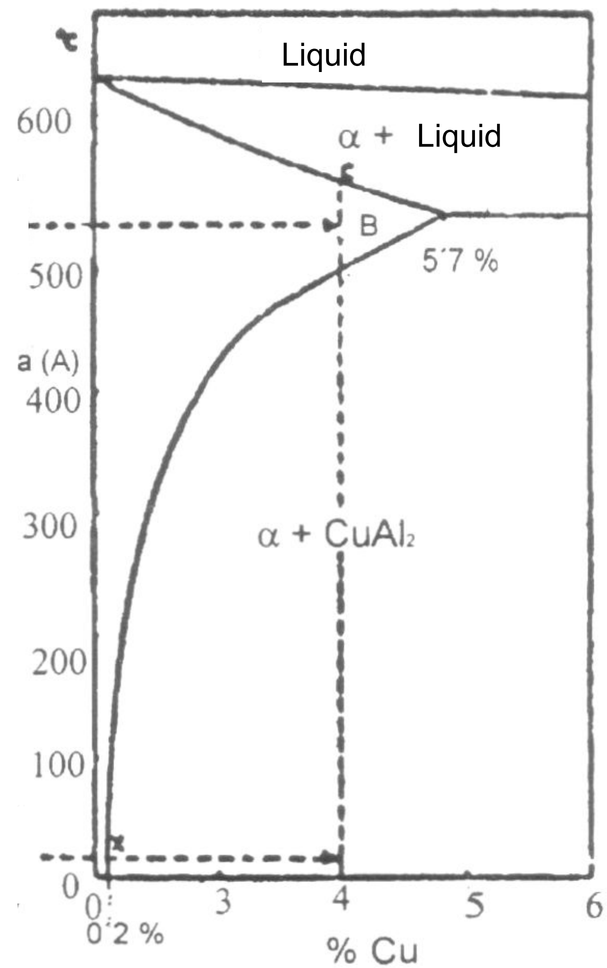
PRECIPITATION HARDENING:

- Dislocations move through the material more or less readily depending on the work required to break and create bonds.
- If within a material rigid particles are introduced, by which the dislocations can not move, they will clog (anchored dislocations) when they reach those particles.
- Passing of a dislocation through a particle.
- If the particle is very rigid, the dislocation will not be able to pass through it.

2.7. HARDENING MECHANISMS

PRECIPITATION HARDENING:

- **Example**: phase diagram Al-Cu.
- Cu solubility decreases when temperature is reduced: 5.7% - 0.2%.
- Heat treatment: solubilization, quenching, CuAl2 precipitate (SOLUTION + AGING).

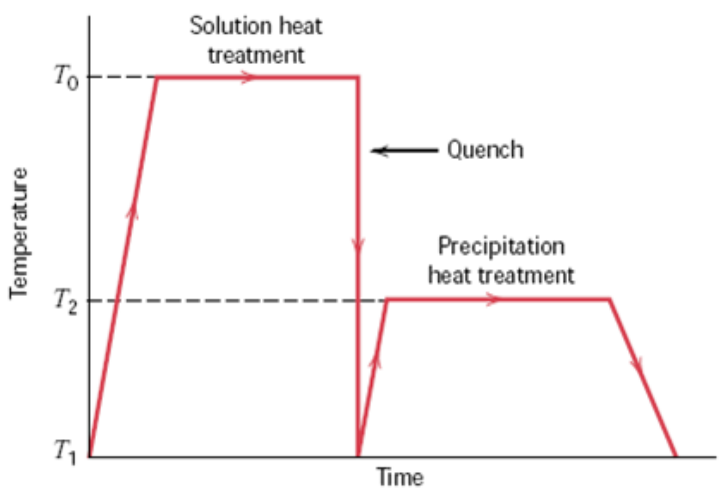


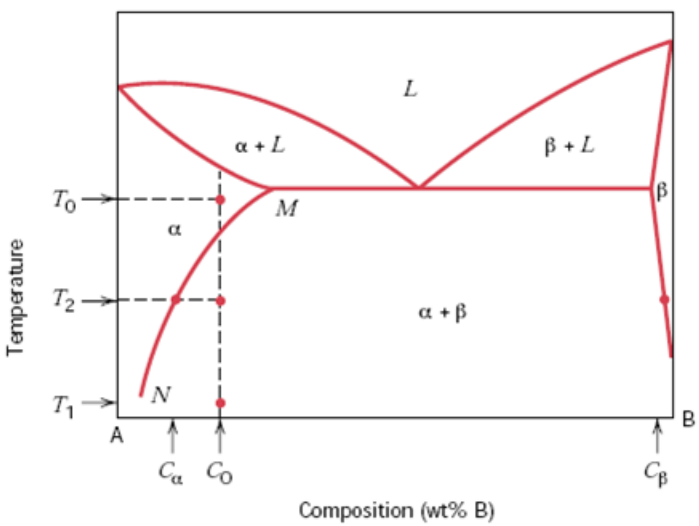
- **Two conditions are needed**:
  - Maximum solubility of B in A must be significant.
  - Solubility limit of B in A must decrease rapidly with temperature.

2.7. HARDENING MECHANISMS

PRECIPITATION HARDENING:

- **1st stage: dissolution heat treatment (solution):**
  - Solute atoms dissolve (T_0) to form a single-phase solid solution (α).
  - It cools down rapidly (quenching to T_1) avoiding diffusion; thus, it generates a supersaturated solid solution.

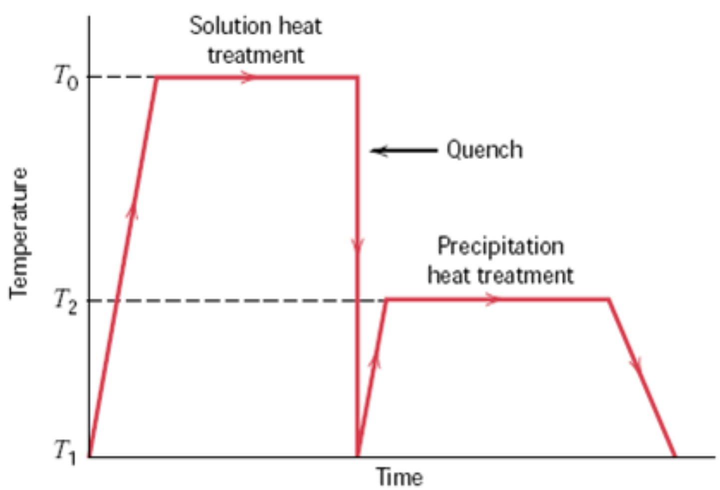


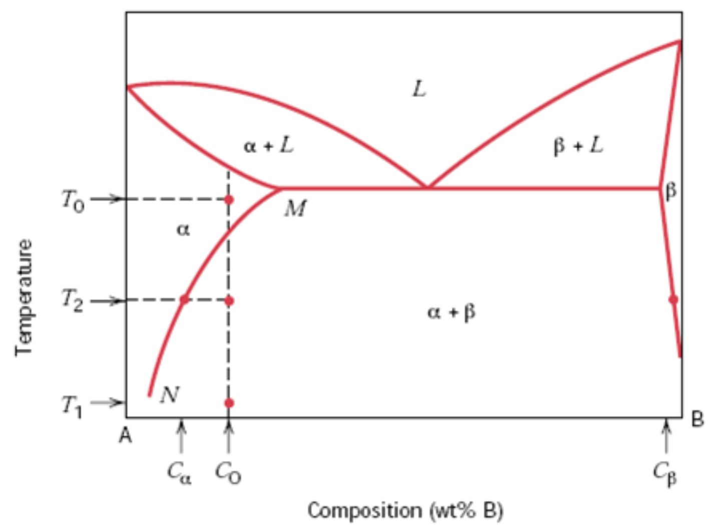


2.7. HARDENING MECHANISMS

PRECIPITATION HARDENING:

- **2nd stage: precipitation heat treatment (aging):**
  - Temperature (T_2) is increased, accelerating the rate of diffusion.
  - Precipitated phase, β , starts to create in the form of a fine dispersion.

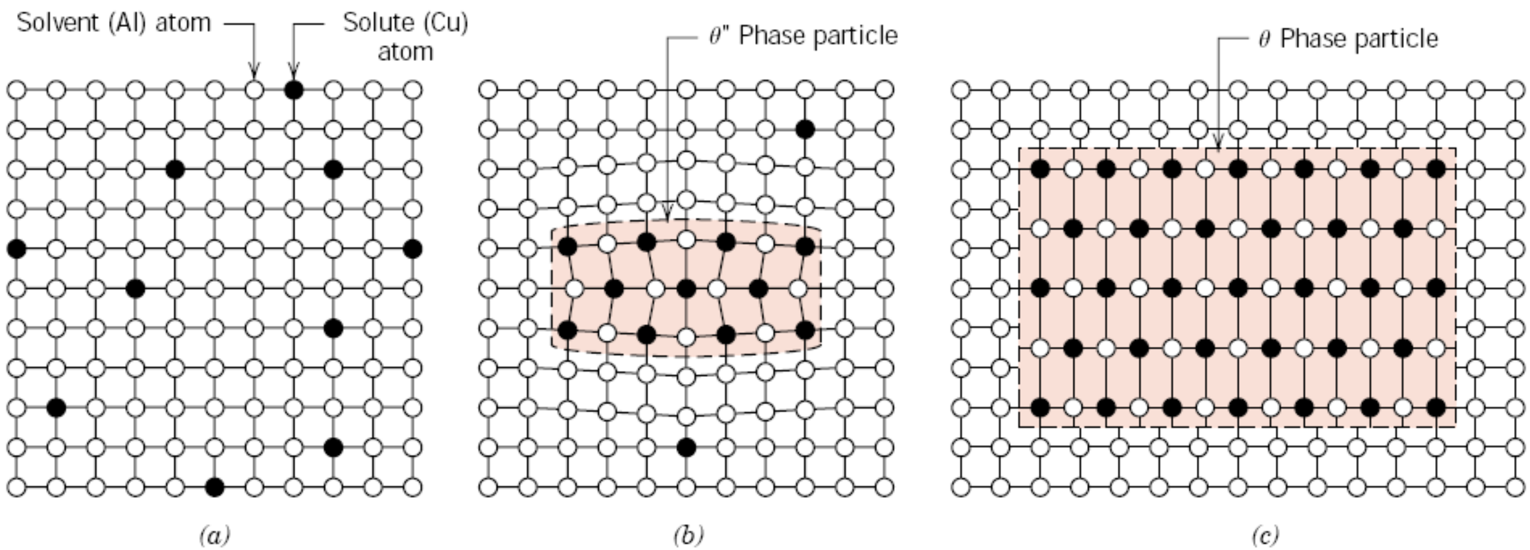




2.7. HARDENING MECHANISMS

PRECIPITATION HARDENING:

- **SOLUTION + AGING:**
  - DESCRIPTION OF THE PROCESS AT A MICROSTRUCTURAL LEVEL.



2.7. HARDENING MECHANISMS

PRECIPITATION HARDENING:

- **SOLUTION + AGING:**
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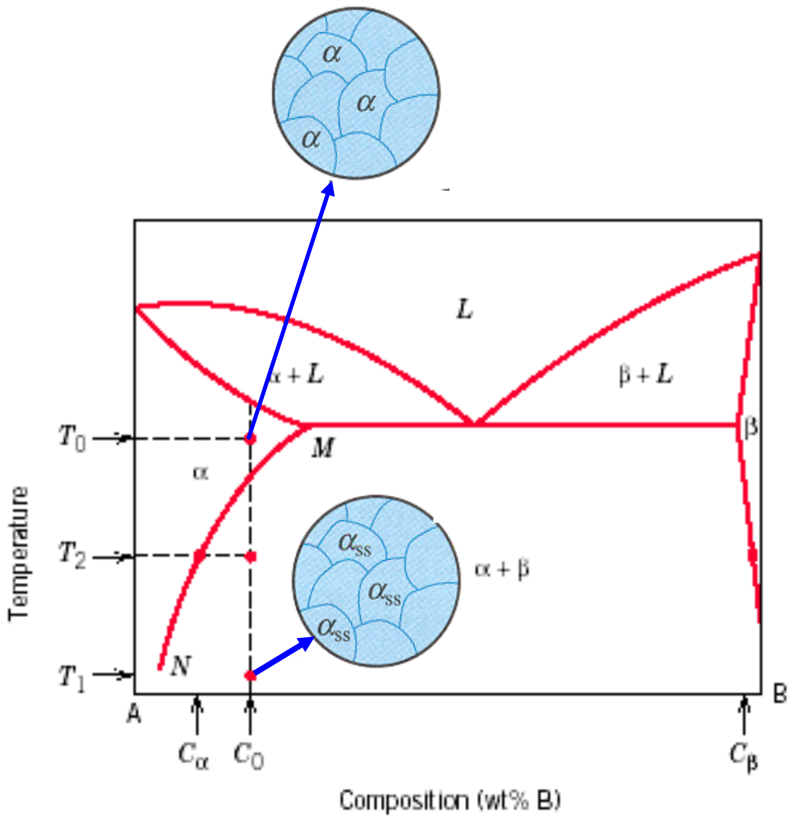
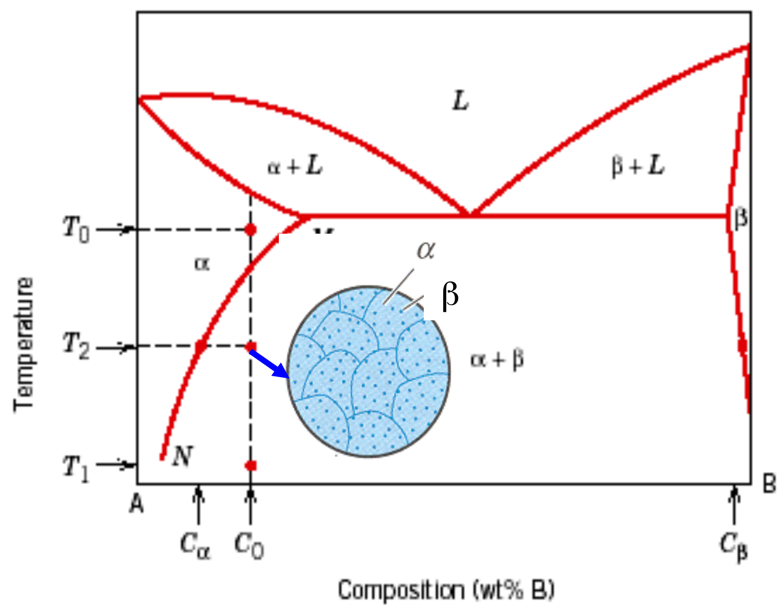
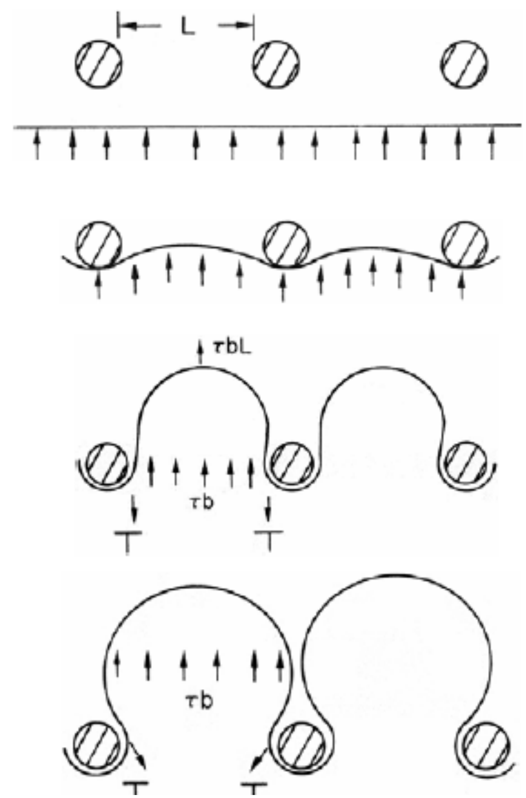




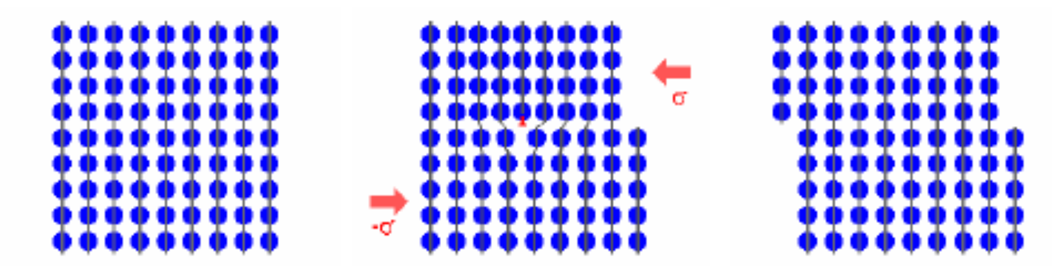
2.7. HARDENING MECHANISMS

PRECIPITATION HARDENING:

- Hardening is due to the fine dispersion of particles that **make it difficult the movement of dislocations** during the plastic deformation.



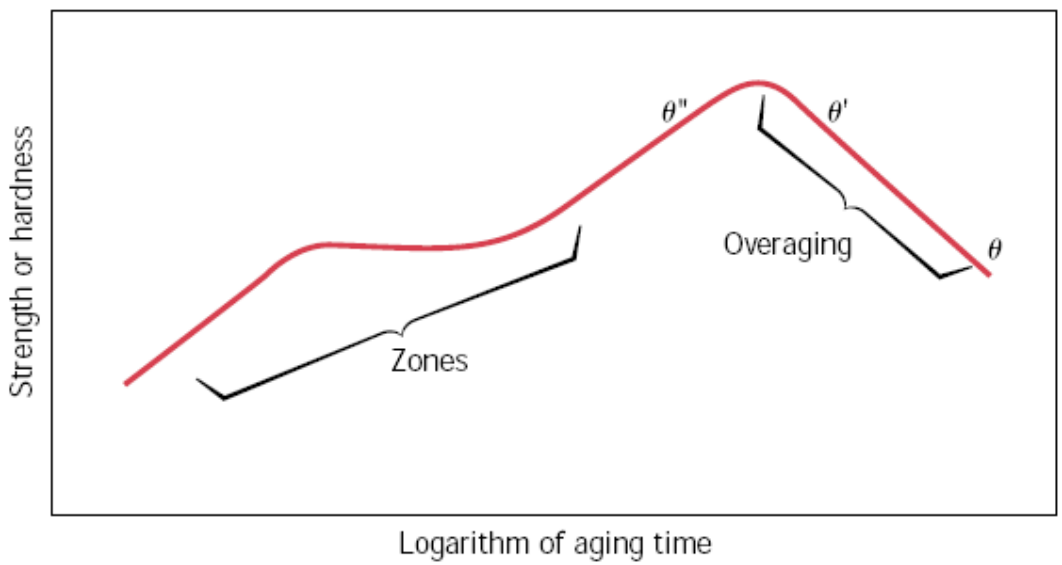
Initial configuration **Movement** **Result**



2.7. HARDENING MECHANISMS

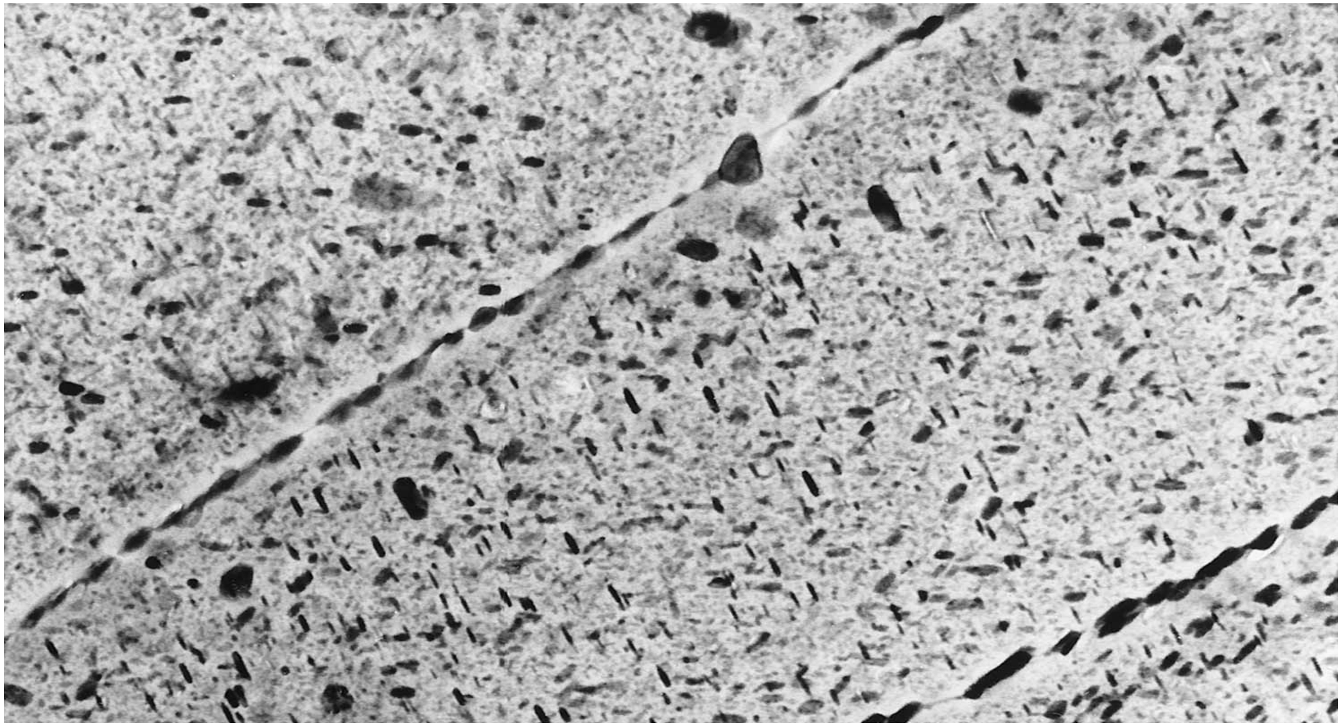
PRECIPITATION HARDENING:

- Some alloys (for example, aluminum) undergo the aging process at room temperature (**natural aging**), but in most cases, it is necessary to increase the temperature (**artificial aging**).
- Aging time is essential to optimize the final properties, excessively prolonged aging can be counterproductive (**overaging**).



2.7. HARDENING MECHANISMS

PRECIPITATION HARDENING:



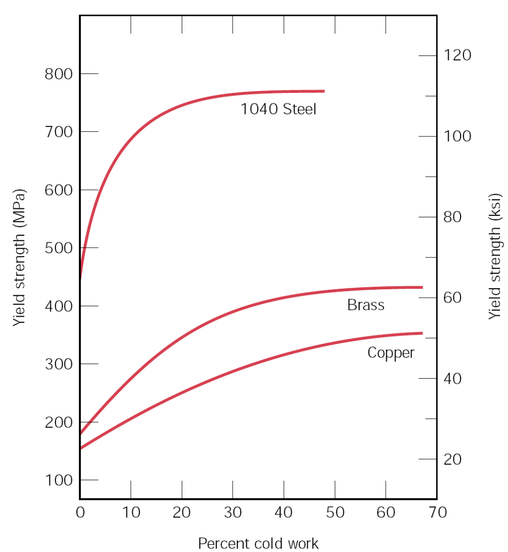
- A transmission electron micrograph showing the microstructure of a 7150-T651 aluminum alloy (6.2Zn-2.3Cu-2.3Mg-0.12Zr-balanced Al) that has been precipitation hardened. The light matrix phase is an Al solid solution.

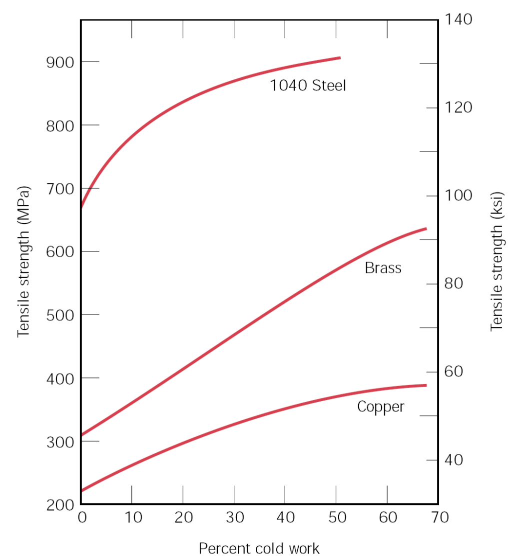
2.7. HARDENING MECHANISMS

STRAIN HARDENING:

- Strain hardening is the phenomenon whereby a ductile metal increases its strength and hardens as it is being plastically deformed.
- It is also called work hardening or cold working.
- Definition:
- **Examples**:

$$\%\mathrm{CW} = \left(\frac{A_0 - A_d}{A_0}\right) \times 100$$

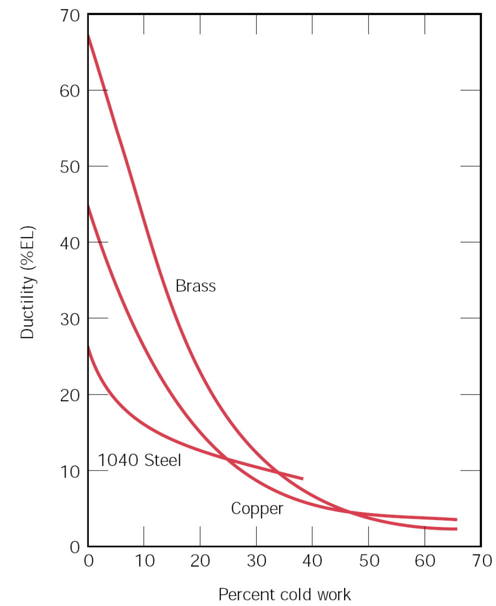




2.7. HARDENING MECHANISMS

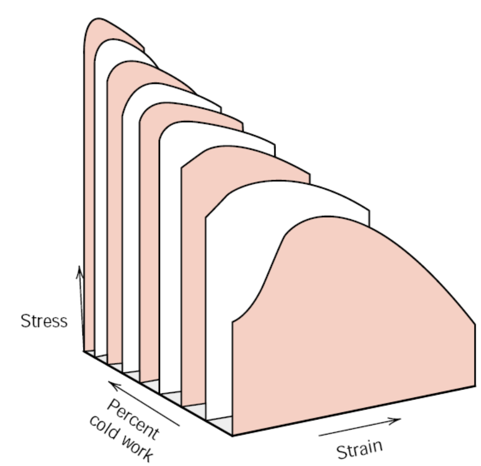
STRAIN HARDENING:

- The drawback is the **loss of ductility**:



JUSTIFICATION:

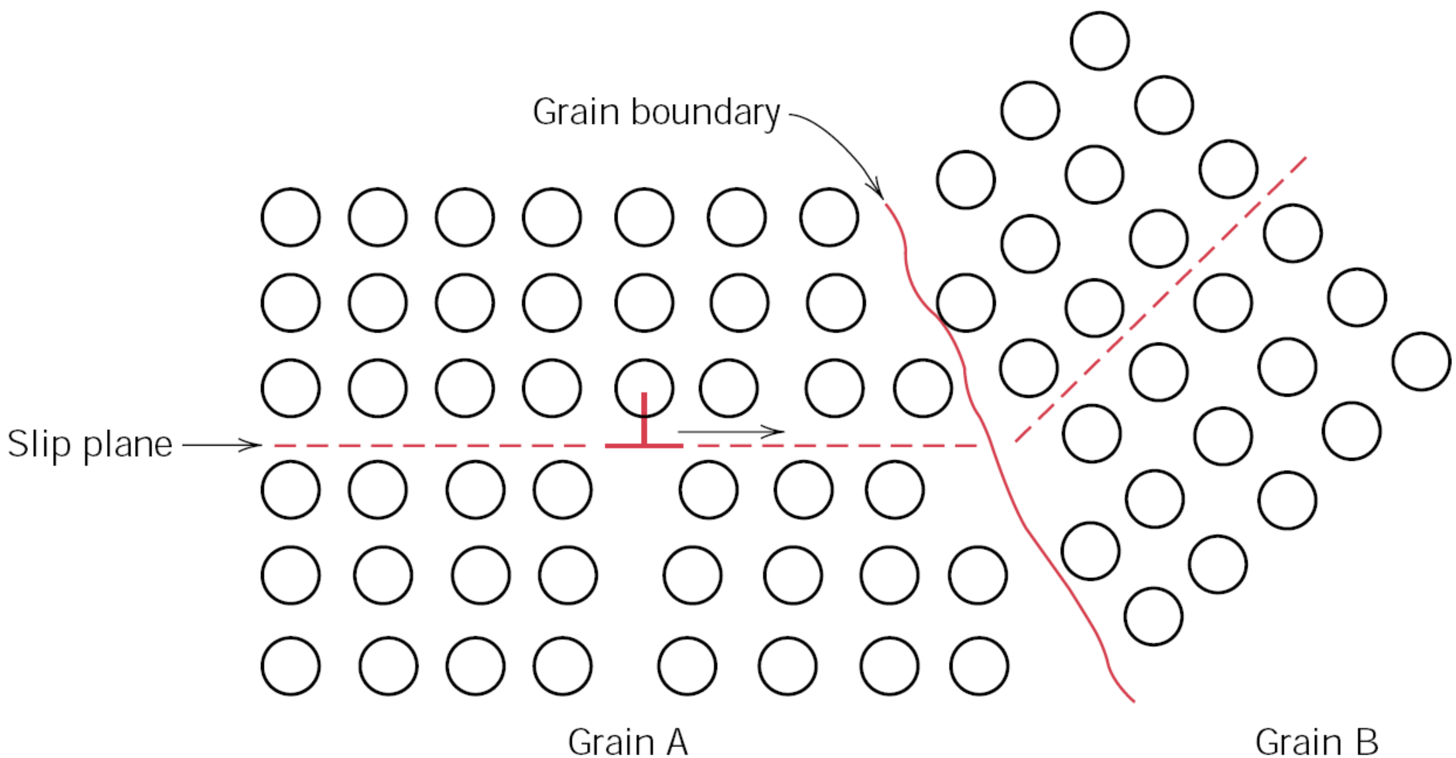
- Dislocations density increases as the applied plastic deformation increases.
- Consequently, the number of interactions between dislocations increases, and they hinder one another.
- Therefore, the external stress has to be increased to continue with the plastic deformation (that is, the material hardens).



2.7. HARDENING MECHANISMS

GRAIN REFINEMENT HARDENING:

- Adjacent grains (that share a common grain boundary) normally have different crystallographic orientations.



2.7. HARDENING MECHANISMS

GRAIN REFINEMENT HARDENING:

- During plastic deformation, the movement of dislocations can take place along the grain boundaries; however, it acts as a barrier, for two reasons:
  - Dislocation must **change its direction of advance** and this is a difficulty.
  - The atomic disorther within the grain boundary blurs the continuity of the sliding planes.
- As a consequence of it, **a finer grain material is tougher and stronger** than coarse grained one, since the first one has a higher surface of grain boundaries.

2.7. HARDENING MECHANISMS

GRAIN REFINEMENT HARDENING:

- For many materials, the elastic limit and fracture strength verify the

Hall-Petch relationship:

$$\sigma_y = \sigma_0 + k_y d^{-1/2}$$

- The size of the grain can be controlled through the solidification rate or by suitable thermal treatments.
- It should be mention that the reduction of the grain size improves not only the mechanical properties but also the fracture toughness.

2.8. PLASTICITY CRITERIA

- Uniaxial stress state: $\sigma = \sigma_Y$
- Multiaxial stress state? $\sigma_{eq}\left(\sigma_1, \sigma_2, \sigma_3\right) = \sigma_Y$
- **TRESCA**: $\sigma_{eq,T} = \sigma_1 - \sigma_3$
- **VON MISES**: $\sigma_{eq,VM} = \frac{1}{\sqrt{2}}\sqrt{\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_1 - \sigma_3\right)^2 + \left(\sigma_2 - \sigma_3\right)^2}$
- The Tresca criterion is more conservative than that of Von Mises.
- The Von Mises criterion works quite well for metals.

2.8. PLASTICITY CRITERIA

Suggested exercises:

- The stress tensor in a point P of an elastic solid is: $\boldsymbol{\sigma} = \begin{pmatrix} 100 & 50 \\ 50 & -170 \end{pmatrix}$

- Apply Von Mises and Tresca criteria to check if plasticity occurred.

- Data:

$$E = 210 \text{ GPa} \quad , \quad \sigma_e = 260 \text{ MPa}$$

- Solution:

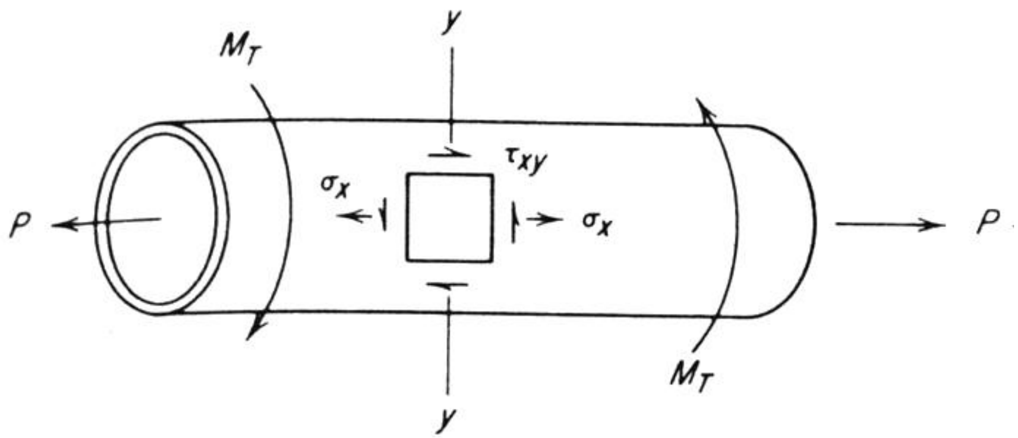
$$\sigma_{VM} = 251,794 \text{ MPa} \qquad \Rightarrow \qquad \sigma_{VM} < \sigma_e$$

$$\sigma_T = 287,924 \text{ MPa} \qquad \Rightarrow \qquad \sigma_T > \sigma_e$$

2.8. PLASTICITY CRITERIA

Suggested exercises:

- Deduce for the tensional state produced in a tensile test – torsion in a thin-walled tube, the limit curves in the plane (σ, τ) for the Tresca and Von Mises criteria.



$$\sigma_1 = \sigma$$

$$\sigma_2 = \sigma_3 = 0$$

$$\tau_{xy} = \tau$$

2.8. PLASTICITY CRITERIA

Suggested exercises:

- **TRESCA**:

$$\left(\frac{\sigma}{\sigma_y}\right)^2 + \frac{\tau^2}{\left(\frac{\sigma_y}{2}\right)^2} = 1$$

- **VON MISES**:

$$\left(\frac{\sigma}{\sigma_y}\right)^2 + \frac{\tau^2}{\left(\frac{\sigma_y}{\sqrt{3}}\right)^2} = 1$$