Plastic deformation and strengthening

How to achieve strength?

41680 Introduction to advanced materials

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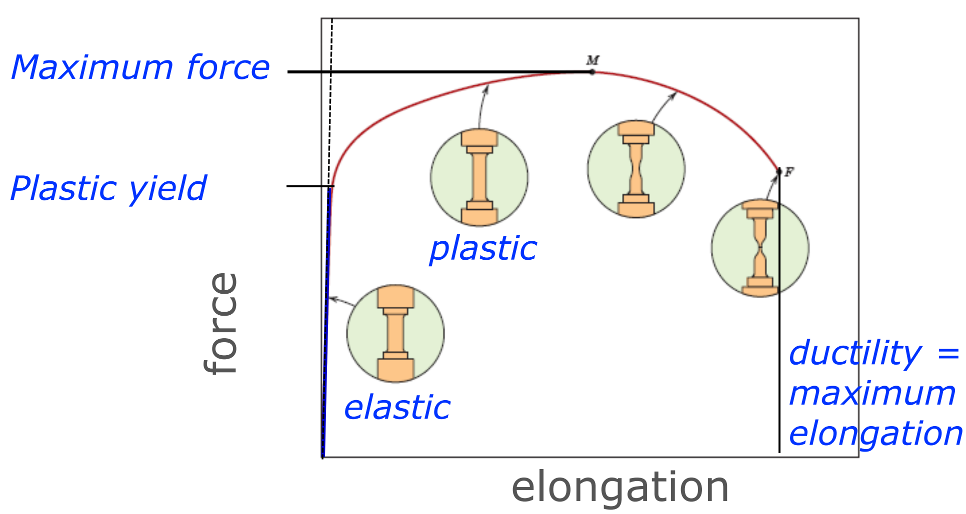
Tensile testing

- Elastic behavior - reversible
- Plastic behavior - irreversible



Tensile testing

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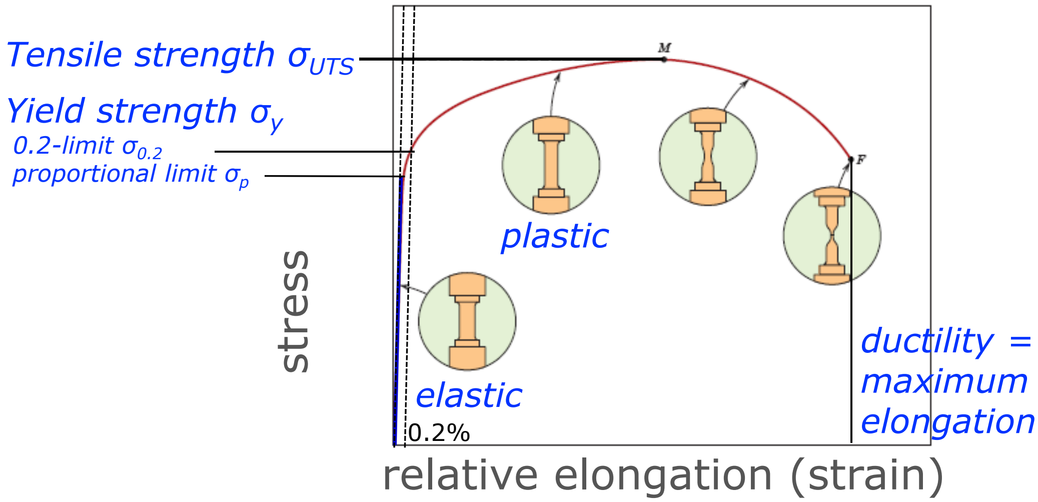
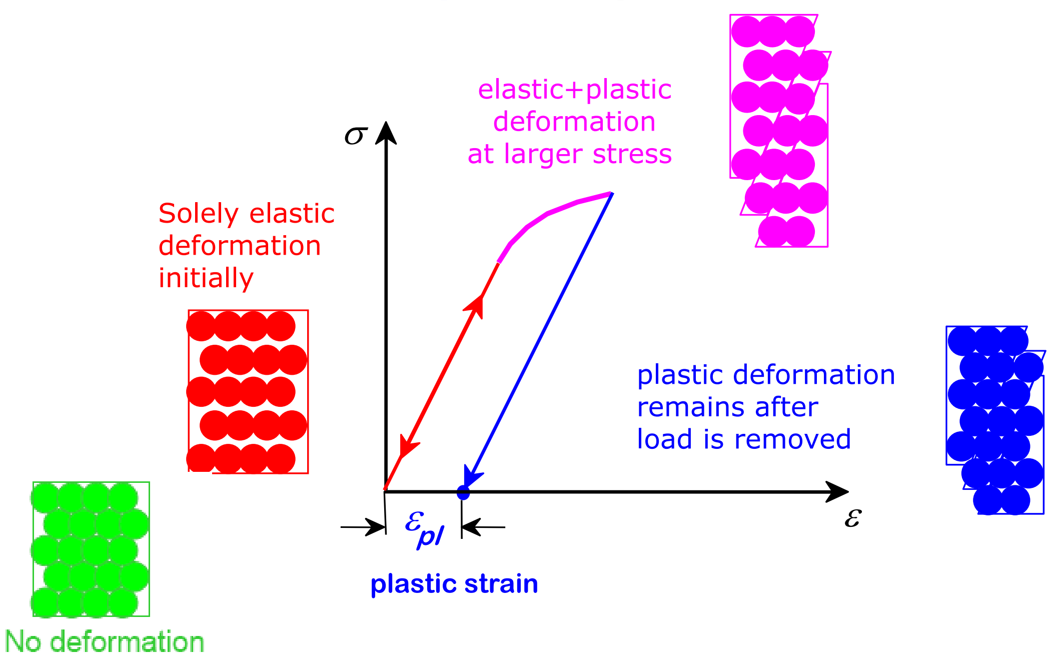
- Plastic behavior - irreversible



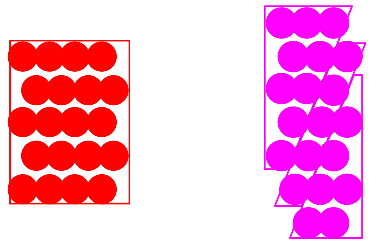
Stress-strain curve

elastic = reversibel, plastic = permanent deformation



Theoretical critical shear stress

- Shear (relative displacement) of lattice planes

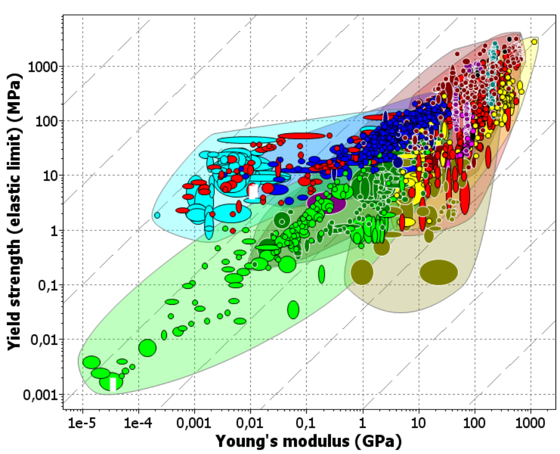


- Shear test
  - Shear modulus $\tau = G\gamma$
  - Elastic isotropy $G = \dfrac{E}{2(1+\nu)}$
- Theoretical critical shear stress

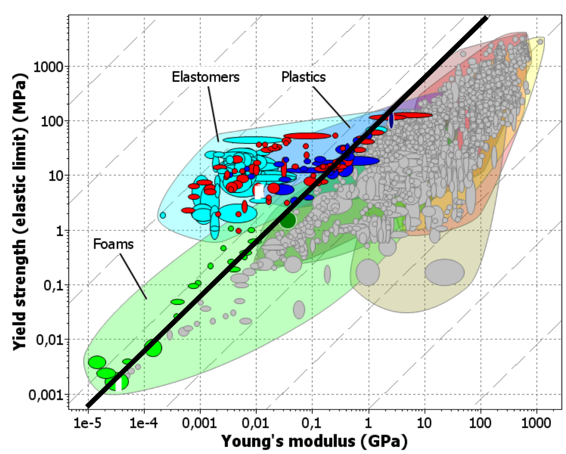
$$\tau_{th} = G/20$$

Property maps

- Correlation between yield strength and *E*



- Theoretical yield strength (defect-free material) $\sigma_{th} = E/20$



Elastomers	$\sigma > \sigma_{th}$	Chains, entropy
General	$\sigma \ll \sigma_{th}$	Defects

Lattice defects

0-dimensional: point defects
vacancies, interstitials, substitutional atoms

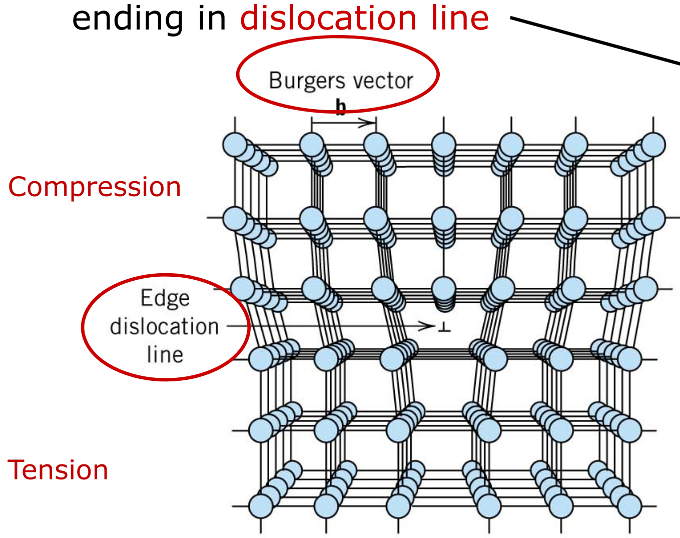
1-dimensional: line defects
dislocations

2-dimensional: area (planar) defects
interfaces (stacking faults, grain-, phase-, twin-boundaries, surfaces)

3-dimensional: volume (bulk) defects
voids, pores, precipitations, inclusions, cracks

Line defects
Dislocations

Extra lattice plane inserted in crystal,
not extending through all of the crystal (half-plane),
ending in dislocation line



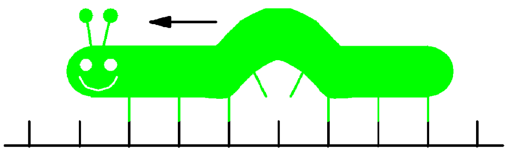
Lattice disturbed along line
→ one-dimensional defect

Edge dislocation

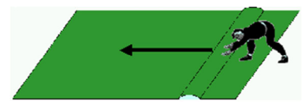
Burgers vector
is a lattice vector

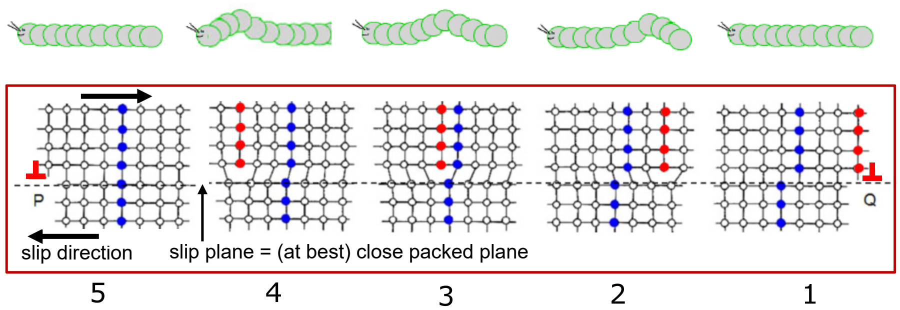
Line defects
Dislocations as carrier of plastic deformation

- Caterpillar technique



- same trick as moving a carpet



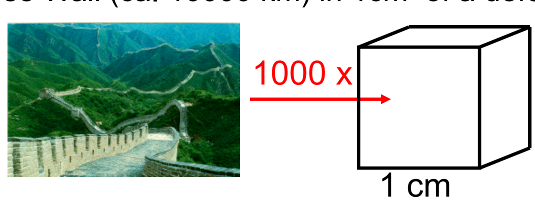


plastic deformation proceeds
- atomic step by atomic step
- by movement of dislocations

Line defects
Dislocation density

- Definition: dislocation line length per volume $\rho = \frac{L}{V}$
- SI unit m/m³ = m^{-2}
  - „dislocation-free“ Si (Si-technology): $\rho = 1\ \mathrm{cm}^{-2}$
  - good single crystals: $\rho \approx (10^3 - 10^5)\ \mathrm{cm}^{-2}$
  - polycrystalline materials: $\rho \approx (10^5 - 10^9)\ \mathrm{cm}^{-2}$
  - heavy deformed crystals: $\rho \leq 10^{12}\ \mathrm{cm}^{-2}$

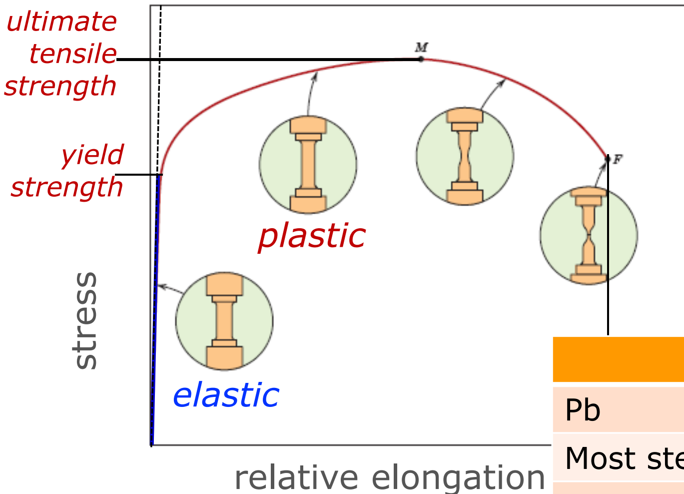
the Chinese Wall (ca. 10000 km) in 1cm³ of a deformed metal



Stress strain curve

- yield strength σ_y
- resistance to plastic deformation

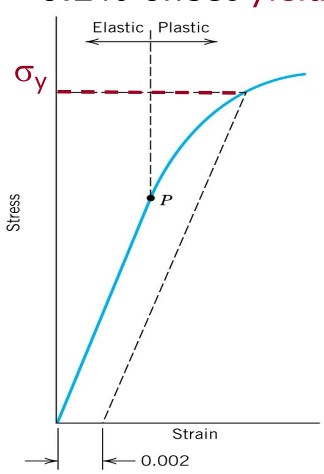
- ultimate tensile strength UTS
- marks the maximum achievable stress before failure (necking)



	UTS
Pb	10..20 MPa
Most steels	400..1200 MPa
Martensitic steels	2500..4500 MPa

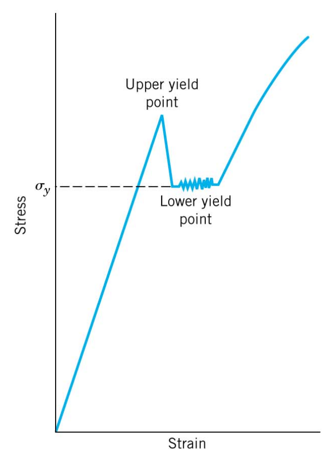
Stress strain curve
Yield strength

- Proof stress or 0.2% offset yield strength



0.2% plastic deformation

- Lower and upper yield point
- Special cases (e.g. steels): initially low dislocation density or initial pinning of dislocations



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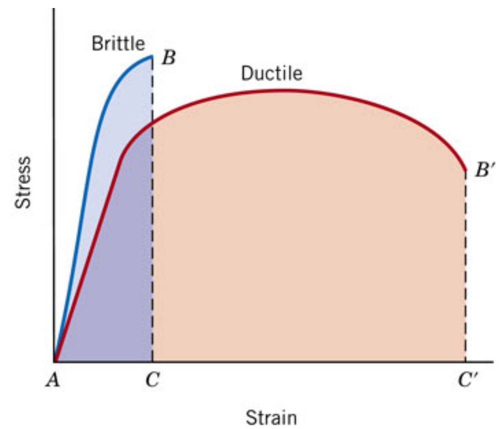
Tensile properties

Ductility

- =Strain to fracture ε_f
- – ability for shape changes without fracture
- – Opposite: brittleness

- Strain to fracture ε_f
  - brittle $\varepsilon_f < 0.1$ %
  - ductile $\varepsilon_f > 10$ %
  - super-plastic $\varepsilon_f \approx 1000$ %
- Depends on
  - material and temperature !!!
  - crystal structure dependent (number of slip systems)



Unit of toughness and resilience

$$1\ \frac{\mathrm{J}}{\mathrm{m}^3} = 1\ \frac{\mathrm{Nm}}{\mathrm{m}^3} = 1\ \frac{\mathrm{N}}{\mathrm{m}^2} = 1\ \mathrm{Pa}$$

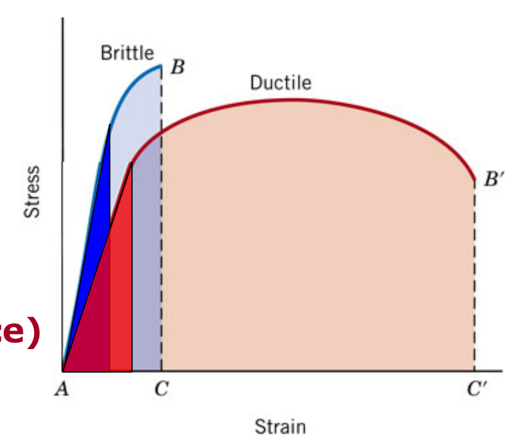
Tensile properties (continued)

Toughness

=Area under stress-strain curve up to point of fracture

=Mechanical work until fracture

- Resistance to fracture
- Brittle materials are less tough



Resilience (modulus of resilience)

=Area under stress-strain curve before yielding

=Mechancial work until yielding

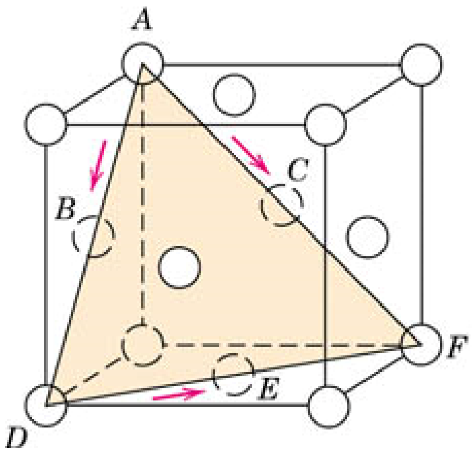
=Stored energy density in elastic regime

- Energy material can absorb without yielding
- Ability to absorb energy and remain elastic (e.g. materials for springs: high σ_y, low E)

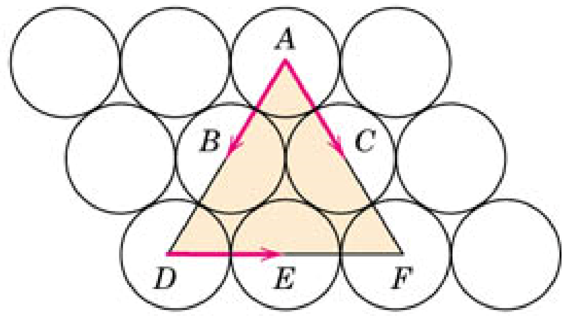
$$\frac{\sigma_y^2}{2E}$$

Slip systems in metals

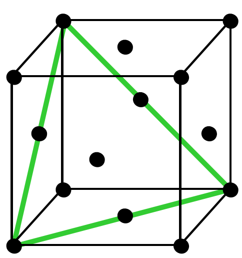
- plastic deformation = dislocation motion = slip (or glide)
- slip system: slip plane {hkl} + slip direction <uvw>
  closest packed plane + closest packed direction
  planes with largest distance + Burgers vector



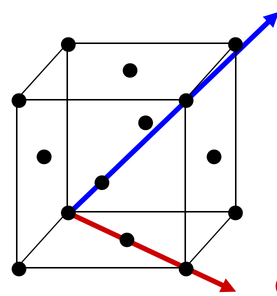
Example: fcc lattice



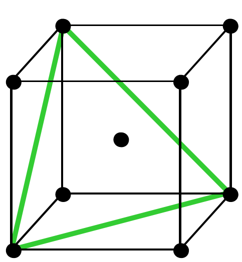
Close-packed planes (hkl) and directions [uvw]



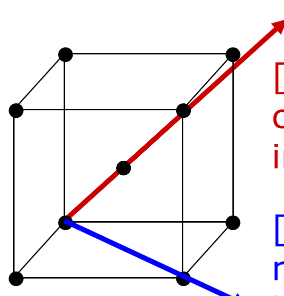
fcc



(111) plane: close-packed in fcc,
but not in bcc



bcc



Slip systems in metals

- plastic deformation = dislocation motion = slip (or glide)
- slip system: slip plane {hkl} + slip direction <uvw>
  closest packed plane + closest packed direction
  planes with largest distance + Burgers vector

Lattice	Examples	Close(st) packed planes (hkl)	Close(st) packed directions [uvw]	Slip systems
fcc	Al, Cu, Ag, Au, Ni, γ-Fe, …	{111} = close-packed	<110> face diagonals	4 x 3 = 12
bcc	Cr, W, α-Fe, …	{110} = not close-packed	<111> volume diagonals	6 x 2 = 12

Strengthening

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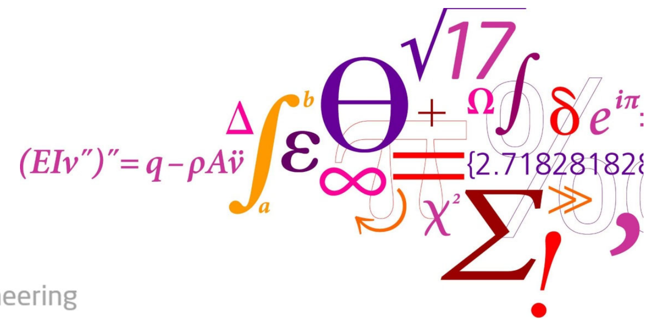
Strengthening

Several additional contributions to strength

$$\sigma = \sigma_0 + \Delta\sigma_{disl} + \Delta\sigma_{gb} + \ldots$$



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Strengthening mechanisms

- increase resistance against plastic deformation
- affect the mobility of dislocations
- create obstacles for dislocation movement

- Lattice defects are obstacles for dislocation motion
  - interaction via strain fields

	Defect	Strengthening mechanism
0D	Solute atoms	Solid solution hardening
1D	Dislocations	Work hardening
2D	Grain or phase boundaries	Grain boundary strengthening
3D	Precipitates	Precipitation hardening

- Depending on temperature, chemical composition, crystal structure, and microstructure

$$\sigma_y = \sigma_0 + \Delta\sigma_{ss} + \Delta\sigma_{disl} + \Delta\sigma_{gb} + \Delta\sigma_{prec}$$

Lattice defects

0-dimensional: point defects
vacancies, interstitials, substitutional atoms

1-dimensional: line defects
dislocations

2-dimensional: area (planar) defects
interfaces (stacking faults, grain-, phase-, twin-boundaries, surfaces)

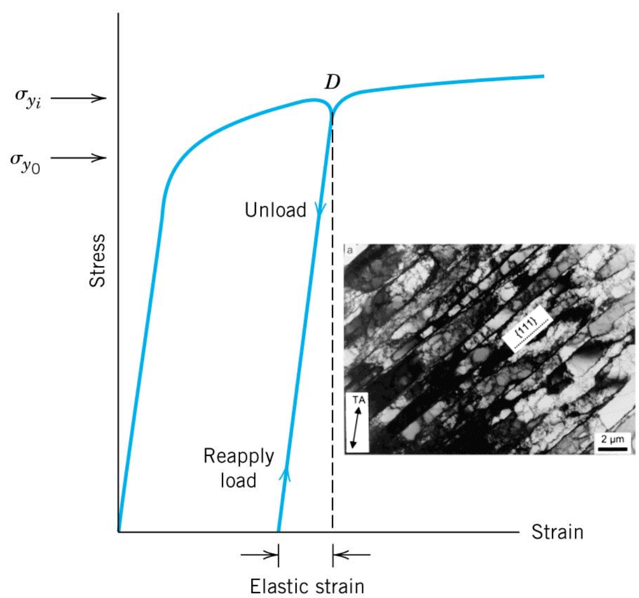
3-dimensional: volume (bulk) defects
voids, pores, precipitations, inclusions, cracks

Work-hardening or strain hardening

- Dislocation–dislocation interaction via their stress fields and mutual intersection
- Dislocation density increases with plastic deformation
- Glide of mobile dislocations is hindered by other dislocations
- Strengthening effect

$$\sigma = \sigma_0 + \Delta\sigma_{disl}$$
$$= \sigma_0 + M\alpha Gb\sqrt{\rho}$$

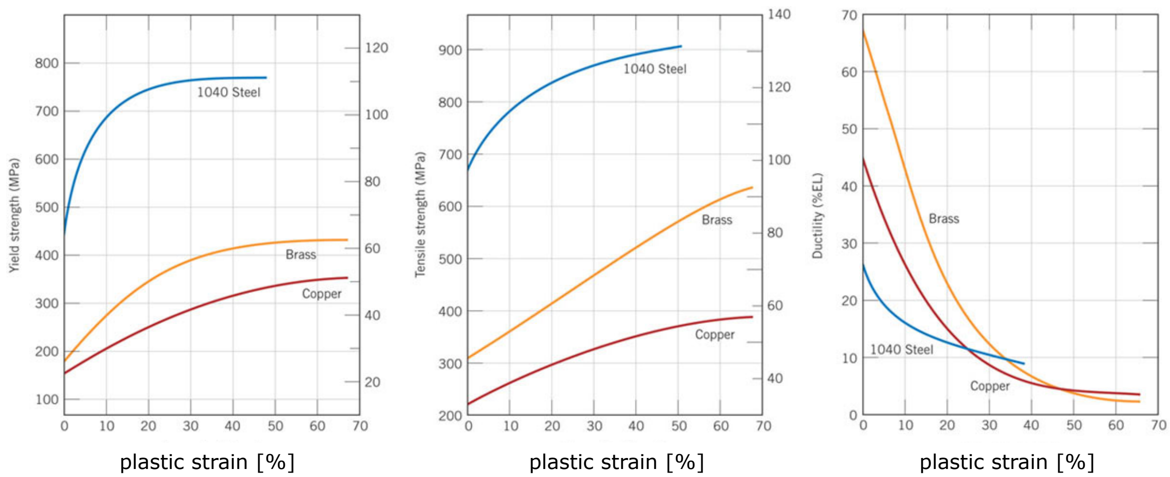
- Work hardening from increased dislocation density
- Ductility is reduced



Taylor factor $M \approx 3$
Interaction coefficient $\alpha \approx 0.5$
Shear modulus G
Burgers vector b

Examples for work-hardening

- Mechanical properties after pre-deformation



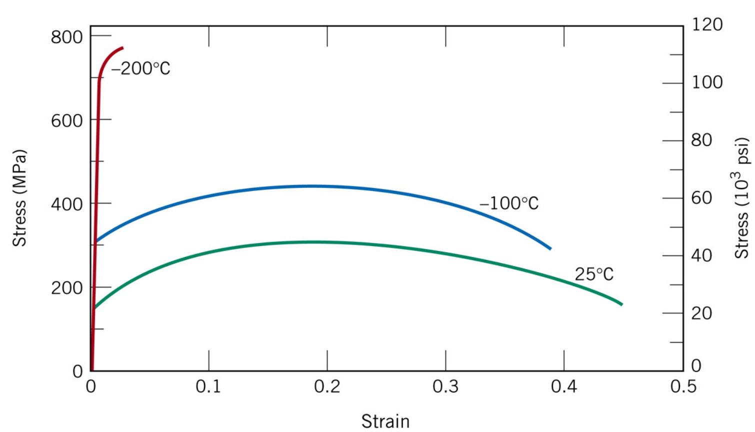
- Proper definition: plastic strain (in %) from pre-deformation
- Callister Rethwisch: percent cold work, e.g. area (A) reduction during cold rolling

$$r = \frac{|\Delta A|}{A_0} = \frac{A_0 - A}{A_0} = \varepsilon$$

Dependence on temperature

In general with increasing temperature:

- Strength decreases
- Ductility increases



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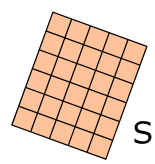
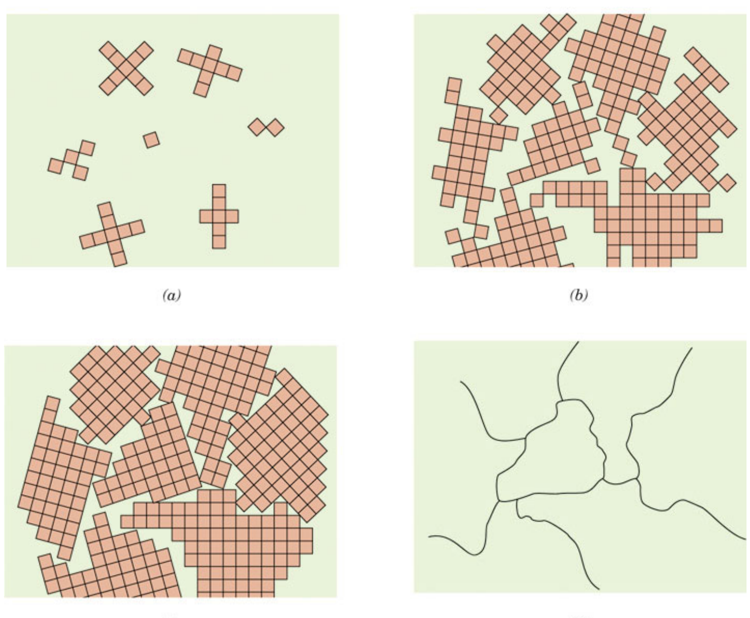
Planar defects
Grain boundaries in polycrystals



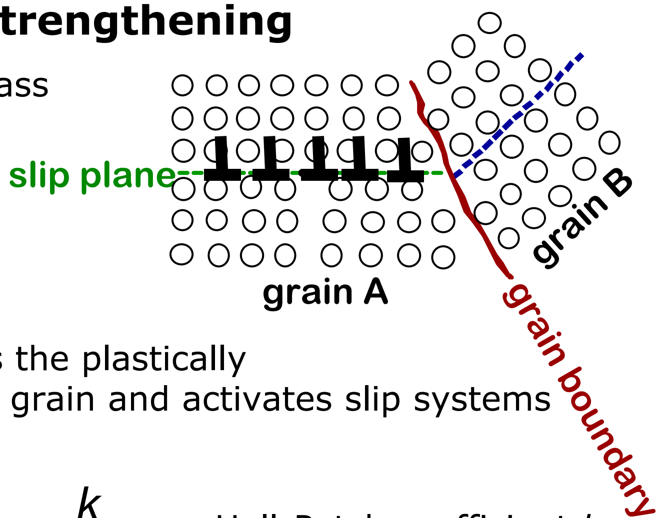
Single crystal



Nuclei form during solidification in melt

Nuclei grow and form grains

Grain boundary strengthening



- Dislocations cannot pass grain boundary
- Dislocations pile up at grain boundaries
- Stress concentration

- Internal stress affects the plastically undeformed neighbor grain and activates slip systems
- Hall-Petch relation

$$\sigma = \sigma_0 + \Delta\sigma_{gb} = \sigma_0 + \frac{k_y}{\sqrt{D}}$$

Hall-Petch coefficient k_y
Grain size D

- Strengthening by grain refinement $\rightarrow$ Nanoscale structures

Example for grain refinement: Copper zinc alloy (brass)

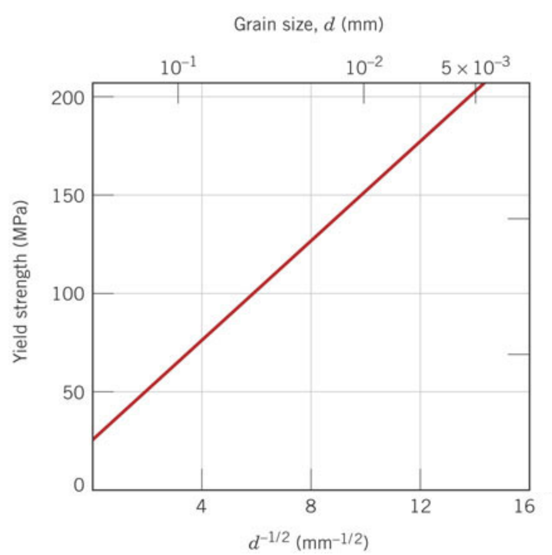
- Hall-Petch relation

$$\sigma = \sigma_0 + \frac{k_y}{\sqrt{D}}$$

Hall-Petch coefficient k_y
Grain size D

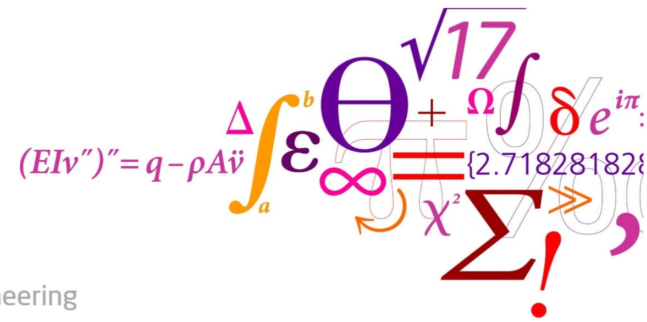
- Cu 70 wt.%, Zn 30 wt.%

- Note: grain refinement improves strength, but does **not** impair toughness



Strengthening in alloys

$$\sigma = \sigma_0 + \Delta\sigma_{ss} + \Delta\sigma_{disl} + \Delta\sigma_{gb} + \Delta\sigma_{prec}$$



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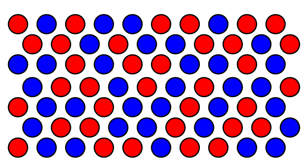
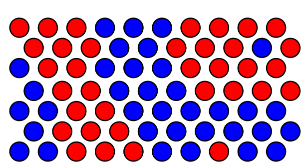
Alloys – three principle types

- Solid solutions = foreign atoms in crystal lattice



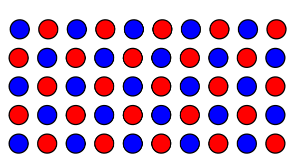
- Atoms unordered in same lattice

- Mixture of different metallic phases



- Distinct phases with different composition and possibly different lattices

- Intermetallic compounds



- Atoms ordered in possibly different lattice

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vacancies, interstitials, substitutional atoms

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3-dimensional: volume (bulk) defects
voids, pores, precipitations, inclusions, cracks

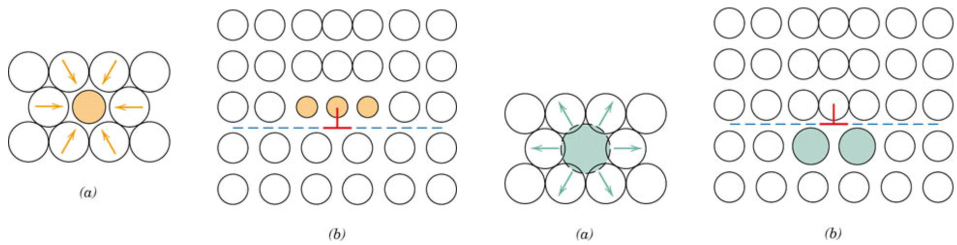
Point defects
in alloys

- **Solid solution** = foreign atoms (impurities) in the crystal lattice of host atoms
- **Interstitial** atoms
  ⇒ interstitial solid solution
- **Substitutional** atoms
  ⇒ substitutional solid solution
- Crystal structure maintained for solid solutions

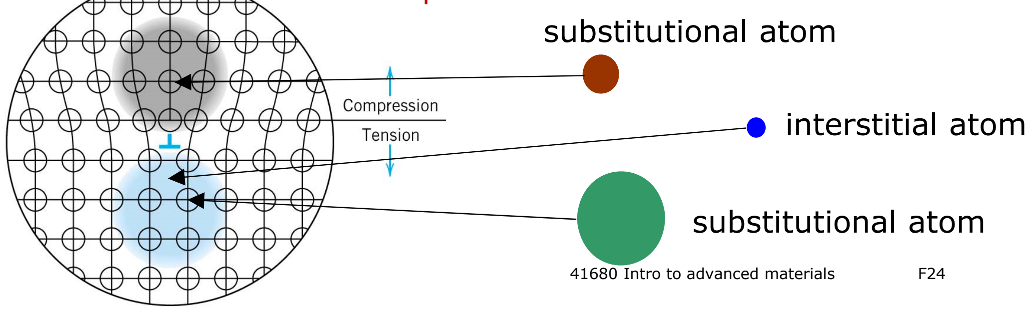
- Alternatives – immiscibility
  – intermetallic compounds
  (new phase of own structure)

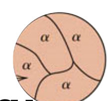
Solid solution strengthening

- Foreign atoms distort lattice and generate stresses

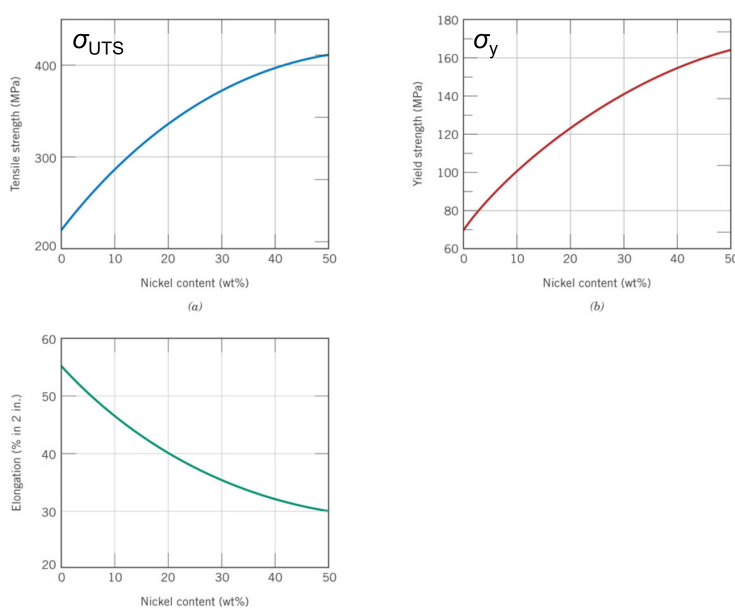


- Interaction of solute atoms with strain field around dislocations
  » Impedes dislocation motion





Example for solid solution strengthening: Copper Nickel alloys



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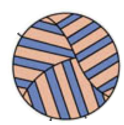
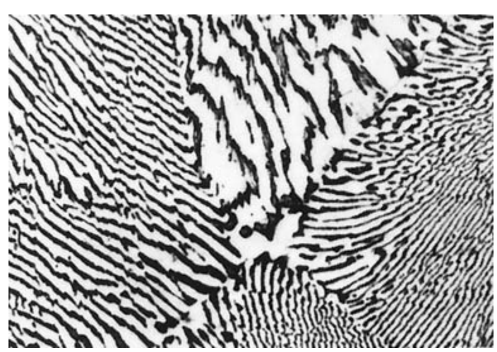


Strengthening by phase boundaries

- Phase boundaries separate different phases with different crystal lattices
- Phase boundaries cannot be passed by dislocations
- Similar to grain boundaries and Hall-Petch effect

Example

- Eutectic microstructures



- Smaller lamellae width results in higher strength

Lattice defects

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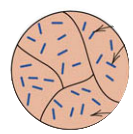
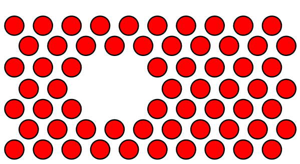


Volume defects

Self defects

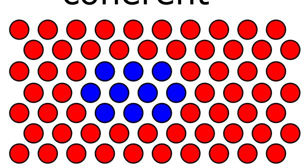
- Clusters of point defects
- Pores = agglomerate of vacancies

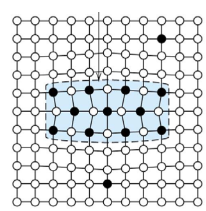


- Requires many missing atoms!

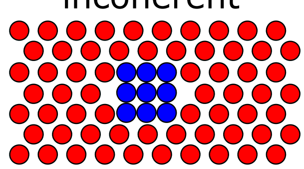
Alien defects

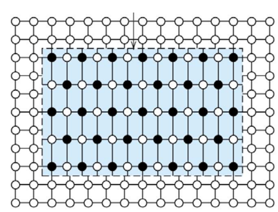
- Second phase particles
- Precipitates
  - coherent





  - incoherent

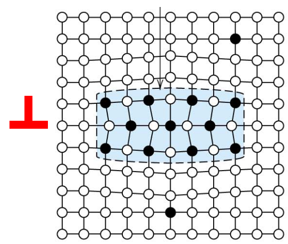




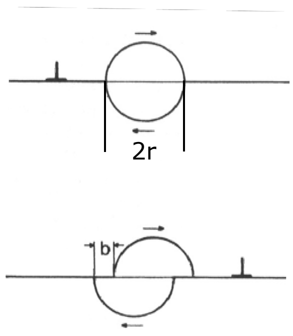
- Requires many atoms!

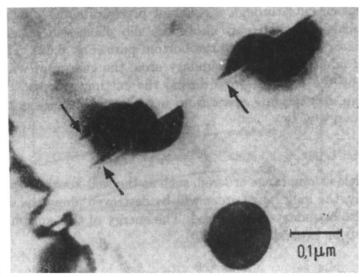
Particle strengthening
with coherent particles

- Dislocations can intersect coherent precipitates



- Creating an interface with energy γ



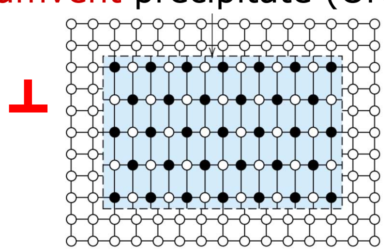


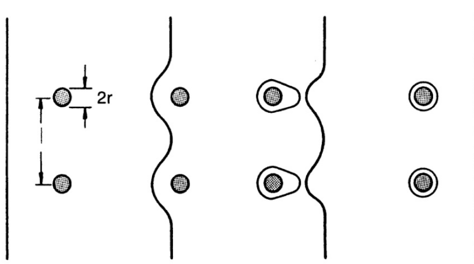
$$\Delta\sigma_{p_{coh}} \propto \frac{\gamma r}{l + 2r}$$

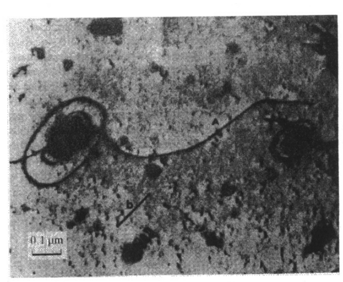
Particle radius r
Particle distance l
Interface energy γ

Particle strengthening
with incoherent particles

- Dislocations can not intersect incoherent particle, instead they circumvent precipitate (Orowan mechanism)





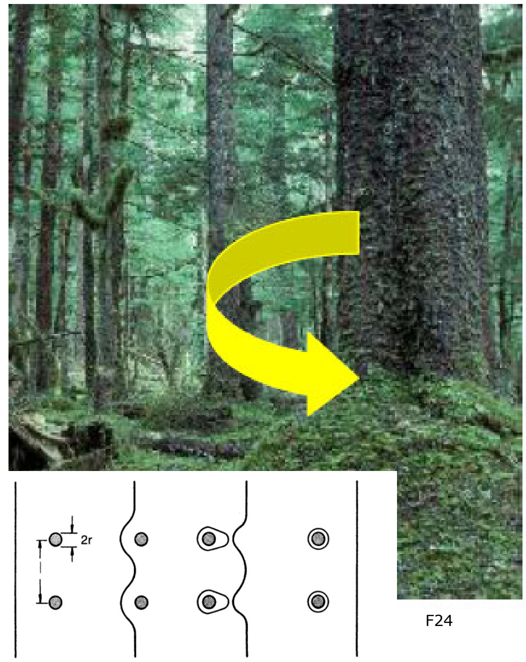


$$\Delta\sigma_{p_{incoh}} \propto \frac{Gb}{l}$$

Shear modulus G
Burgers vector b
Particle distance l

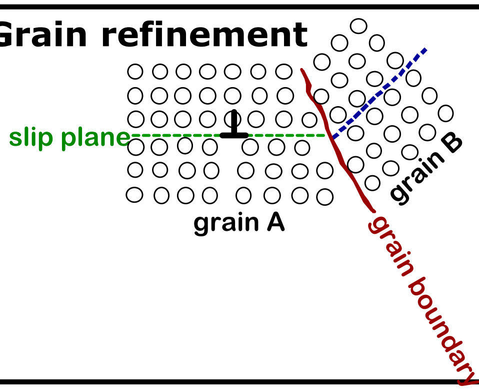
Particle hardening

What gives higher strength: small or large particles?

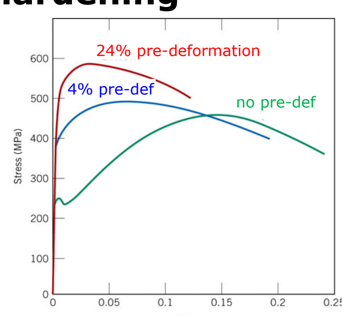


Summary of strengthening mechanisms

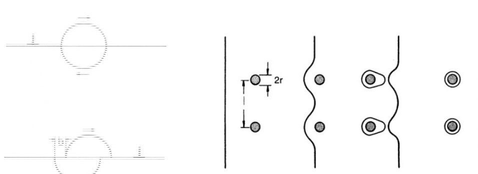
Grain refinement



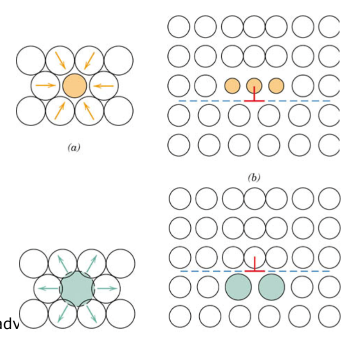
Work-hardening



Particle strengthening



Solid solution strengthening

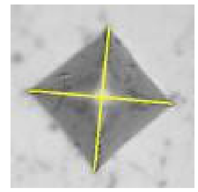


Hardness

- Resistance of materials to (localized) plastic deformation

- Micro-indentation and nano-indentation
  hardness of individual grains or microstructure constituents
- Macro-indentation (macrohardness)
  Average over several grains and microstructure constituents

- Indentation of diamond indenter with given force
- Diamond is the hardest of all materials

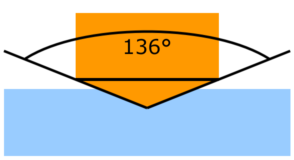


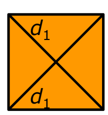
Vickers indent

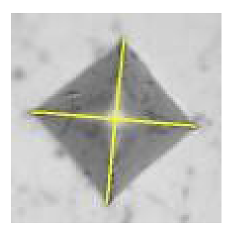
- Qualitative: Which materials scratch others? Mohs scale
- Quantitative: Hardness value from size of indentation marks on material

Hardness testing

- hardness values from size of indentation marks in the material







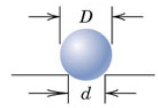
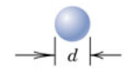
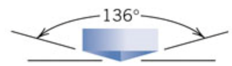
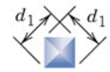
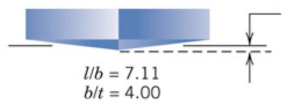
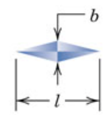
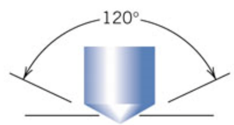
$$HV = 2\sin 68^\circ \frac{P}{d_1^2} = 1.854\frac{P}{d_1^2} \quad \text{or } HV = 0.1891\frac{F}{d_1^2}$$

Vickers indent

- Applied force (P in kgf (kp) or F in N)
- Diagonal in mm

Vickers hardness number in kgf/mm^2 (can be converted to N/mm^2 or MPa)
Example: 100 HV10 = 100 kgf/mm2 = 981 MPa (loaded with 10 kg)

Hardness tests after Rockwell, Brinell, Knoop, and Vickers

Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View
Brinell	10-mm sphere of steel or tungsten carbide		
Vickers microhardness	Diamond pyramid		
Knoop microhardness	Diamond pyramid		
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}$ in. diameter steel spheres		
			

Relation between hardness values and tensile strength

- Relation between Brinell and Vickers hardness

$$HB \approx 0.95\ HV$$

- Relation between Brinell hardness and tensile strength

$$UTS \approx c_{emp} HB$$

Materials	c_{emp}
Steel	3.5
Cu and Cu alloys (annealed)	5.5
Cu and Cu alloys (deformed)	4.0
Al and Al alloys	3.7

Effect of work-hardening

Exercise 06.1

Sketch (qualitatively) the flow curves of the following materials in a common stress strain diagram.

a) Pure annealed copper

b) Cupronickel with 25 wt.% Ni

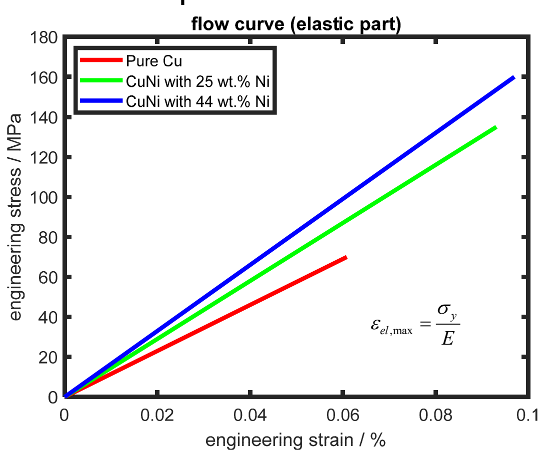
c) Cupronickel with 44 wt.% Ni (Konstantan)

Compare the three flow curves with respect to their Young's modulus, yield strength, tensile strength and ductility (can be found in presentations of lecture 05 and 06). Why do the curves look different?

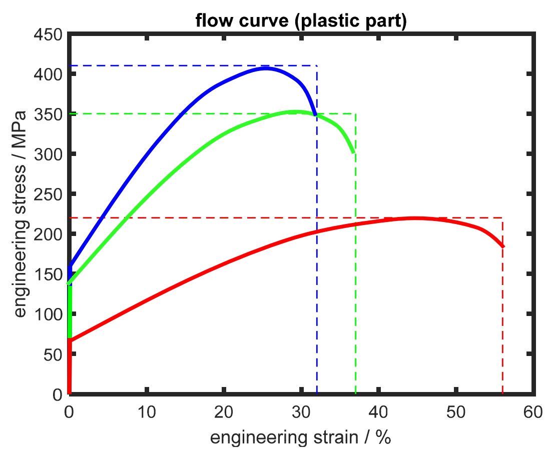
Exercise 06.1

Flow curves cupronickel

- Elastic part



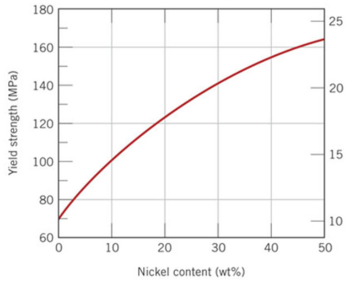
- Plastic part

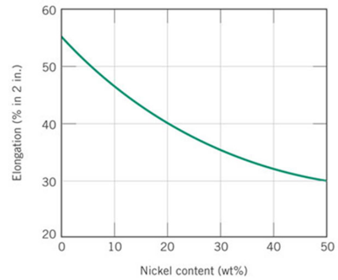


Material	Young's modulus	Yield strength	Tensile strength	Ductility (fracture strain)
Pure copper	115 GPa	70 MPa	220 MPa	56%
Cupronickel with 25 wt% nickel	145 GPa	135 MPa	350 MPa	37%
Cupronickel with 44 wt% nickel	165 GPa	160 MPa	410 MPa	32%

Exercise 06.2

The dependence of yield strength and ductility of cupronickel is shown below for compositions with maximum nickel content of 50 wt.%. How do the curves continue to higher nickel contents and to pure nickel?

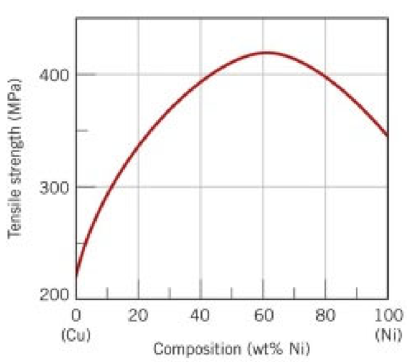




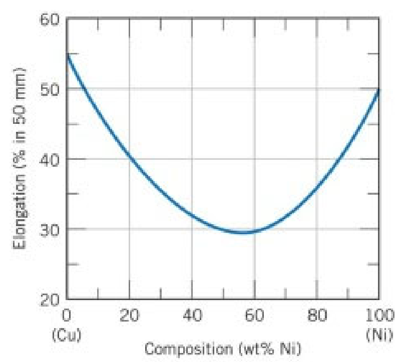
Sketch the dependence of the electrical conductivity of the alloys in dependence on the nickel content.

Exercise 06.2

Example for solid solution strengthening: Copper Nickel alloys



(a)



(b)

Exercise 06.3 Brass

Sketch the flow curve of (alpha) brass (copper with 30 wt.% zinc) after five different treatments in one and the same stress strain diagram:

a) Undeformed brass with grain size 8 μm

b) Brass with grain size 8 μm deformed to 20 % strain

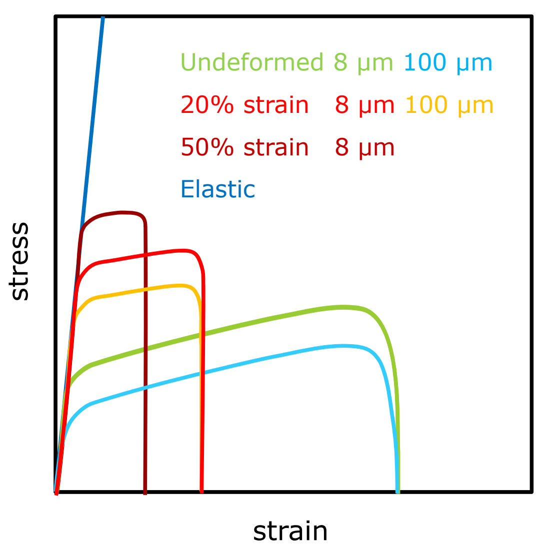
c) Brass with grain size 8 μm deformed to 50 % strain

d) Undeformed brass with grain size 100 μm

e) Brass with grain size 100 μm deformed to 20 % strain

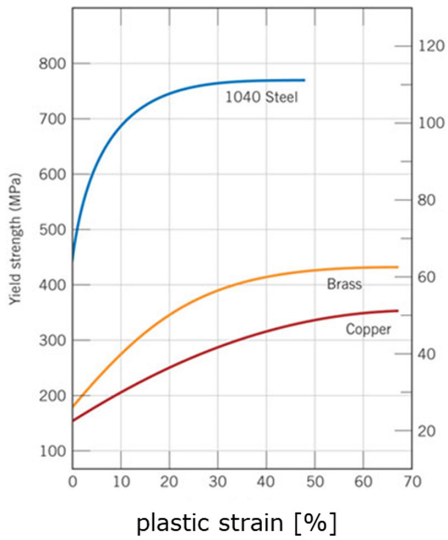
Compare the flow curves with respect to their Young's modulus, yield strength, tensile strength and ductility. Why do the curves look different?

Flow curves of brass (qualitative)



Exercise 06.4 Pure copper

Pure copper with a relatively large grain size (500 µm) and a low dislocation density ($2 \cdot 10^{10}$ m^{-2}) is deformed at room temperature; its flow stress increases as shown in the figure. What is the dislocation density after 30 % and after 60 % plastic strain (M = 3, α = 0.5, $k_y = k_{HP}$ = 0.11 MPa m$^{1/2}$, G = 46 GPa, b = 0.255 nm)?



Exercise 06.5

Assess the yield strength of three specimens:

(A) Pure Cu.

(B) Pure Cu, which has been rolled at room temperature.

(C) A copper alloy with 50 wt.% Ni, which has been rolled at room temperature as (B).

Explain the mechanisms affecting the yield strength assume that all specimens have the same grain size. No quantitative values for the yield strength are required, just compare them using ”larger than” or ”smaller than”.