Properties of Materials

Theme: Deformation

Lecture 1: Single Crystals

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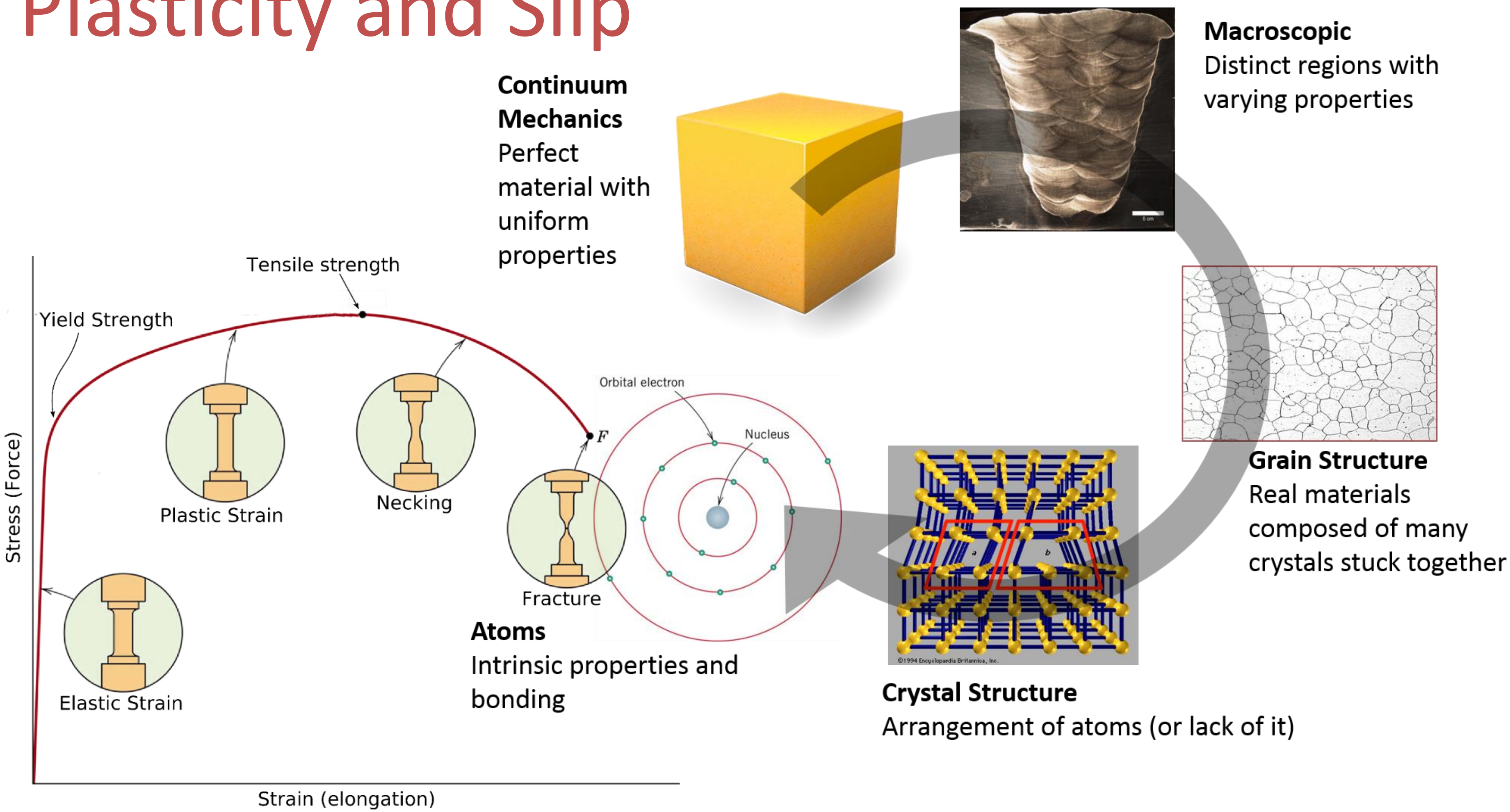
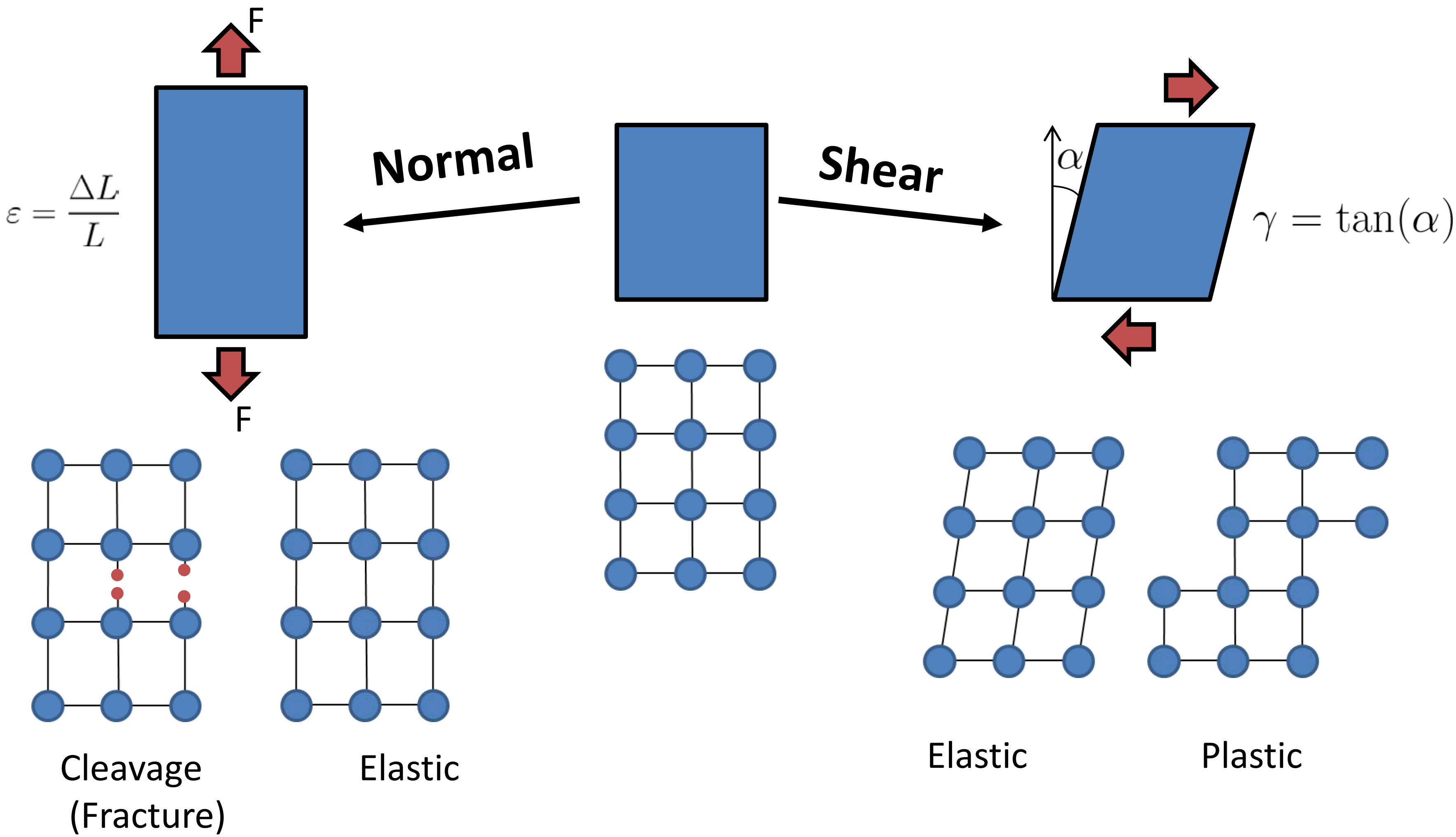
Plasticity and Slip



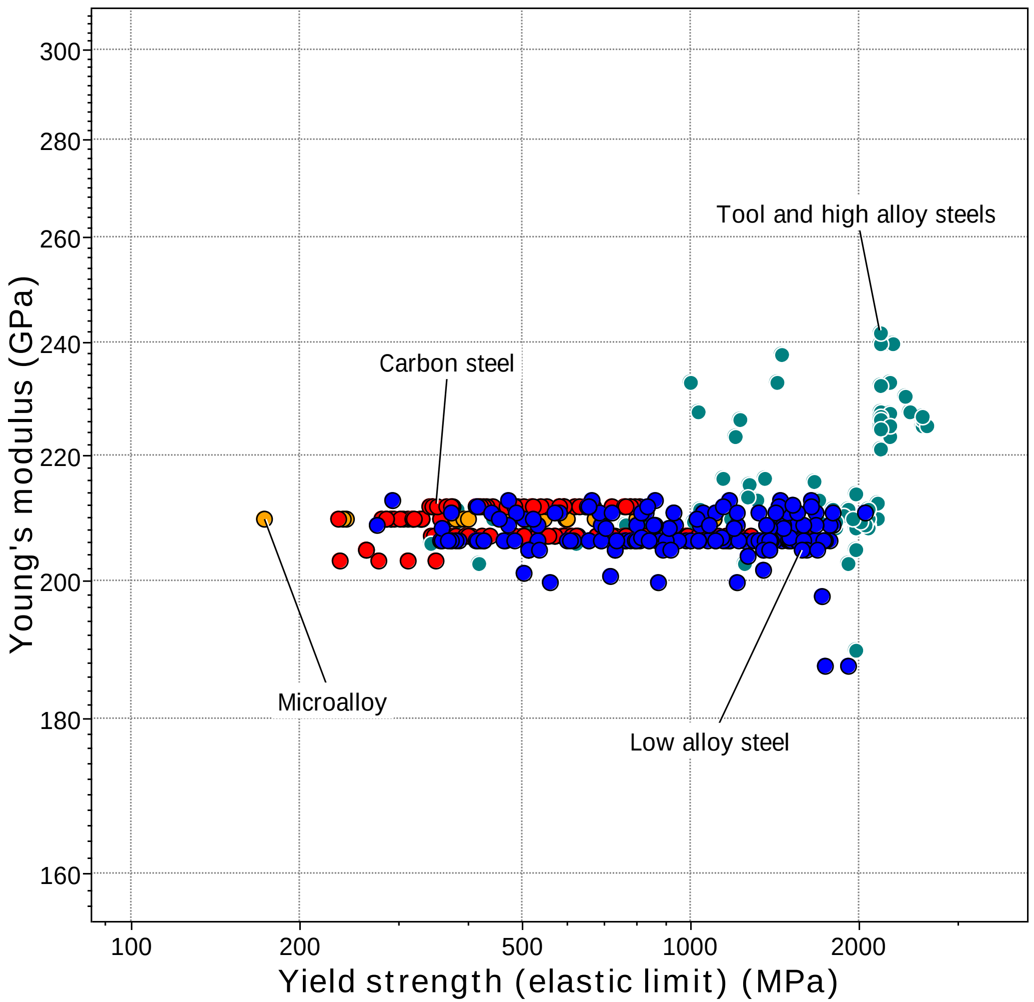
Try to relate crystalline (and polycrystalline) mechanics to structure

Plastic Slip

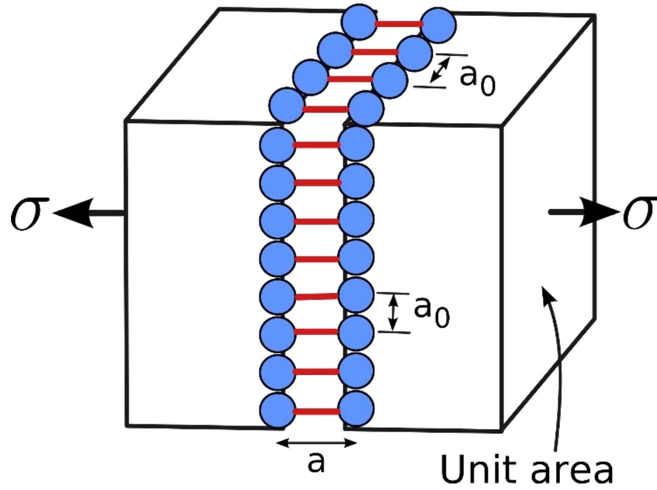


Modulus *vs.* Strength

- Young's modulus
  - Resistance to small strains
  - Almost constant for steel
- Yield Strength
  - Resistance to permanent 'shear strains'
  - Order of magnitude change



Modulus



$$a = a_0 + \delta$$

Number of bonds per unit area

$$N \approx \frac{1}{a_0^2}$$

Force for one bond

$$F = S(a - a_0)$$

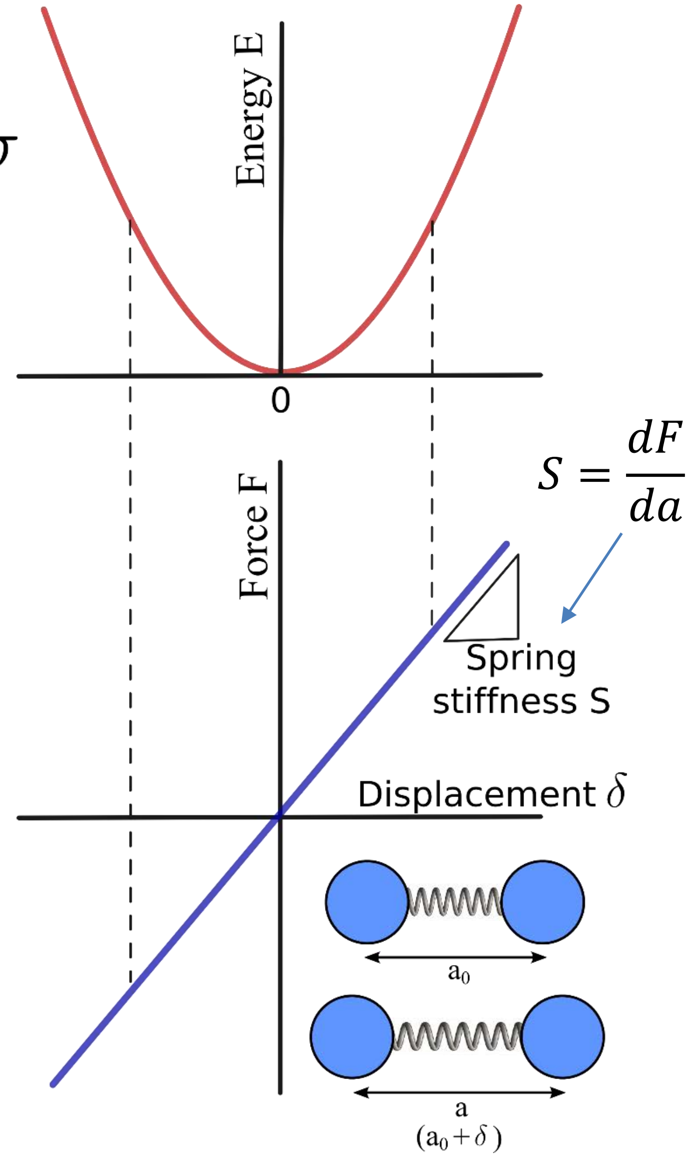
$$\sigma = \frac{F}{A} = NS(a - a_0)$$

$$e = \frac{a - a_0}{a_0}$$

$$\sigma = \frac{S}{a_0} e$$

$$E = \frac{S}{a_0}$$

$$\sigma = Ee$$



Modulus

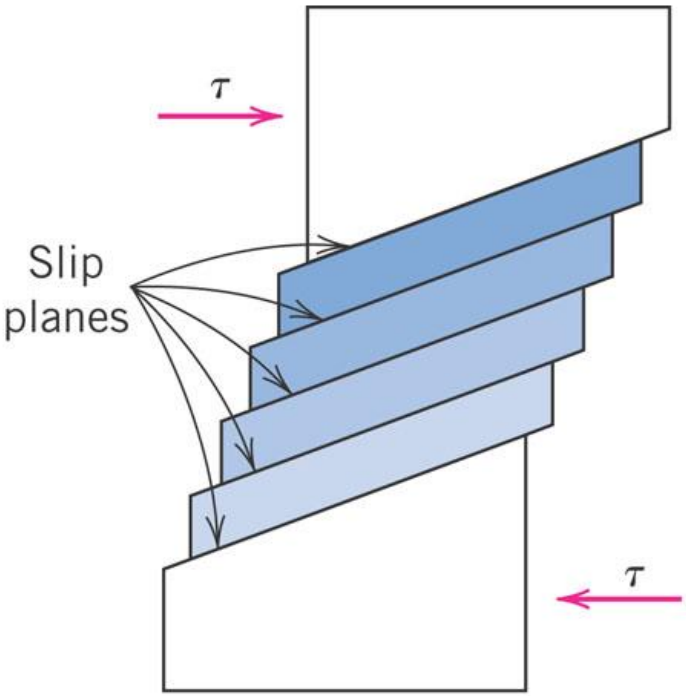
Bond Type	$S_0\ (Nm^{-1})$	**E (GPa)**
Covalent (e.g. C-C)	50-180	200-1000
Metallic e.g Cu-Cu	15-75	60-300
Ionic e.g. Na-Cl	8-24	32-96
H-bond e.g. water ice	2-3	8-12
Van der Waals e.g. polymers	0.5-1	2-4

$$E = \frac{S}{a_0}$$

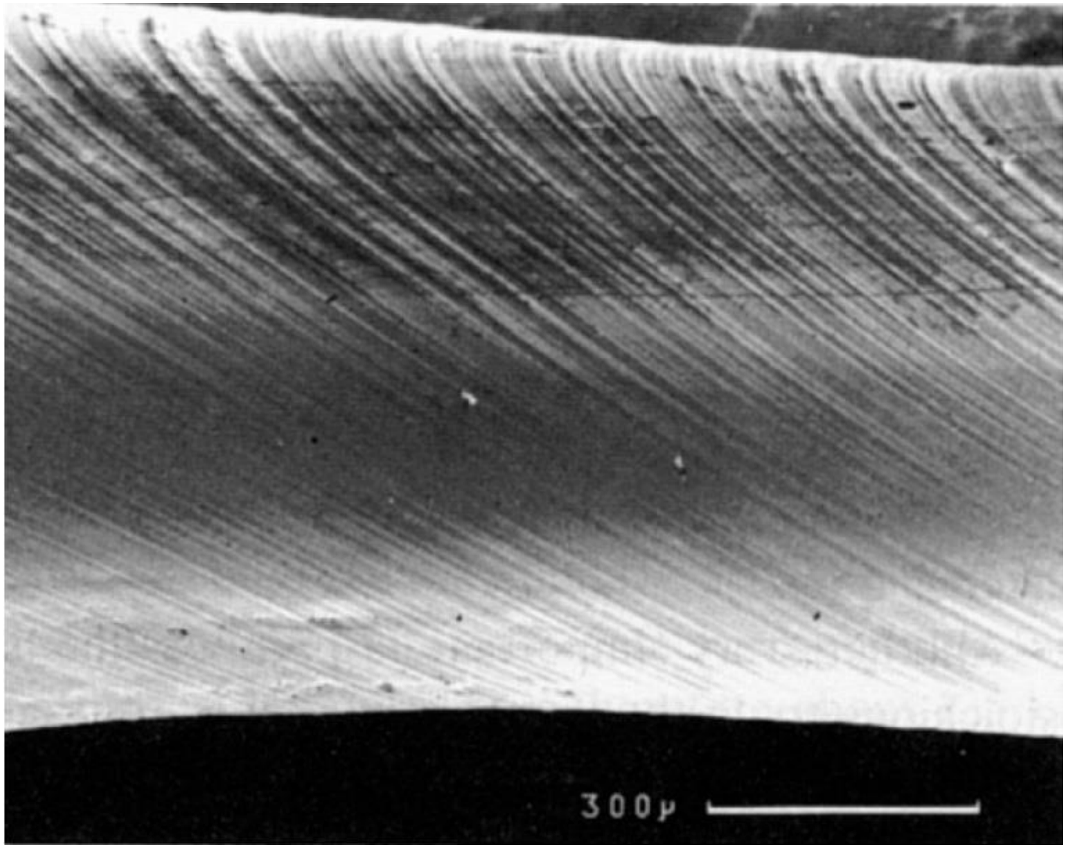
Stiff materials have stiff bonds and close packing

All atoms contribute – dominated by host system *e.g.* Fe

Slip Systems (yielding *via* shear)



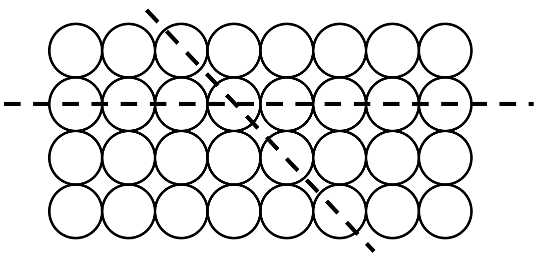
Slip on parallel planes in slip system in single crystal



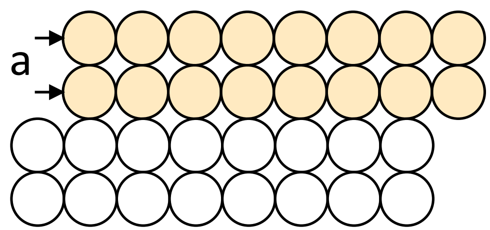
Slip

Crystals deform by shear and must maintain symmetry after deformation

Primitive cubic before shear

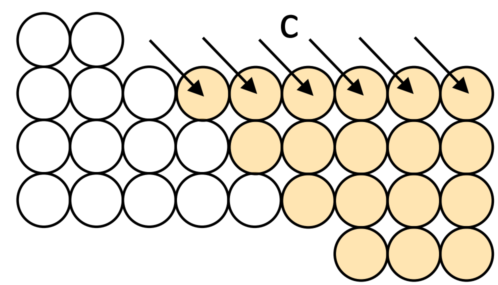


Shear in close packed direction



010 direction

Shear in non-close packed direction



110 direction

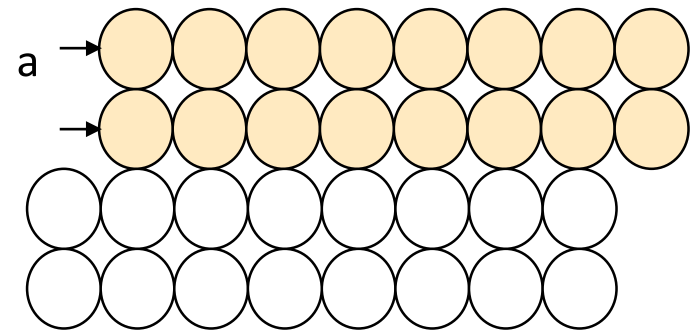
001 planes

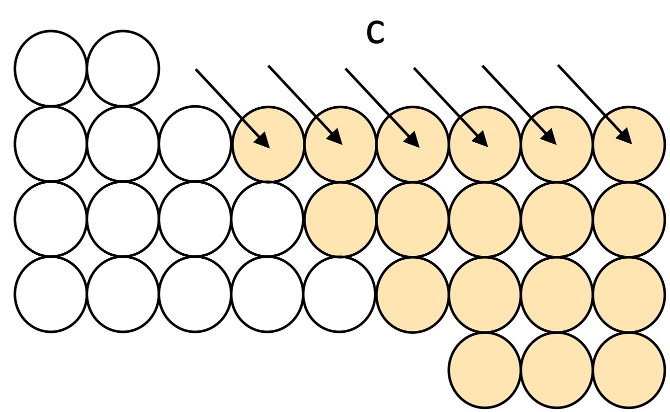
Combination of plane + direction = slip system

Ease of Slip

- Easier if distance is short
  - Atoms are closely packed in the direction of slip
- Easier if the plane has lots of room to move
  - Not sitting in dimples of plane below
  - No need to raise up and over atoms
  - High packing in plane = lower packing out of plane
  - Close packed (hexagonal) 2D lattice very good

Low $\tau_c < \tau = \sigma \cos\phi \sin\lambda$

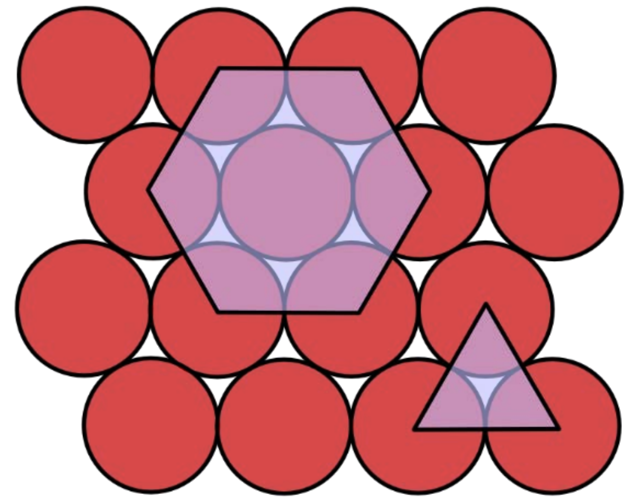


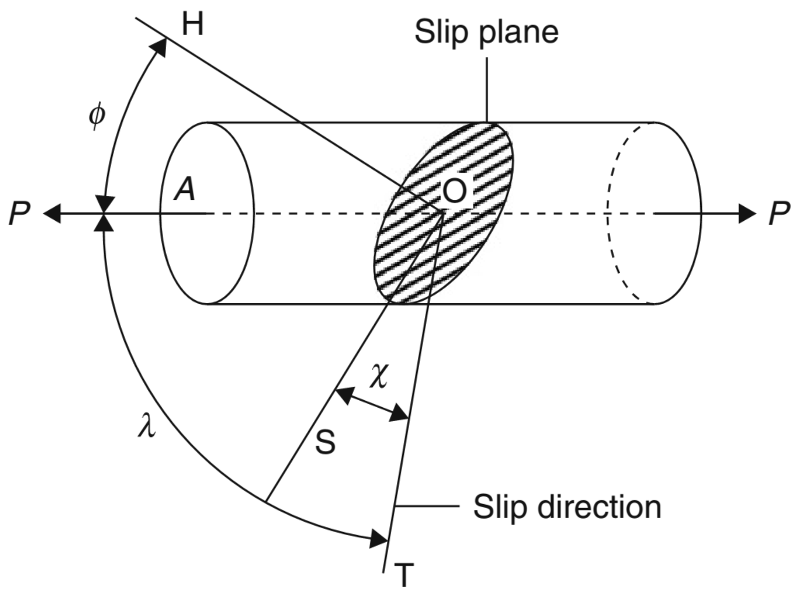


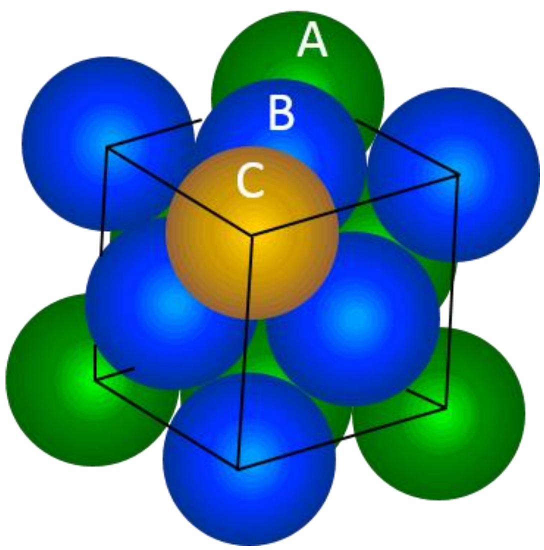
High $\tau_c < \tau = \sigma \cos\phi \sin\lambda$

Determining slip systems

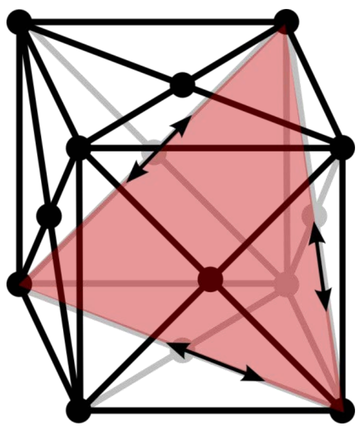
- 'Rules'
  - Closest packed directions
  - Closest packed planes
  - Slip happens on system with largest resolved shear stress (highest Schmid factor)

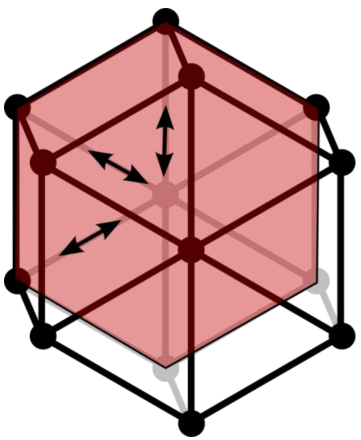


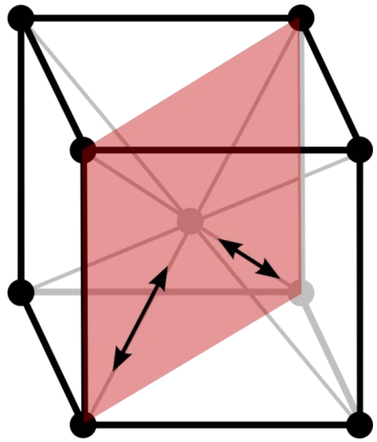




Slip Systems







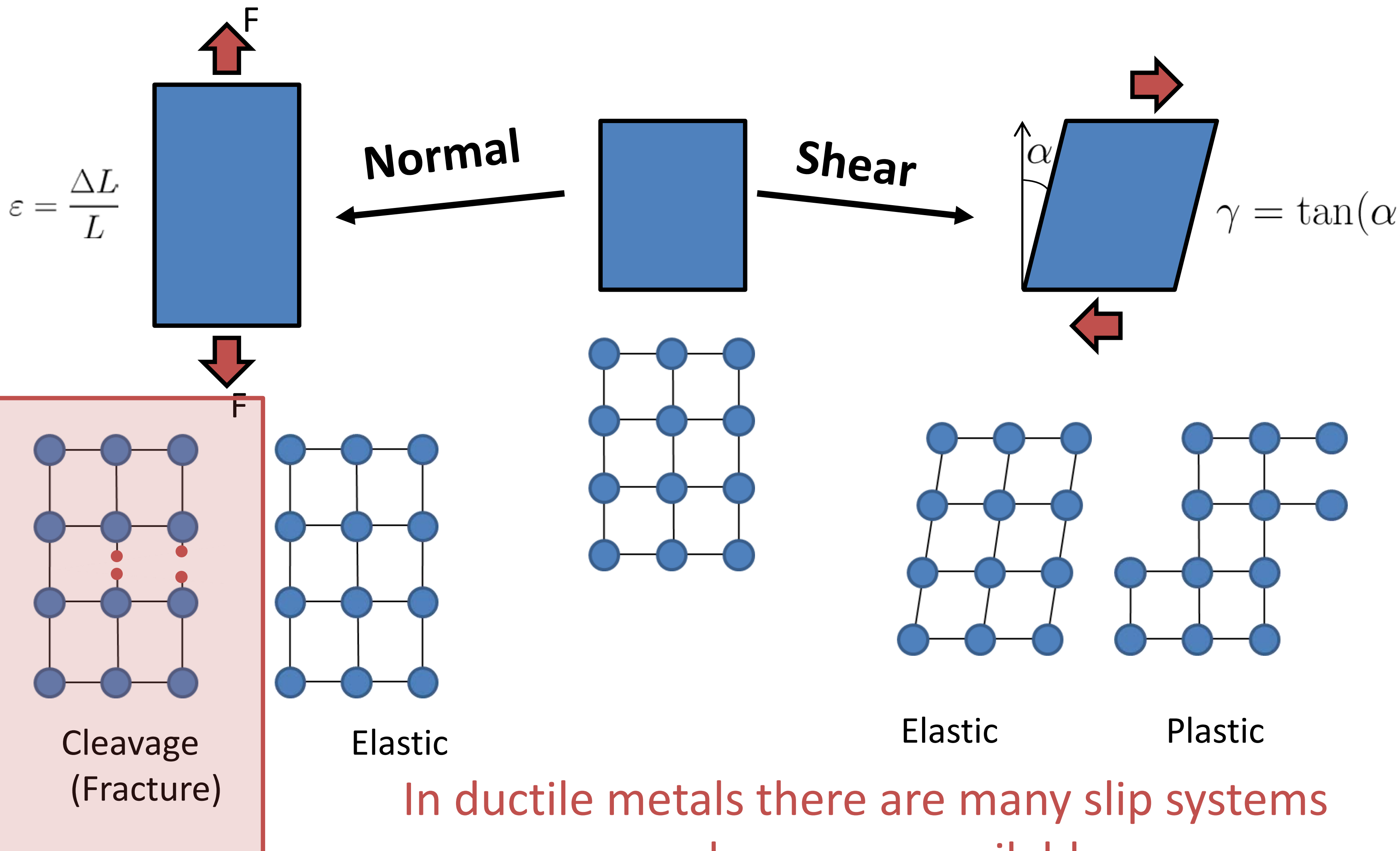
Metals	*Slip Plane*	*Slip Direction*
	Face-Centered Cubic	
Cu, Al, Ni, Ag, Au	$\{111\}$	$\langle 1\bar{1}0\rangle$
	Body-Centered Cubic	
α-Fe, W, Mo	$\{110\}$	$\langle \bar{1}11\rangle$
α-Fe,W	$\{211\}$	$\langle \bar{1}11\rangle$
α-Fe, K	$\{321\}$	$\langle \bar{1}11\rangle$
	Hexagonal Close-Packed	
Cd, Zn, Mg, Ti, Be	$\{0001\}$	$\langle 11\bar{2}0\rangle$
Ti, Mg, Zr	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$
Ti, Mg	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$

<> Means equivalent directions related by symmetry

{} Means equivalent planes related by symmetry

Ignore 4 index notation – not taught any more

What if there is no slip?



In ductile metals there are many slip systems so always one available

Summary

- Slip systems are close packed (planes and directions)
  - Low critical shear stress
- Slip (plasticity) happens on plane and direction with highest resolved shear stress
- If slip is impossible (low *resolved* shear stress) then get fracture first
  - Brittle materials have few available slip systems or high critical shear stress (next lecture)

Properties of Materials

Theme: Deformation

Lecture 2: Polycrystals

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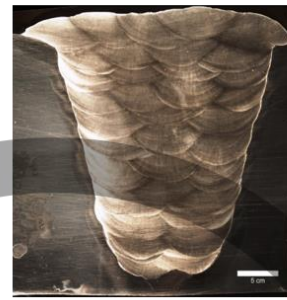
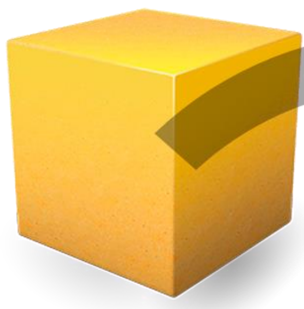
Introduction

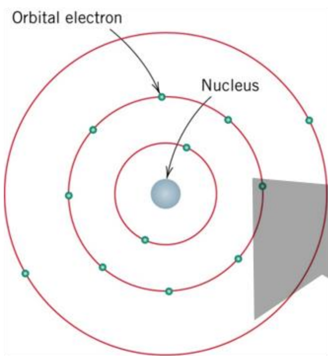


Macroscopic
Distinct regions with varying properties

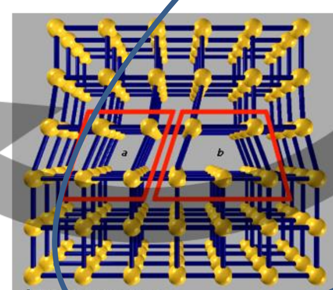


Continuum Mechanics
Perfect material with uniform properties

Grain Structure
Real materials composed of many crystals stuck together



Atoms
Intrinsic properties and bonding



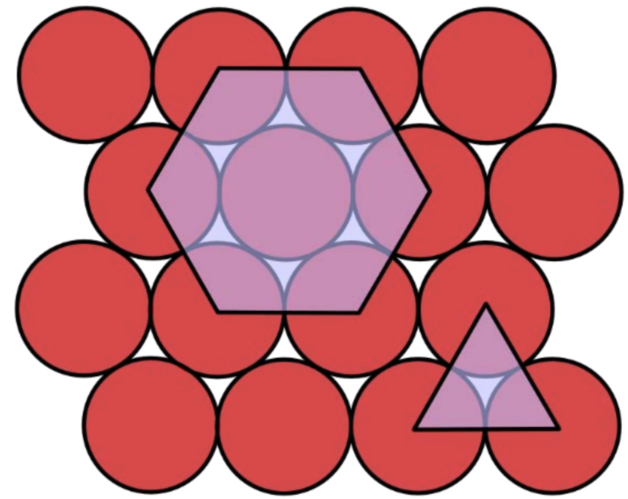
Crystal Structure
Arrangement of atoms (or lack of it)

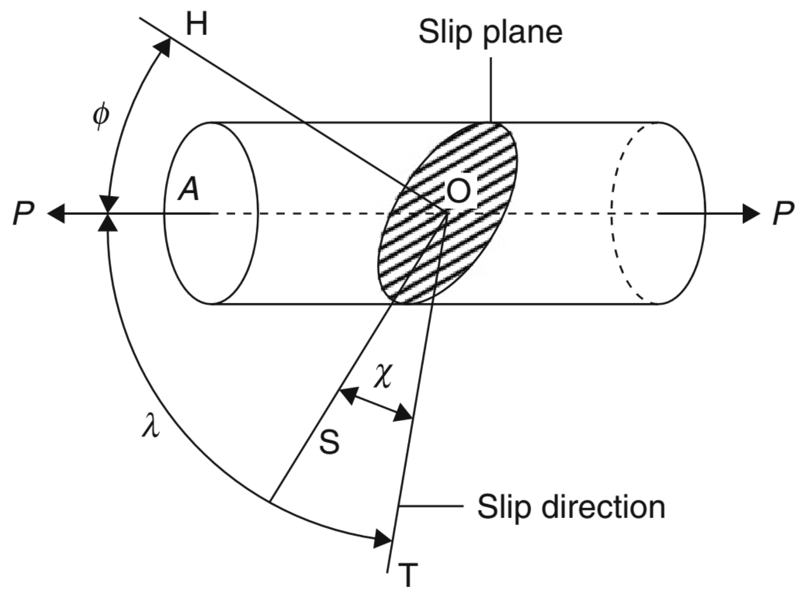
Strength of polycrystals from single crystals

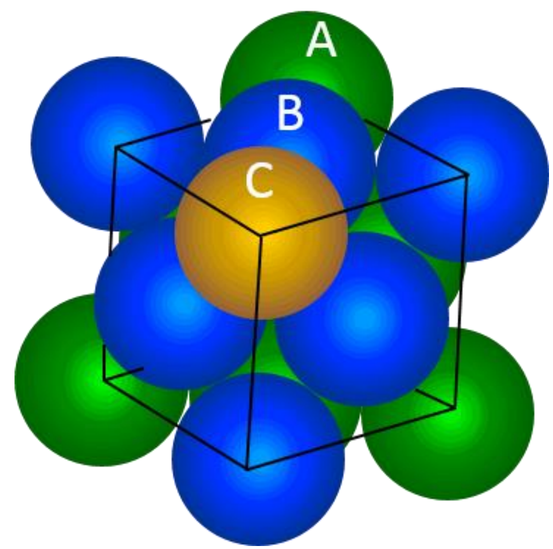
How do we change strength?

Remember when slip occurs:

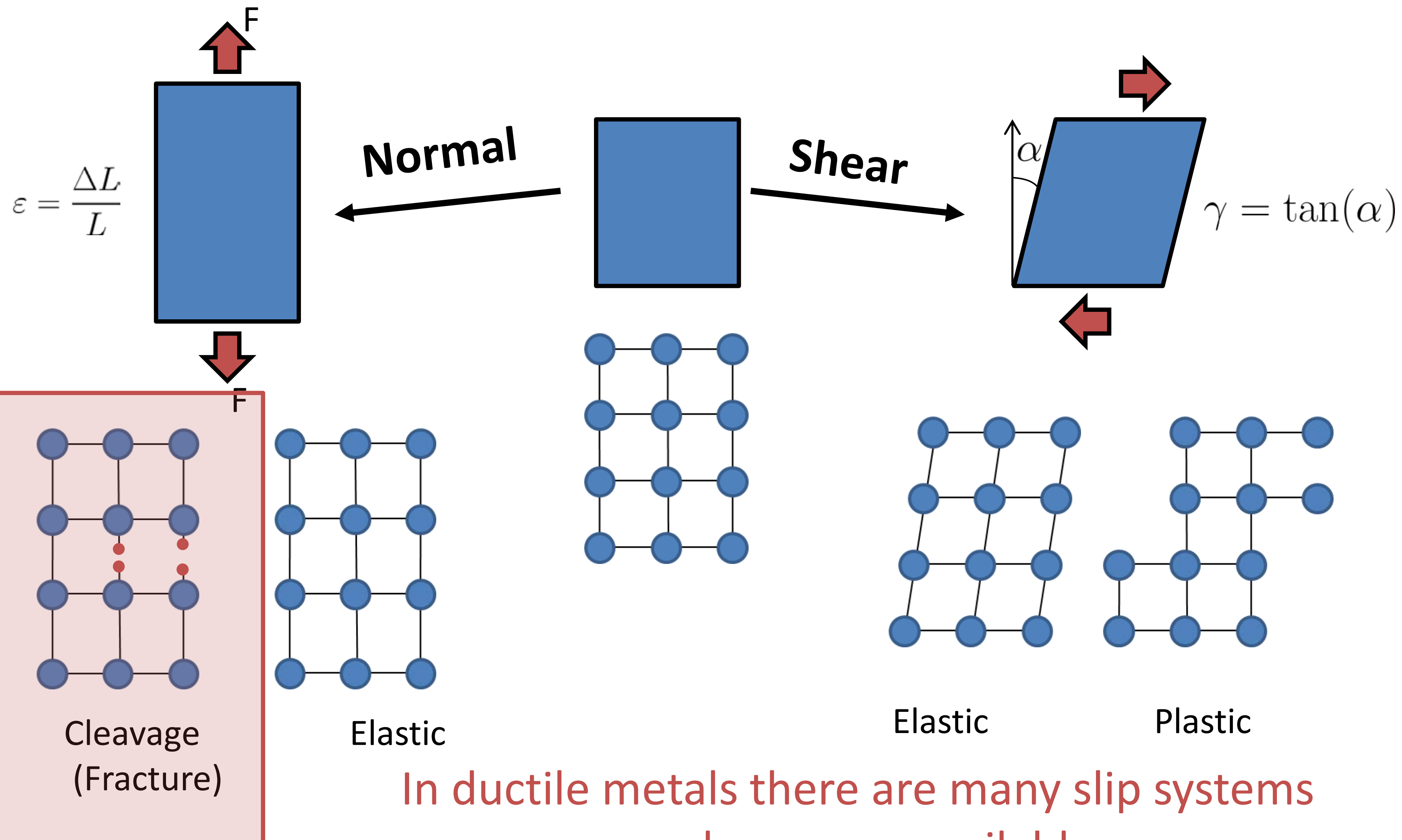
- ‘Rules’
  - Closest packed directions
  - Closest packed planes
  - Slip happens on system with largest resolved shear stress (highest Schmid factor)







What if there is no slip?

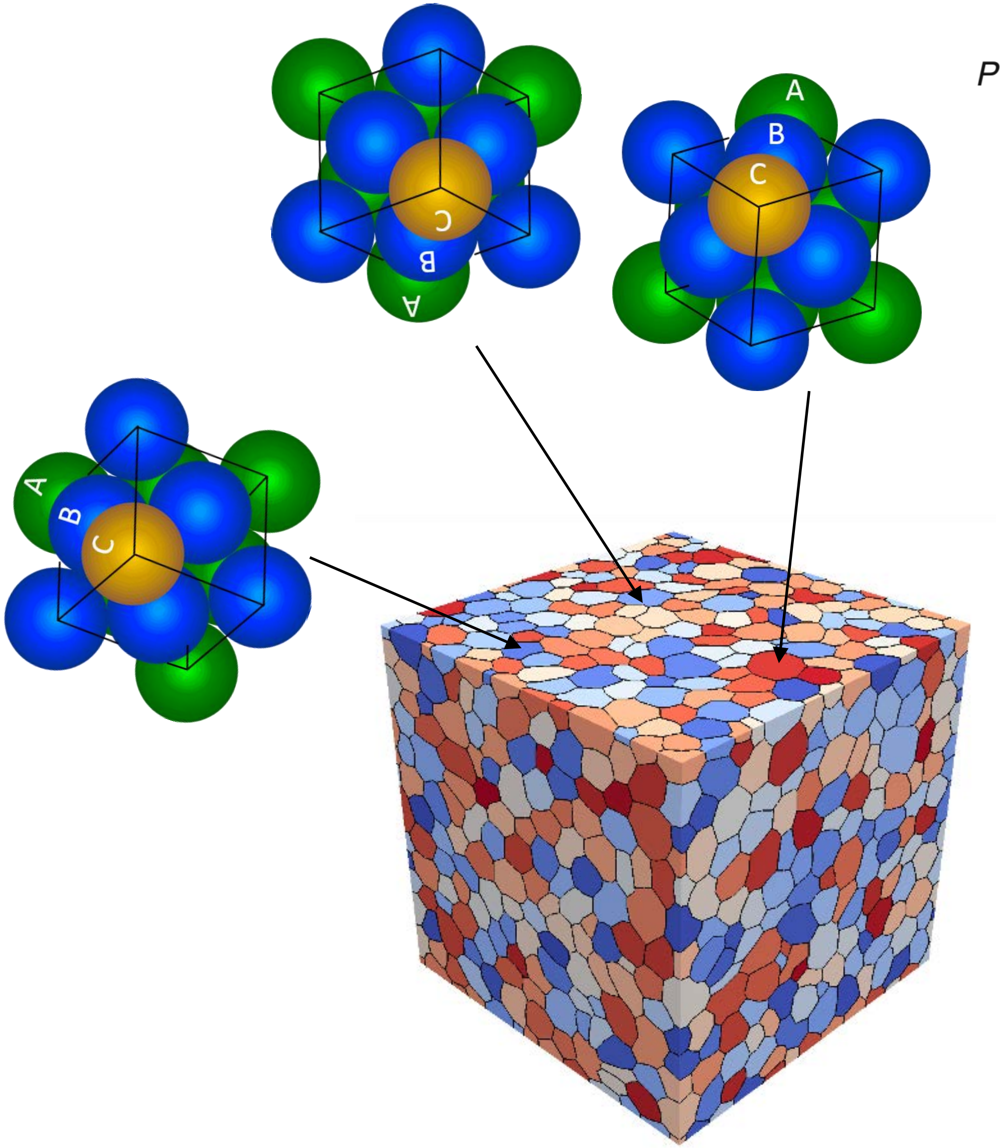


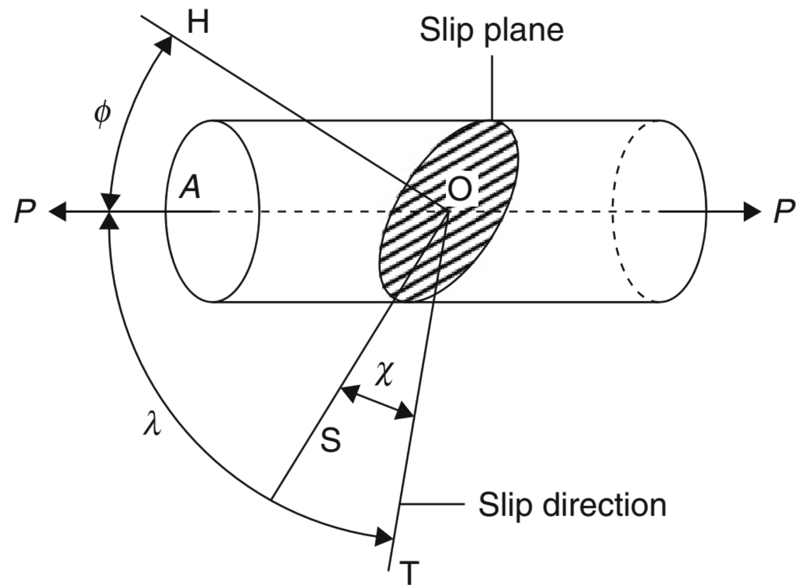
In ductile metals there are many slip systems so always one available

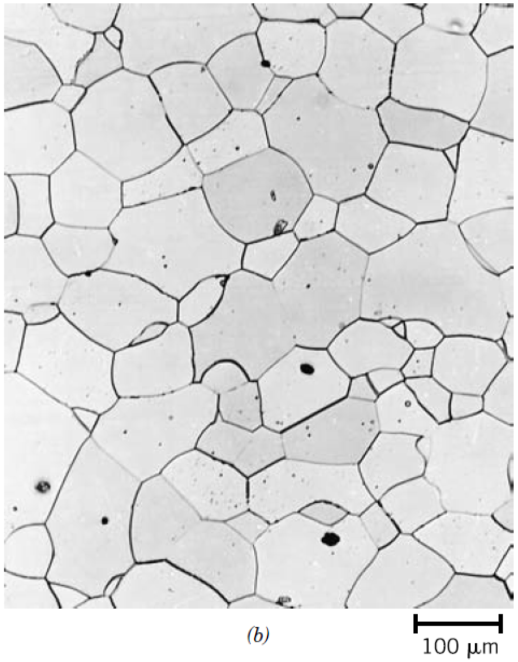
Summary

- Slip systems are close packed (planes and directions)
  - Low critical shear stress
- Slip (plasticity) happens on plane and direction with highest resolved shear stress
- If slip is impossible (low *resolved* shear stress) then get fracture first
  - Brittle materials have few available slip systems or high critical shear stress (next lecture)

Polycrystals







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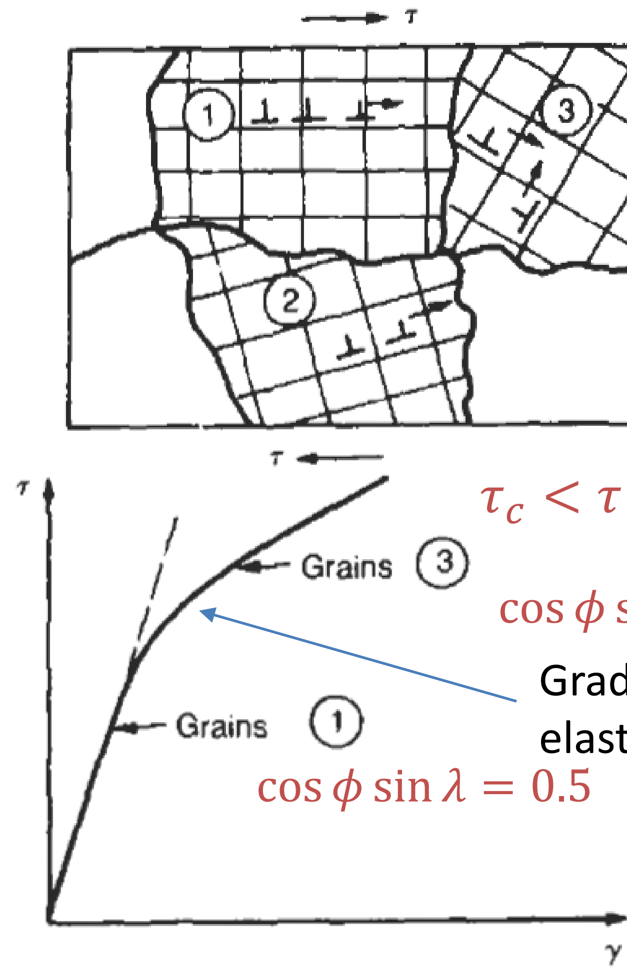
Polycrystals

Ductile failure in tension
- necking

From lecture 2

Slip and failure occurring at about 45° to applied load but all the way around sample

Cup and cone fracture



$\tau_c < \tau = \sigma \cos\phi \sin\lambda$

$\cos\phi \sin\lambda = 0.25$

Gradual change from elastic to plastic

$\cos\phi \sin\lambda = 0.5$

Statistical approach with many random grains

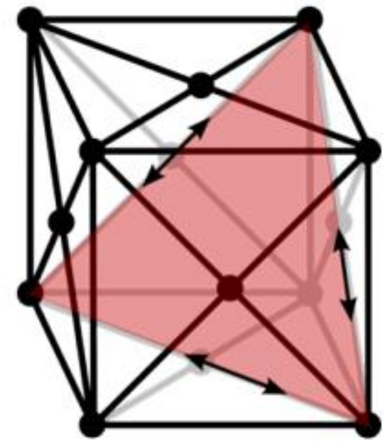
$$\sigma_0 = 3\tau_0$$

Polycrystal slightly stronger than single crystal would suggest

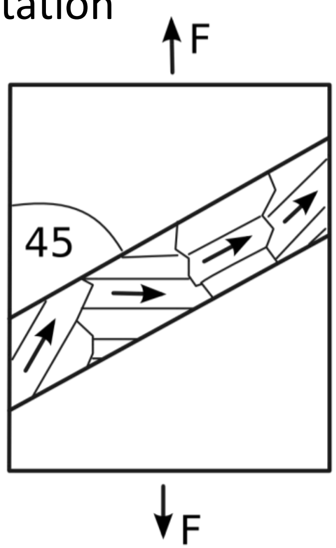
Ductility by Crystal Structure

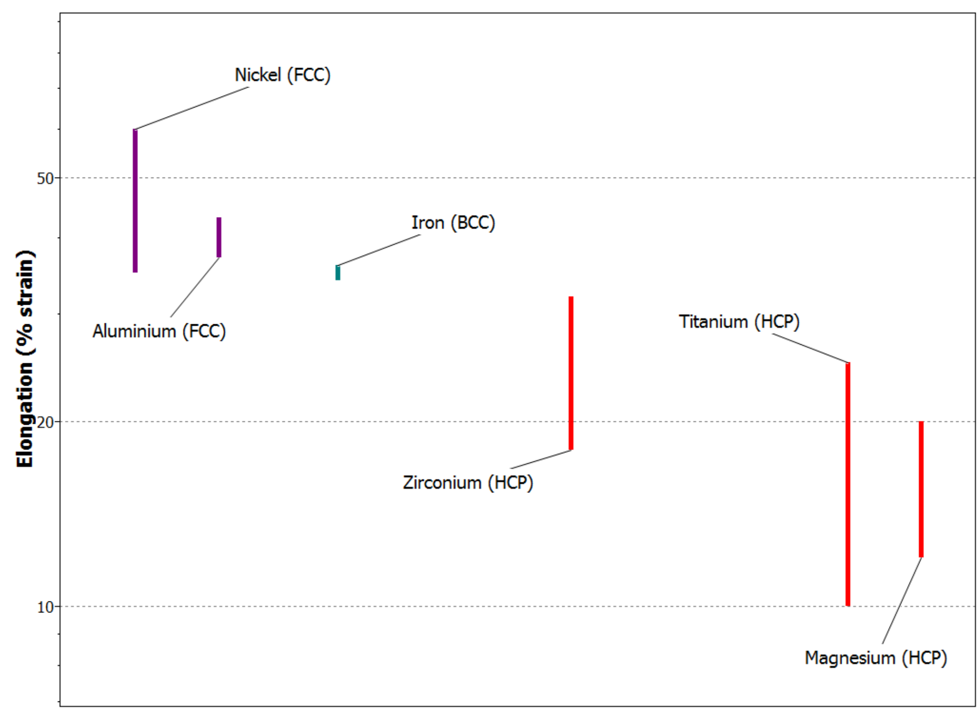
Crystal	Metal	Slip Plane	Slip Direction	Number
FCC	Al,Cu,Ni,Ag,Au	{111}	$\langle 1\bar{1}0\rangle$	12
BCC	Fe,W,Mo	{110}	$\langle 1\bar{1}1\rangle$	12
	Fe,W	{211}	$\langle 1\bar{1}1\rangle$	12
	Fe	{321}	$\langle 1\bar{1}1\rangle$	24
HCP	Zn,Mg,Ti,Mg	(001)	$\langle 1\bar{1}1\rangle$	3
	Ti,Mg,Zr	{100}	$\langle 1\bar{1}1\rangle$	3

No need to learn number

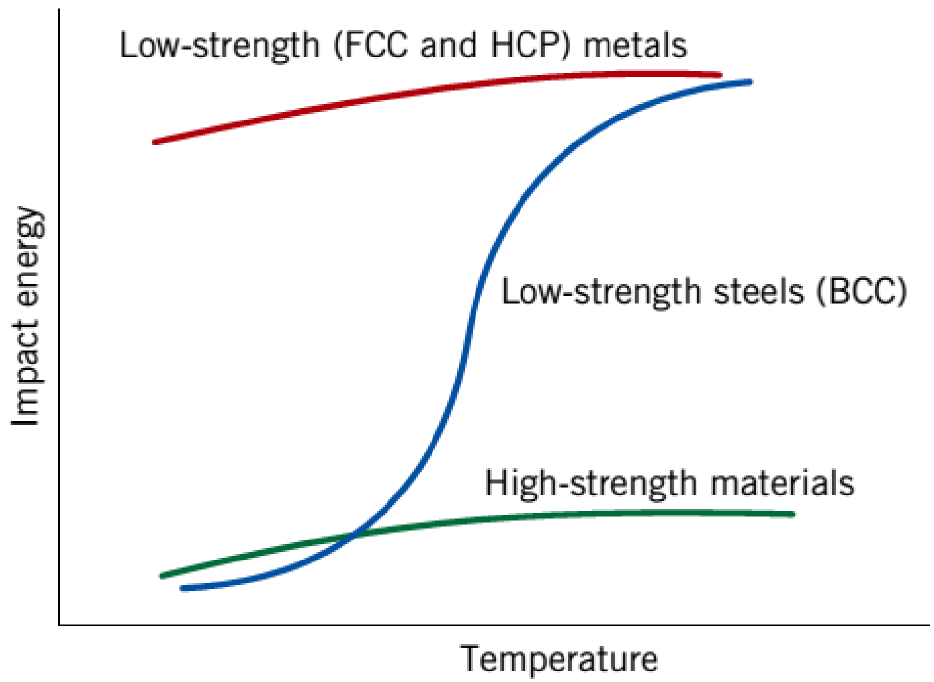


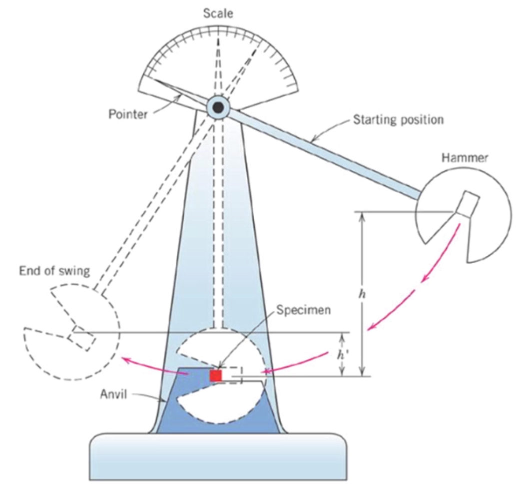
This needs lots of slip systems so there is one nearby whatever the orientation

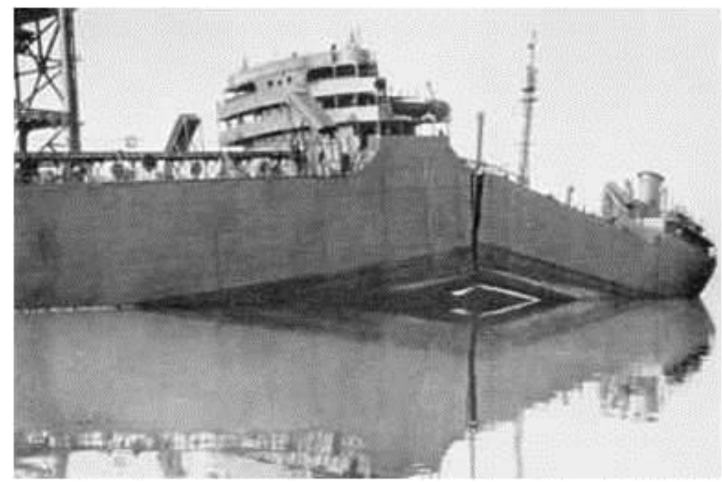


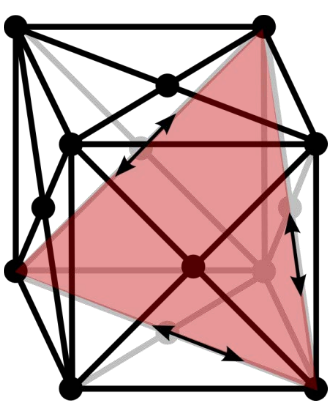


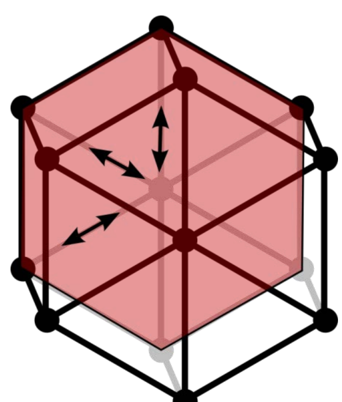
Brittle-Ductile Transition

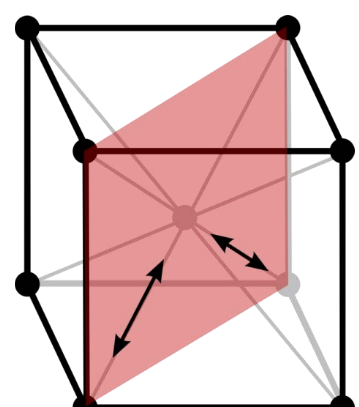


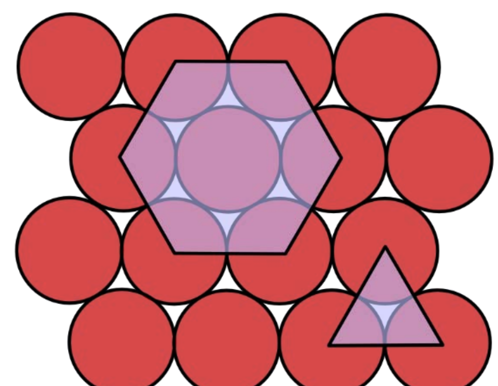






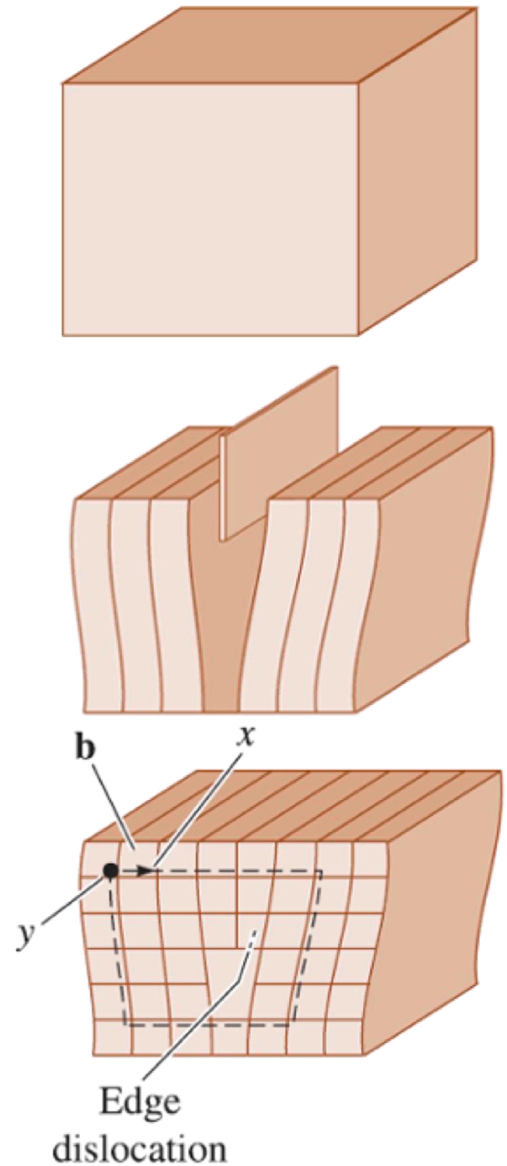




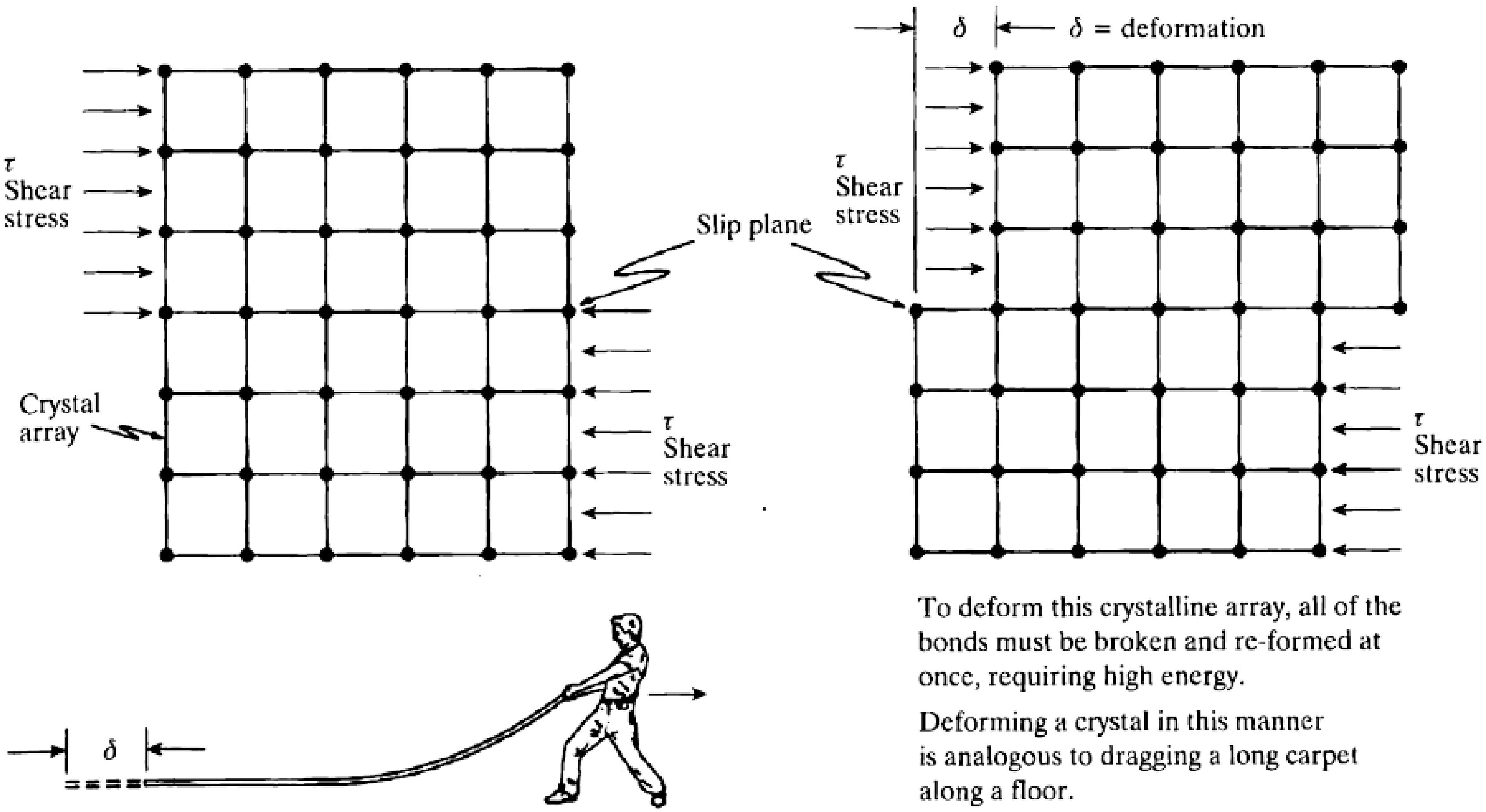


Dislocations

- Why?
  - Trying to shear whole planes sideways is physically impossible
- Dislocation
  - Extra half plane of atoms
  - Allows and created by plastic deformation
  - Explains most strengthening of metals



Without dislocations



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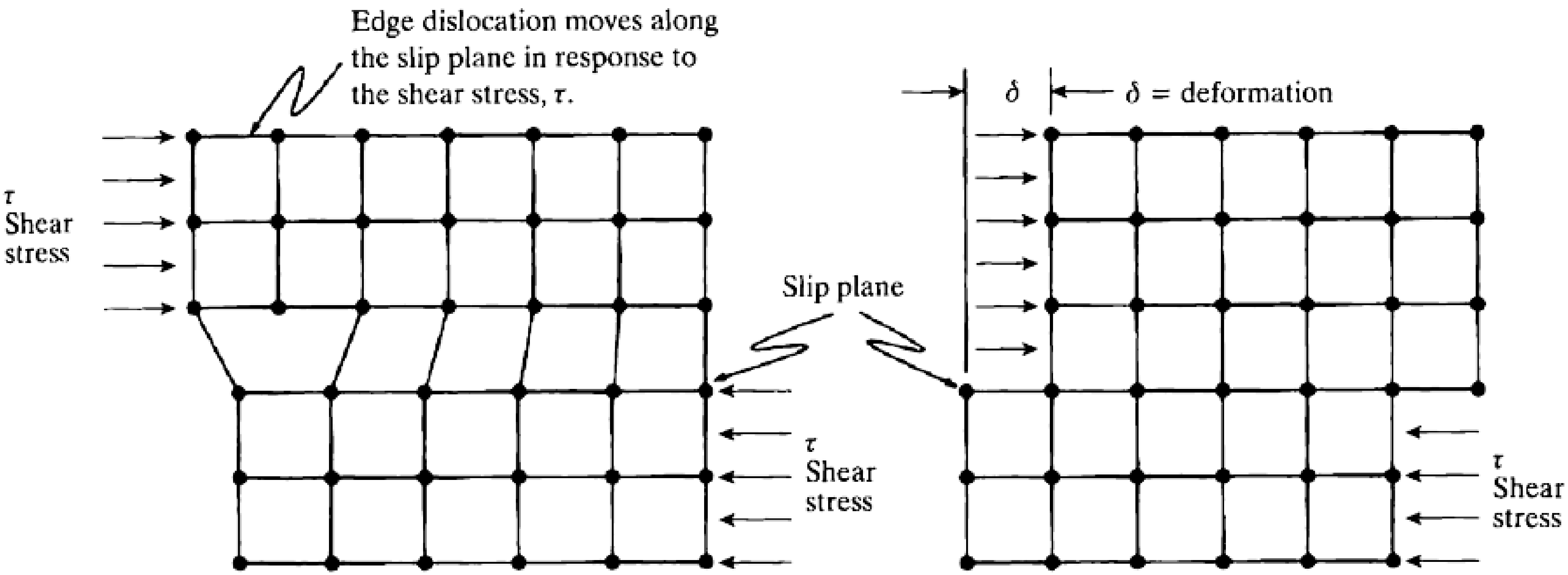
With dislocations



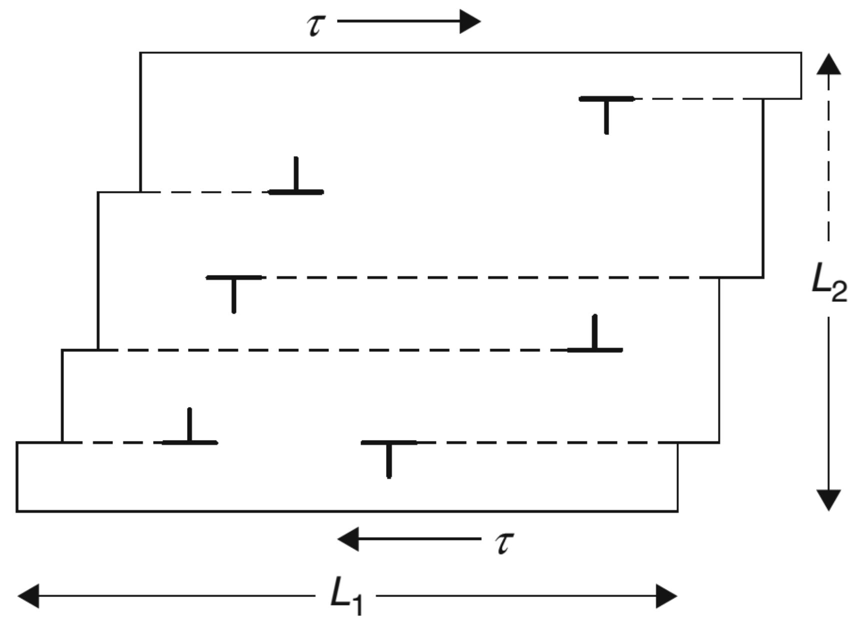
To deform a crystalline array with dislocations, only one row of bonds is broken and re-formed at once, requiring less energy than the example above.

Deforming a crystal in this manner is analogous to pushing a raised hump in a long carpet along a floor — a lower energy way of moving a carpet by distance, δ.

Dislocations

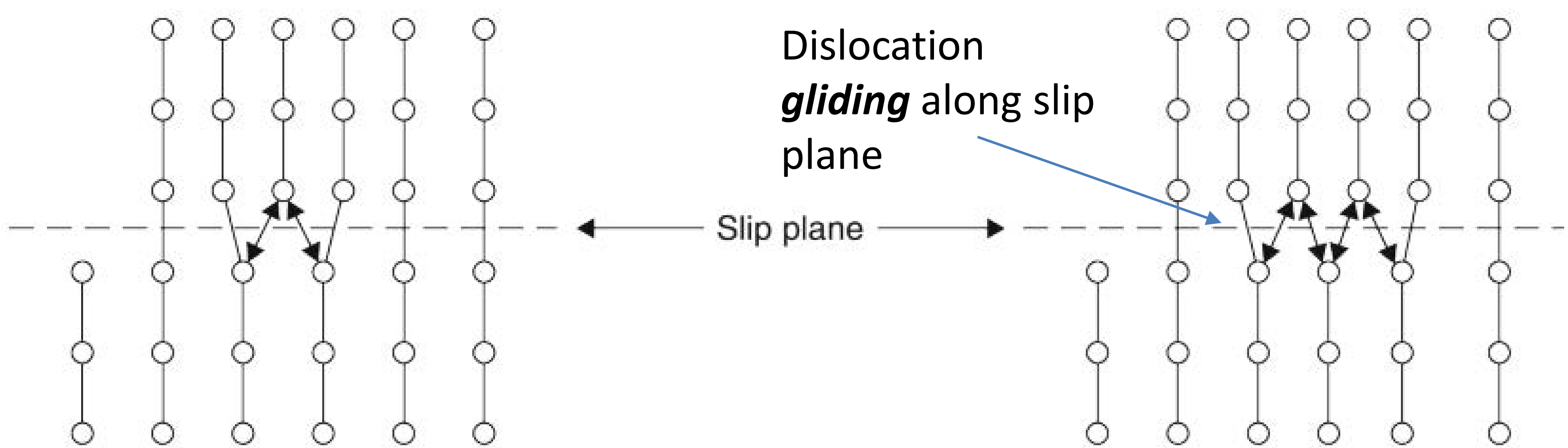
1 dislocation = 1 lattice shift on one plane

Many dislocations = macroscopic deformation



The force needed to overcome small forces is ***intrinsic*** strength of lattice

Dislocation ***gliding*** along slip plane



Dislocation in equilibrium (forces balance)

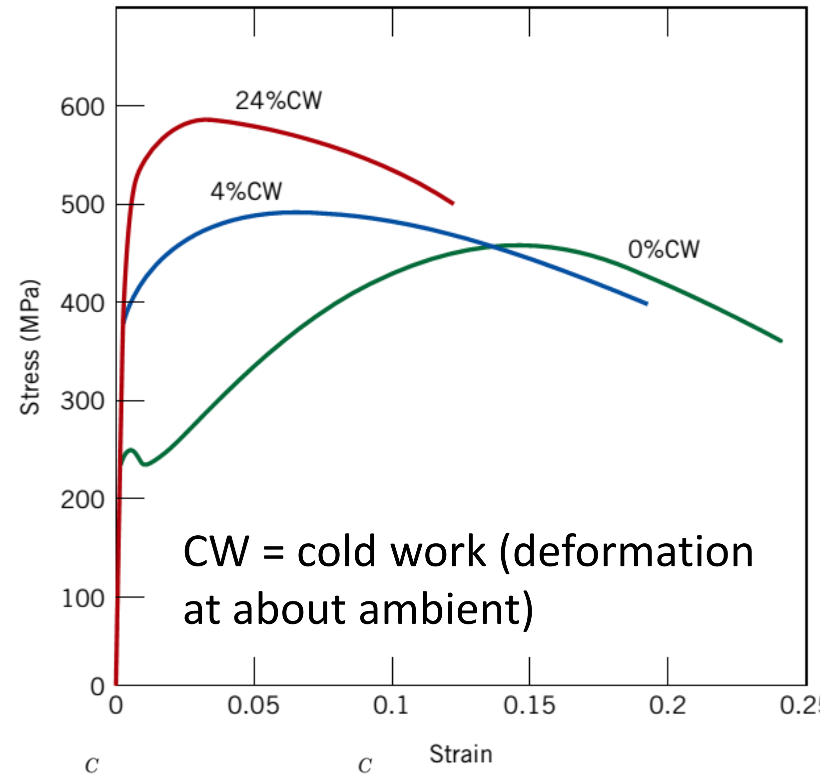
Dislocation in metaequilibrium (forces balance)

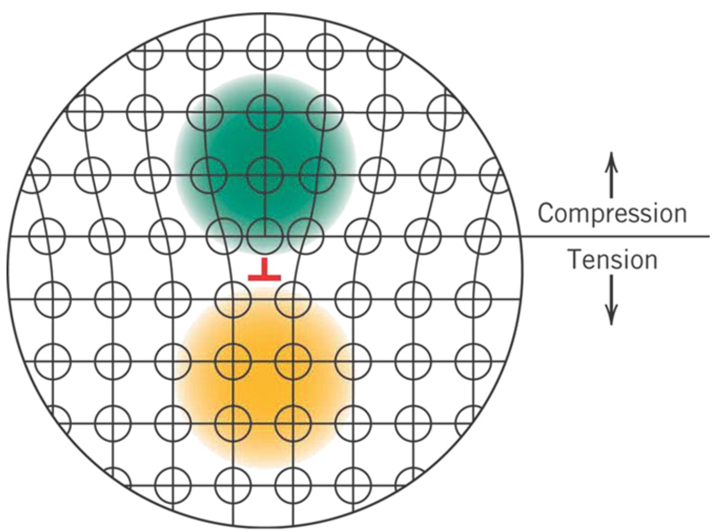
Work hardening

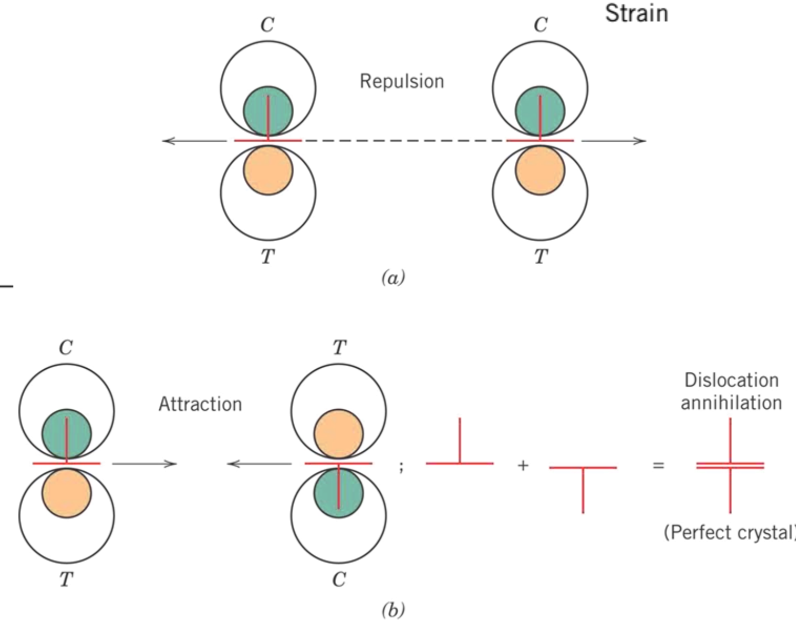
Cold work produces more dislocations

Dislocations restrict each other

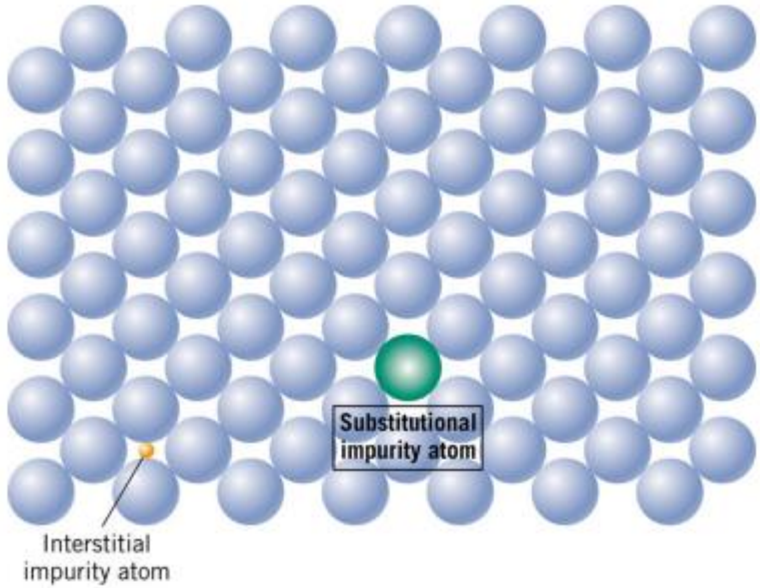
Increase in strength – reduction in ductility

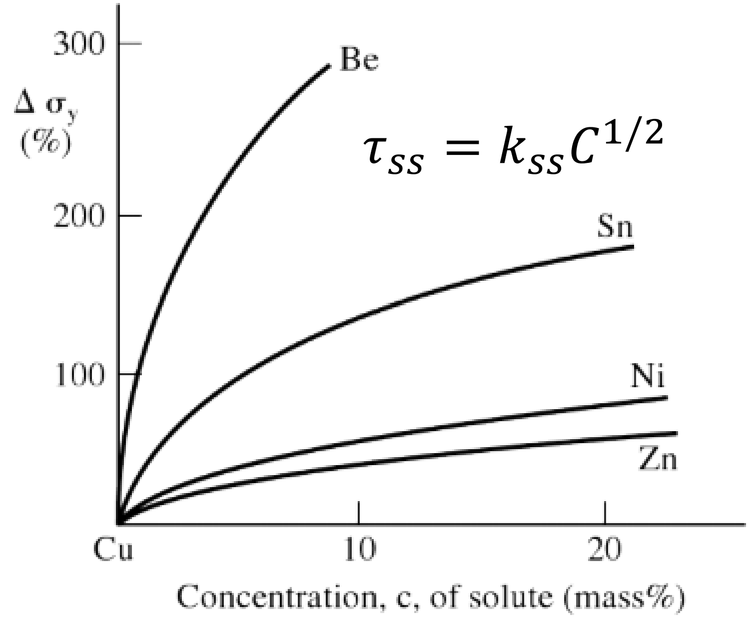




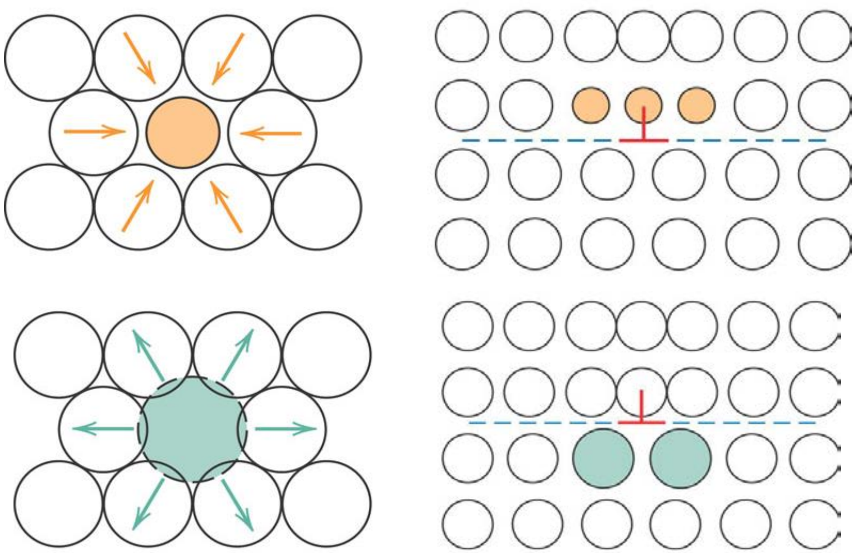


Solute strengthening



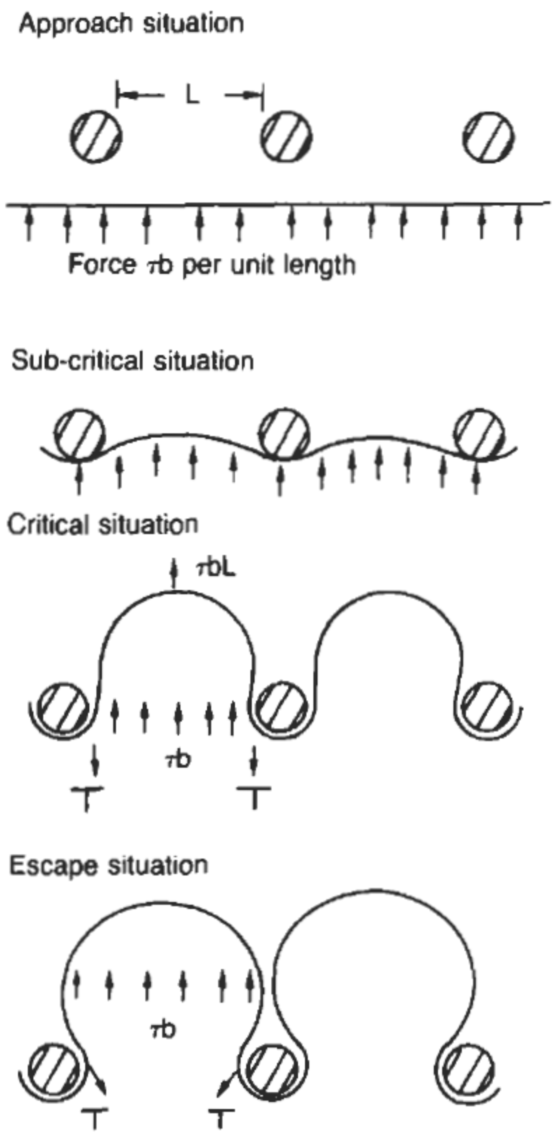


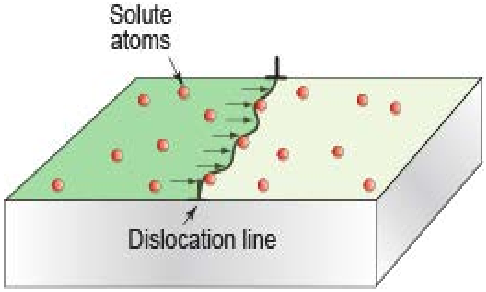
$$\tau_{ss} = k_{ss}C^{1/2}$$



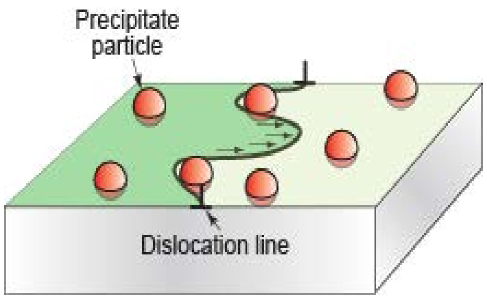
- Strain fields around alloying elements stop dislocations moving easily

Dispersion strengthening





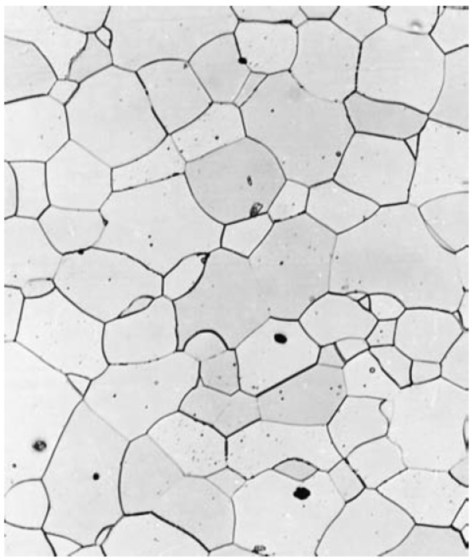
Solid solution hardening
(Chemistry)



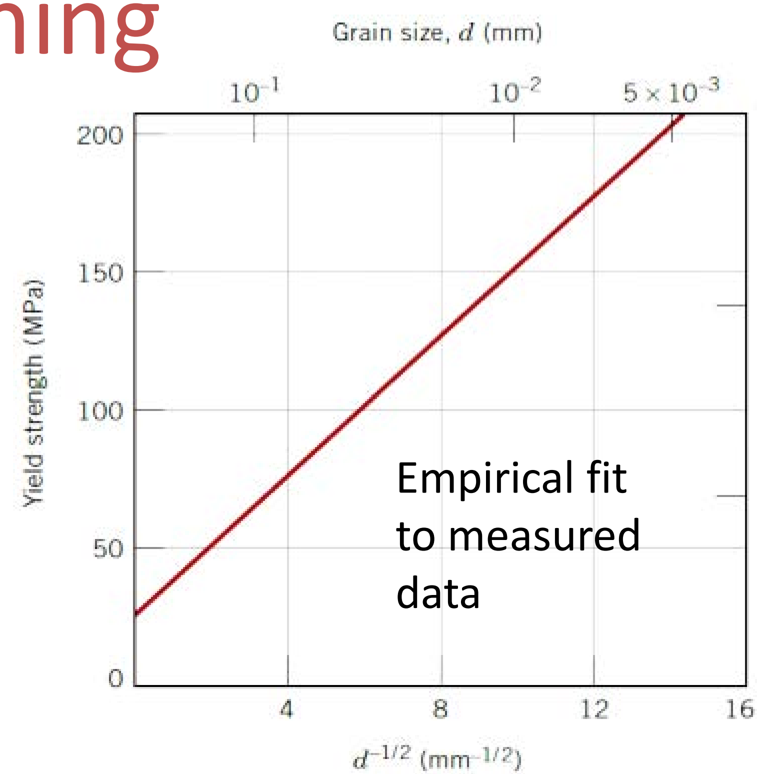
Precipitation/dispersion hardening
(Microstructure)

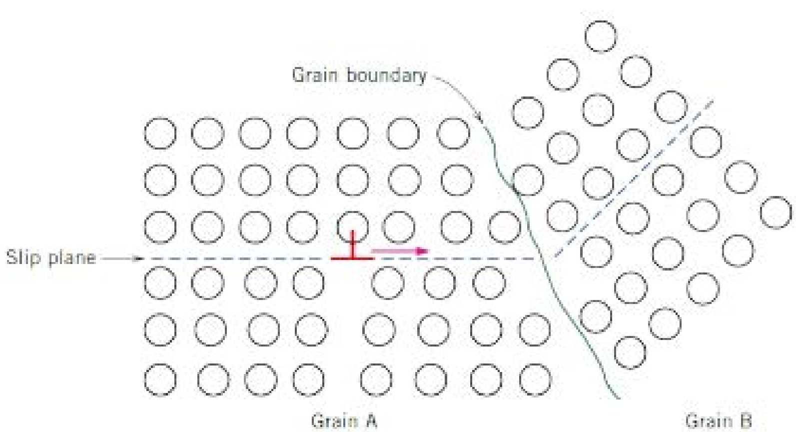
- We can often produce hard particles in metals
  - Carbides in steel, intermetallics in aluminium
  - Stop dislocations moving

Grain size strengthening



IMPORTANT:
Usually improves toughness as well – small grains are **really** desirable





Hall-Petch Equation

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

Grain size (diameter)

Tensile yield strength

Intrinsic yield strength

Constant

Combining Strengthening Effects

Critical shear strength of crystal

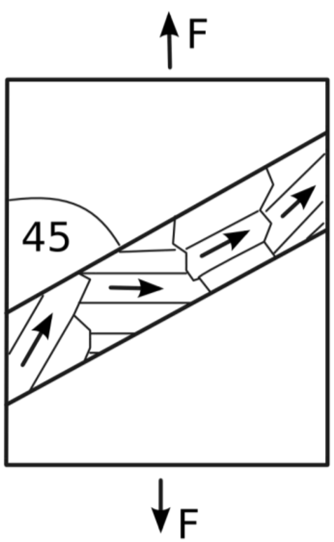
$$\tau_0 \approx \tau_i + \tau_{wh} + \tau_{ss} + \tau_{ds}$$

Dispersion strengthening

Intrinsic strength of crystal (often taken as 0 for metals)

Work hardening

solution strengthening



Uniaxial strength of large grained polycrystal

$$\sigma_0 = 3\tau_0$$

Estimated critical shear strength (sometimes called τ_c in the notes)

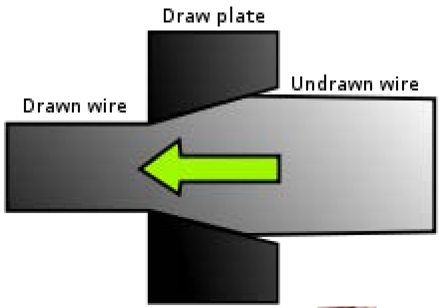
Rough approximation

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

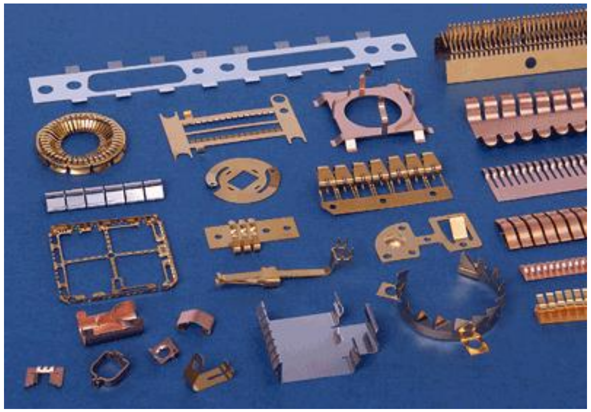
Uniaxial strength of smaller grained polycrystal

Grain diameter

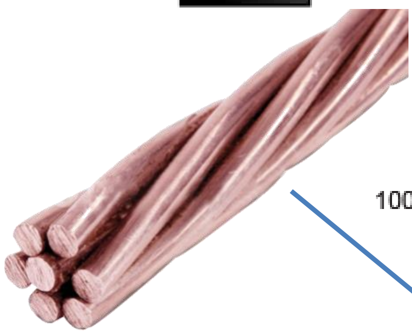
Copper



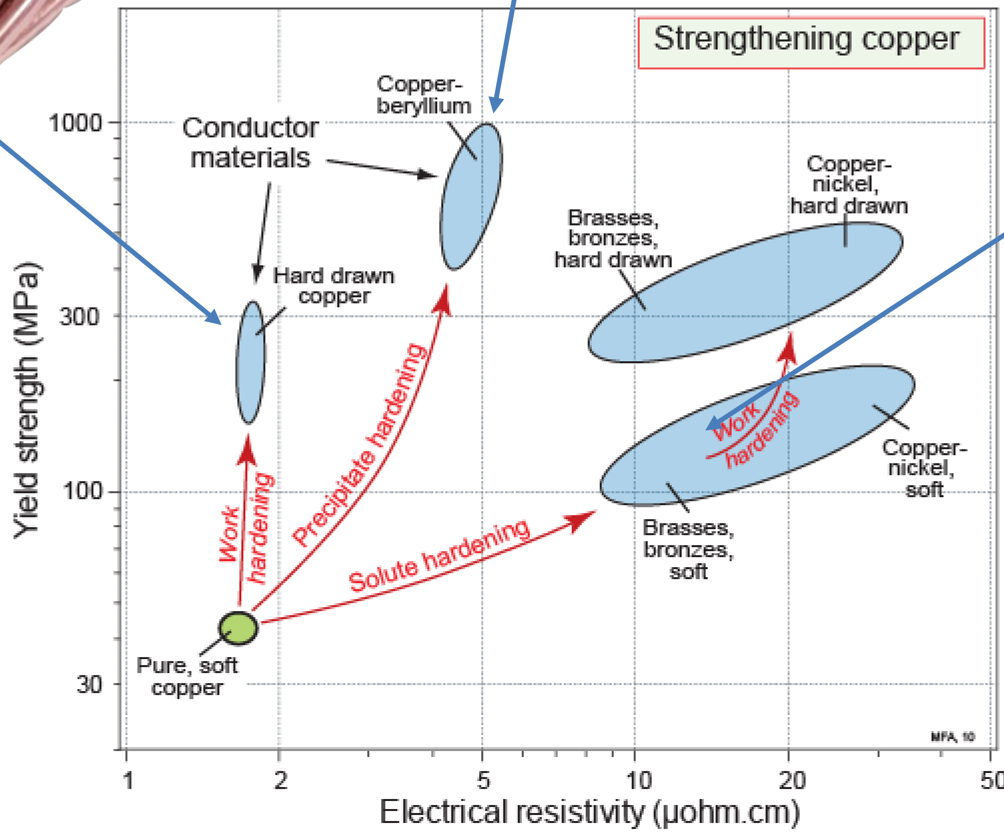
High-end electrical components



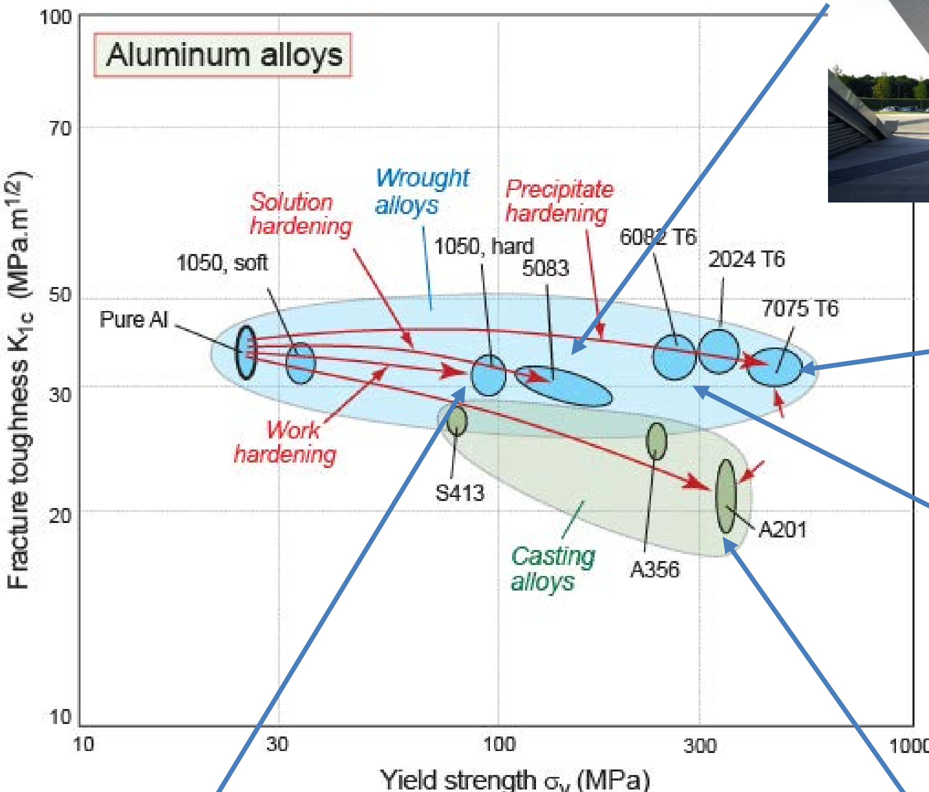
Brass bearings

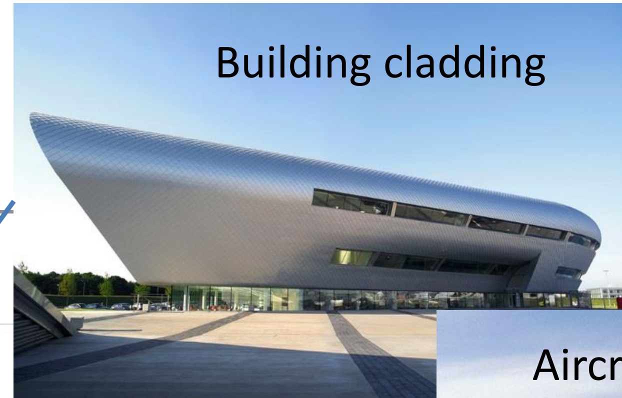


Electrical wire



Aluminium

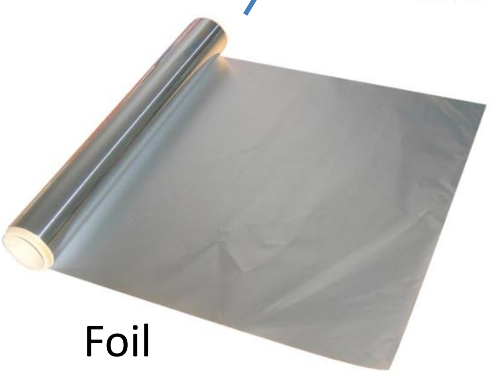




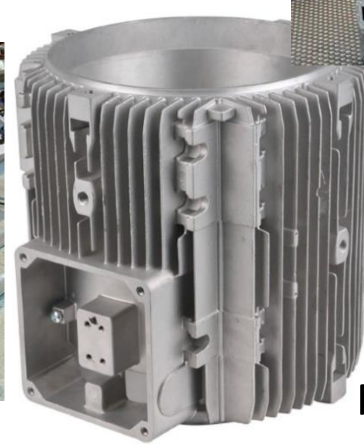
Building cladding

Aircraft skins/structure

Car bodies



Foil



Net shape castings

Steels

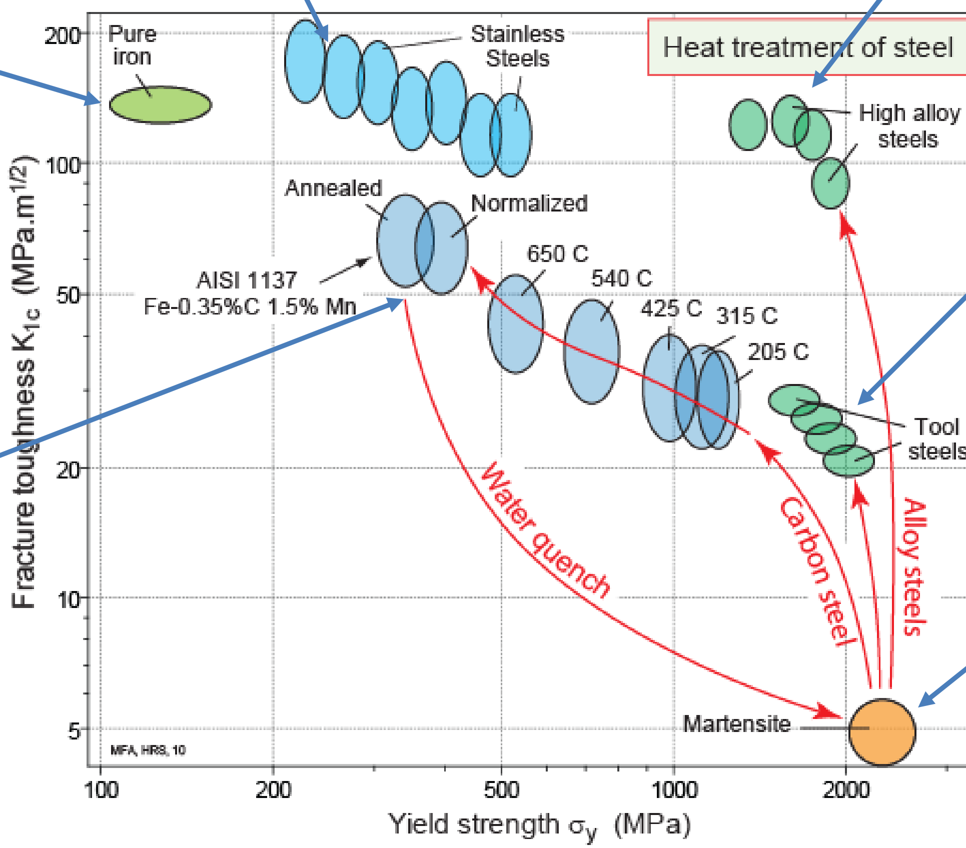
Architectural metalwork

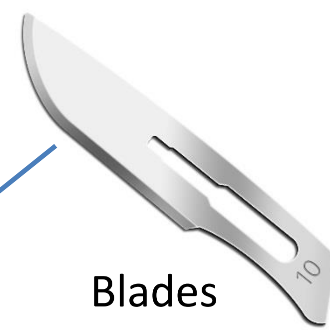
Pressure vessels

Transformer cores

Drill bits

Crankshaft





Blades

Titanium Applications in Aerospace

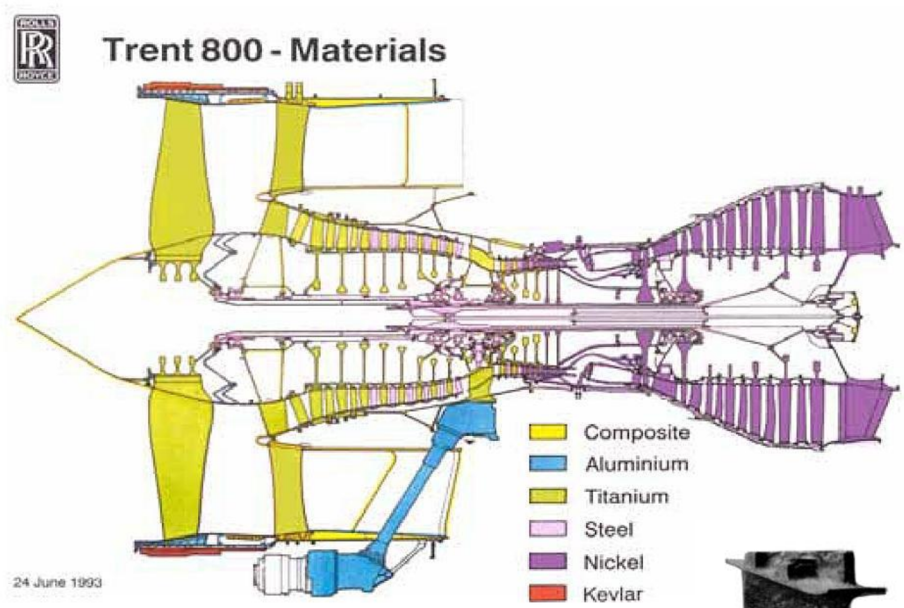
Fan Blades for Civil Jet Engines
37% by weight of Ti used for jet engines in commercial aircraft

Fan Blades for Military Jet Engines
24% by weight of Ti used for jet engines in military aircraft

Outer fuel tank sheathing and wings for Space vehicles

Titanium skeleton of Orion space capsule

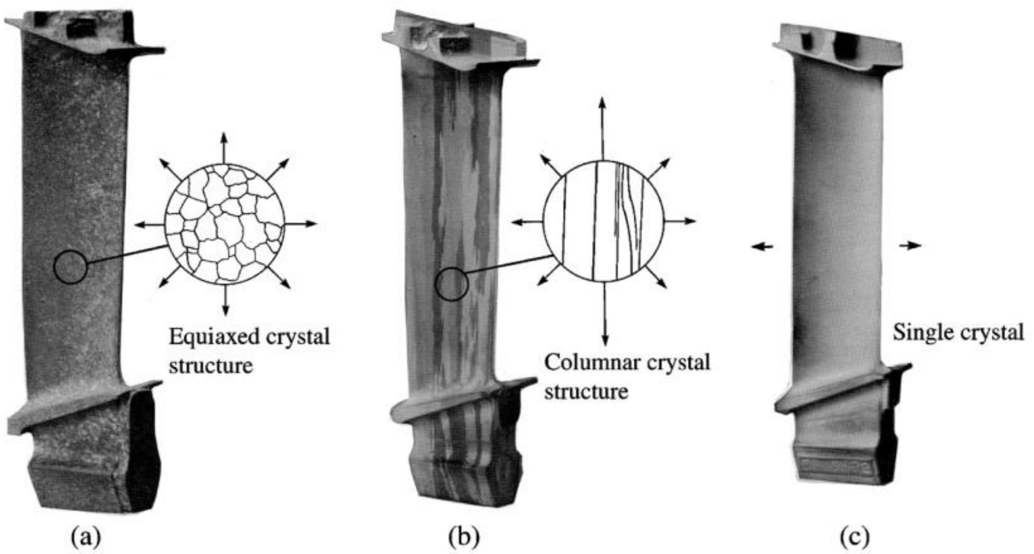
Single Crystals



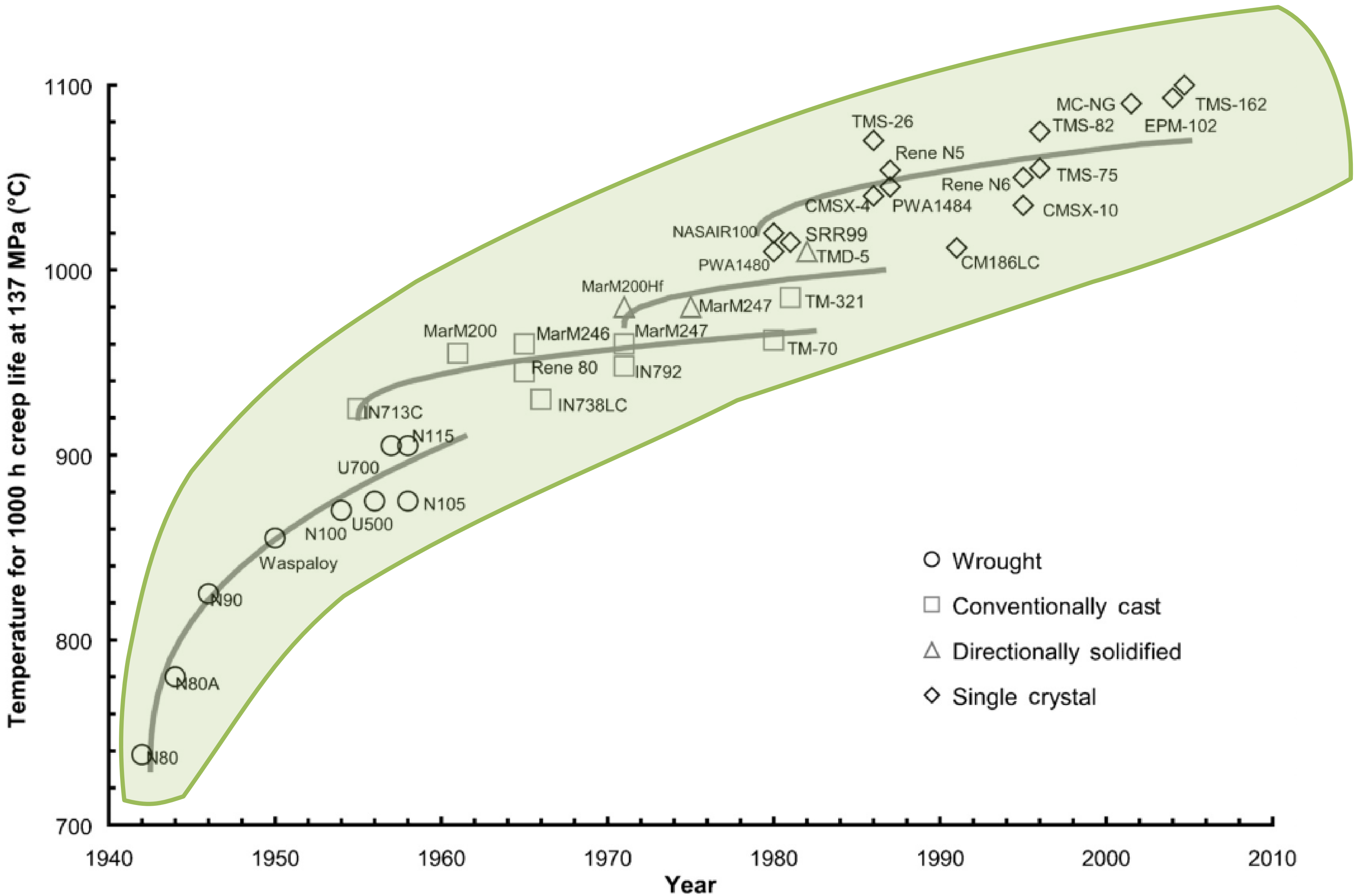
$$\eta = 1 - \frac{T_2}{T_1}$$

Efficiency of turbine increased operating at higher turbine temp

- High temperature properties
  - Dominated by grain boundaries (quick diffusion)
  - Solution: remove grain boundaries



Processing to Properties



Summary

- Polycrystals resemble continuum mechanics when there are many grains with lots of slip systems
  - Problems with HCP (few systems)
  - Problems with BCC (when cold the slip systems stop working)
- Strength of polycrystals constructed from strength of single crystals
  - Plasticity due to dislocations – if they can’t move the strength increases
  - Many mechanisms for increasing strength
  - Polycrystals are stronger than single crystals