Universidad
Carlos III de Madrid
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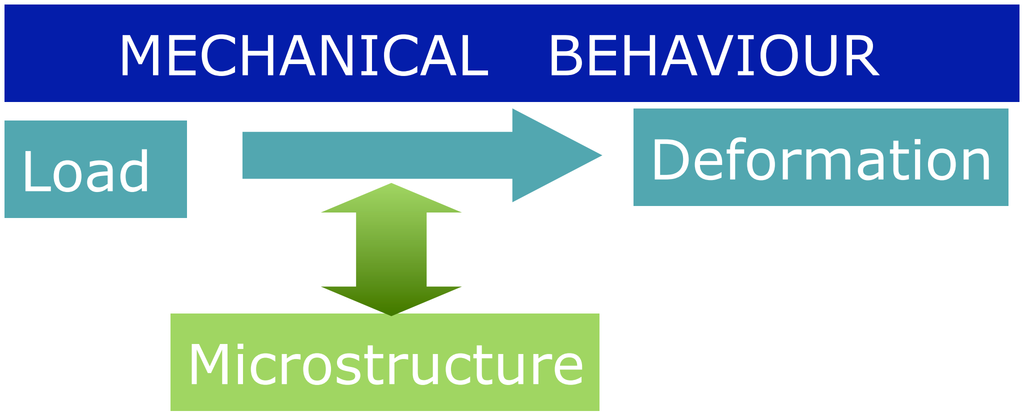
Materials Science and Engineering

TOPIC 4. MECHANICAL PROPERTIES

1. Definition of mechanical properties.
2. Stress-strain concepts
3. Elastic Deformation.
4. Plastic Deformation.
   - Slipping Systems.
   - Strengthening mechanisms: Solid Solution, Grain Size Reduction and Strain Hardening.
5. Ceramics : Flexural Strength or Modulus of Rupture
6. Polymers: Particularities. Deformation Mechanisms, rate, temperature. Creep testing .
7. Hardness: definition, qualitative and quantitative testing: Brinell, Rockwell and Vickers. Relation of hardness with other mechanical properties.

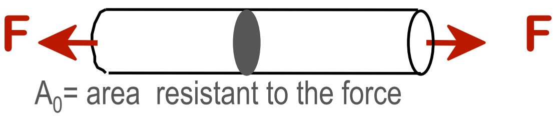
MECHANICAL PROPERTIES



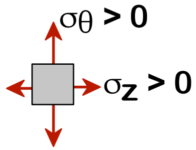
Mechanical properties: strength, hardness, ductility, stiffness …

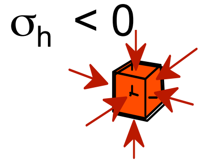
Mechanical properties determine the behaviour of materials ⇒ determine applications.

Simple tension : wire



$(\sigma < 0)$





MECHANICAL PROPERTIES

How is the response of a material to a $F_{applied}$ measured?

Test types

- **Tension**
- **Compression**
- **Impact**
- **Bending**
- **Shear**
- **Torsion**
- **Hardness**

Knowledge of mechanical properties:

↳ TESTS
Service Conditions

- Determine materials properties and determine their possible uses.
- Quality control in the fabrication process.
- Determine the previous history and composition of materials.
- Establish the failure causes of the material during service
- Study new type of materials

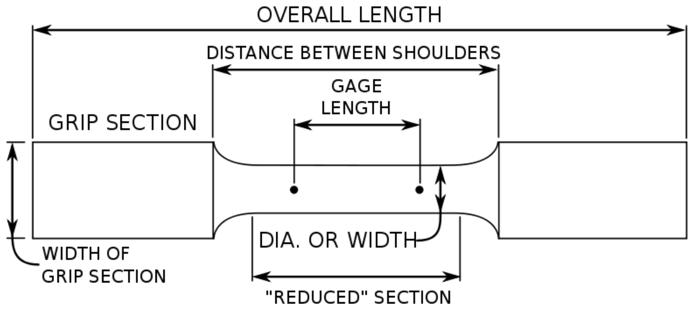
UNIAXIAL TENSION TEST

Test mostly used **NORMALIZED**

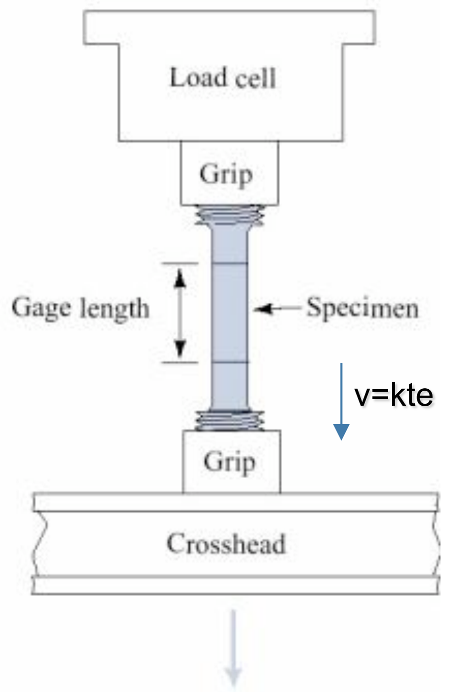
- It is realized at a constant load velocity
- Destructive test

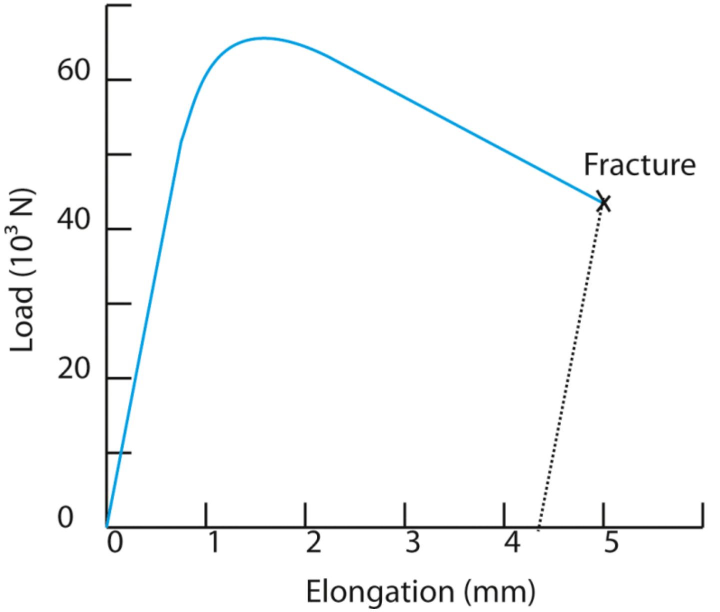
Material to test : SPECIMEN➔ uniform transversal section

Calibration length ≡ Should be long enough so that σ is transmitted in a uniform way



http://commons.wikimedia.org/wiki/File:Tensile_specimen_nomenclature.svg





SHACKELFORD, J.F.: "Int. to Materials Sci. for Engineers", Prentice Hall, 4ª Ed.,

STRESS - STRAIN CURVE

CURVE PARAMETERS

- Young's modulus
- Yield stress (σ_y)
- Strain
- Tensile Strength
- Resilience
- Toughness

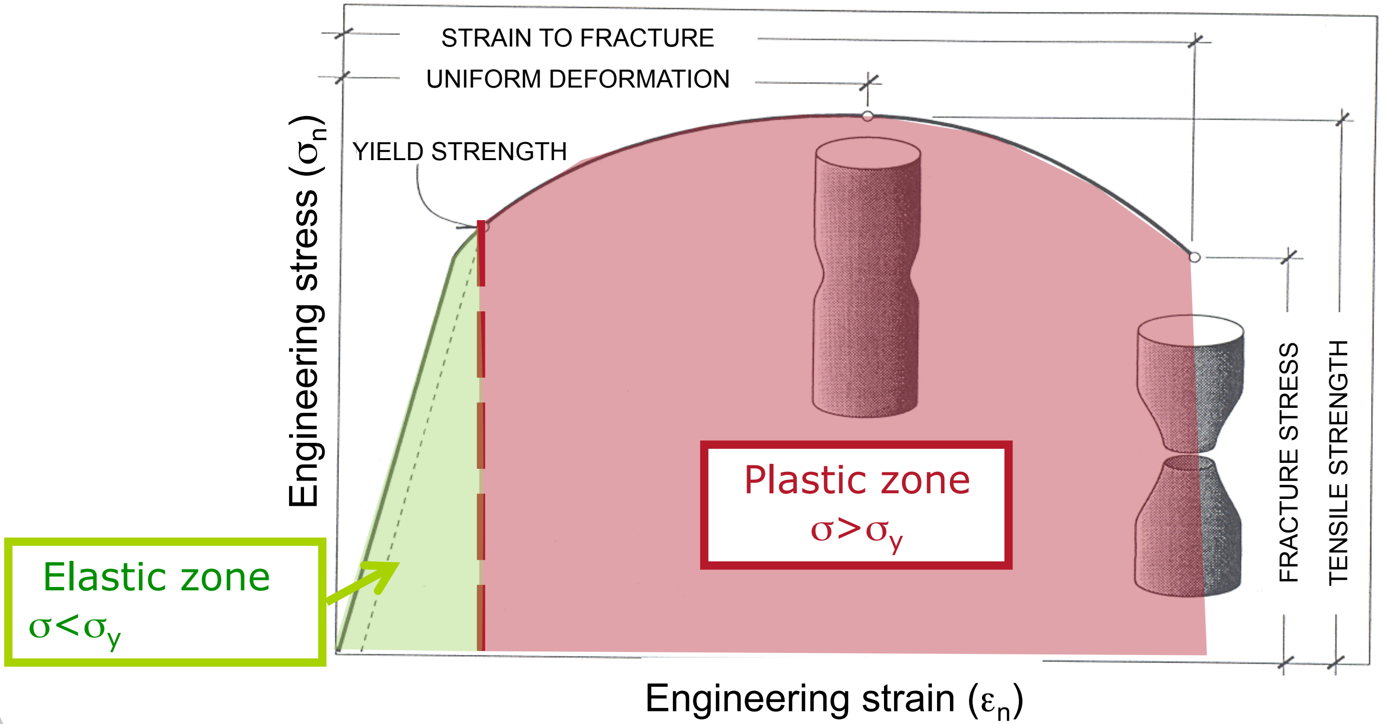
Nominal stress (σ_n):

$$\sigma_n = \frac{F}{A_0}$$

- MPa (10^6 N/m²)
- psi (pounds/inch²)

Nominal strain (ε_n):

$$\varepsilon_n = \frac{l - l_0}{l_0}$$



yielding occurs at the onset of plastic or permanent deformation

STRESS-STRAIN CURVE: ELASTIC ZONE $\sigma<\sigma_y$

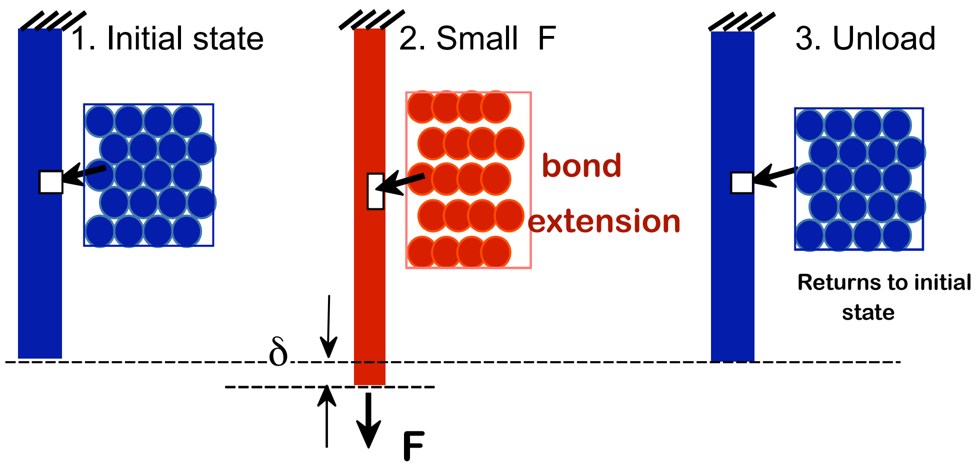
When the load is removed ⇒ The specimen recovers its original shape

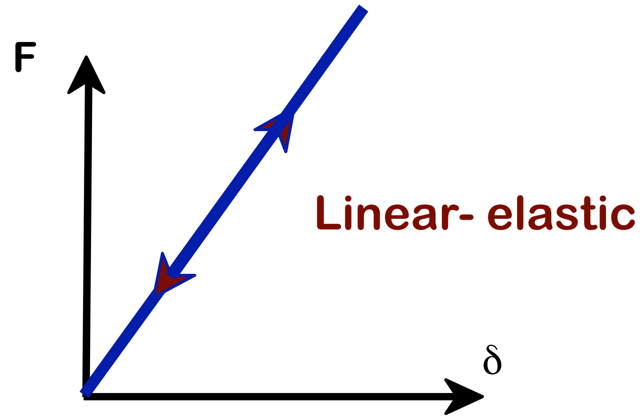
E: Young's Modulus or Elastic Modulus

Stiffness of material or resistance to elastic deformation

a) Linear

$$\sigma = E\ \varepsilon$$ *Hooke's law*





Elastic means reversible!

STRESS-STRAIN CURVE: ELASTIC ZONE $\sigma<\sigma_y$

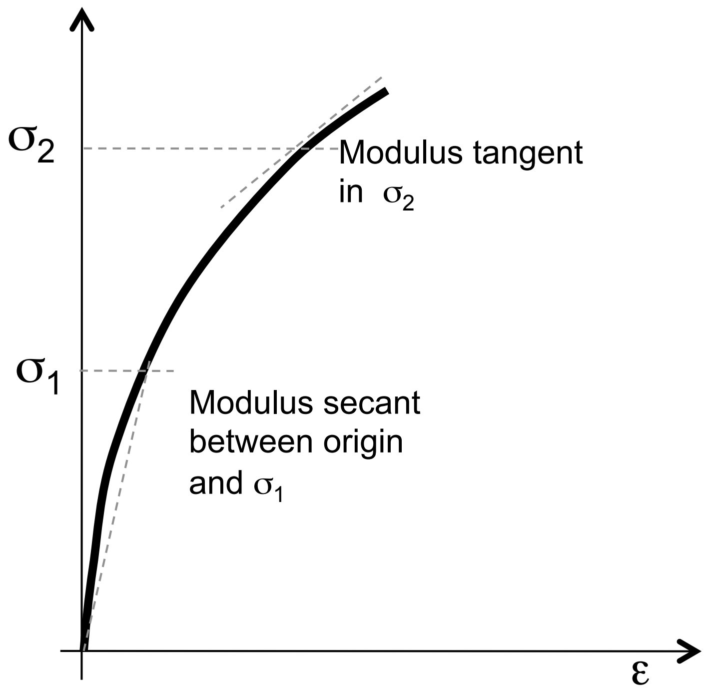
When the load is removed ⇒ The specimen recovers its original shape

E: Young's Modulus or Elastic Modulus

Stiffness of material or resistance to elastic deformation

b) <u>Non linear</u>

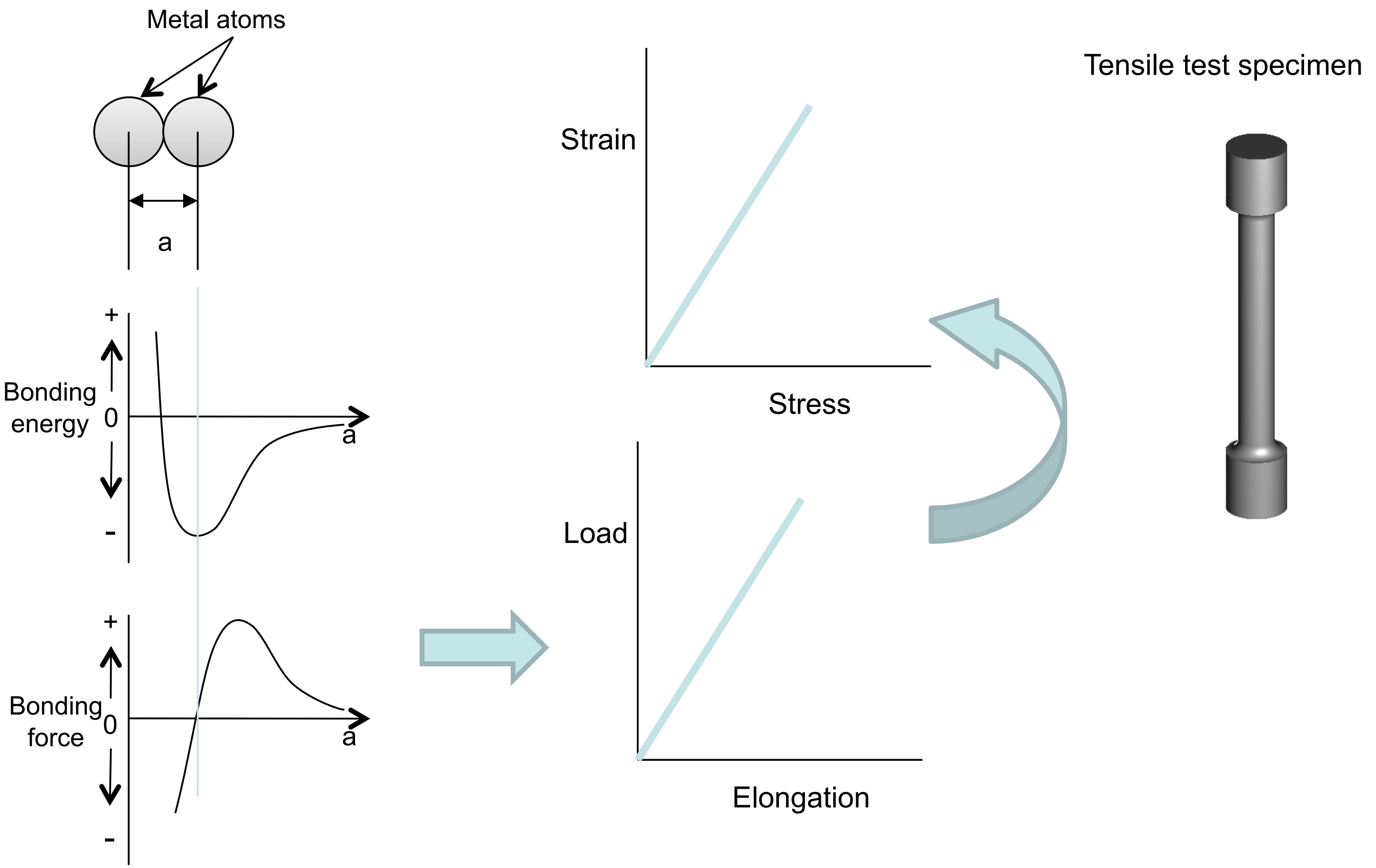
It is produced in some materials (some polymers, concrete, gray cast irons)



ELASTIC DEFORMATION: ATOMIC SCALE

The atoms tend to ⇒ minimize energy.

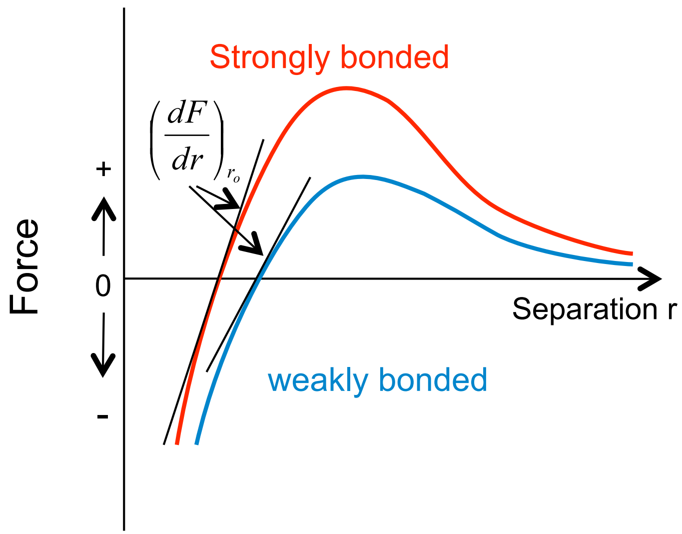
Position of atoms = f (bond, attractive forces…)



ELASTIC DEFORMATION: ATOMIC SCALE

E= f (bond strength)⇒ if ↑ bond strength ⇒ ↑E

Mechanism associated with Elastic deformation= Bonds relaxation.



At atomic scale the macroscopic elastic deformation it appears as small changes in the interatomic space and the bonds between atoms are stressed

(the atoms are displaced from the original positions without reaching other positions)

$$E \propto \left(\frac{\partial F}{\partial r}\right)_{r_0}$$

Material	Modulus E (GPa)	Density ρ (Mg m^{-3})	Specific modulus E/ρ (Gpa/Mg m^{-3})
Steels	210	7.8	27
Al alloys	70	2.7	26
Alumina Al_2O_3	393	3.9	100
Silica SiO_2	69	2.6	27
Cement	45	2.4	19

$E_{ceramics} > E_{metals} > E_{polymers}$

Bond force ↔ T melting

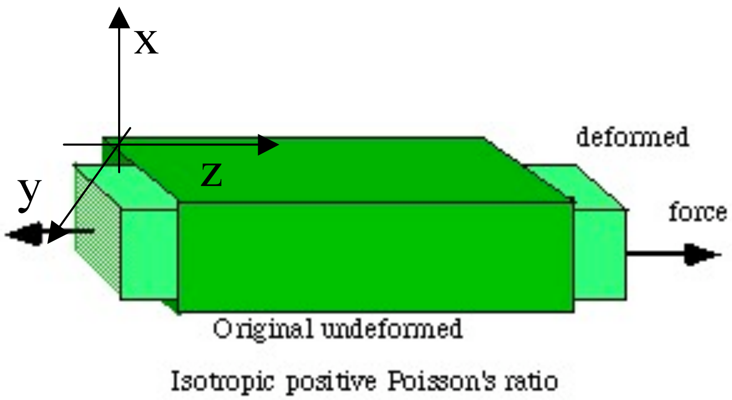
E VALUES FOR DIFFERENT MATERIALS

Material	Modulus of Elasticity (GPa)	Modulus of Elasticity (10^6 psi)
Metal alloys		
Tungsten	407	59
Nickel	207	30
Titanium	107	15
Ceramic Materials		
Alumina (Al_2O_3)	393	57
Silicon nitride Si_3N_4	345	50
Zirconia	205	30
Magnesium Oxide (MgO)		
Soda-lime glass	69	10
Polymers		
PVC	2.41-4.14	0.35-0.60
PET	2.76-4.14	0.40-0.60
PS	2.28-3.28	0.33-0.47
PMMA	2.24-3.24	0.33-0.47
HDPE	1.08	0.16

STRESS-STRAIN CURVE: ELASTIC ZONE $\sigma<\sigma_y$

Poisson's ratio ≅ Relation between transverse and axial strain

All **elastic** longitudinal deformation⇒ Δdimensional transverse



For $F = F_z$

$$\upsilon = \frac{-\varepsilon_{\text{transverse}}}{\varepsilon_{\text{longitudinal}}} = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$$

Ideal materials: υ=0.5

Real materials : υ=0.2-0.4

	υ
natural rubber	0,499-0,49
Polymers	0,3-0,45
Metals	0,25-0,4

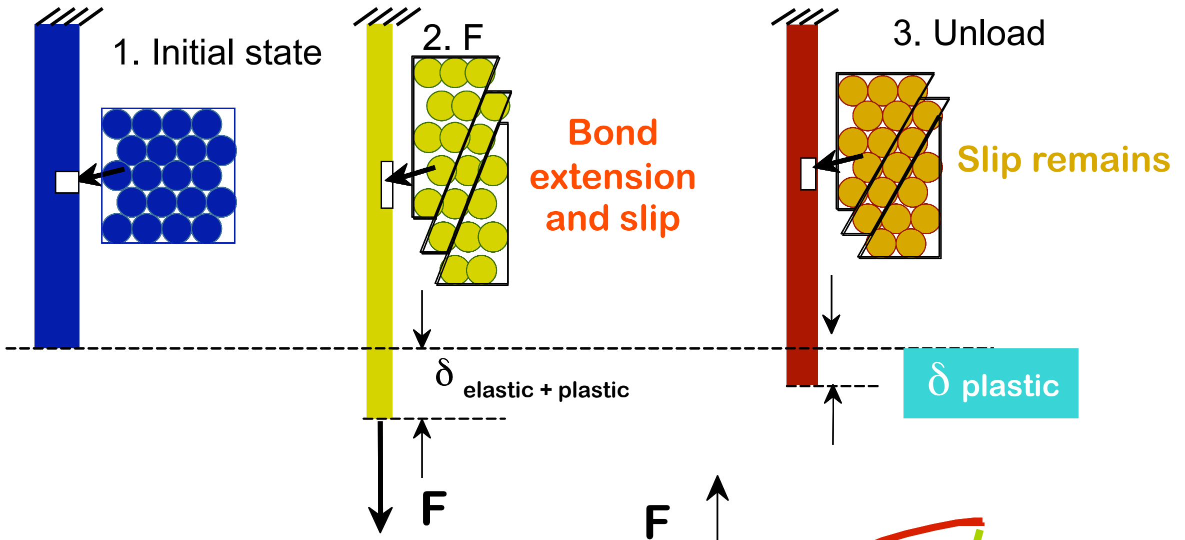
STRESS-STRAIN CURVE: PLASTIC ZONE $\sigma > \sigma_y$

ε is not proportional to $\sigma \Rightarrow$ Permanent deformation

- If $F=0 \Rightarrow \varepsilon > 0$

In the majority of metals $\varepsilon_{plastic\ max.} = 0{,}5\%$

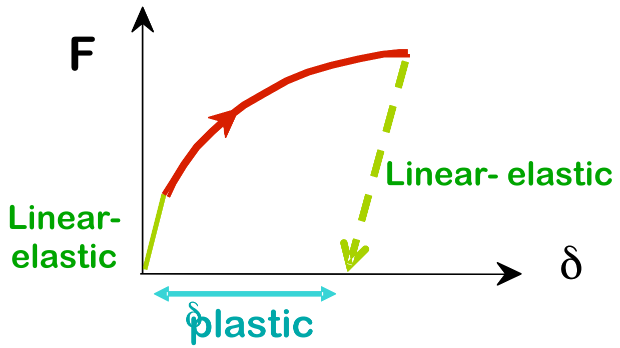
Breaking and formation of new bonds $\Rightarrow$ no recovering of initial form



Dislocations movement

Forming through deformation

Plastic means permanent !



The atoms are displaced permanently from their initial positions to new positions

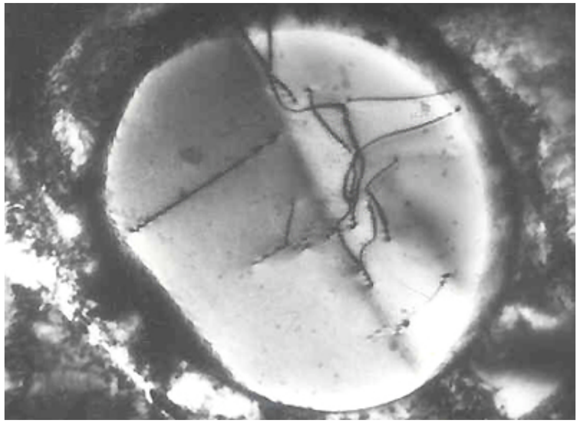
PLASTIC DEFORMATION: SLIPPING OF DISLOCATIONS

Gliding of dislocations

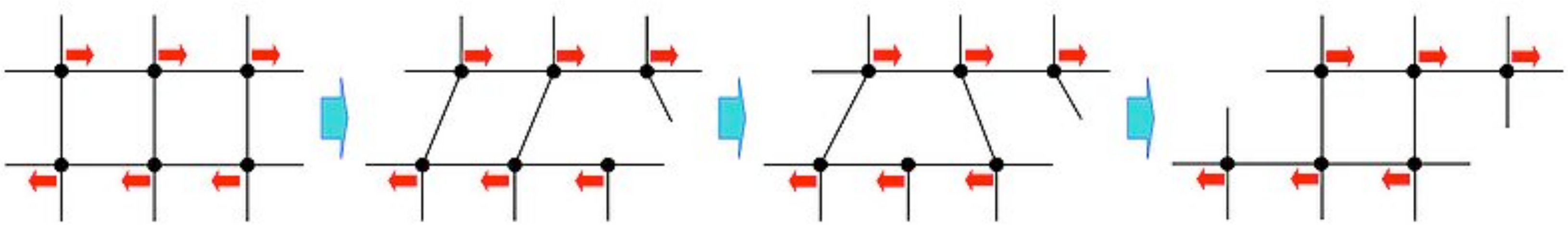
- ε_P **without dislocations:** we have to break simultaneously various bonds and remake them through slipping.
- ε_P **with dislocations:** The breakage and formation of bonds is sequential ➔ Lower energy consumption→ When dislocations are moving, it is easier to glide atoms

Consequences: they could be displaced inside the crystal with relatively low forces and produce the complete displacement on crystalline planes .

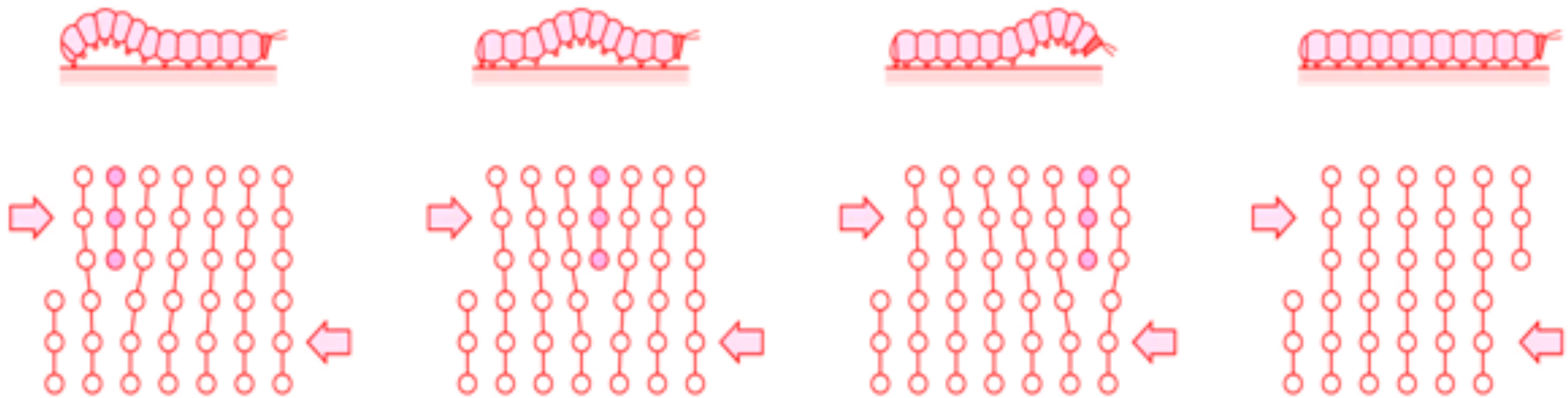
Explain:
- Plastic deformation in metals (workability and ductility)
- $E_{theoretical} > E_{exp}$.



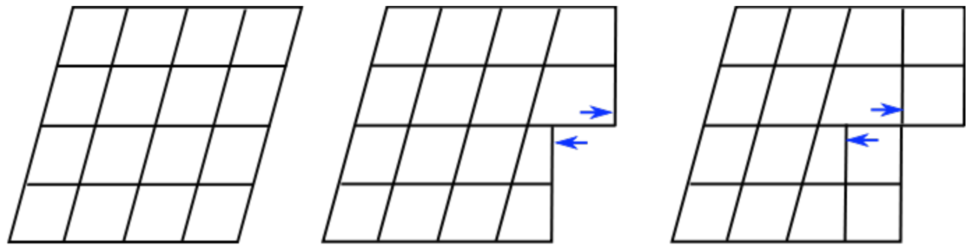
TEM micrograph of (precipitate and dislocations in austenitic stainless steel http://en.wikipedia.org/wiki/File:TEM2.jpg



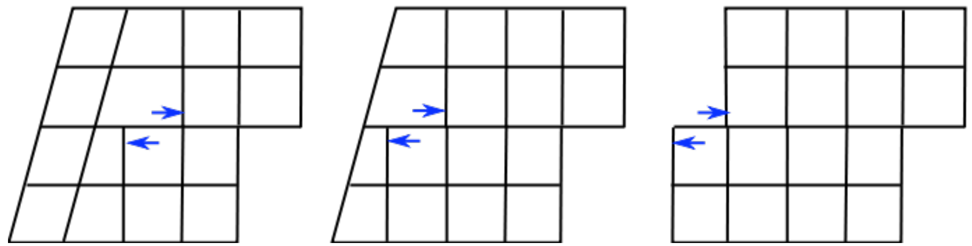
PLASTIC DEFORMATION: SLIPPING OF DISLOCATIONS



For plastic deformation without dislocations: several bonds have to be broken simultaneously and remade after sliding.



Dislocations allow for a step by step (incremental) breaking and creation of bonds: much less energetic cost!

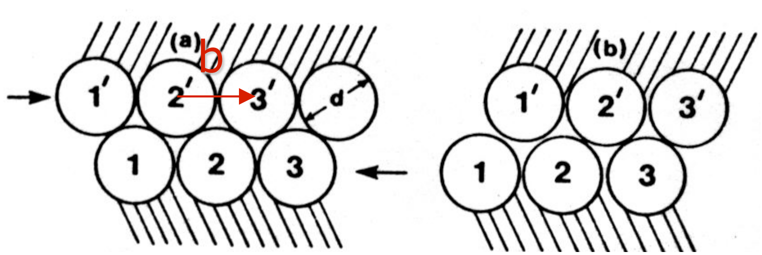


PLASTIC DEFORMATION: SLIPPING OF DISLOCATIONS

Dislocations movement parallel to the directions of maximum packing ⇨ smaller burgers vector (repeat distance) and greater distance between planes ⇨ easy slipping

E used to move a dislocation= $E \propto |b|^2$

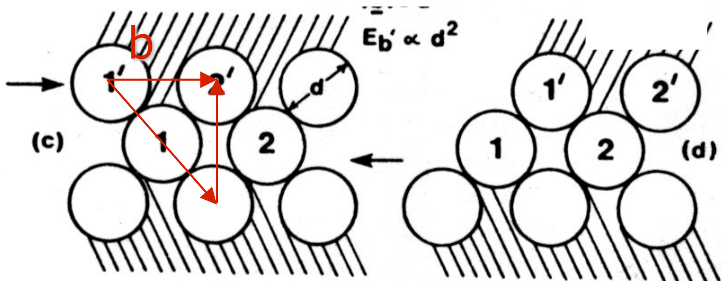
Compact Direction



$|b| = 2R$

$E_b \propto 4R^2$

NON Compact Direction



$$b^2 + b^2 = (4R)^2 \Rightarrow b = 2\sqrt{2}\cdot R$$

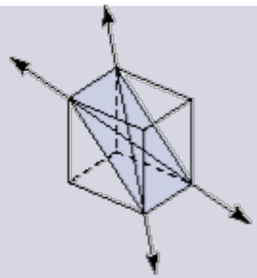
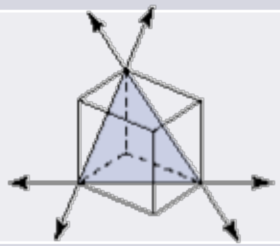
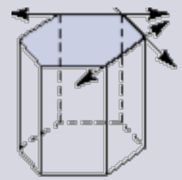
$E_b \propto 8R^2$

A.R. West. "Solid State Chemistry and its applications". Wiley.Chichester,1992

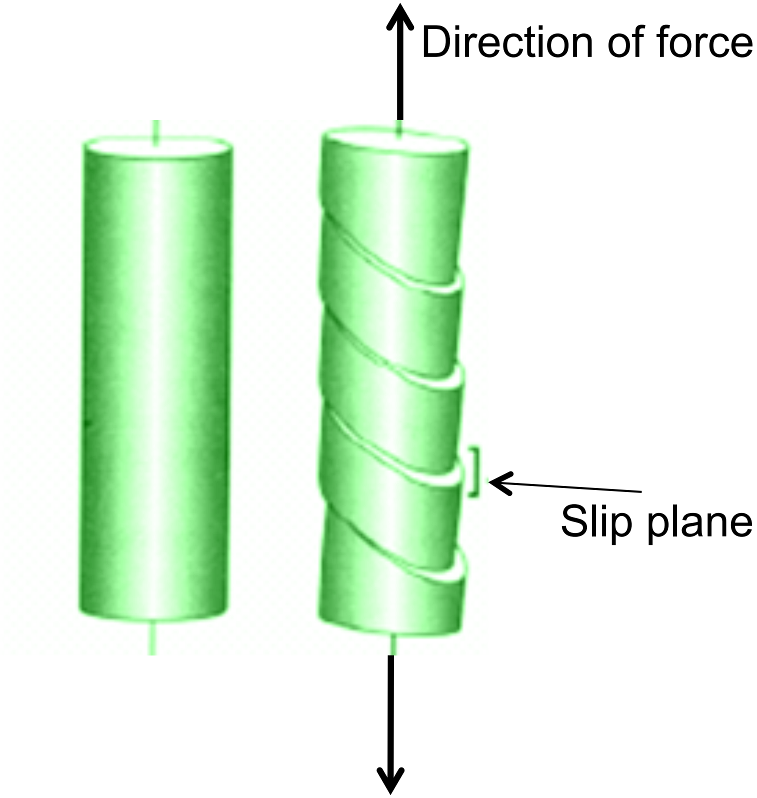
PLASTIC DEFORMATION: SLIP SYSTEMS

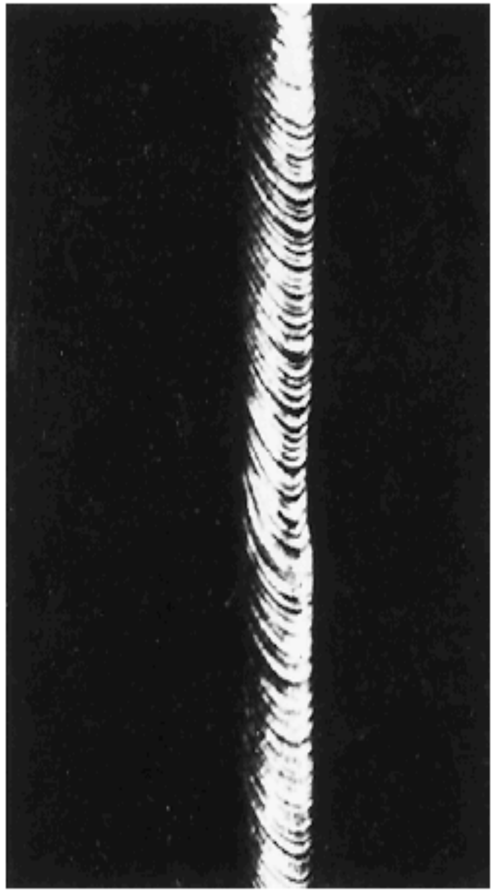
- Permanent plastic deformation takes place when the atoms slip between them.
- Slip occurs along specific crystallographic planes that depend on the structure

Slipping directions and planes ⇨ **SLIPPING SYSTEMS**

Crystal Structure	Slip plane	Slip diraction	Number of slip systems	Examples	Unit cell geometry
bcc	{110}	<111>	12	α-Fe, Mo, W	
fcc	{111}	<110>	12	Al, Cu, γ–Fe, Ni	
hcp	(0001)	<1120>	3	Cd, Mg, α-Ti, Zn	

PLASTIC DEFORMATION: SLIP SYSTEMS





Slip in a zinc single crystal. (From C. F. Elam, *The Distortion of Metal Crystals*, Oxford University Press, London, 1935.)

In a single crystal slip commences on the most favorably oriented slip system when the resolved shear stress reaches some critical value.

Slip occurs at various positions along the specimen length along a number of equivalent and most favorably oriented planes and directions

STRESS-STRAIN CURVE: CALCULATION OF THE YIELD STRESS

Yield stress (σ_y) or Yield Strength

σ above which permanent deformation is produced

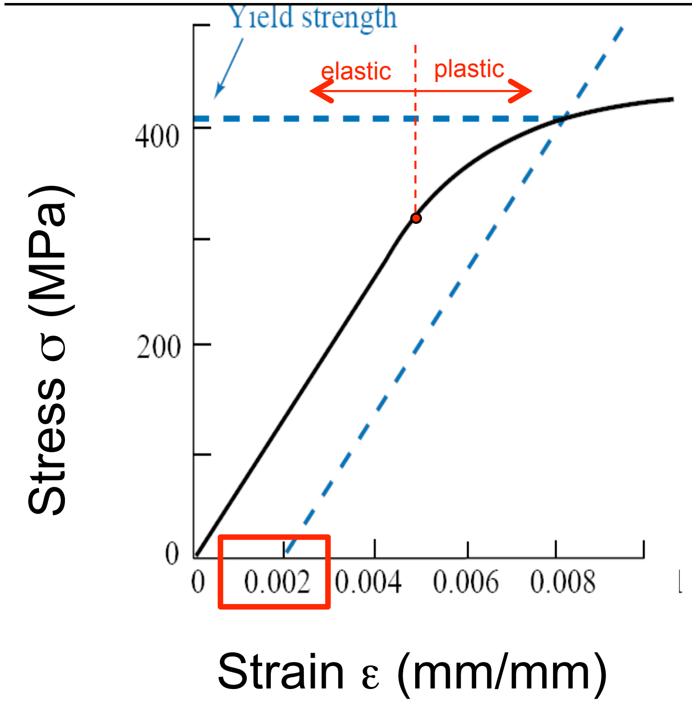
$F \neq 0$, $\varepsilon_t = \varepsilon_e + \varepsilon_p$
$F = 0$, $\varepsilon_t = \varepsilon_p$

Design parameter

Criteria for the calculation of the Yield Stress

Depending on the deformation of material we adopt ≠ criteria

Conventional Yield Stress: The most frequently used in metals ≈ 0,2% of ε



$\sigma_y = \sigma$ (0,2% of ε)

STRESS-STRAIN CURVE: CALCULATION OF THE YIELD STRESS

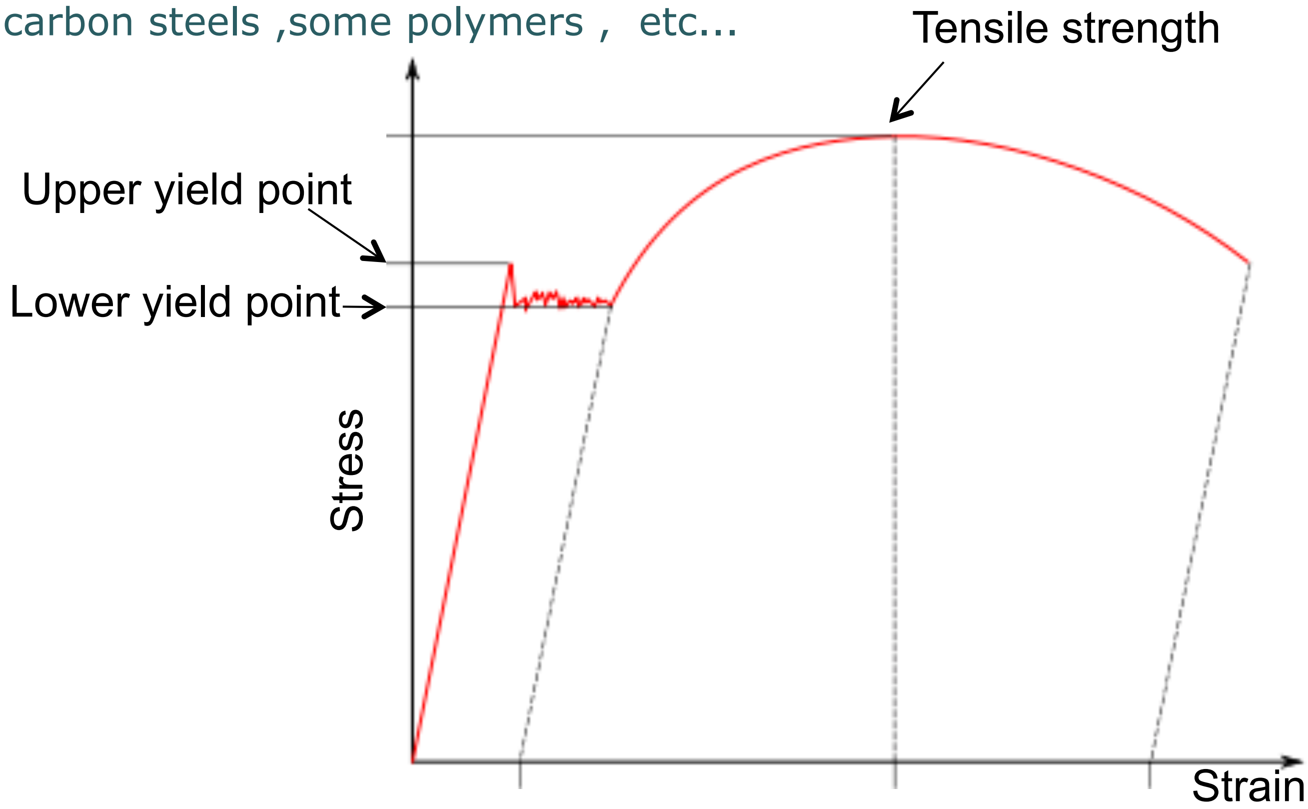
Yield stress (σ_y) or Yield Strength

σ above which permanent deformation is produced

Criteria for the calculation of the Yield Stress

Depending on the deformation of material we adopt ≠ criteria

Discontinuity phenomena in the yield point:
Low carbon steels ,some polymers , etc...



$$\sigma_y = \frac{\sigma_{max} + \sigma_{min}}{2}$$

STRESS-STRAIN CURVE: SECURITY FACTOR

Due to the variability in mechanical properties

Design $\Rightarrow \sigma_{security}$ (σ_w) working stress

$$\sigma_w = \frac{\sigma_y}{N}$$

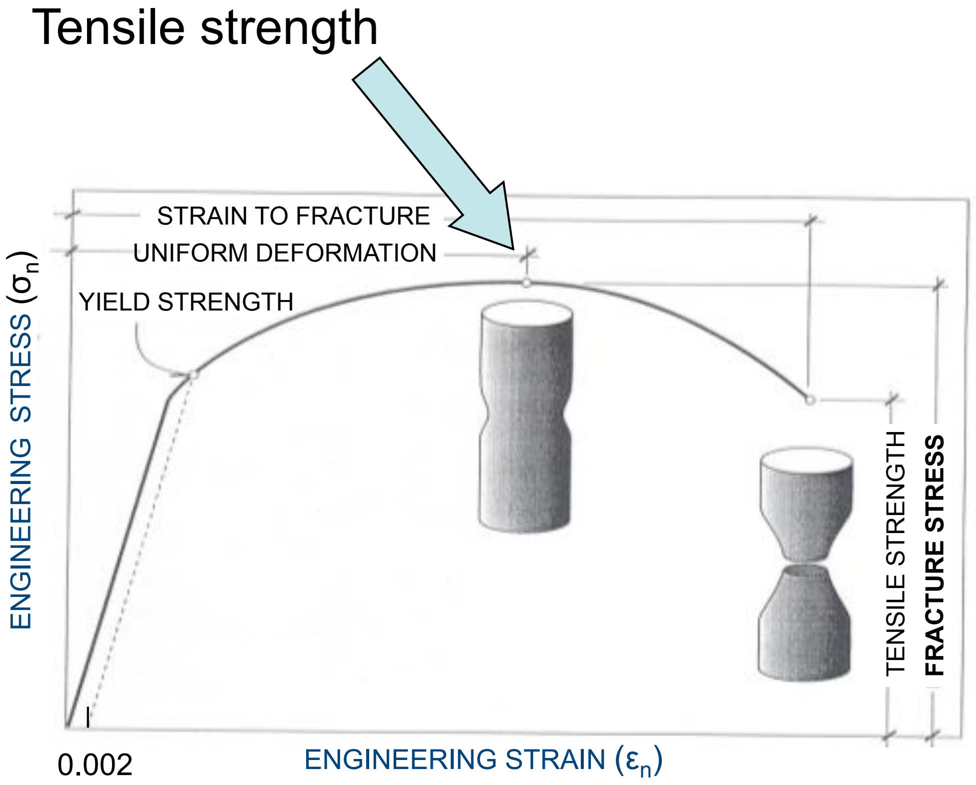
σ_y = yield strength

N= 1.2 –4 (+ usually 2)

STRESS-STRAIN CURVE: CALCULATION OF UTS AND $\sigma_{fracture}$

Tensile Strength or Ultimate Tensile Strength (UTS)

Maximum nominal stress that supports the specimen under tension



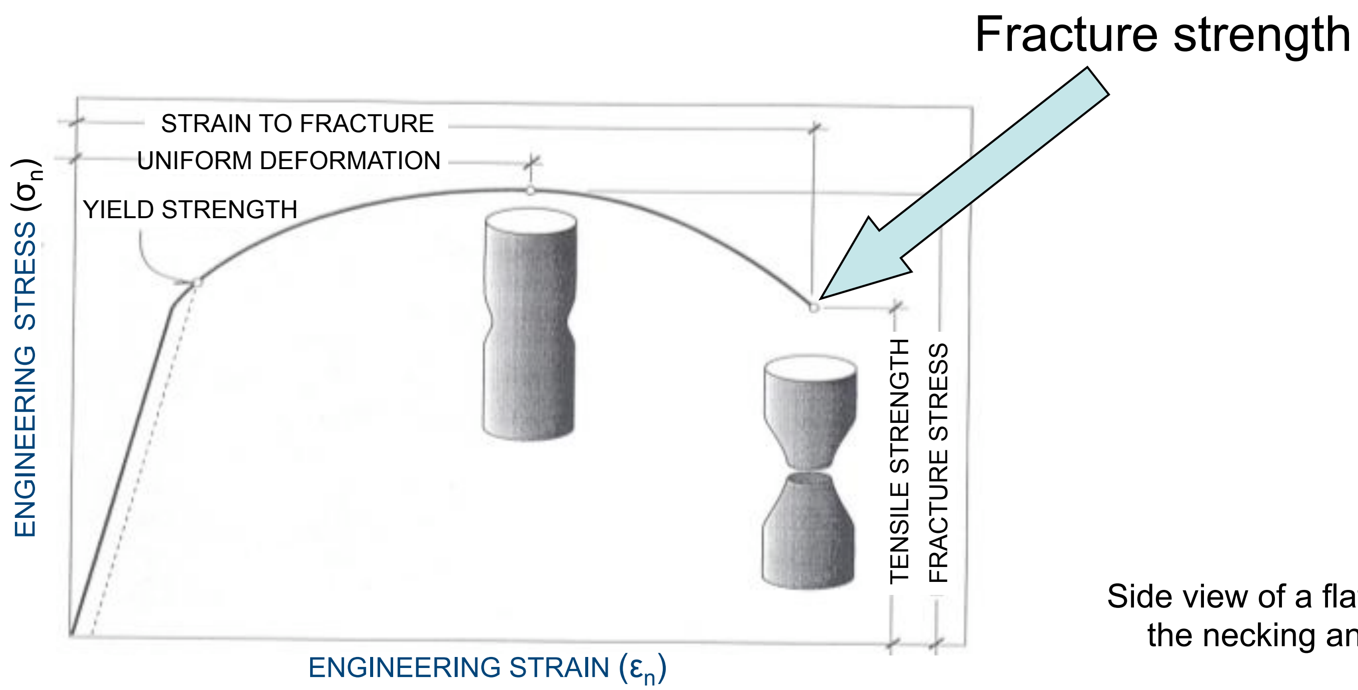
James F. Shackefold, Introduction to materials science for engineers, Prentice Hall

Necking of the material begins at maximum stress

STRESS-STRAIN CURVE: CALCULATION OF UTS AND $\sigma_{fracture}$

Fracture stress or Fracture strength

Stress that the material supports at the point of fracture



Side view of a flat broken tensile sample, showing the necking and the 45° direction of fracture.

The more ductile the material, the higher the amount of "necking" or constriction,

The $\sigma_{fracture}$ gives an idea of the presence of defects (porosity, inclusions) in the material if the value is very low

STRESS-STRAIN CURVE: DUCTILITY

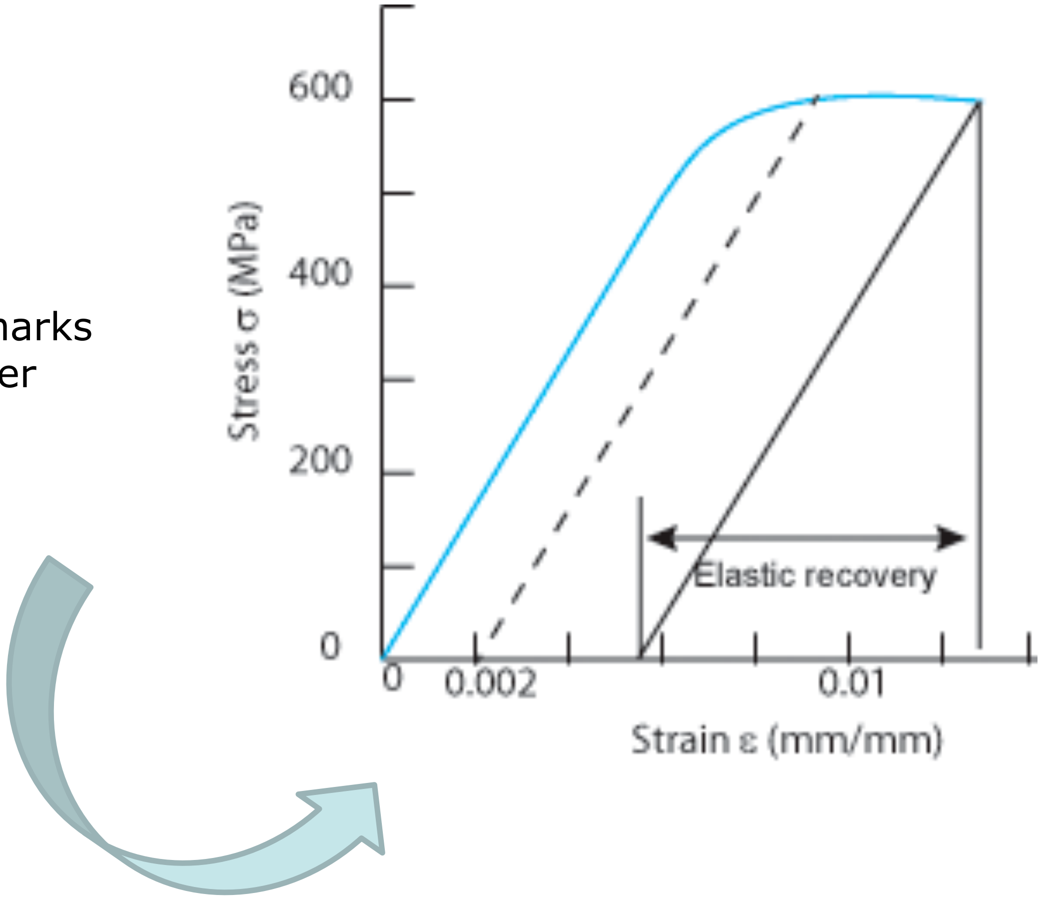
It is a measure of the degree of plastic deformation grade that can be supported by a material before fracture, f(T)

% Elongation after failure *Percentage of plastic strain at fracture*

$$EL(\%) = \frac{l_f - l_0}{l_0} x\, 100$$

l_o is the initial gauge length between marks
l_f is the final length between marks after fracture

It is measured once the specimen has fractured ➔ The material has recovered the elastic deformation



Before fracture F≠0 , $\varepsilon_t = \varepsilon_e + \varepsilon_p$
After fracture F=0, $\varepsilon_t = \varepsilon_p$

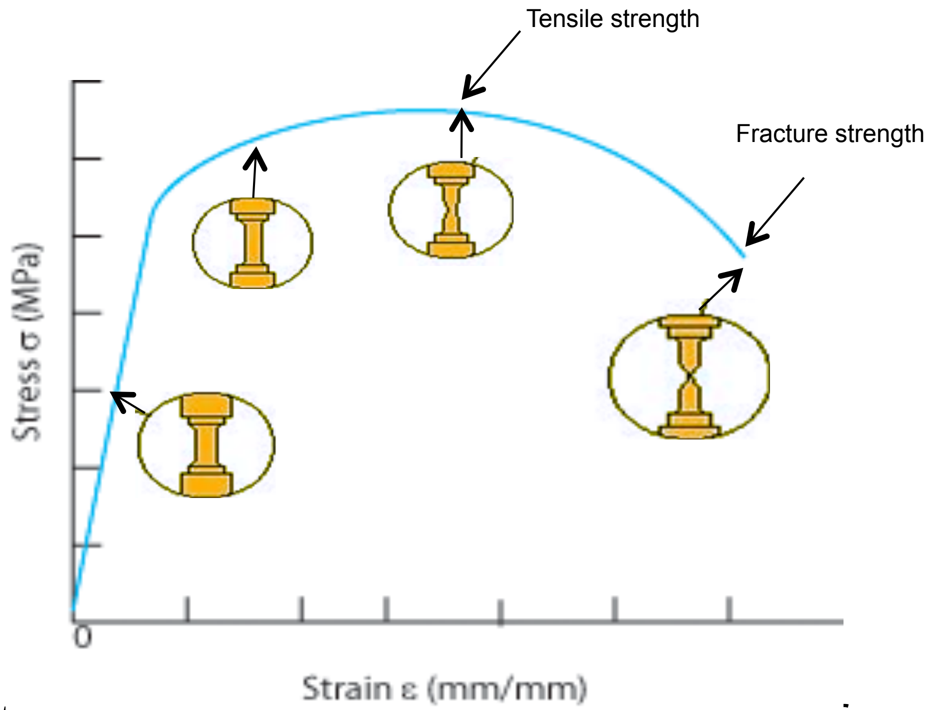
STRESS-STRAIN CURVE: DUCTILITY

% Reduction in area (constriction)

$$RA(\%) = \frac{A_0 - A_f}{A_0} \times 100$$

It is measured when the specimen has fractured. A_o is the initial cross sectional area

A_f is the final cross sectional area

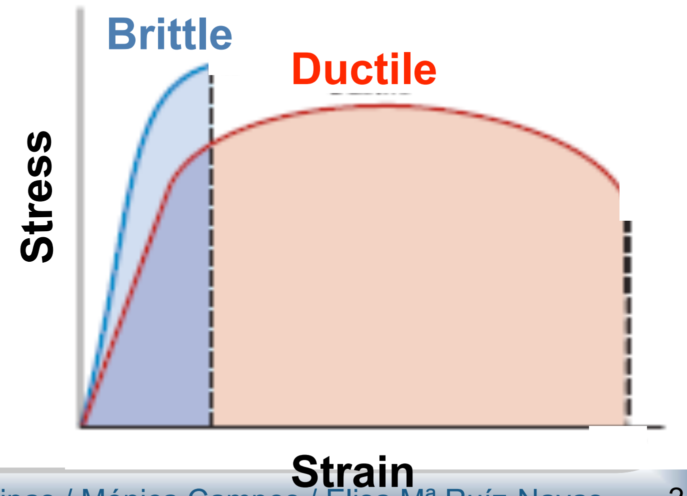


Normally ε (%) ≠ AR(%)

The ductility indicates to the designer up to what point a material can deform before it fractures and how many forming operations can be performed. Eg.: lamination

Area under the curve

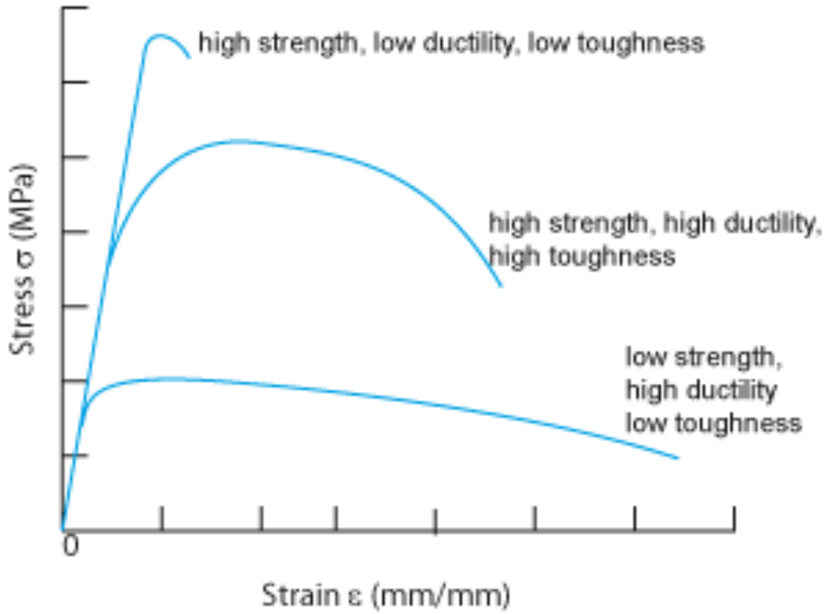
It is a measure of **toughness**: "Ability to absorb energy up to fracture, by elastic and plastic deformation



STRESS-STRAIN CURVE: TOUGHNESS

"Ability of a material to absorb energy up to fracture, by elastic and plastic deformation"

$E_{\text{elastic+plastic deformation}}$ per unit Volume (Pa or J/m^3)



- Important in structural applications
- Ability to absorb energy

(protection and security systems, automotion)

- Fracture type (ductile, brittle)
- Fracture toughness

The stress-strain curve gives the ability of the material to absorb energy up to fracture, by elastic and plastic deformation

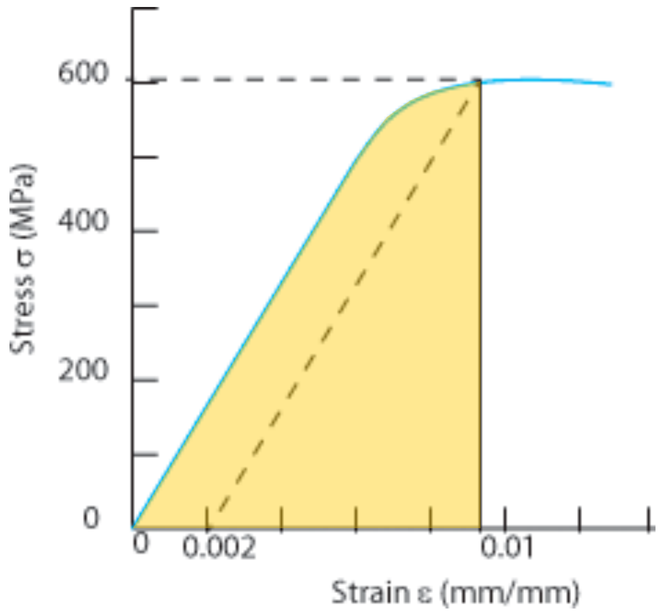
STRESS-STRAIN CURVE : RESILIENCE

Modulus of Resilience U_r

Capacity of a material to absorb $E_{elastic}$ when it is deformed elastically.

$E_{deformation}$ per unit Volume (Pa or J/m^3) necessary to deform a material up to the yield point

Area under the curve



$$U_r = \int_0^{\varepsilon_y} \sigma \, d\varepsilon$$

Integrating, if the elastic region is linear

$$U_r = \frac{1}{2} \sigma_y \varepsilon_y$$

$$\varepsilon_y = \frac{\sigma_y}{E} \quad \text{(Hooke's law)}$$

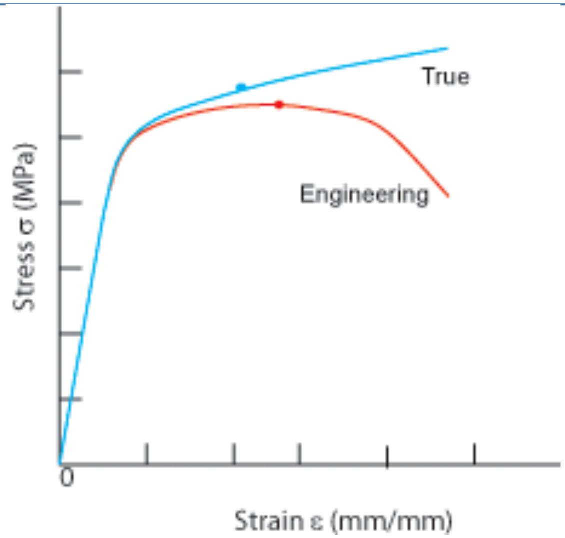
$$U_r = \frac{1}{2} \frac{\sigma_y^2}{E}$$

Materials with ⇑ Resilience:
↑ σ_y ↓E

Application: alloys to fabricate springs

TRUE STRESS-STRAIN CURVES

Original dimensions change during the test $\Rightarrow \sigma_{real} > \sigma_{eng}$ and $\varepsilon_{real} < \varepsilon_{eng}$



True Strain: when the strains are large (plastic zone) the longitudinal base changes during the test.

$$\varepsilon_r = \frac{L_1 - L_0}{L_0} + \frac{L_2 - L_1}{L_1} + \frac{L_3 - L_2}{L_2} + \ldots \rightarrow \varepsilon_r = \int_{L_0}^{L} \frac{dL}{L} = \ln \frac{L}{L_0}$$

$\rightarrow$ We define $L = L_0 (1 + \varepsilon_{eng})$

Before necking

$\Rightarrow$ $\varepsilon_r = \ln(1 + \varepsilon_{eng})$

After necking

After necking: deformation is not uniform. The volume affected remains the same $\Delta V = 0 \Rightarrow$ it is true that $AL = A_0 L_0$

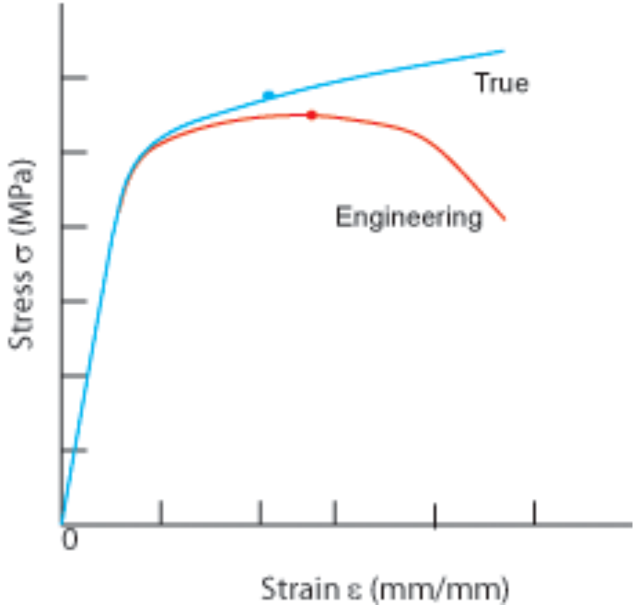
$$\varepsilon_r = \ln \frac{A_0}{A} = 2 \ln \frac{D_0}{D}$$

A: area at any instant

A_0: initial area

TRUE STRESS-STRAIN CURVES

Original dimensions change during the test $\Rightarrow$ $\sigma_{real} > \sigma_{eng}$ y $\varepsilon_{real} < \varepsilon_{eng}$



True or real stress (σ_r):

$$\sigma_r = \frac{F}{A} = \frac{F}{A_0}\frac{A_0}{A} = \sigma_{eng}\frac{A_0}{A}$$

Since $\Delta V = 0 \Rightarrow$ it is true that $AL = A_0 L_0$

$$\sigma_r = \sigma_{eng}\frac{L}{L_0} = \sigma_{eng}(1+\varepsilon_{eng})$$

(until the beginning of necking)

$$\sigma = \frac{F_i}{A_i}$$

After necking:

STRENGTHENING MECHANISMS

The plastic deformation ➔ dislocations movement

A restriction exists towards the movement of dislocations ➔ ↑ Necessary stress to activate the slip system ➔ STRENGTHENING

TYPES:

- Strain Hardening
- Solid Solution Strengthening
- Precipitation Hardening
- Grain Size Reduction Strengthening.

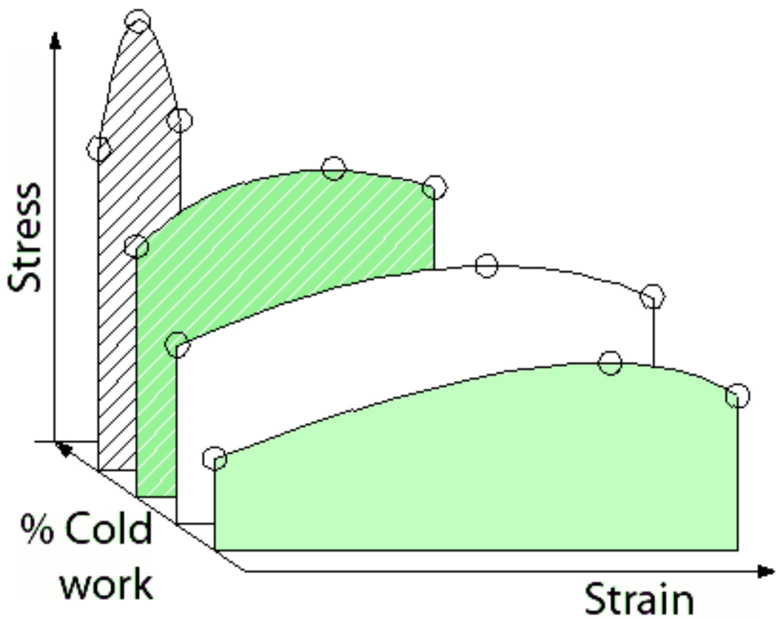
STRAIN HARDENING

It is the increase in strength and hardness when a material is plastically deformed

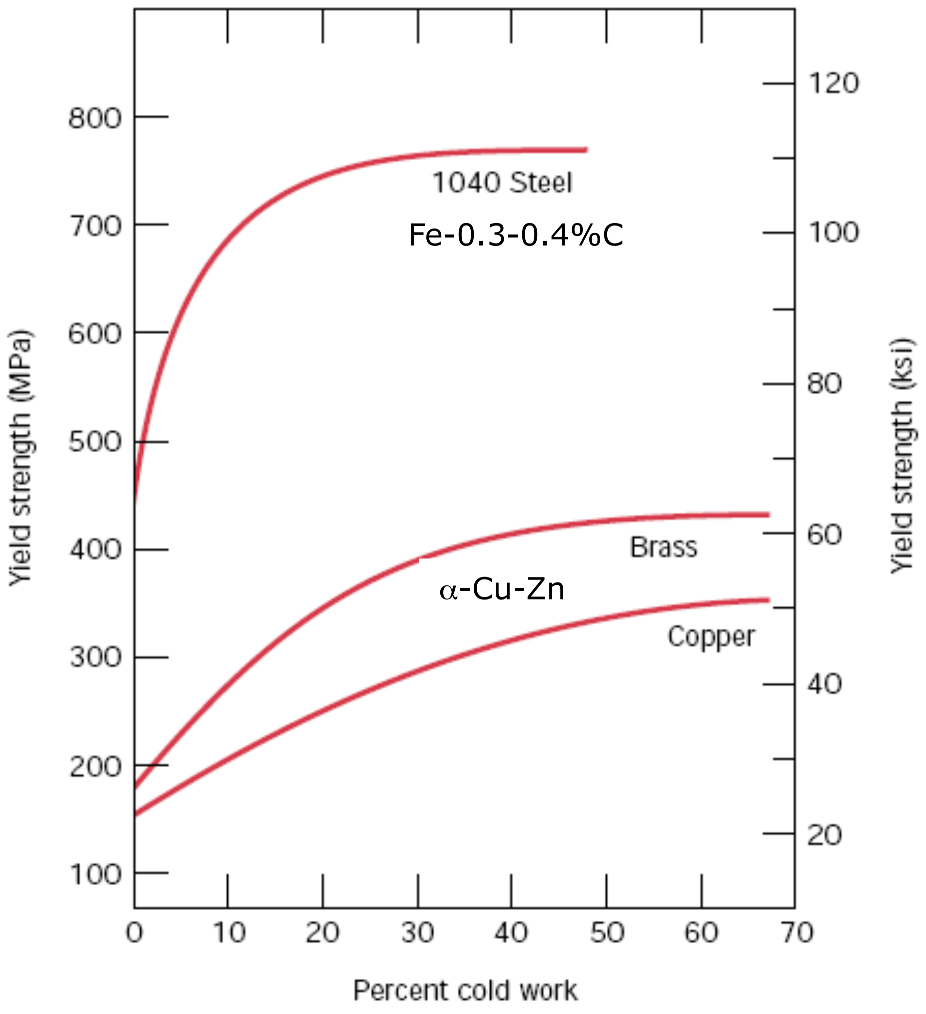
The cold plastic deformation generates dislocations (of 10^6 m/m^3 to 10^{12}m/m^3) and the increase in dislocation density makes difficult further plastic deformation

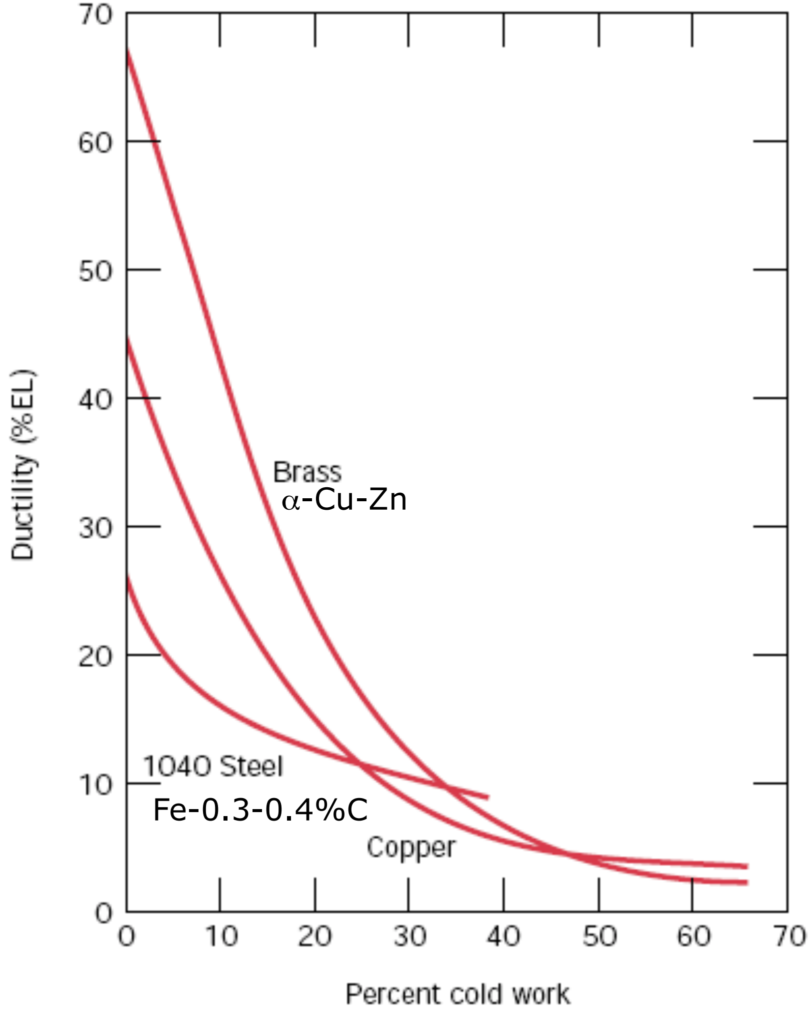
⇒A material hardened through plastic deformation requires greater forces to be applied in order to obtain the components ⇒ Machines of greater capacity

⇒ If it is considered in the process design ⇒ during processing the strength and hardness of the material ↑ ⇒ material cost ↓



STRAIN HARDENING





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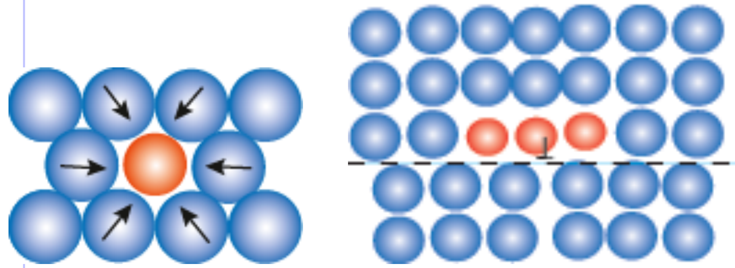
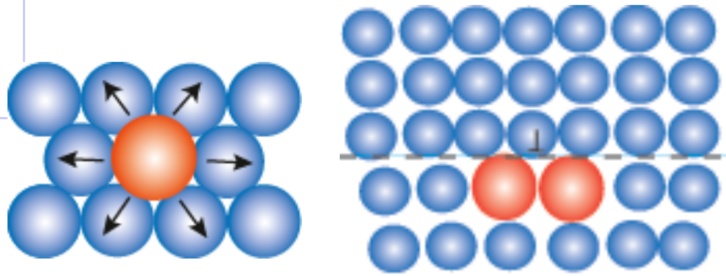
SOLID SOLUTION STRENGTHENING

Interstitials

A vacancy occupied by a solute of **smaller radius**: atoms of the solvent submitted to **tension**

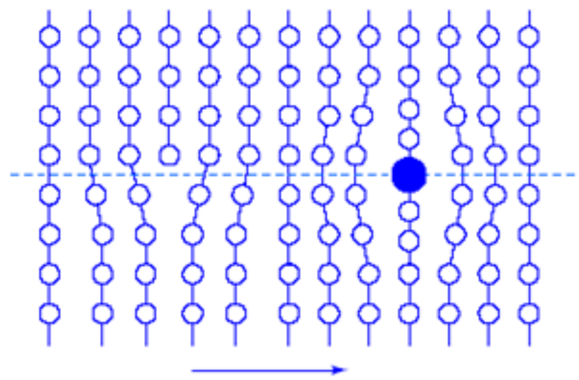


A vacancy occupied by a solute of **greater radius**: atoms of the solvent submitted to **compression**



Lattice Distortion

The movement of dislocations becomes difficult



Hardening

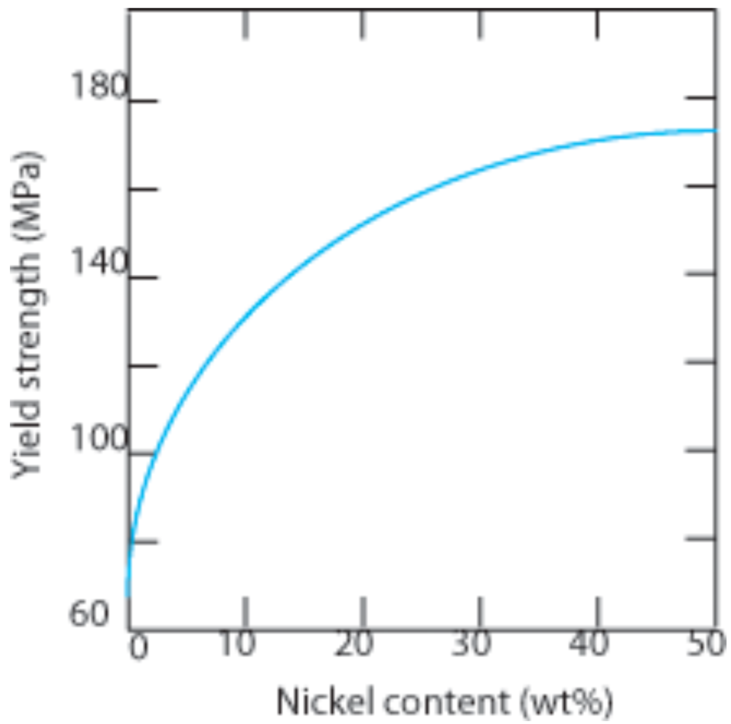
SOLID SOLUTION STRENGTHENING

Alloying elements:

- Improve mechanical properties (yield strength, UTS,hardness)

-Decrease ductility, $R_{corrosión}$, $\sigma_{electric}$

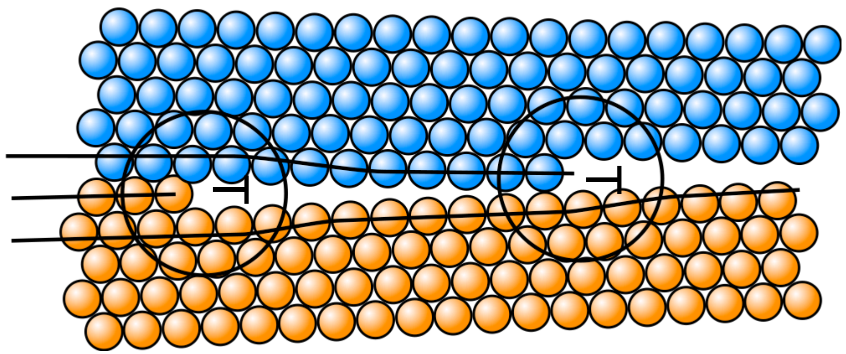
Cu-Ni

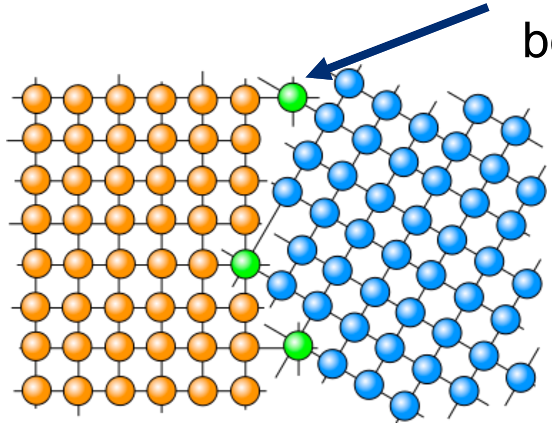


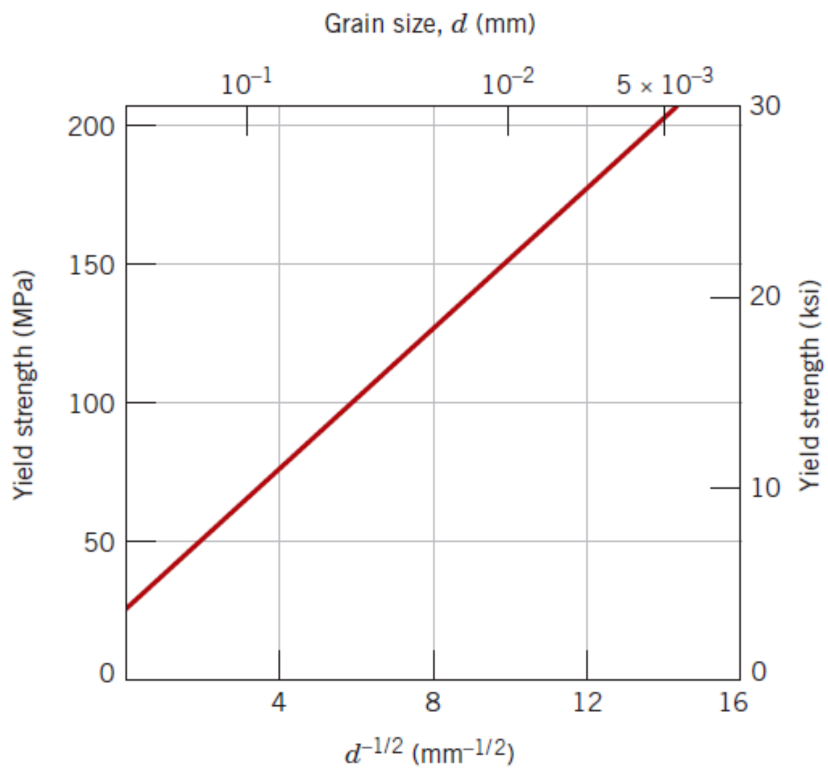
GRAIN SIZE REDUCTION STRENGTHENING

The grain boundaries separate crystals with different orientation.
The grain boundary width: 2-5 interatomic spaces

The grain boundary makes difficult dislocations sliding ➔ **Angle between grains**







http://commons.wikimedia.org/wiki/File:Joint_de_faible_desorientation.svg
http://commons.wikimedia.org/wiki/File:Joint_de_grain_reseau_coincidence.svg

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