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소성재료역학
(Metal Plasticity)

Chapter 4: Physical Plasticity

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Plasticity in Physical Metallurgy

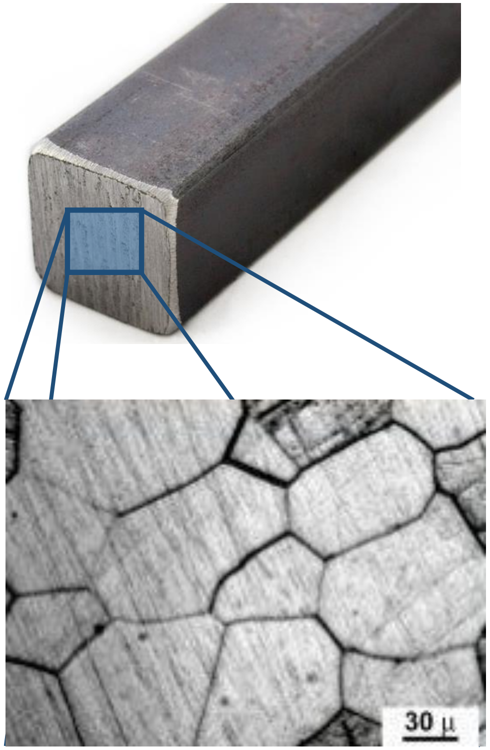
- Crystal plasticity
  - W.F. Hosford: The Mechanics of Crystals and Textured Polycrystals, Oxford University Press, 1993.
  - K.S. Havner: Finite Plastic Deformation of Crystalline Solids, Cambridge University Press, 1922.

- Dislocation
  - A.H. Cottrell: Dislocation and Plastic Flow in Crystals, Oxford University Press, 1956.
  - D. Hull and D.J. Bacon: Introduction to Dislocations, Pergamon Press, 1989.
  - J.P. Hirth and J. Lothe: Theory of Dislocations, Krieger Publishing Company, 1991.

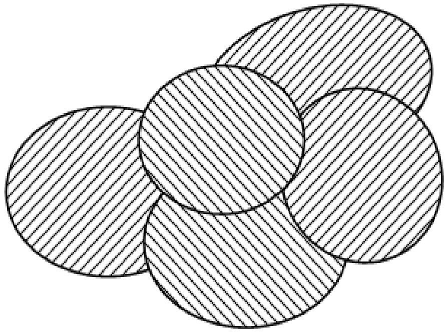
Single crystal vs Polycrystal

Diamond – huge single crystal

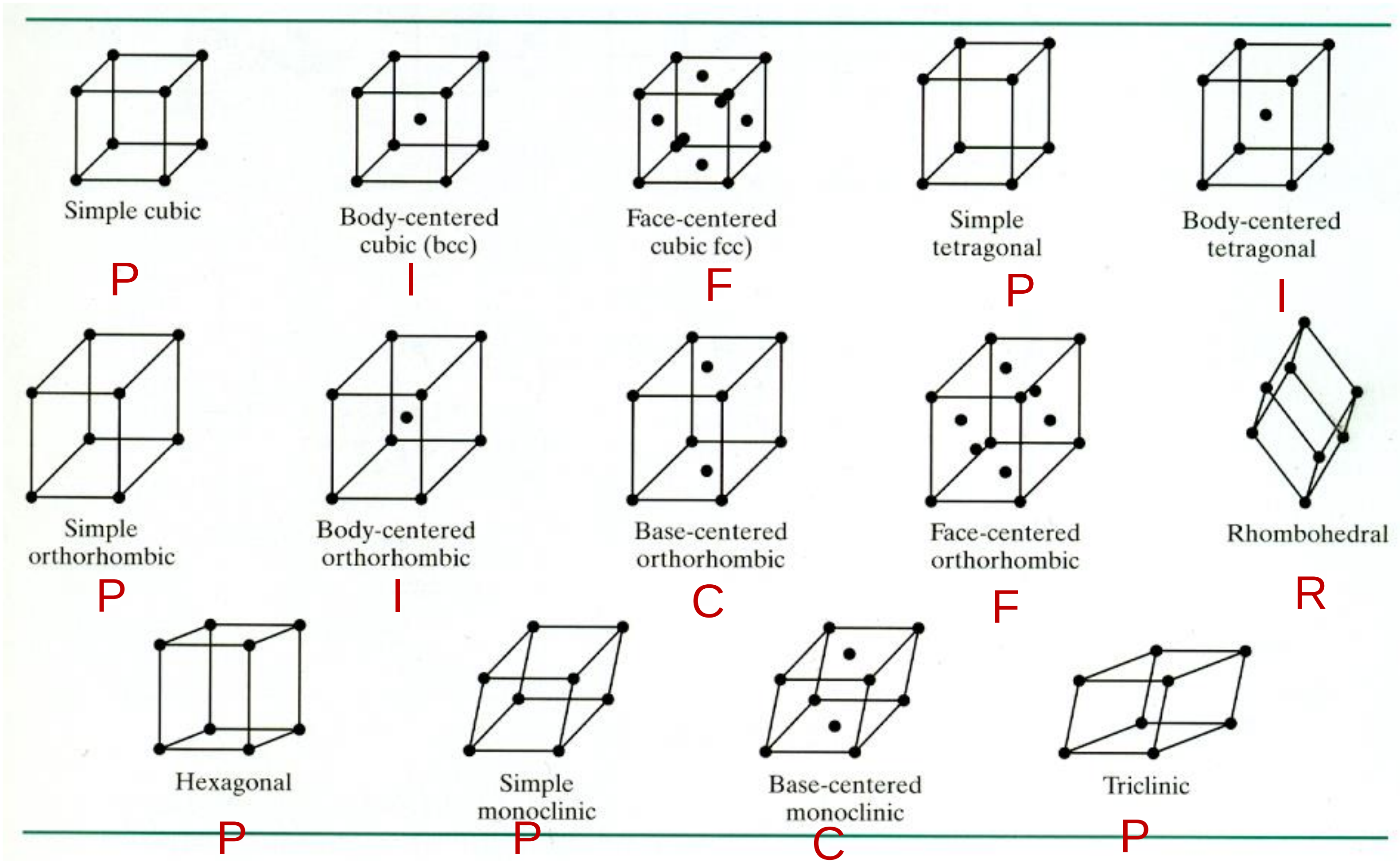
Most metals - polycrystal



Schematics of polycrystal



Crystal structures – 14 Bravais lattice

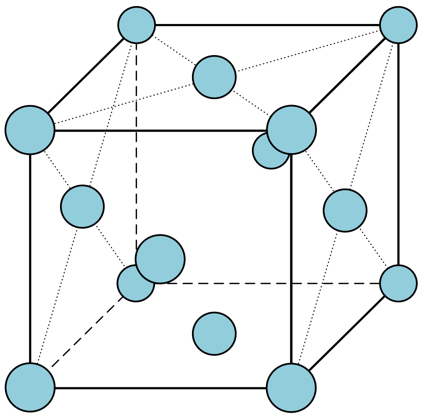


- simple (1), body-centered (2), base-centered (2)
  face-centered (4 atoms/unit cell)

Crystal structures of materials

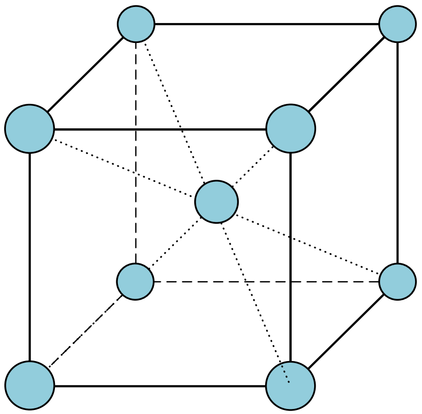
FCC - Face centered cubic

Fe-γ, Al, Ni, Cu, etc…



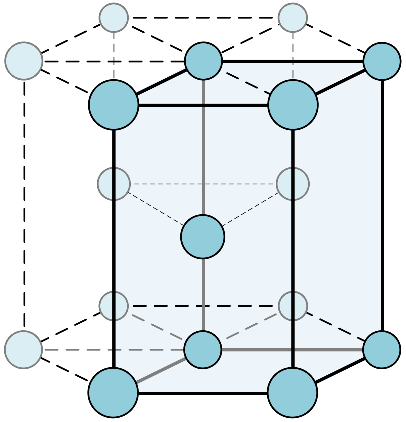
BCC – Body centered cubic

Fe-α, Cr, Co, etc…



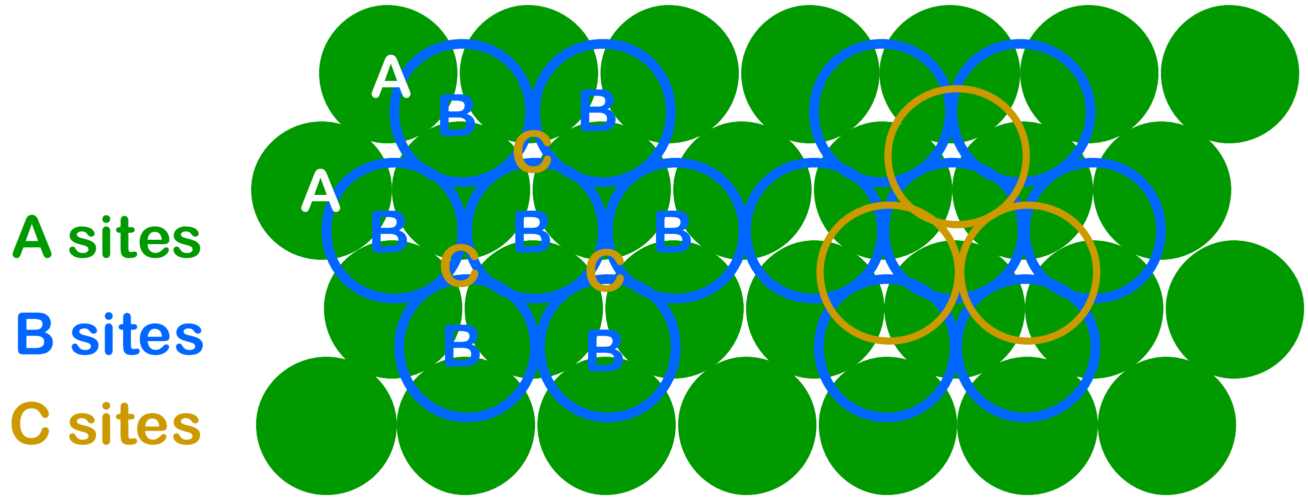
HCP – Hexagonal close packed

Mg, Ti, Zn etc…

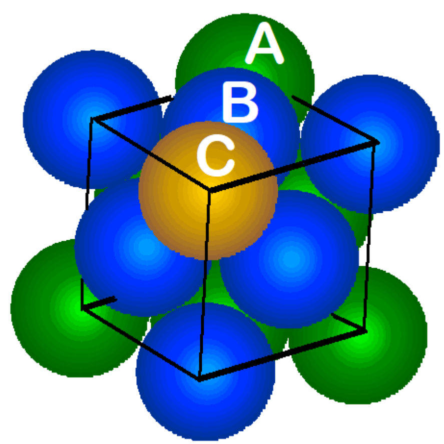


Crystal structures – FCC

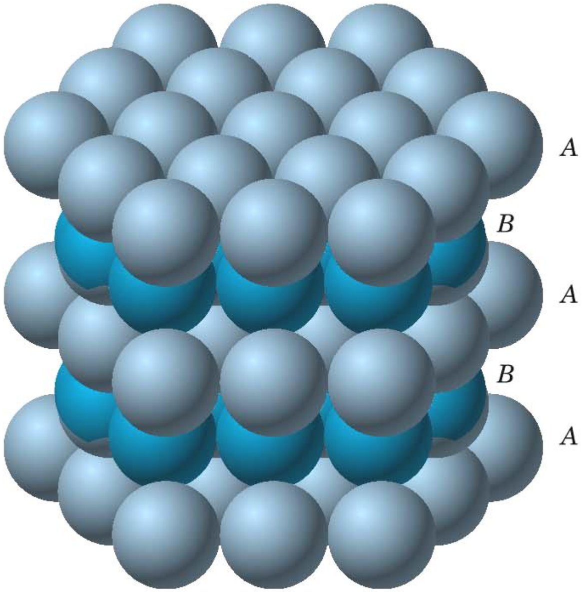
- ABCABC… Stacking Sequence
  - 2D projection



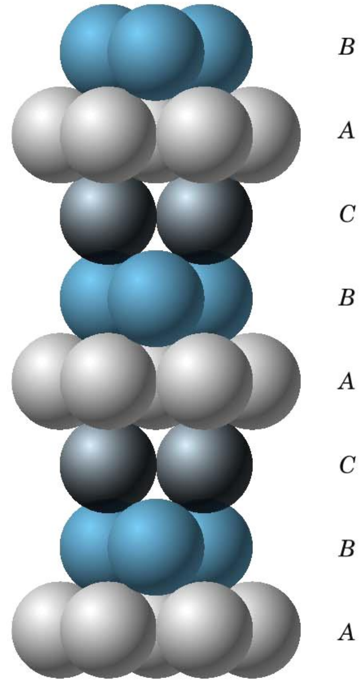
  - FCC unit cell



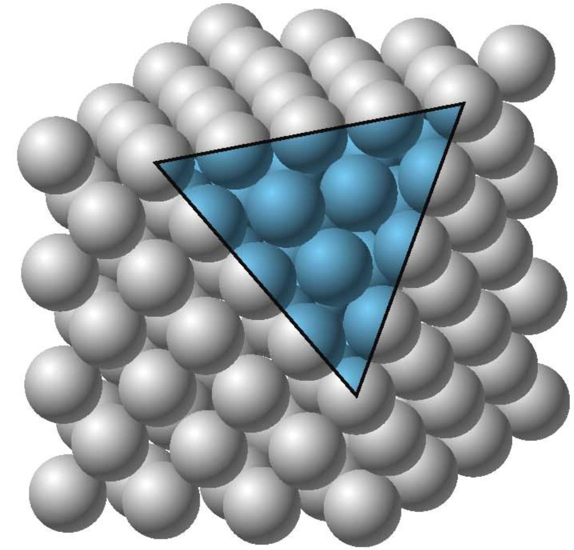
Crystal structures – Close packing



HCP



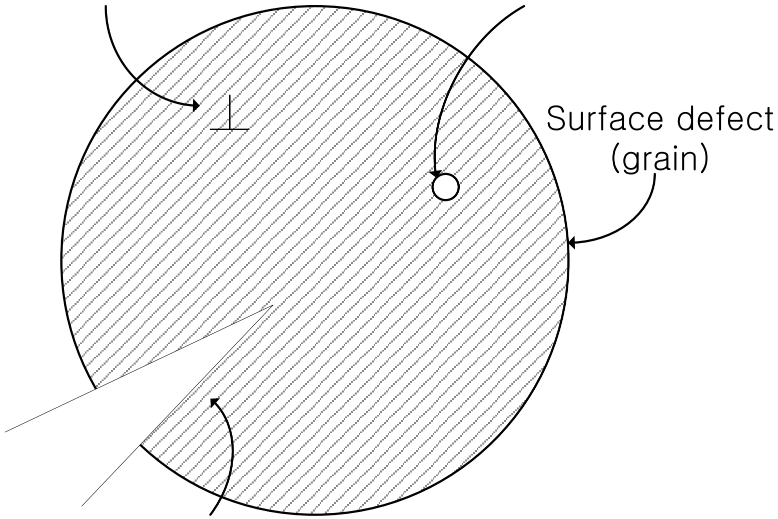
FCC



FCC

Stacking sequence in Close-packed plane
HCP : ABABAB….   FCC : ABCABC…

Defects(or imperfections) in crystals



- 0D : point defects
  - Vacancy, interstitial, etc..
- 1D : line defect
  - dislocations
- 2D : surface defects
  - grain boundary, twinning, stacking-faults
- 3D : bulk defects
  - micro(or macro) void, crack, precipitates, etc…

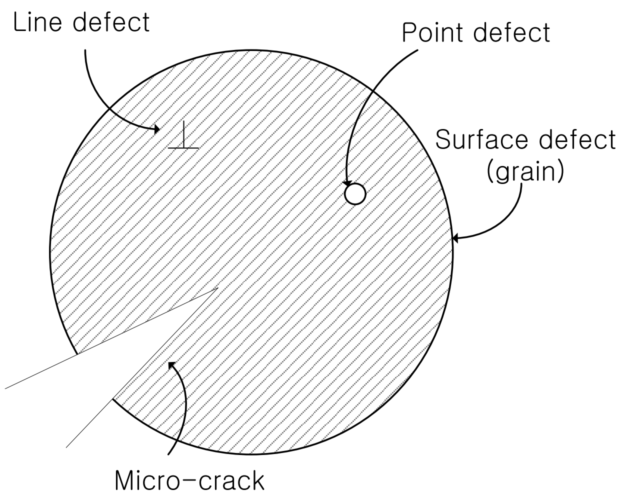
Plastic deformation

- Plastic deformation occurs by shear stress, which involves sliding of atoms and moving dislocations for crystals.

- There exist slip systems (slip planes and slip directions for easy sliding) and the critical shear stress for a single crystal.

- Point/line/surface defects contribute the magnitude of the critical shear stress.

- Initially, the elastic deformation is introduced by the applied force, then, as force increases, normal force component and shear force component on a plane compete for fracture and plastic deformation during deformation.



Theoretical strength of crystals

Tensile strength by Orowan(1949)

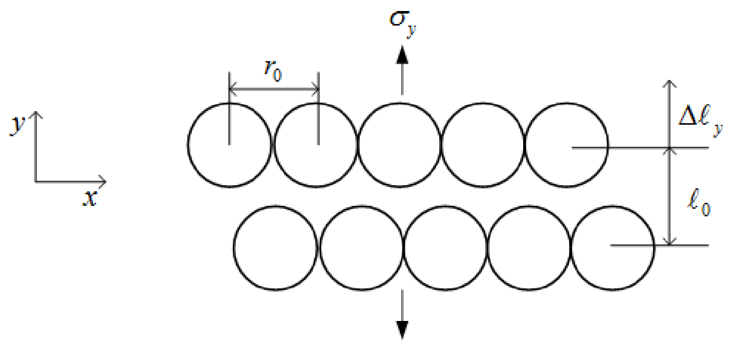
$$\sigma_y = K_y \sin\left(\frac{2\pi \cdot \Delta l_y}{d}\right)$$

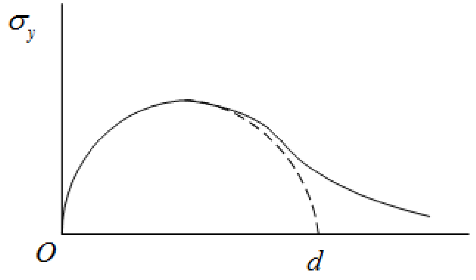
$$\approx \frac{K_y \pi \cdot \Delta l_y}{d} \qquad \cdots\cdots ①$$

$$\sigma_y = E\varepsilon_y = \frac{E \cdot \Delta l_y}{l_0} \qquad \cdots\cdots ②$$

From ① and ②

$$\boxed{\sigma_y^{\max} = K_y \approx \frac{E \cdot d}{\pi l_0} \approx \frac{E}{\pi}}$$





Crystal structures of materials

Shear strength by Frenkel (1926)

$$\sigma_{xy} = K_{xy} \sin\left(\frac{2\pi \cdot \Delta l_{xy}}{r_0}\right)$$

$$\approx \frac{2K_y \pi \cdot \Delta l_{xy}}{r_0} \qquad \cdots\cdots\cdot ①$$

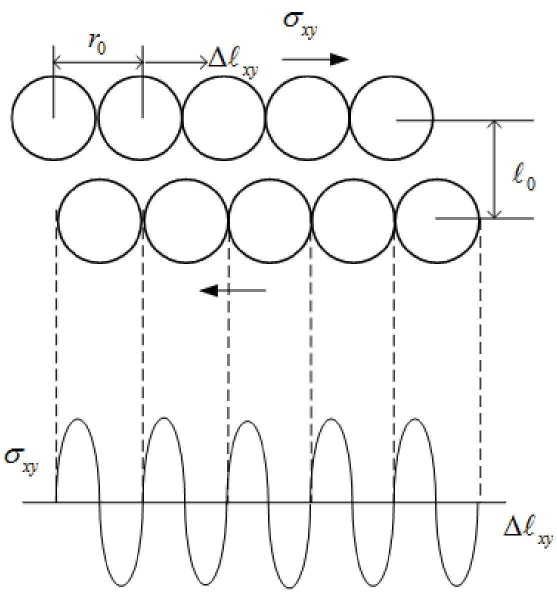
$$\sigma_{xy} = G2\varepsilon_{xy} = \frac{G \cdot \Delta l_{xy}}{l_0} \qquad \cdots\cdots\cdot ②$$

From ① and ② ($l_0 \approx r_0$)

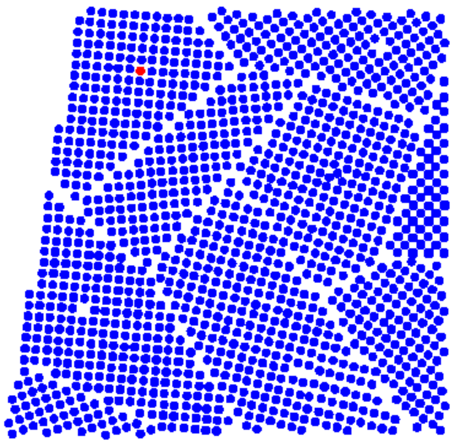
$$\boxed{\sigma_{xy}^{\max} = K_{xy} \approx \frac{G \cdot r_0}{2\pi l_0} \approx \frac{G}{2\pi}}$$

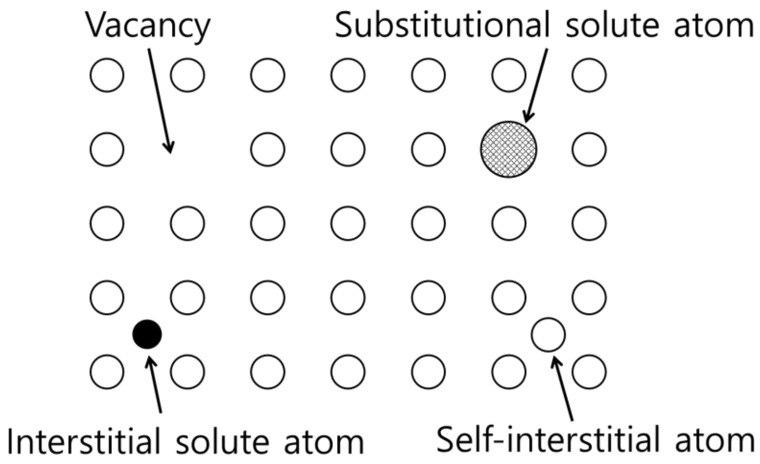
Considering relation of G and E

$$\boxed{\sigma_{xy}^{\max} \approx \frac{G}{2\pi} = \frac{E}{4\pi(1+\nu)} = \frac{\sigma_y^{\max}}{4(1+\nu)}}$$



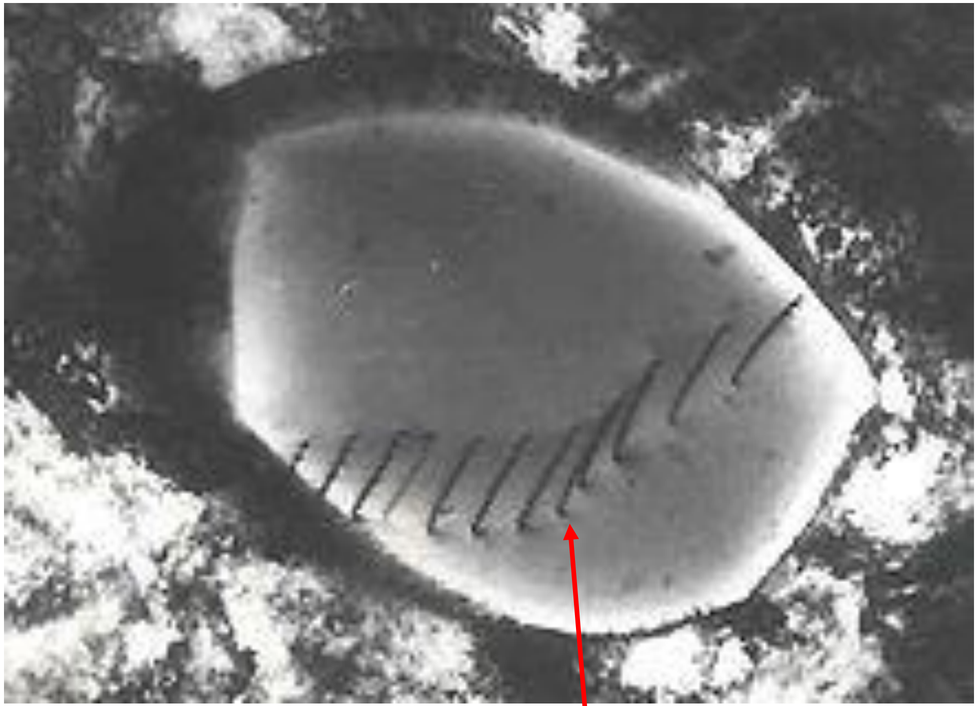
Point defects





- A single atom changes to the normal crystal array.
- Three major point defects: Vacancies, Interstitials and Substitutional impurities
- Vacancies: A vacancy is the absence of an atom from a site normally occupied in the lattice.
- Interstitials: An interstitial is an atom on a non-lattice site.
- Substitutional impurities: An impurity is the substitution of a regular lattice atom with an atom that does not normally occupy that site.

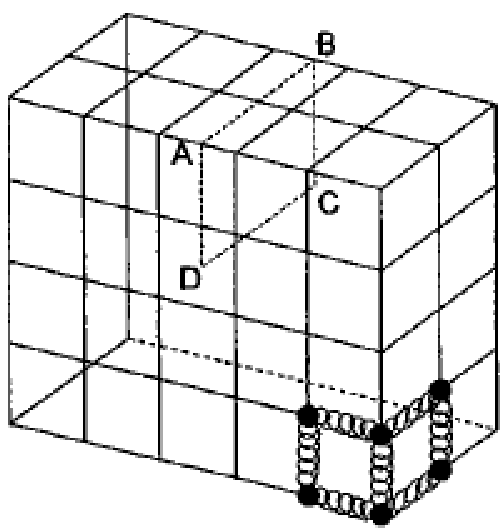
Line defects - dislocations

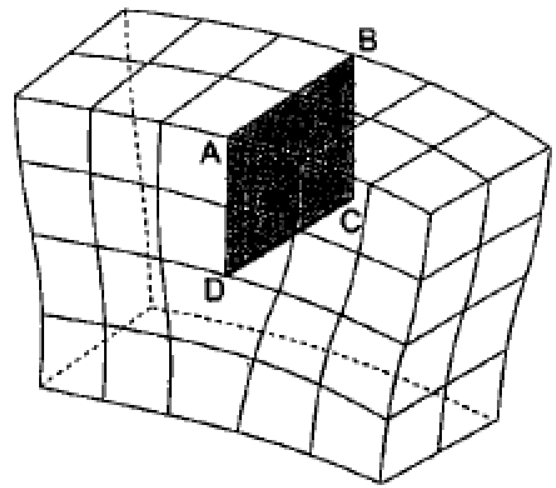


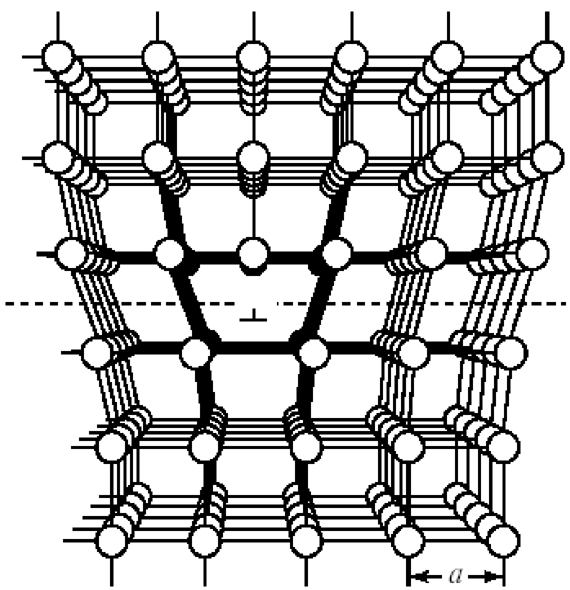
Dislocations (TEM image)

* https://en.wikipedia.org/wiki/Dislocation#/media/File:TEM_micrograph_dislocations_precipitate_stainless_steel_1.jpg

Line defects - dislocations



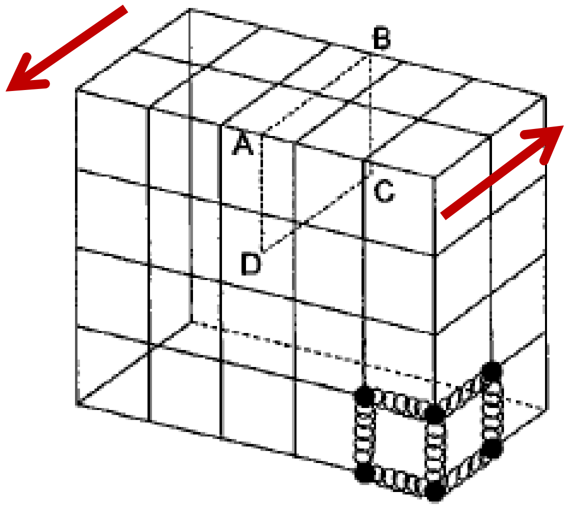




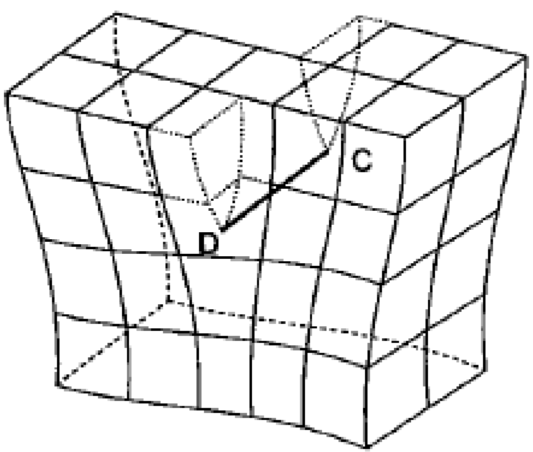
$\perp$: positive edge dislocation

$\top$: negative edge dislocation

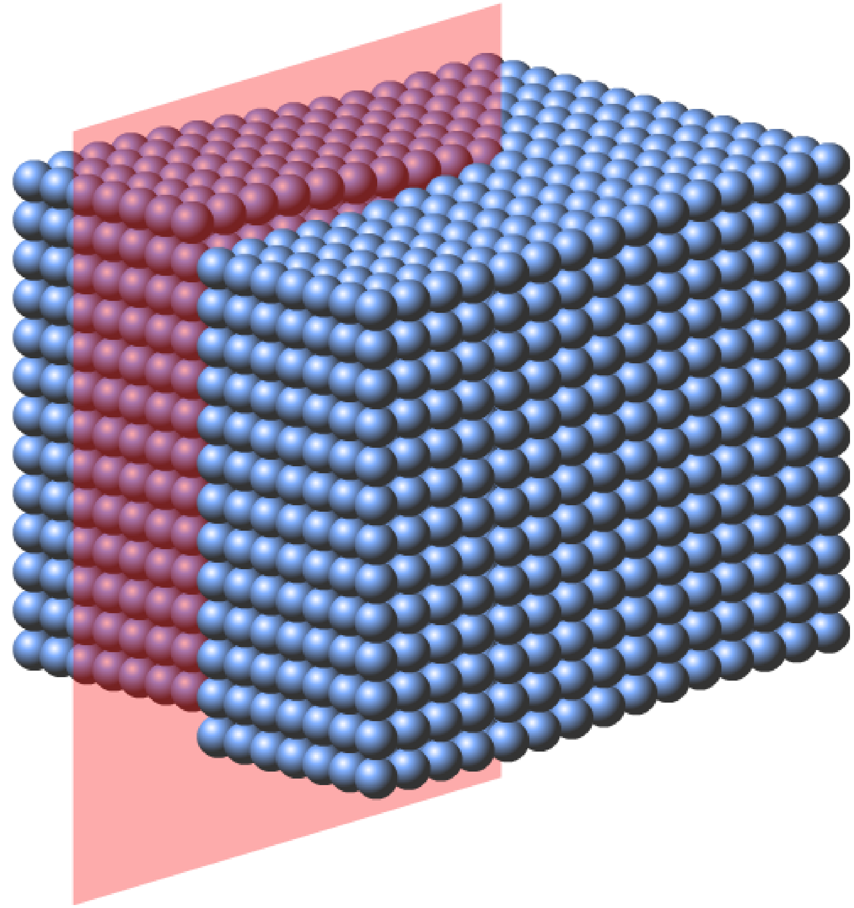
Line defects - dislocations



(a)



(c)



Line defects - dislocations

- Dislocation density, ρ

= total length of dislocation in unit volume of crystal (m/m^3)

- Typical values for dislocation density

  Well-annealed metallic material ~ 10^{10}-10^{12} (m/m^3)

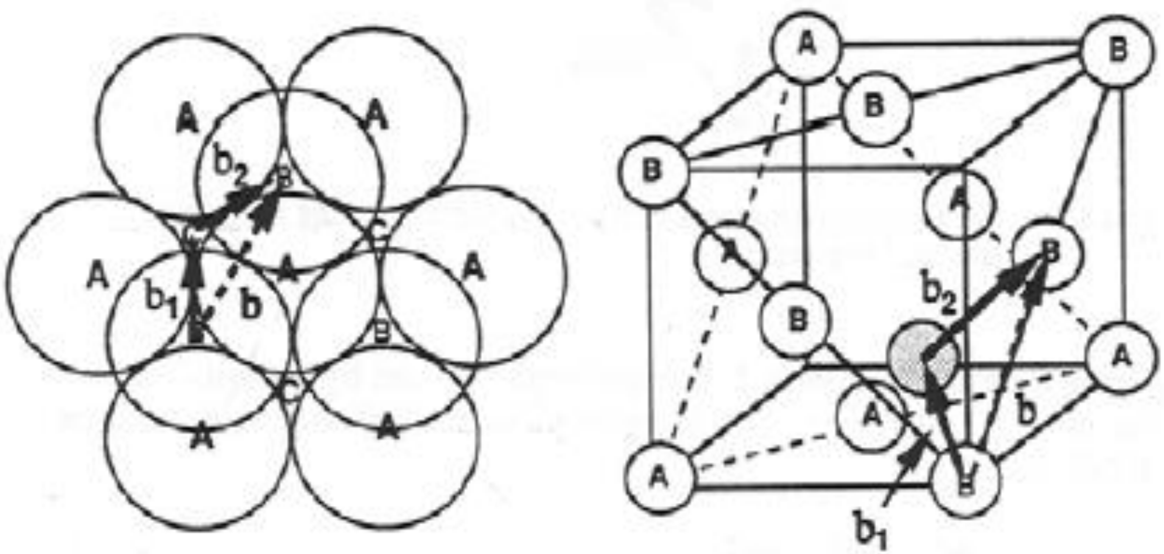
  Cold-rolled metal ~ 10^{14}-10^{15} (m/m^3)

- Average distance between dislocations

= $1/\sqrt{\rho}$ (~10μm for well-annealed metals)

Line defects - dislocations

- Perfect dislocation: its Burgers vector is the lattice translation vector
- Partial dislocations: its Burgers vector is not a lattice translation vector

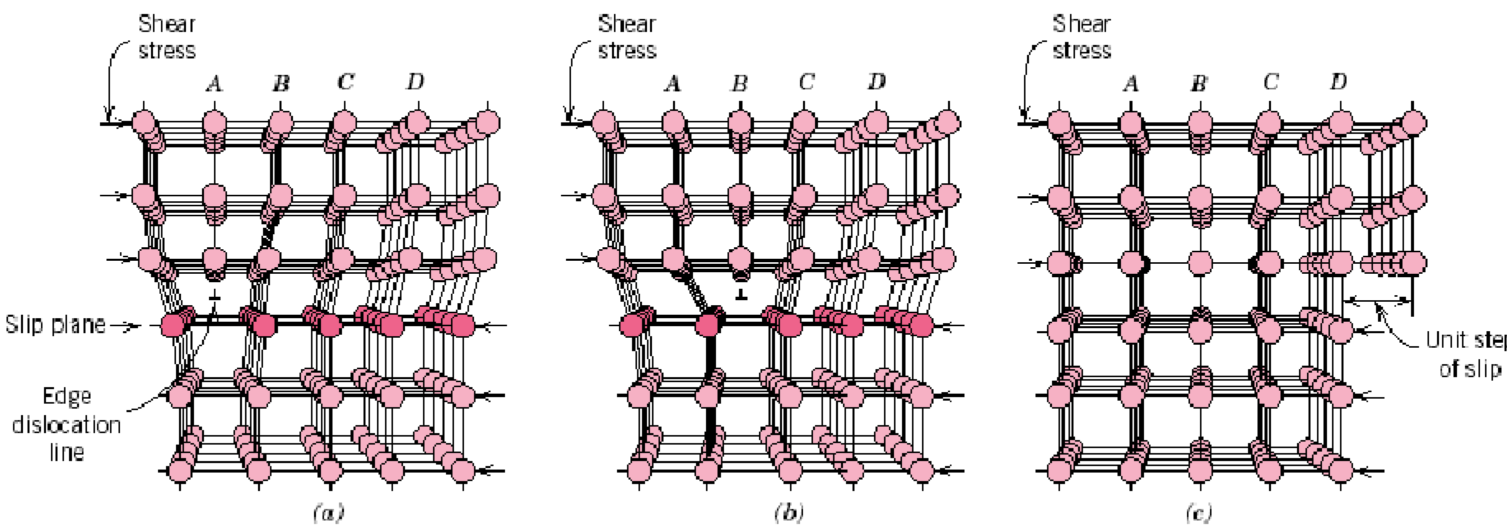


For FCC materials, $\mathbf{b} = \frac{1}{2}\ [\bar{1}\ 0\ 1]$

$\mathbf{b_1} = \frac{1}{6}\ [\bar{1}\ \bar{1}\ 2]$, $\mathbf{b_2} = \frac{1}{6}\ [\bar{2}\ 1\ 1]$

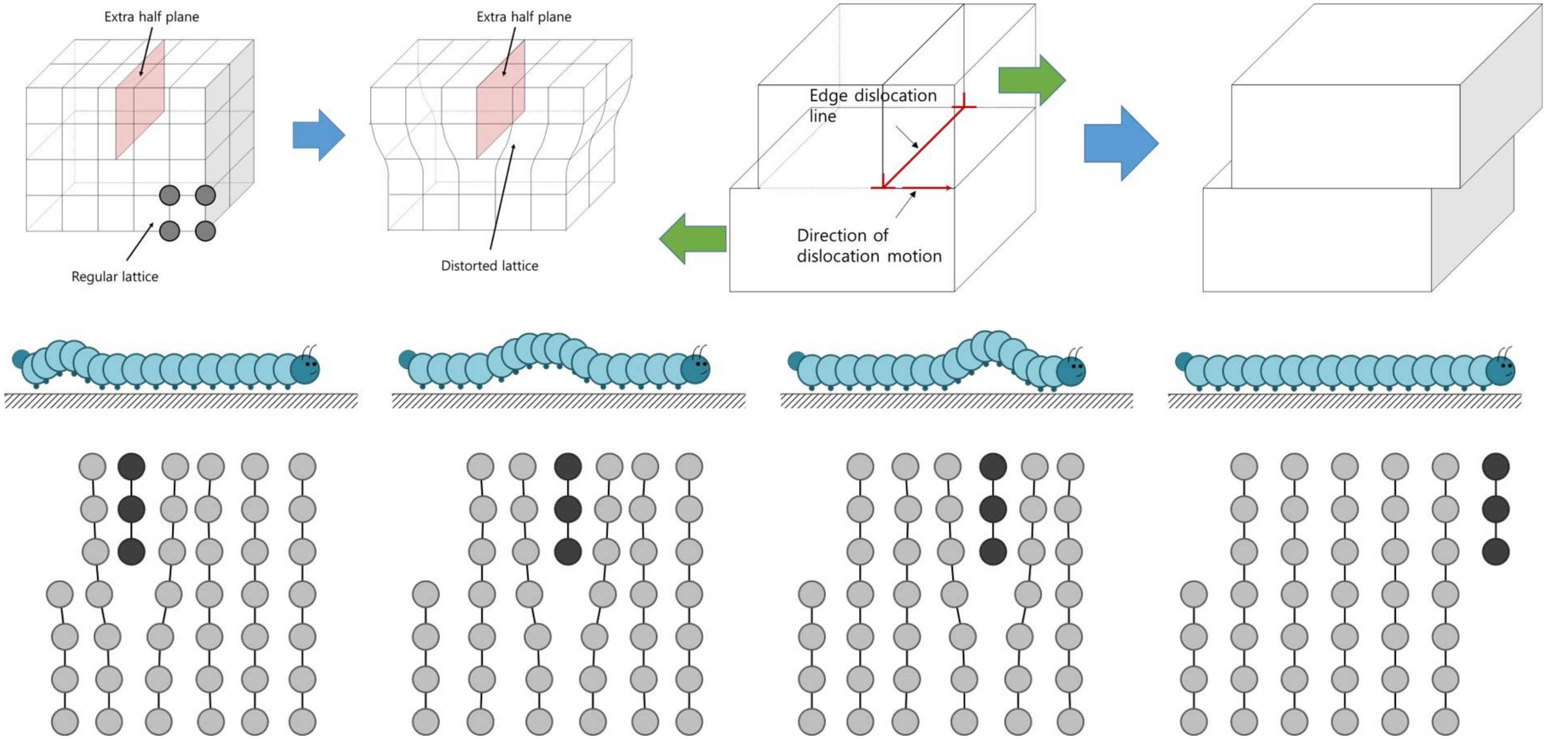
Motion of dislocation

- Produces plastic deformation
- Depends on incrementally breaking bonds
- If dislocations don't move, plastic deformation doesn't happen! (But fracture will, like in a ceramic)



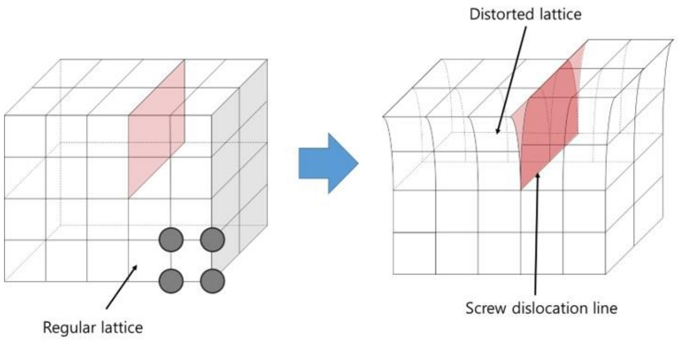
Motion of dislocation

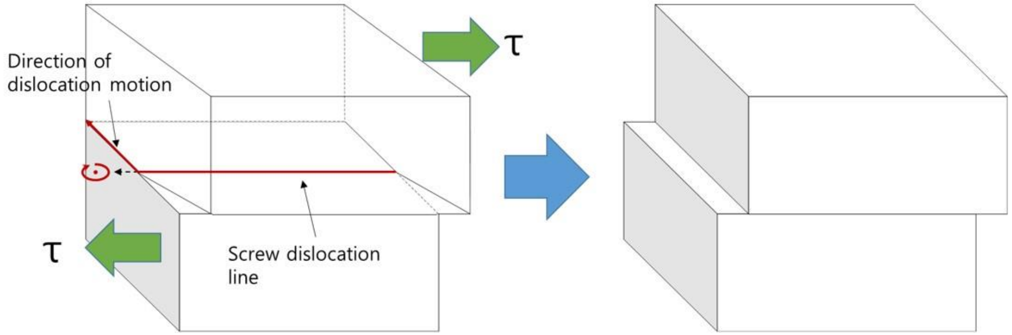
- Edge dislocation: edge dislocation line moves parallel to applied stress



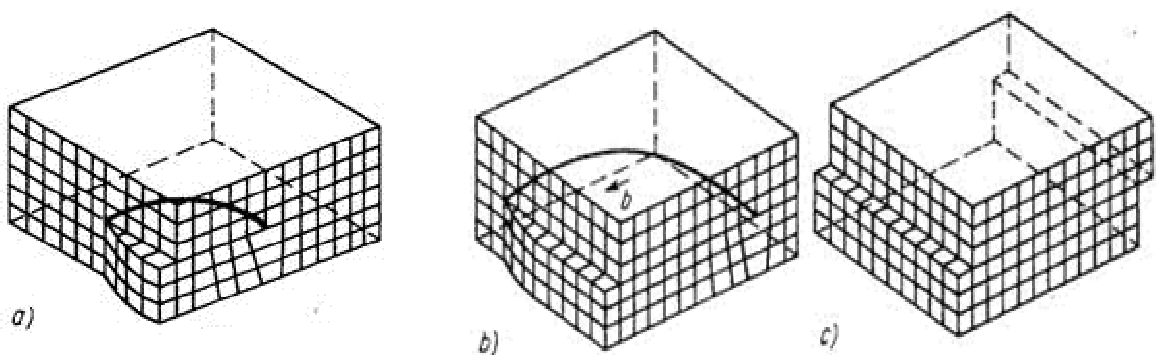
Motion of dislocation

- Screw dislocation: screw dislocation line moves perpendicular to applied stress





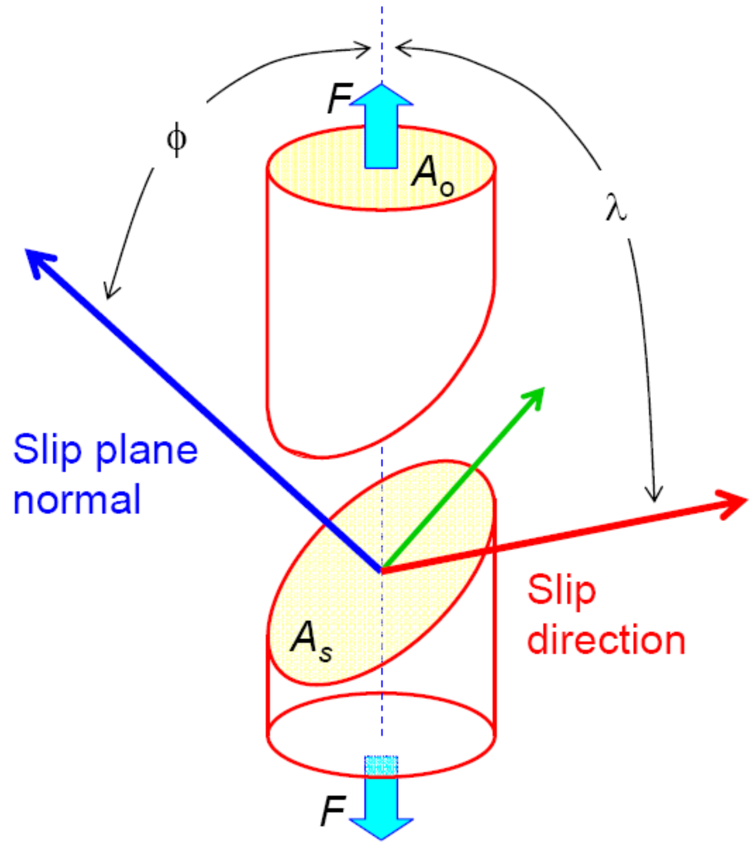
- Mixed dislocation*



* Hensel A., Spittel Th., Kraft- und Arbeitsbedarf bildsamer Formgebungsverfahren, VEB Deutscher Verlaf fur Grundstoffindustrie Leipzig

Plastic deformation in single crystal

- Plastic deformation is initiated at a critical stress the critical resolved shear stress (CRSS).
- The CRSS is the stress at which dislocations begin to move.



Resolved Shear Stress

Taylor factor

$$\tau_{RSS} = \frac{F}{A_o} \underbrace{\cos\phi \cos\lambda}_{\text{Schmid Factor}} = \sigma / m$$

Plastic flow is initiated when τ_{RSS} reaches a critical value, characteristic of the material, called *critical RSS,* when $m\ \tau_{CRSS} = \sigma_{ys}$ *(Schmid law)*.

Plastic deformation in single crystal

Resolved Shear Stress

$$\tau_{RSS} = \frac{F}{A_o} \underbrace{\cos\phi \cos\lambda}_{\text{Schmid Factor}}$$

- The active slip system will have the largest Schmid factor.

- Macroscopic tensile yield stress:

$$\sigma_y = \frac{\tau_{CRSS}}{\cos\phi \cos\lambda}$$

or $\tau_{CRSS} = \sigma_y \cos\phi \cos\lambda$

- τ_{CRSS} is the *resolved shear stress* required *to cause plastic deformation via slip*.

Plastic deformation in single crystal

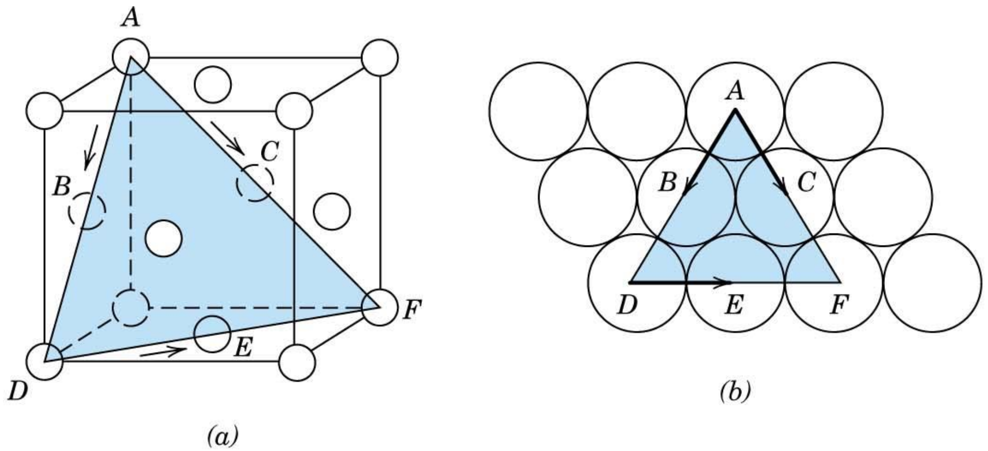


FIGURE 7.6 (*a*) A {111}⟨110⟩ slip system shown within an FCC unit cell. (*b*) The (111) plane from (*a*) and three ⟨110⟩ slip directions (as indicated by arrows) within that plane comprise possible slip systems.

- FCC (Al, Cu, Ni, Ag, Au)
  - Close packed planes: {111}, e.g., ADF
  - Close packed directions: <110>, e.g., AD, DF, AF
  - Slip system: {111}<110> (12 independent slip systems)
- BCC (Fe, W, Mo): {110}<111> (12 independent slip systems)
- HCP (Zn, Cd, Mg, Ti, Be): 3 independent slip systems

- FCC & BCC metals: ductile, HCP metals: brittle

Plastic deformation in single crystal

Table 4-4 Room-temperature slip systems and critical resolved shear stress for metal single crystals

Metal	Crystal structure	Purity, %	Slip plane	Slip direction	Critical shear stress, MPa	Ref.
Zn	hcp	99.999	(0001)	$[11\bar{2}0]$	0.18	a
Mg	hcp	99.996	(0001)	[1120]	0.77	b
Cd	hcp	99.996	(0001)	$[11\bar{2}0]$	0.58	c
Ti	hcp	99.99	(1010)	$[11\bar{2}0]$	13.7	d
		99.9	(1010)	$[11\bar{2}0]$	90.1	d
Ag	fcc	99.99	(111)	[110]	0.48	e
		99.97	(111)	[110]	0.73	e
		99.93	(111)	[110]	1.3	e
Cu	fcc	99.999	(111)	[110]	0.65	e
		99.98	(111)	[110]	0.94	e
Ni	fcc	99.8	(111)	[110]	5.7	e
Fe	bcc	99.96	(110) (112) (123)	[111]	27.5	f
Mo	bcc	. . .	(110)	[111]	49.0	g

[a] D. C. Jillson, *Trans. AIME*, vol. 188, p. 1129, 1950.
[b] E. C. Burke and W. R. Hibbard, Jr., *Trans. AIME*, vol. 194, p. 295, 1952.
[c] E. Schmid, "International Conference on Physics," vol. 2, Physical Society, London, 1935.
[d] A. T. Churchman, *Proc. R. Soc. London Ser. A*, vol. 226A, p. 216, 1954.
[e] F. D. Rosi, *TRans., AIME*, vol. 200, p. 1009, 1954.
[f] J. J. Cox, R. F. Mehl, and G. T. Horne, *Trans. Am. Soc. Met.*, vol. 49, p. 118, 1957.
[g] R. Maddin and N. K. Chen, *Trans. AIME*, vol. 191, p. 937, 1951.

Plastic deformation in single crystal

- What is most likely initial slip system?
- If CRSS is 50 MPa, what is the tensile stress at which Cu will start to deform plastically?

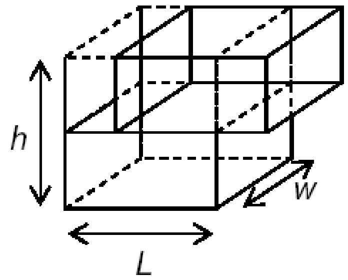
Slip Plane **n**	Slip direction **s**	**n·l** $\cos\phi$	**s·l** $\cos\lambda$	Schmidt factor $\cos\phi\ \cos\lambda$	σ (MPa)
(111)	$[\bar{1}10]$	$2\sqrt{2}/3$	0	0	Not def.
	$[\bar{1}01]$		$\sqrt{3}/6$	$\sqrt{6}/9$	184
	$[0\bar{1}1]$		$\sqrt{3}/6$	$\sqrt{6}/9$	184
$(\bar{1}11)$	$[110]$	$\sqrt{2}/3$	$\sqrt{3}/3$	$\sqrt{6}/9$	184
	$[101]$		$-\sqrt{3}/2$	$-\sqrt{6}/6$	-122
	$[0\bar{1}1]$		$\sqrt{3}/6$	$\sqrt{6}/18$	367
$(1\bar{1}1)$	$[110]$	$\sqrt{2}/3$	$\sqrt{3}/3$	$\sqrt{6}/9$	184
	$[\bar{1}01]$		$-\sqrt{3}/6$	$-\sqrt{6}/18$	-367
	$[011]$		$\sqrt{3}/2$	$\sqrt{6}/6$	122
$(11\bar{1}) = (\bar{1}\bar{1}1)$	$[\bar{1}10]$	0	0	0	Not def.
	$[101]$		$\sqrt{3}/2$	0	Not def.
	$[011]$		$\sqrt{3}/2$	0	Not def.

smallest stress to cause slip (yielding)

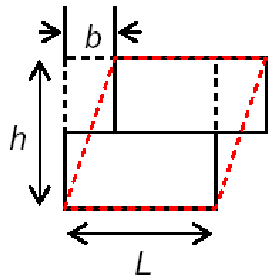
Initial Slip Systems (plane, direction) are then $(\bar{1}11)[101], (1\bar{1}1)[011]$

Plastic deformation in single crystal - How much?

- If a single dislocation passes through the crystal, what will be the resulting strain?



3-D



2-D

Cubic crystal after passage of a single dislocation

First we recognize that the shear strain is simply defined by the equation:

$$\text{shear strain} = \gamma = \frac{b}{h}$$

Plastic deformation in single crystal - How much?

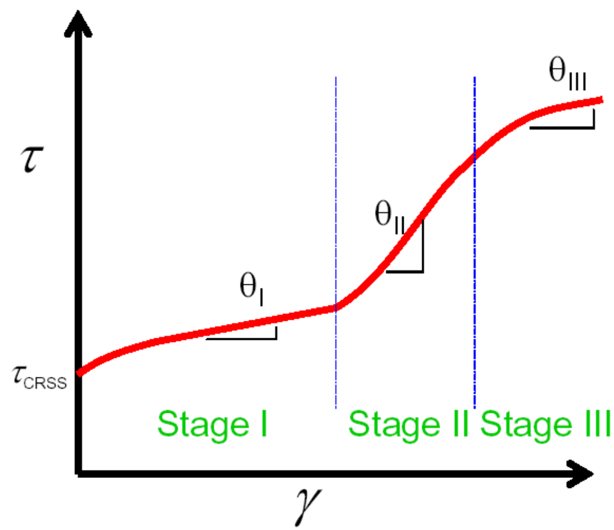
Assuming that the original crystal has dimension are 1 cm $\times$ 1 cm $\times$ 1 cm and that b = 1 Å (which is roughly of the correct order of magnitude), the shear strain can be calculated as:

$$\gamma = \frac{b}{h} = \frac{1\times10^{-10}\ \text{m}}{1\times10^{-2}\ \text{m}} = 1\times10^{-8} \text{ or } \boxed{1\times10^{-6}\%}$$

This amount is not really perceptible so how can dislocations cause strain?

Plastic deformation in single crystals

- Deformation of single crystal



Stage I:

- Easy glide.

Stage II:

- Linear hardening

Stage III:

- Parabolic hardening

Stage I:

- This is typical when there is a single slip system operative. Dislocations do not interact much with each other. "Easy glide"
- Active slip system is one with maximum Schmid factor

Stage II:

- The shear stress needed to continue plastic deformation begins to increase in an almost linear fashion.
- This stage begins when slip is initiated on multiple slip systems.
- Work hardening is due to interactions between dislocations moving on intersecting slip planes.

Stage III:

- There is a decreasing rate of work hardening.
- This decrease is due to an increase in the degree of cross slip resulting in a parabolic shape to the curve.

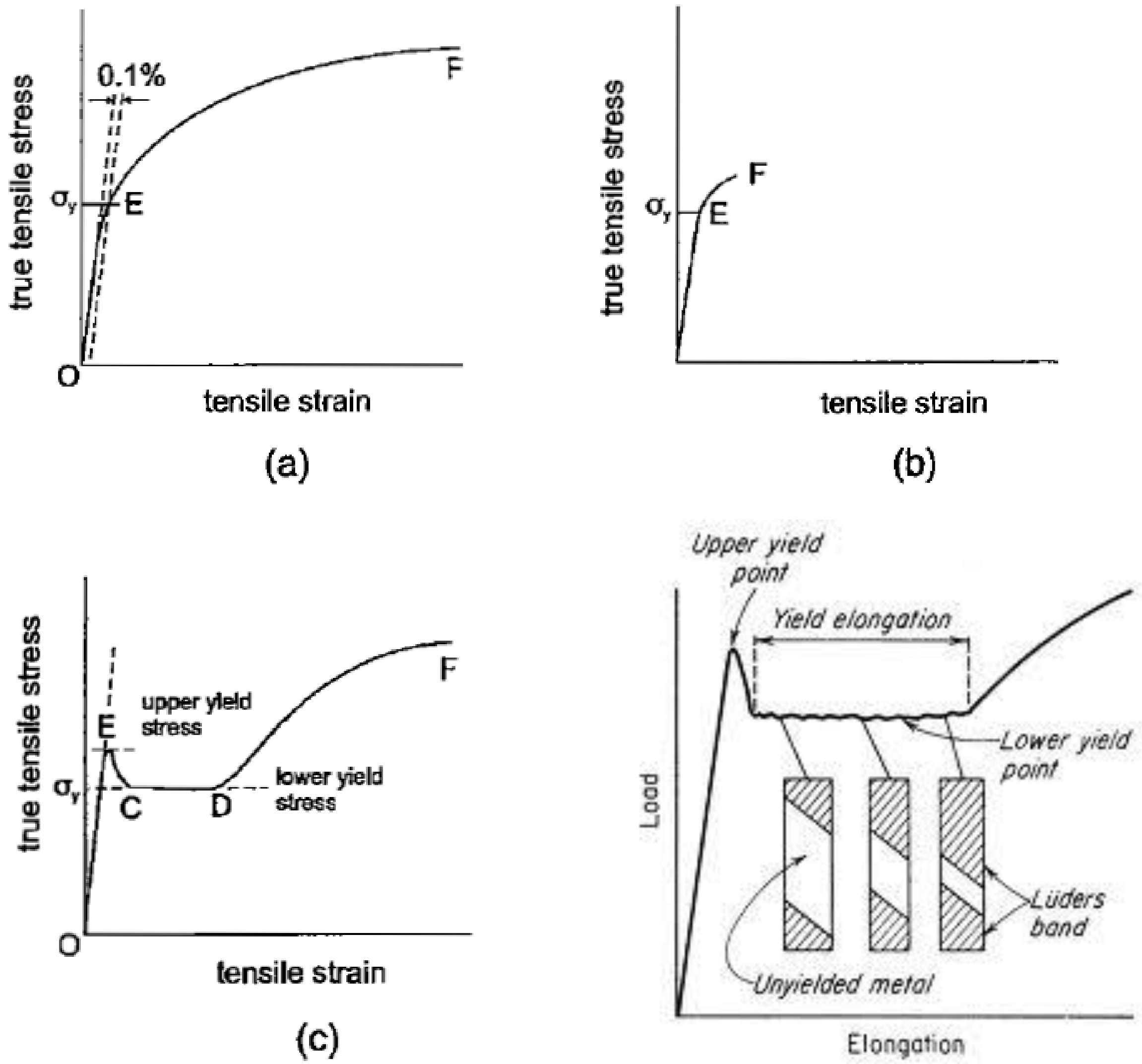
Plastic deformation in polycrystals

- Slip planes & directions (λ, ϕ) change from one crystal to another.
- τ_R will vary from one crystal to another.
- The crystal with the largest τ_R yields first.
- Other (less favorably oriented) crystals yield later.

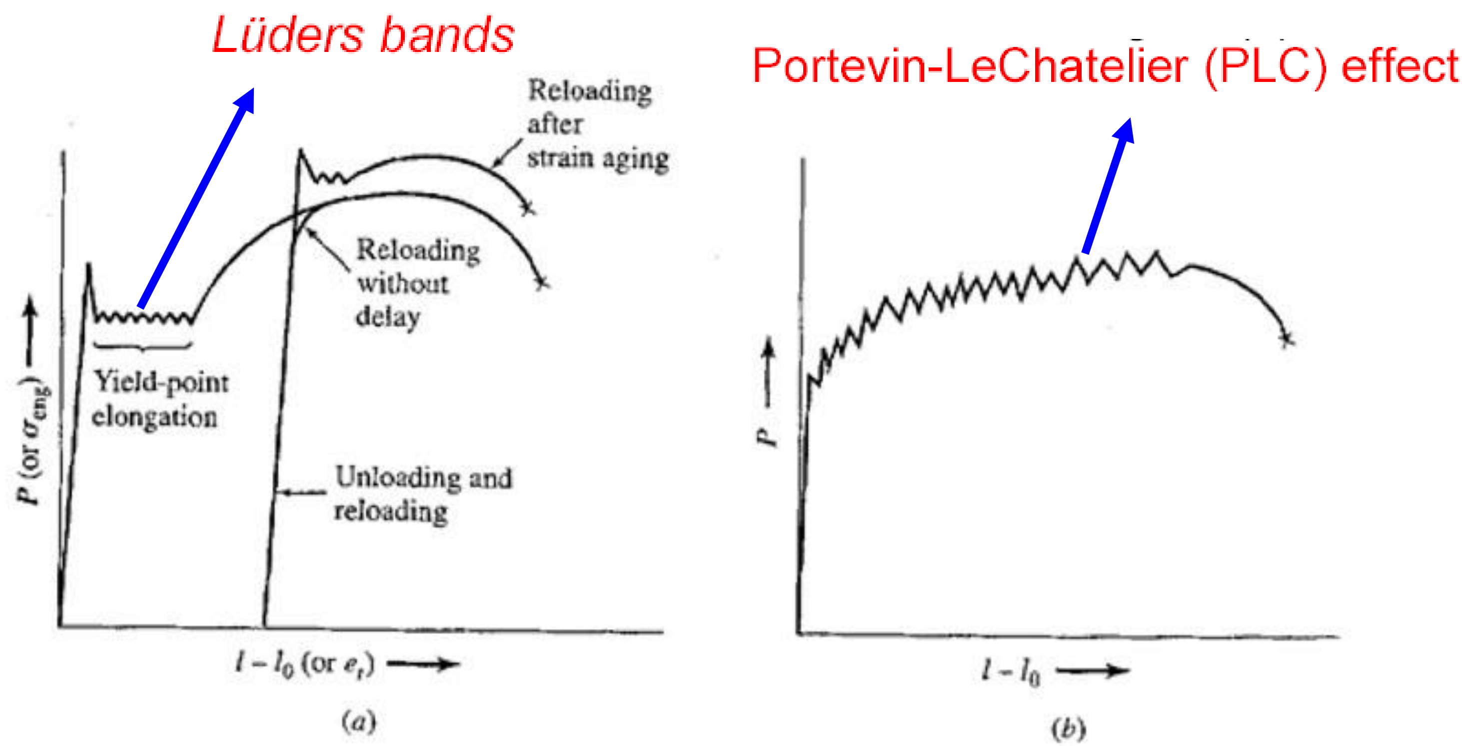
Adapted from Fig. 7.10, *Callister 6e.* (Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

Plastic deformation in polycrystals

- Stress-strain curves of crystalline materials



Plastic deformation in polycrystals

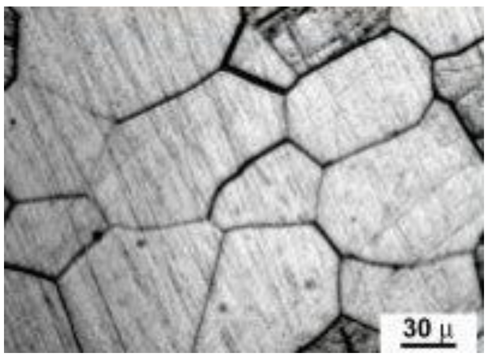


Schematic illustrations of (a) upper yield point formation characteristic of static strain aging and (b) serrated yielding characteristic of dynamic strain aging.

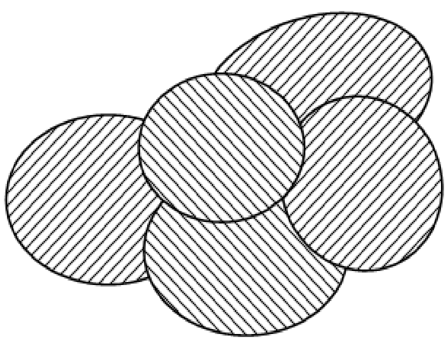
Surface defects

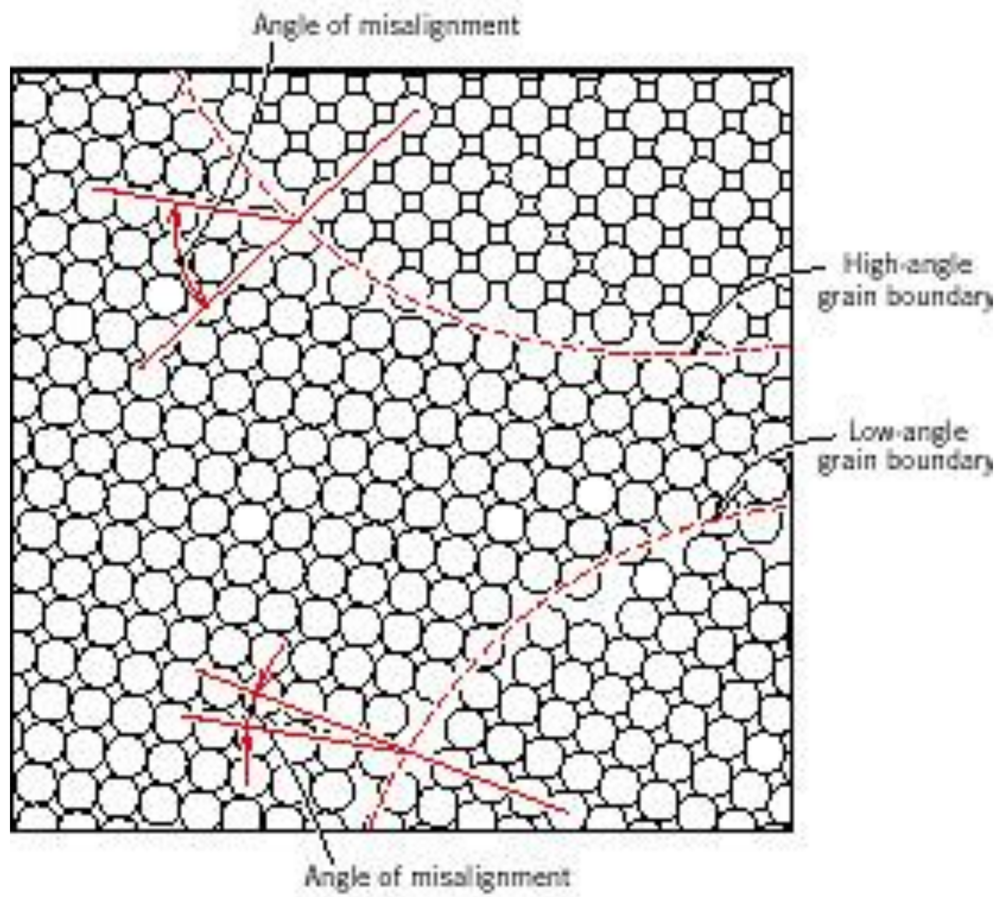
- Grain boundaries

A grain boundary is a general surface defect that separates regions of different crystalline orientation (grains) within a polycrystalline solid



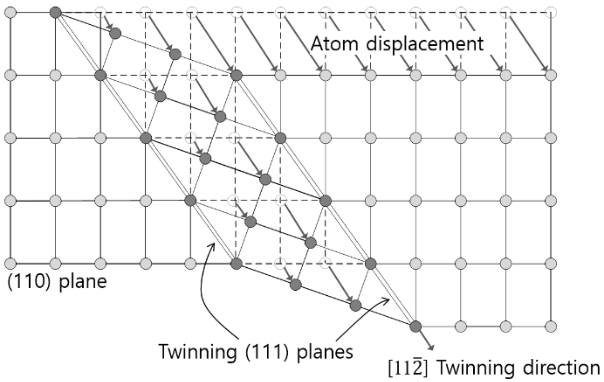
Schematics of polycrystalline & orientation



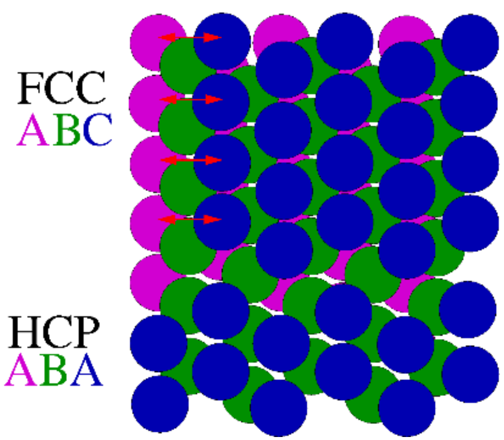


Surface defects

- Twin boundaries

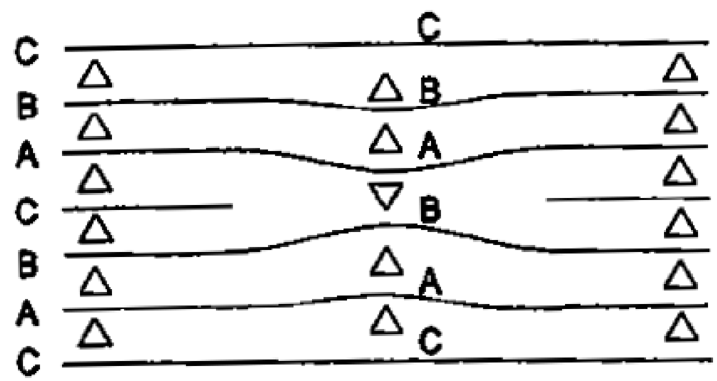


- Stacking fault

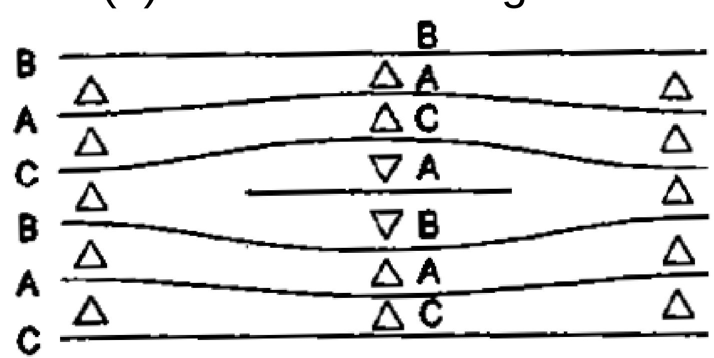


- Stacking fault vs. Twin boundaries

A change in the stacking sequence over a few atomic spacings produces a stacking fault whereas a change over many atomic spacings produces a twin region.

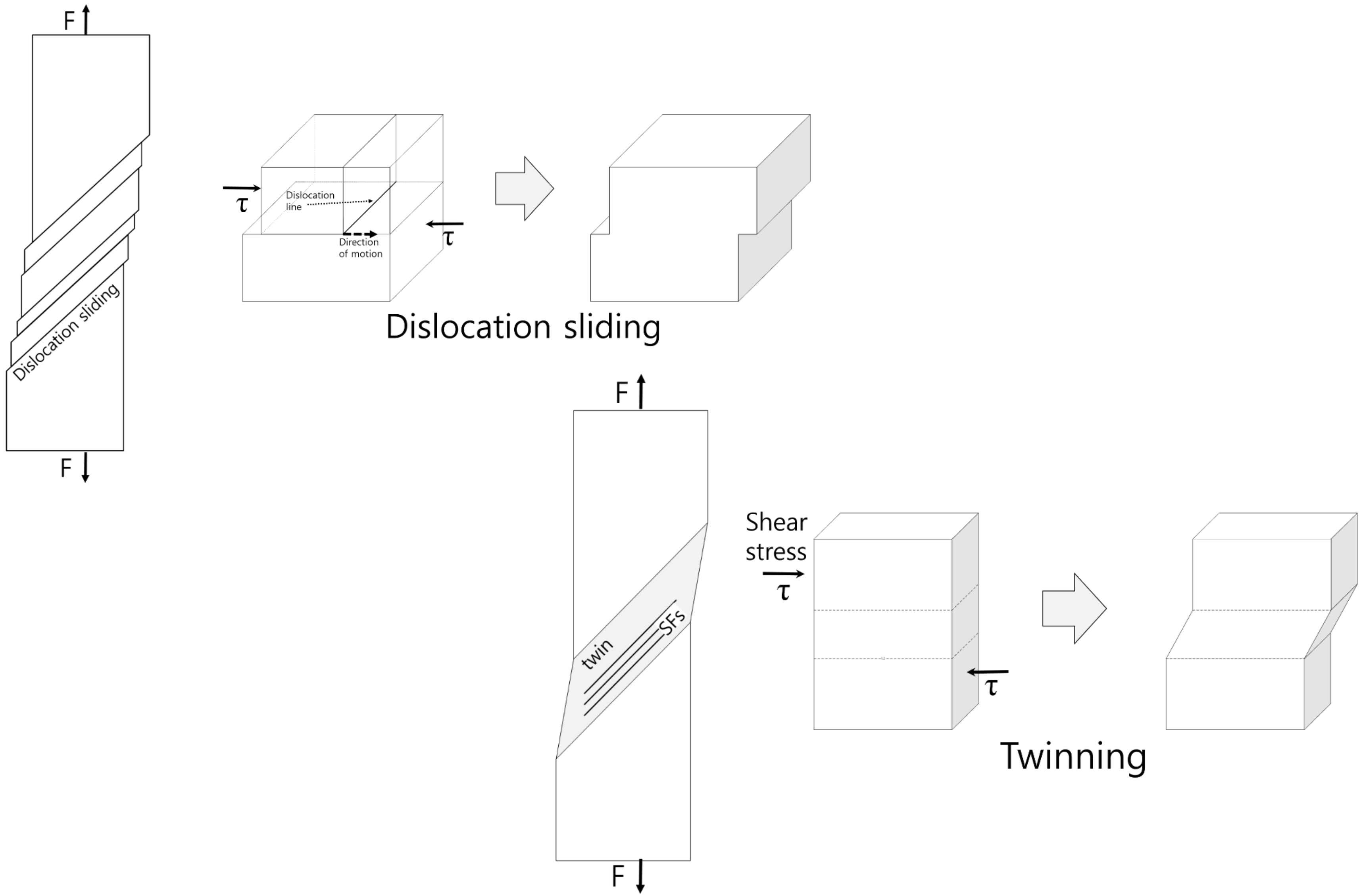


(a) Intrinsic stacking fault

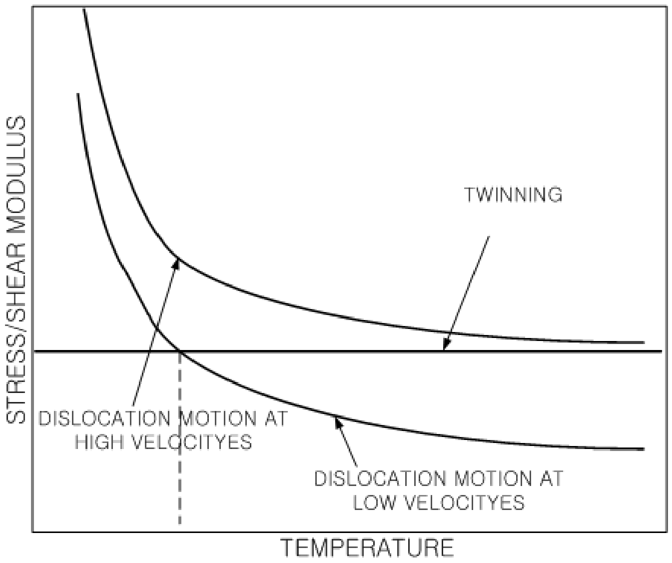


(b) Extrinsic stacking fault

Plastic deformation mechanism
- dislocation sliding & twinning



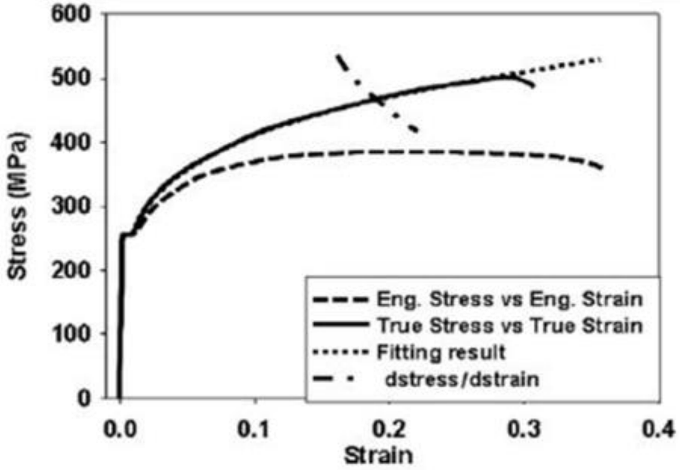
Effect of temperature on plastic deformation



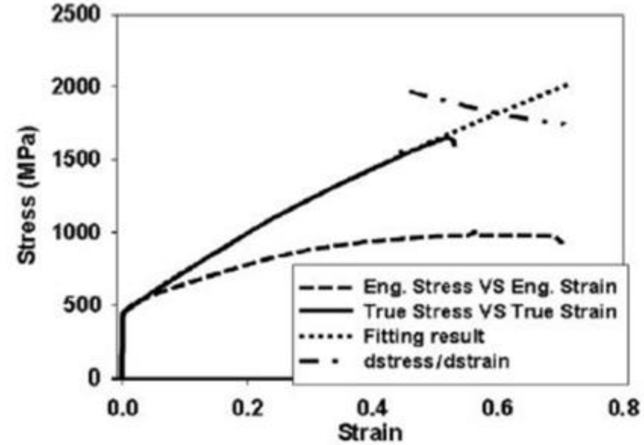
- Dislocation slip involves diffusion of atoms (and friction between atoms) so that it is temperature dependent, while twinning is not.
- In general, at low strain rates, slip is easier.
- At lower temperatures and high strain rates, twining is easier.
- As for the crystal structure effect, HCP has less of a slip system so it is more prone to twinning, while BCC is prone to twinning at low temperatures. On the other hand, twinning is more difficult for FCC.

Different hardening behavior of various metals

Steel – 340R



Steel – TWIP



Mg alloy