Plastic Deformation of Metals

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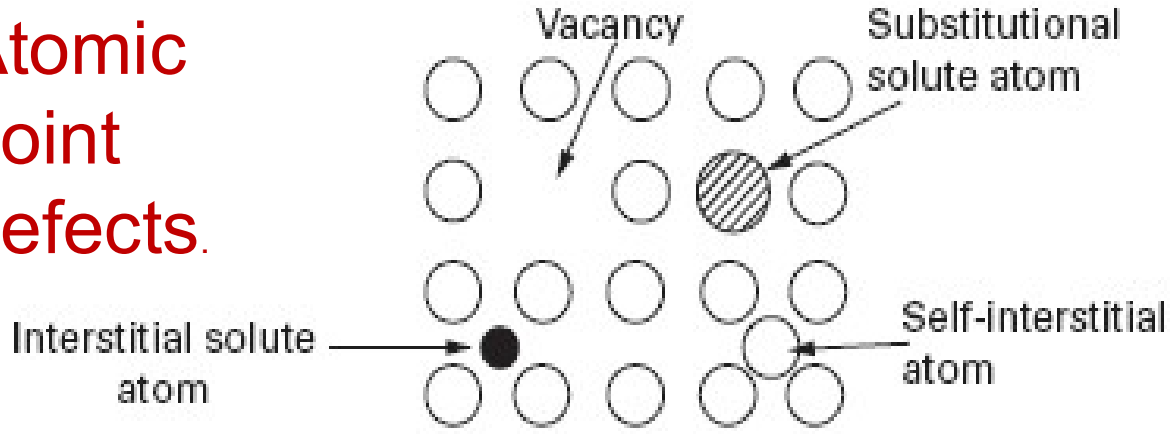
Crystalline Imperfection

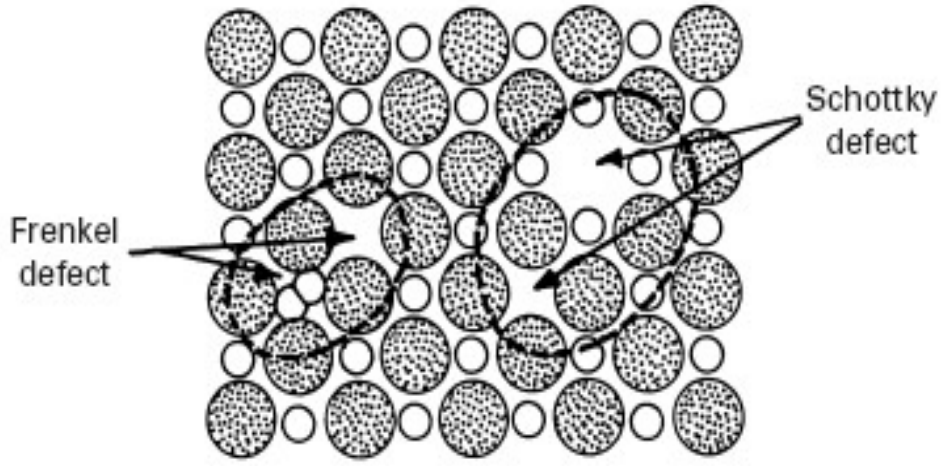
- Crystalline defect is meant a lattice irregularity having one or more of its dimensions on the order of an atomic diameter.
- Types of defect:
  - Point defect
  - Line defect
  - Surface defect
  - Volume defect

Point Defects

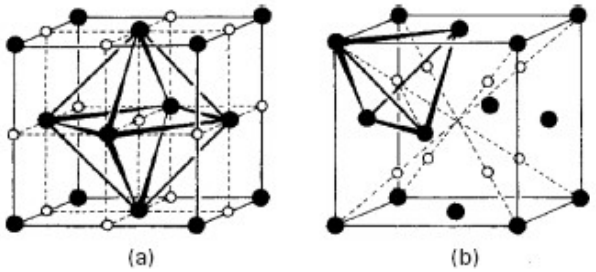
Atomic point defects.



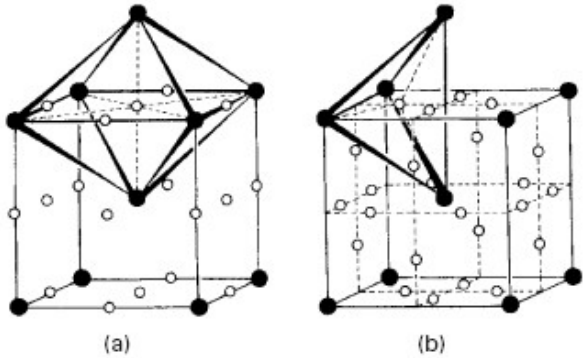
Two most common point defects in compounds: Schottky and Frenkel defects.



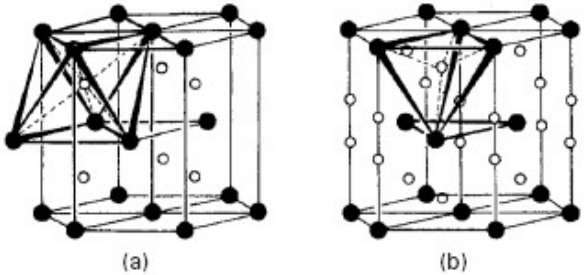
Point Defects



Interstices in FCC structure. (a) Octahedral void. (b) Tetrahedral void.



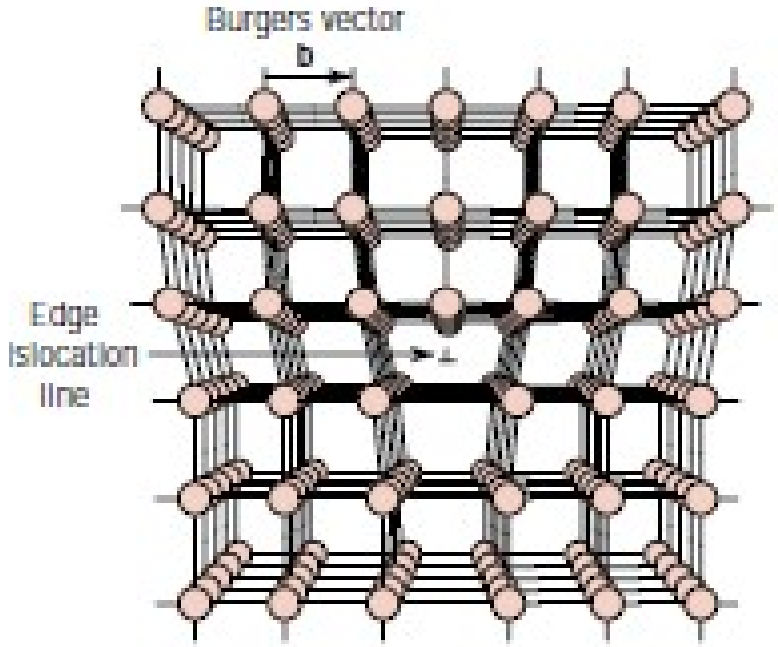
Interstices in the BCC structure. (a) Octahedral void. (b) Tetrahedral void.



Interstices in the HCP structure. (a) Octahedral void. (b) Tetrahedral void.

Line / Linear Defects

- One-dimensional defect around which some of the atoms are misaligned

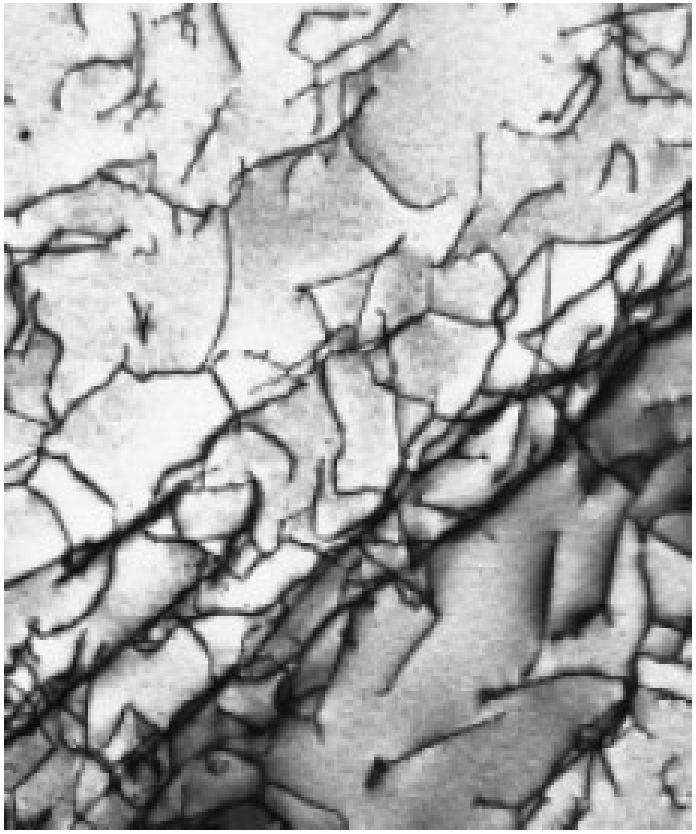


Volume Defect

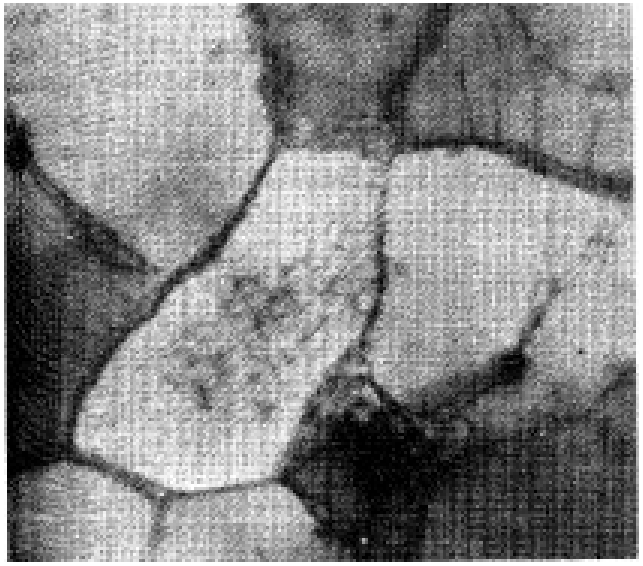
- Pores, cracks, foreign inclusion and other phases
- Volume defect normally introduced during processing and fabrication steps.

Dislocation

- A *dislocation* *is a linear or one-dimensional defect around which some of the atoms* are misaligned
- Types
  - Edge dislocation
  - Screw dislocation

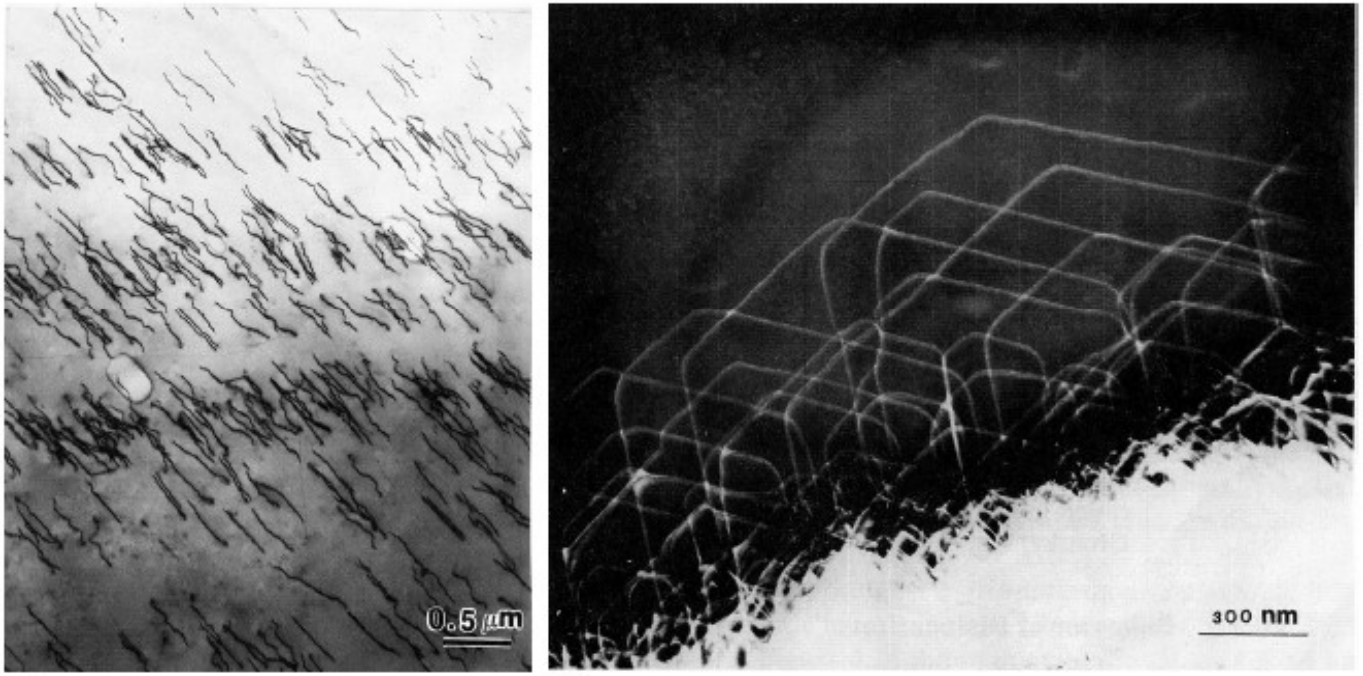


A transmission electron micrograph of a titanium alloy in which the dark lines are dislocations. 51,450X.



Dislocation network in cold worked aluminum. 32,500X

Dislocation in Metals

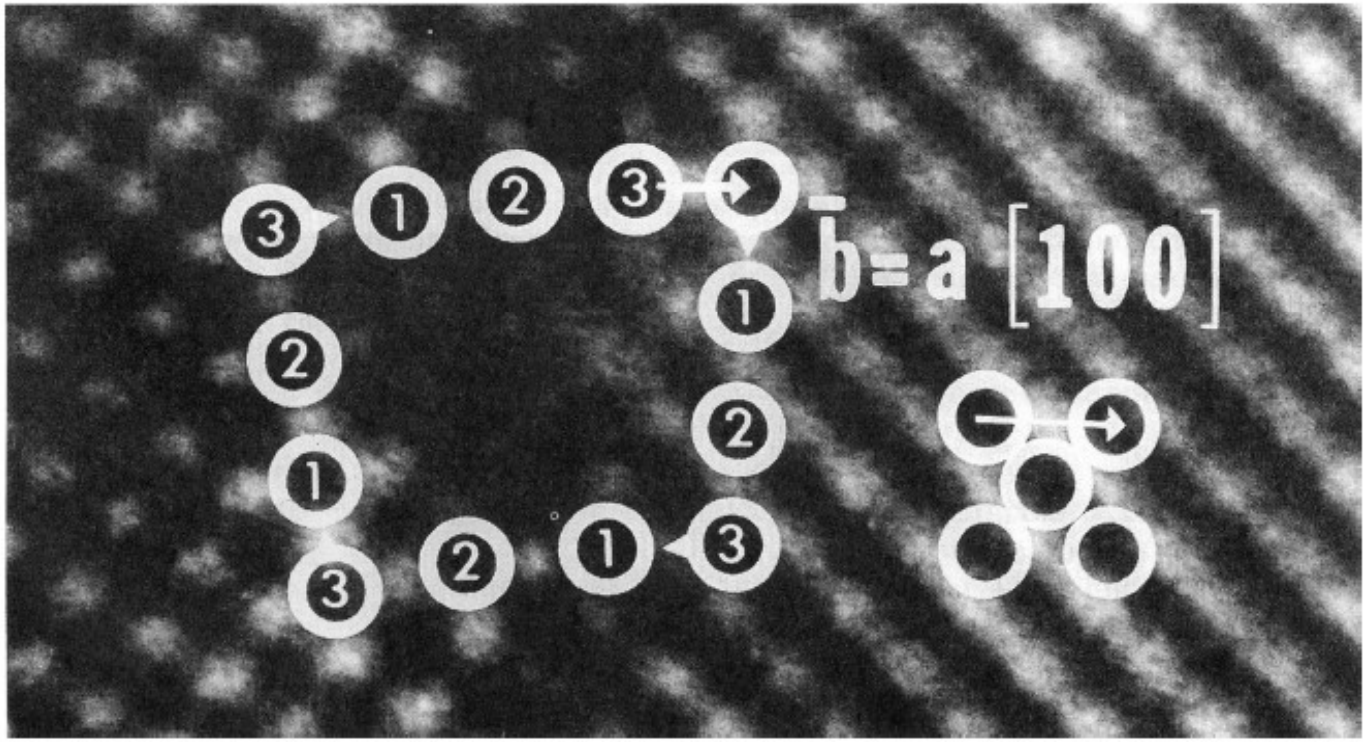


Dislocations in metals. (a) Titanium. (Courtesy of B. K. Kad.) (b) Silicon.

Dislocations in Al_2O_3 and TiC

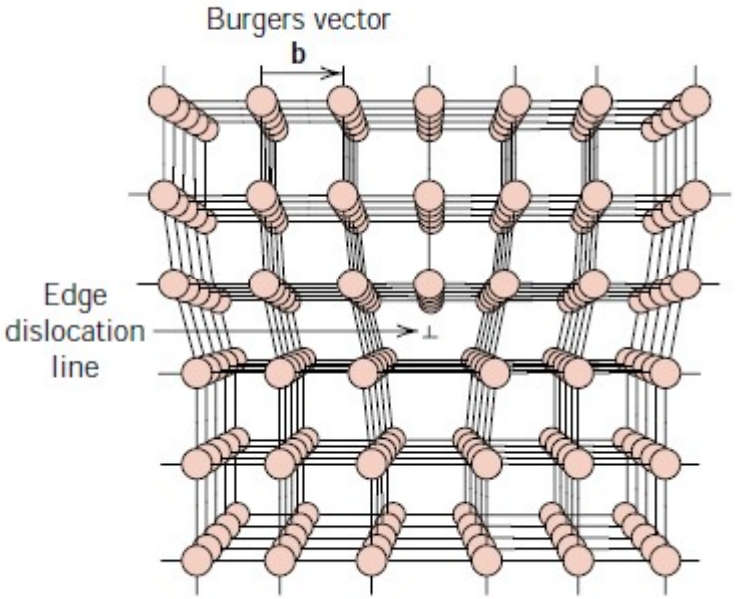
Dislocations in (a) Al2O3 and (b) TiC. (Courtesy of J. C. LaSalvia.)

Dislocation in Molybdenum

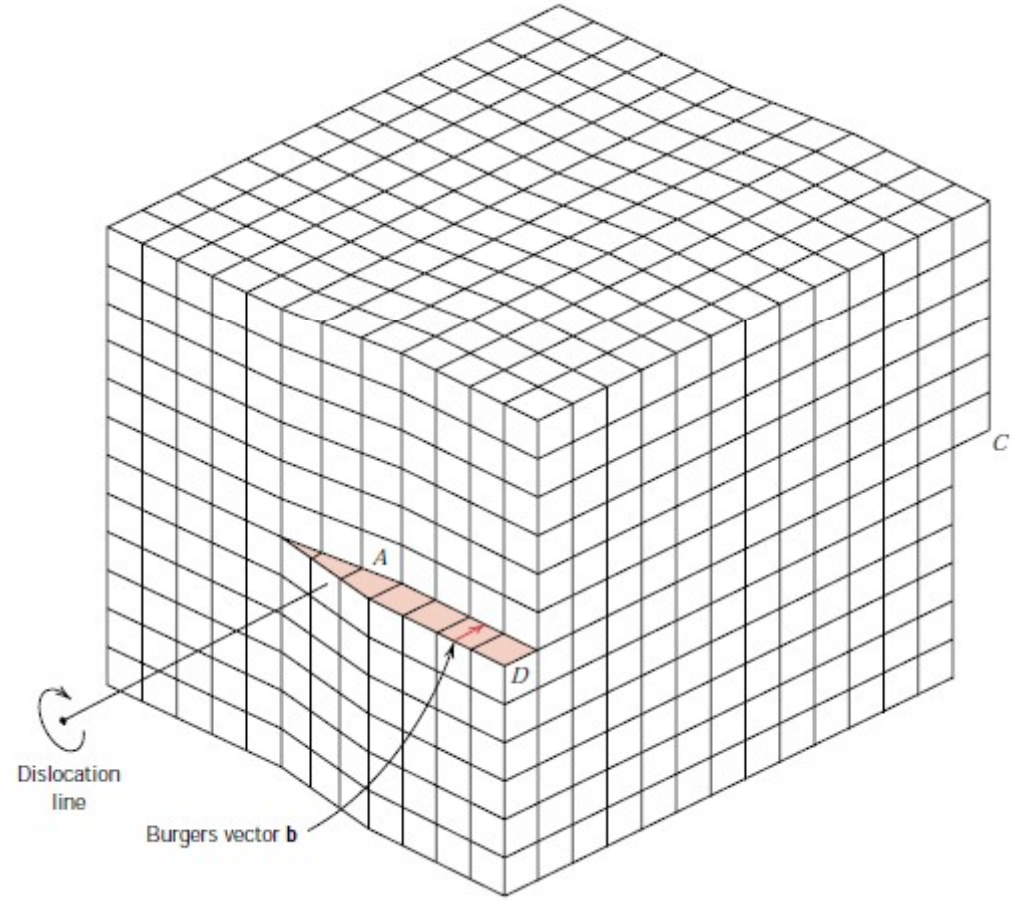


Atomic resolution transmission electron micrograph of dislocation in molybdenum with a Burgers circuit around it. (Courtesy of R. Gronsky.)

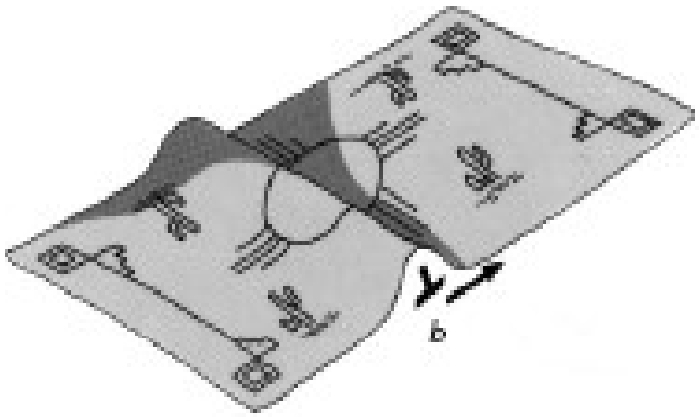
Edge dislocation



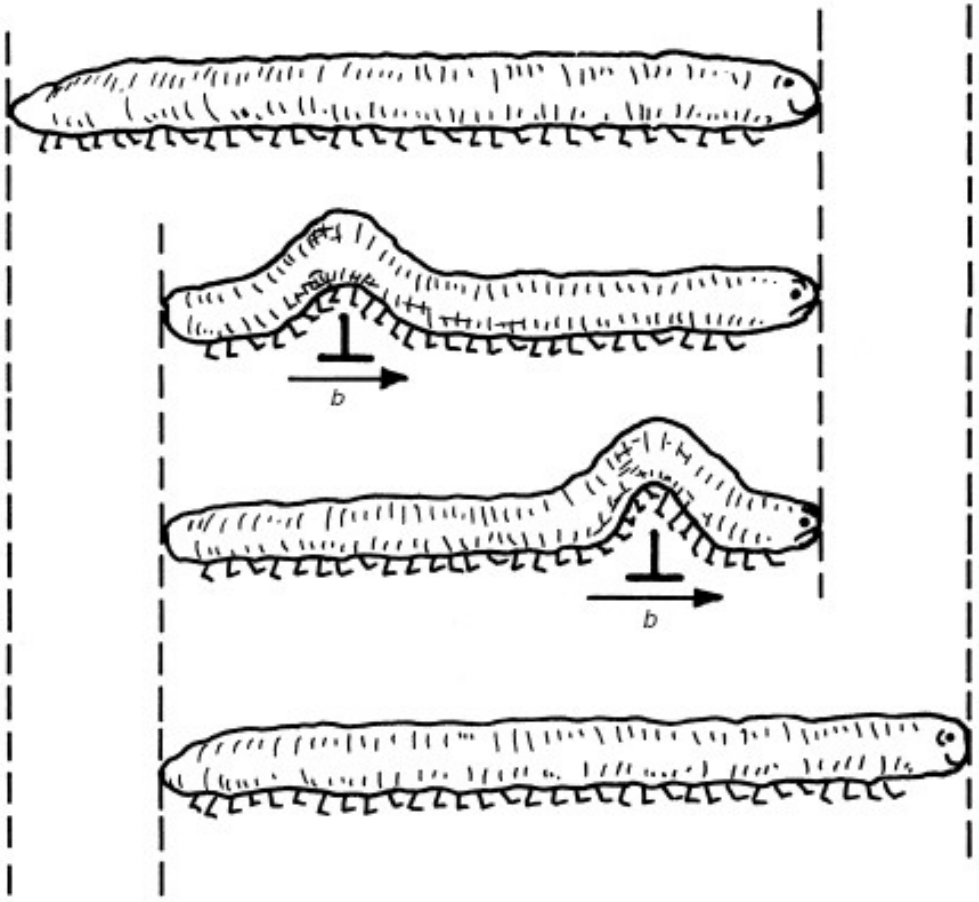
Screw dislocation



Dislocation Movement



(a) Rug with a fold.



Caterpillar with a hump.

Edge Dislocation

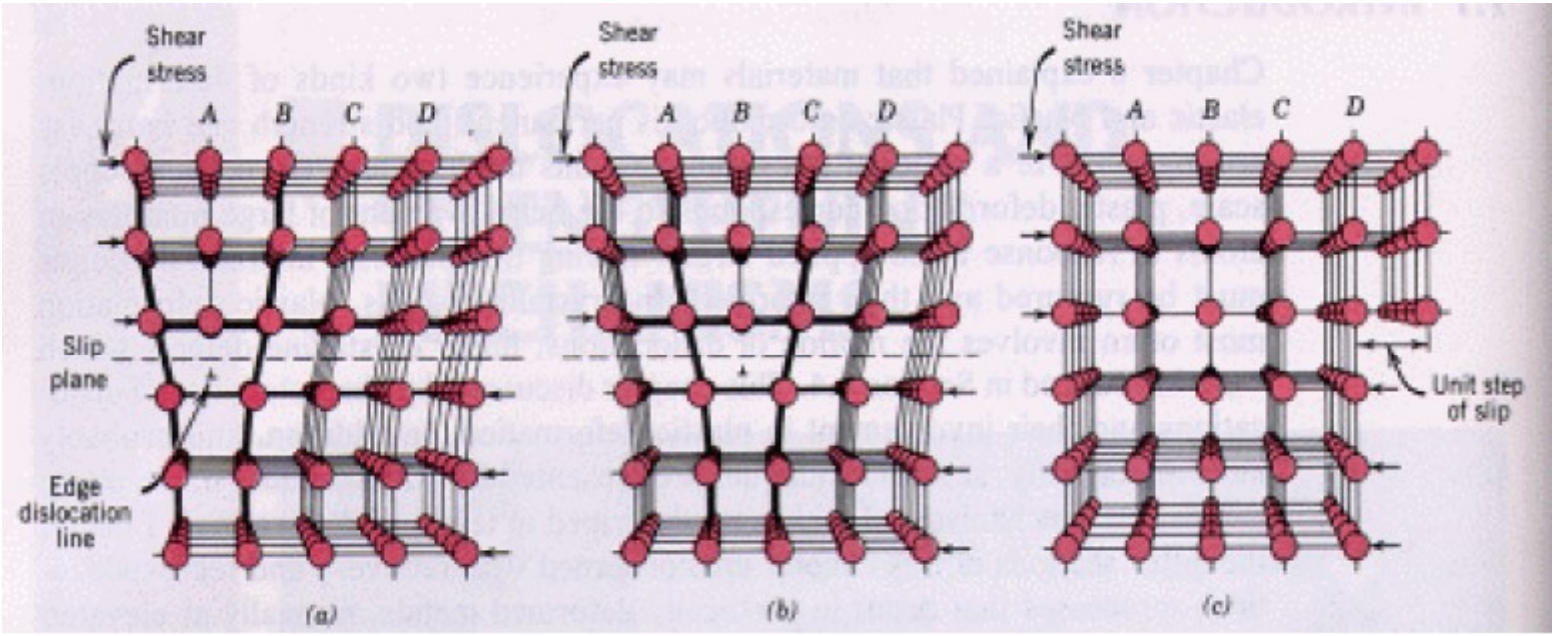
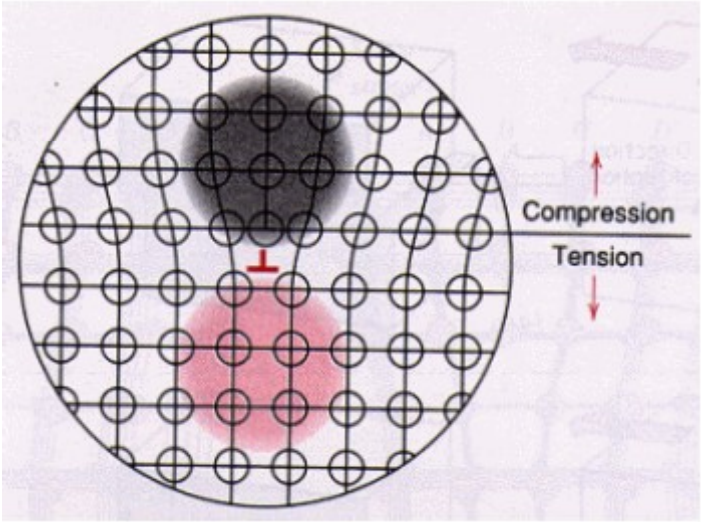


Figure: Movement of edge dislocation along the slip plane

Dislocations create lattice distortions and stress and strain fields



Screw Dislocation

Figure: A screw dislocation within a crystal.

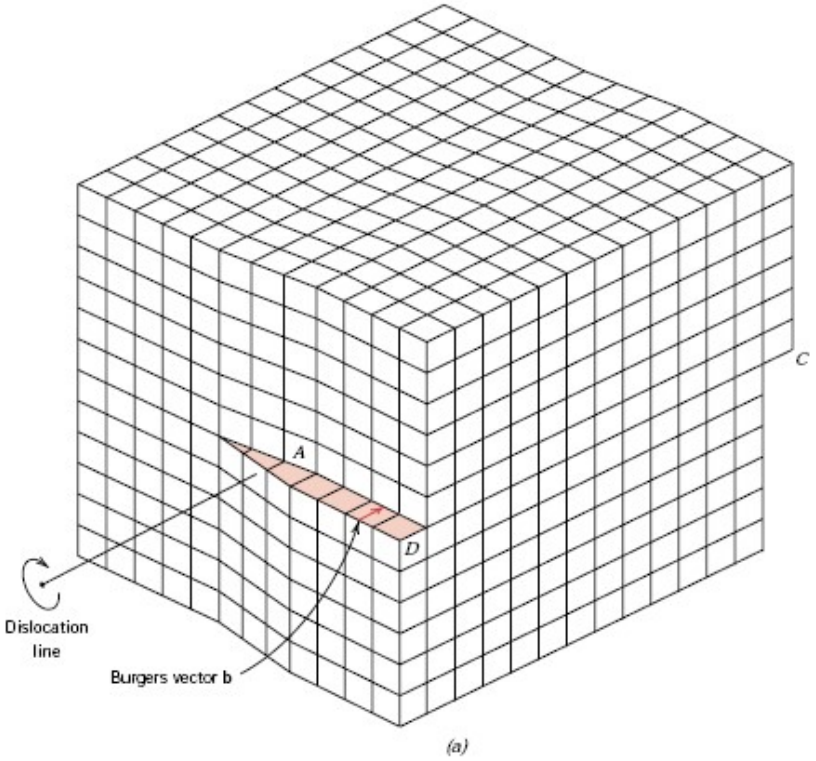
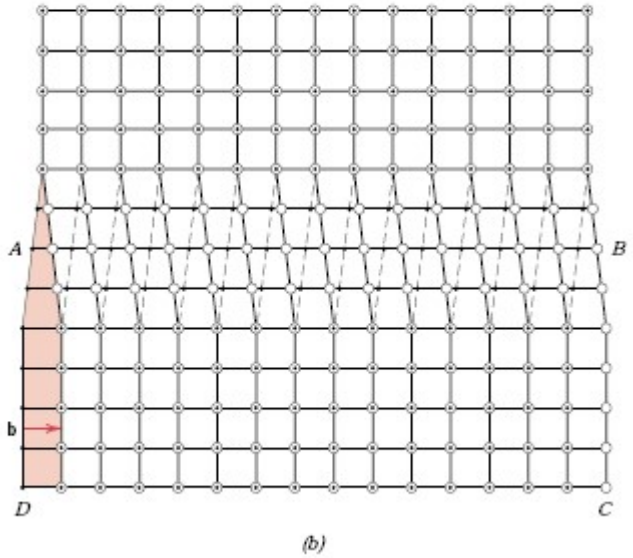
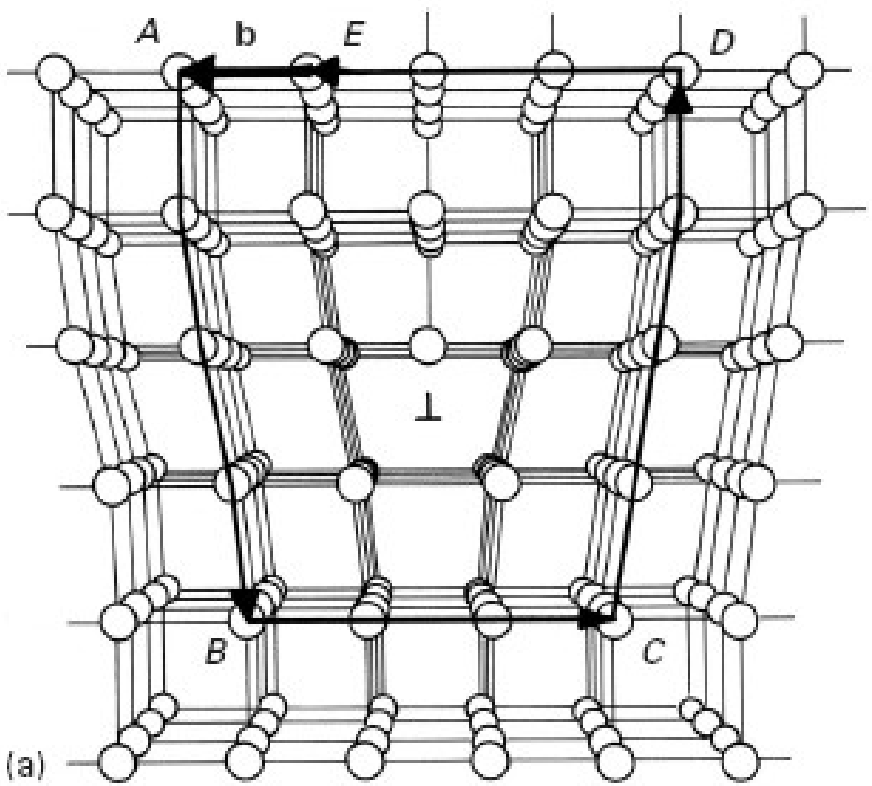
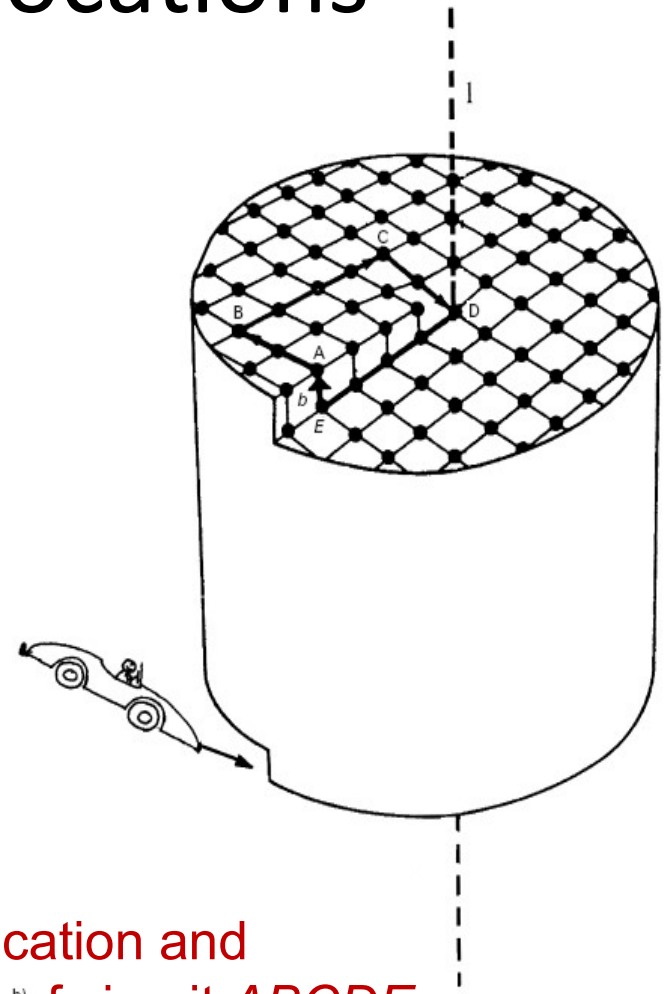


Figure: The screw dislocation in (*a) as* viewed from above.



Edge and Screw Dislocations





(a) Arrangement of atoms in an edge dislocation and the Burgers vector **b** that produces closure of circuit *ABCDE*.
(b) Arrangement of atoms in screw dislocation with "parking garage" setup. (Notice car entering garage.)

Burgers Vectors

- The Burgers vector ‘b’ is the vector which defines the magnitude and direction of slip
- It is the characteristic feature of a dislocation.
- Edge dislocation is perpendicular Burgers vector
- Screw dislocation is parallel to Burgers vector

- Both shear stress and final deformation are identical for both situations.

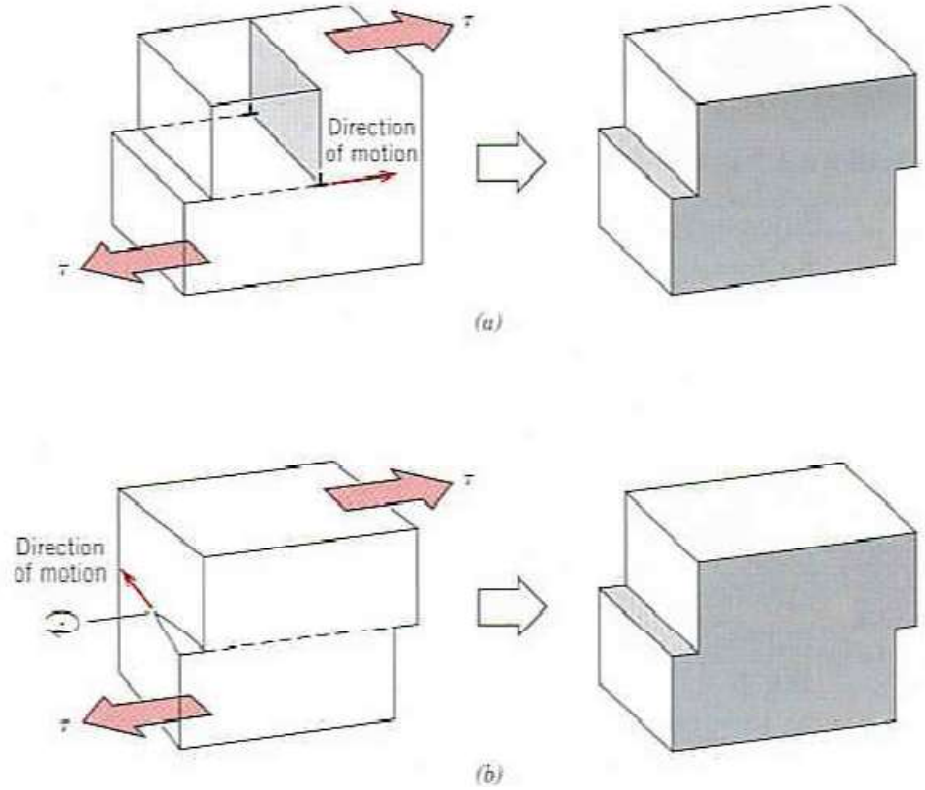


Figure: Macroscopic deformation produced by slip of (a) edge dislocation and (b) screw dislocation.

Burgers circuit

- The Burgers vector is determined by Burgers circuit.

- Start at a lattice point and a clockwise path traced from atom to atom an equal distance in each direction. At finish of the path the circuit does not closed

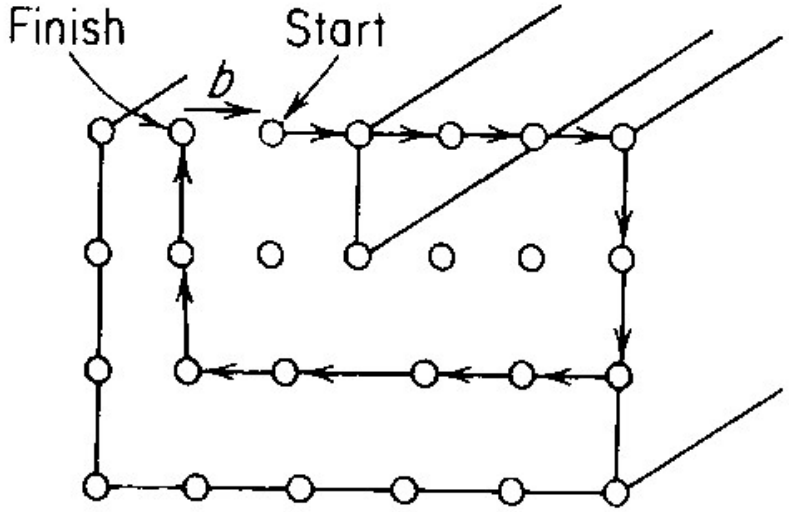


Figure: Burgers circuit around the positive Edge dislocation

The closure error pointing out of the front face of the crystal.

The closure failure from finish to start is the Burger vector b of the dislocation.

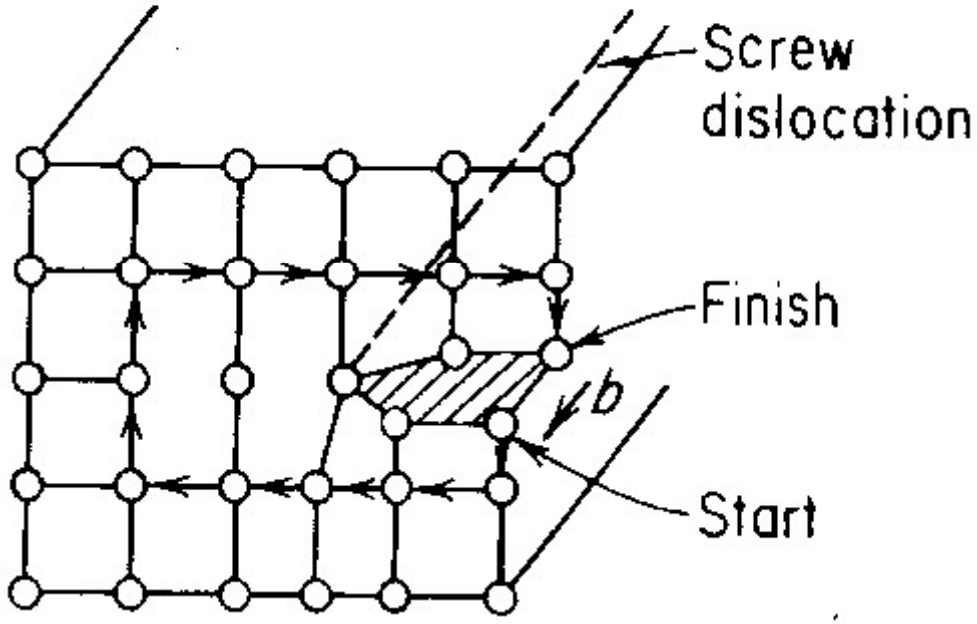


Figure: Burgers circuit around a right hand screw dislocation

Dislocation Curves or Loops

- In real crystal, the dislocation will be partly edge and partly screw is character.
- Then, the dislocation will take form of curves or loops.
- The dislocation loop in three dimension form an interlocking dislocation network
- In dislocation curve or loop, Burgers vector of a dislocation is invariant

Dislocation Curves

Figure: Schematic representation of a dislocation that has edge, screw, and mixed character.

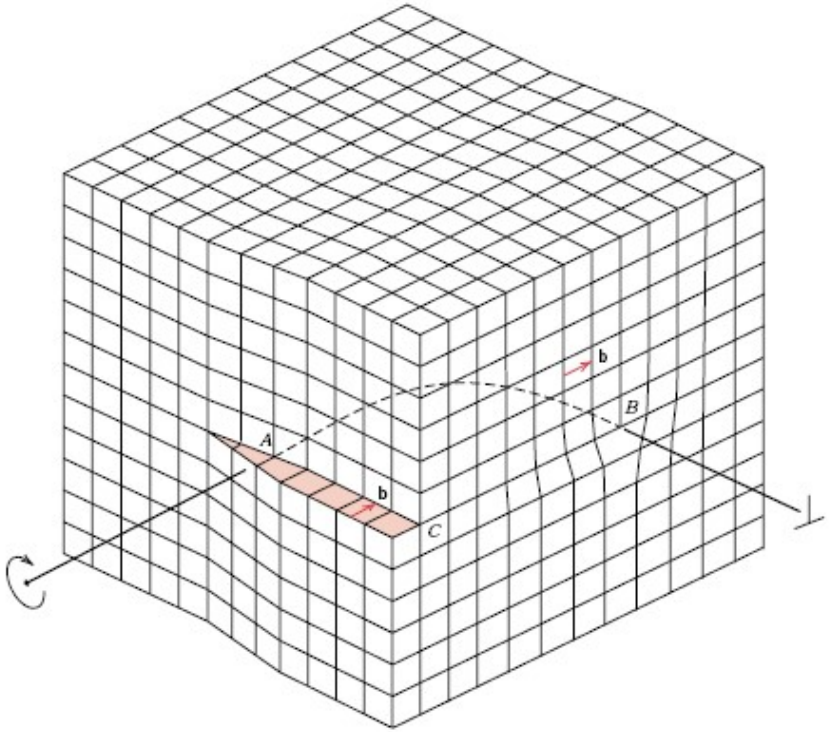
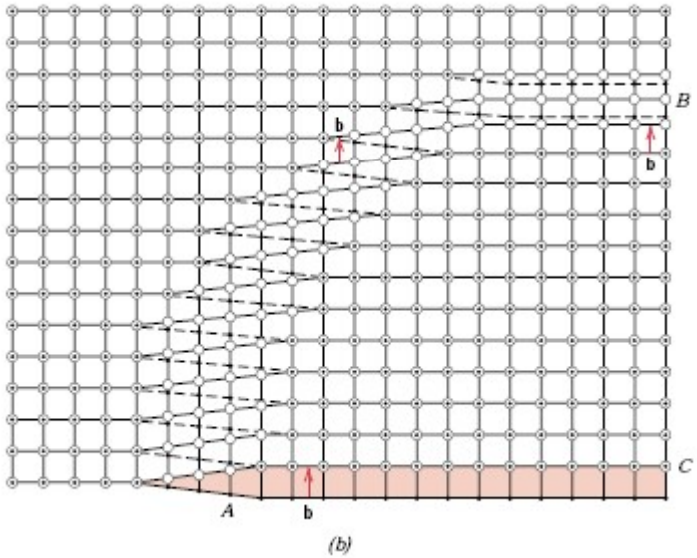


Figure: The dislocation curve viewed from above.



In the dislocation curve AB, any small segments other than point A and B, can be resolved into edge and screw components.

Dislocation Loop

- The dislocation loop is pure screw at point A and pure edge at point B.
- The dislocation loop has mixed edge and crew components along most of its length.
- The Burgers vector is the same along the entire dislocation loop.

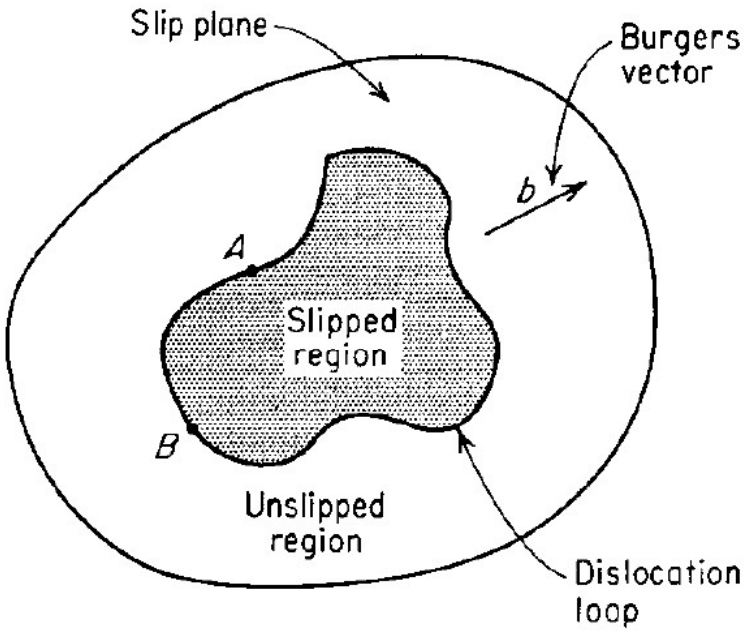
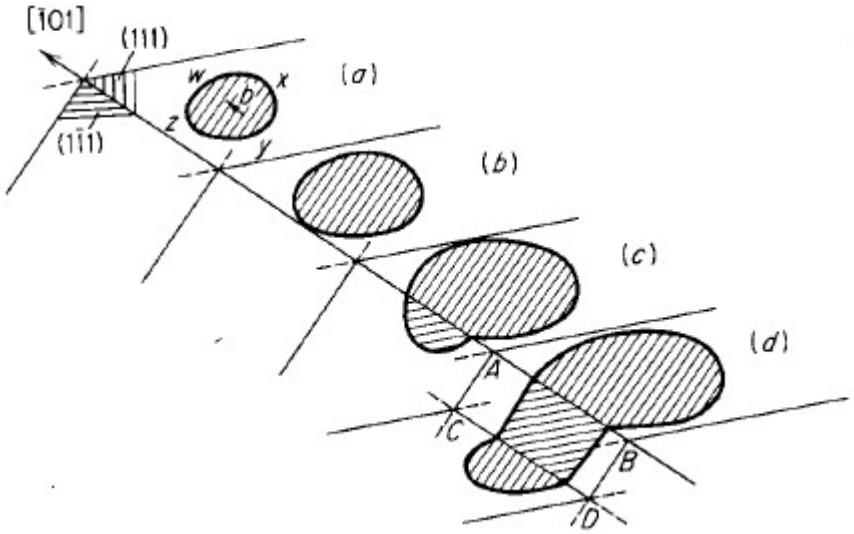


Figure : Dislocation loop lying in the slip plane

Cross slip

- In FCC cubic metals, the screw dislocations move in {111} type planes, but can switch from one {111} type plane to another if it contains the direction of b. This process is called cross-slip.



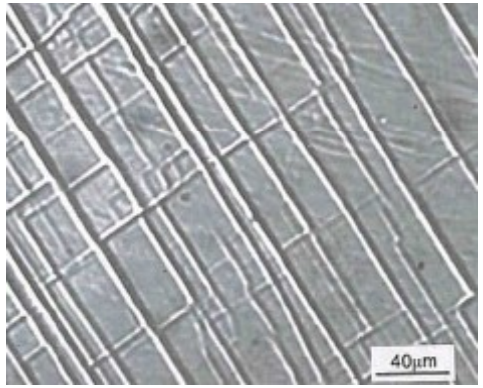


Figure: Cross slip on the polished surface of a single crystal of 3.25% Si iron.

Figure: Cross slip in a face-centred cubic crystal. Double cross slip is shown in (d).

Geometric Properties of Dislocation

Dislocation property	Type of Dislocation	
	Edge Dislocation	**Screw dislocation**
Relationship between dislocation	Perpendicular	Parallel
Relationship between slip direction and Burger vector	Parallel	Parallel
Direction of dislocation movement relation of Burger vector	Parallel	Perpendicular
Process by which dislocation may leave slip plane	Climb	Cross-slip

Vector Notation for Dislocation

- Unit dislocation : A dislocation with a Burgers vector equal to one lattice spacing is said to be dislocation of unit strength. It is also called as dislocation of unit strength.
- The dislocation strength larger than unity are generally unstable. Those dislocations dissociate into two or more dislocations of lower strength.
- The dissociation reaction $b_1 \rightarrow b_2 + b_3$ when $b_1^2 > b_2^2 + b_3^2$
- Strain energy of dislocation $\alpha \quad b^2$

- Magnitude of Burgers vector $b=a_o[uvw]$

$$|b|=a_0(u^2+v^2+w^2)$$

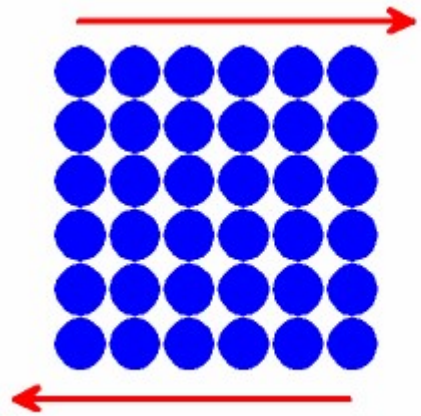
- The Burgers vector connect one equilibrium lattice with another. The crystal structure determines the possible Burgers vectors.
- The Burgers vector is the closest distance between equilibrium positions of atoms.

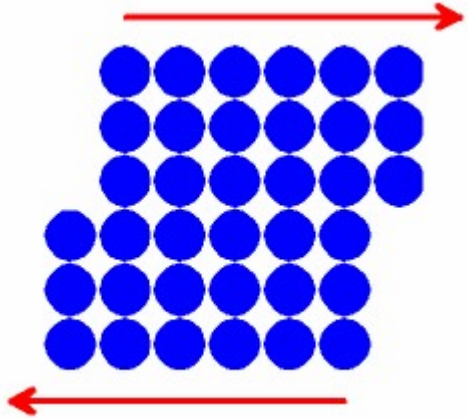
Plastic deformation

- deformation which remains after load is removed
- atomic rearrangements (change of neighbours)
- Plastic deformation of crystals preserves lattice structure.
- There are two basic modes of plastic deformation called
  - Slip
  - Twinning.

SLIP

- At low temperatures / high stresses: Deformation of crystals occurs exclusively by slip of lattice planes
- Slip: shearing of lattice planes against each other
- Slip occurs at ambient and high temperature





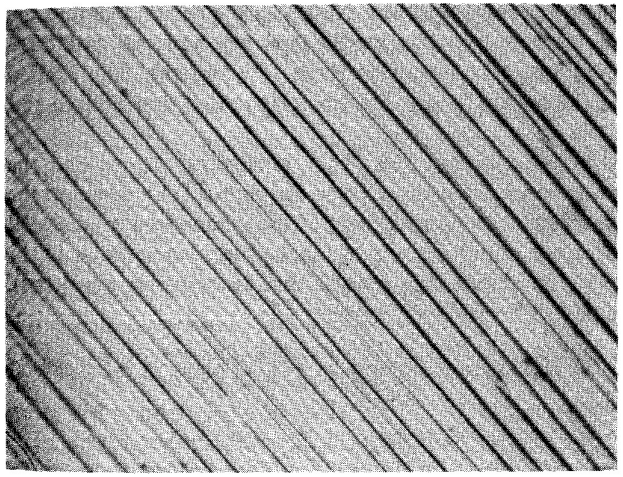


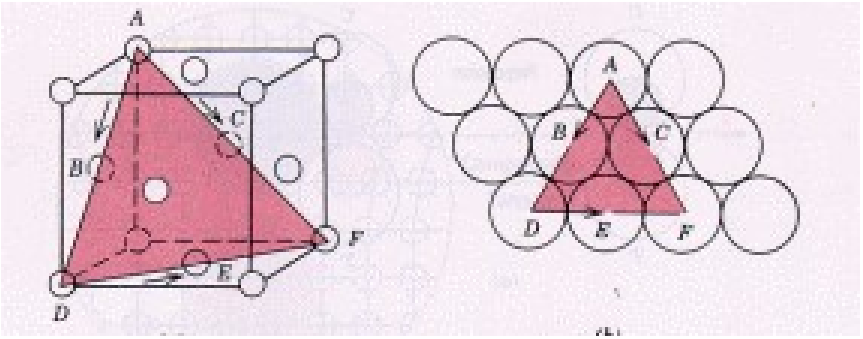
Figure 4-12 Straight slip lines in copper (500 ×). *(Courtesy W. L. Phillips.)*

Slip system is characterized by:

- slip plane: The crystallographic plane at which dislocation moves
- slip direction: The crystallographic direction at which dislocation move

Note:

- often slip planes are most densely packed lattice planes
- slip directions are most densely packed lattice directions



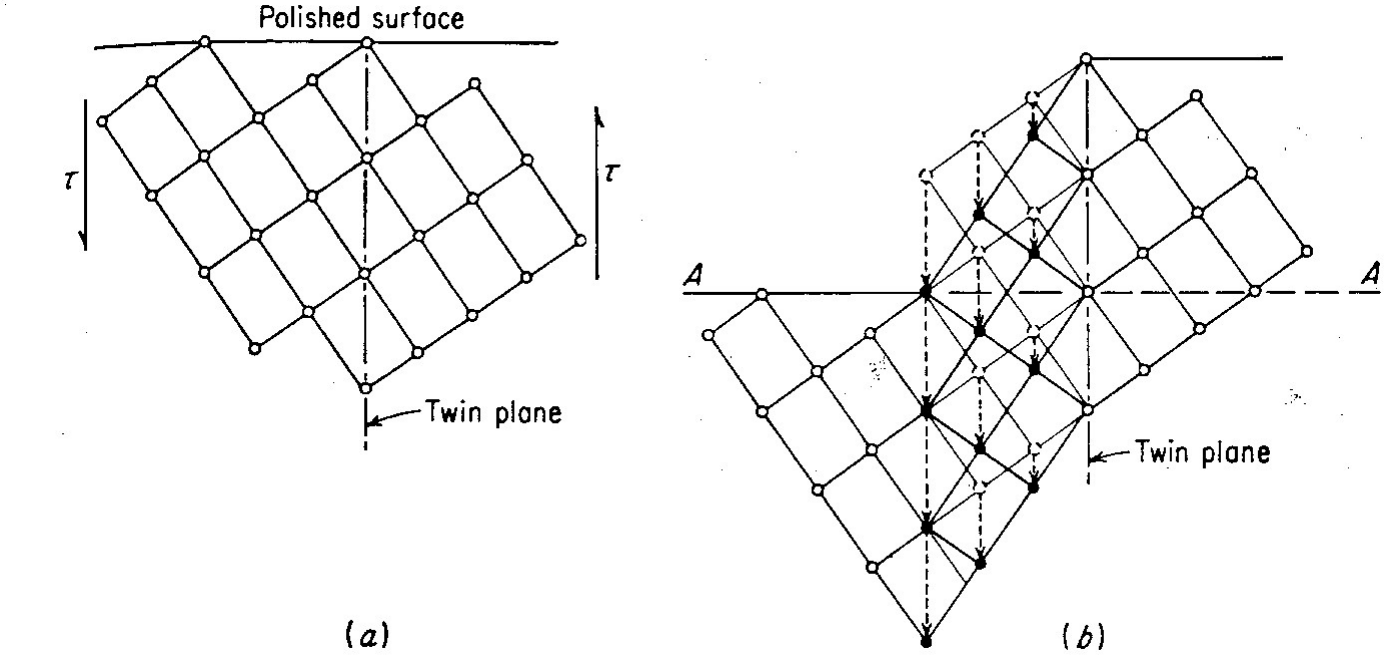
Crystal Structure	Typical examples	Slip Plane	Slip Direction	No . of slip system
BCC	Fe, W, Nb	{110}	<111>	48
FCC	Ag, Au, Cu	{111}	<110>	12
HCP	Zn, Cd, Mg, Ti	{0001}	<1120>	3

Note:

- BCC is not closed packed structure like FCC and HCP.
- Even though it has 48 slip system, the planes are not as close packed as in the fcc structure, high shearing stress are required to cause slip.

TWINNING

- The second important mechanism by which metals deform known as twinning.
- Twinning: A portion of crystal takes up orientation in such way to a mirror image of the parent crystal.
- Twinning plane: The plane of symmetry between the two portion



(a) (b)

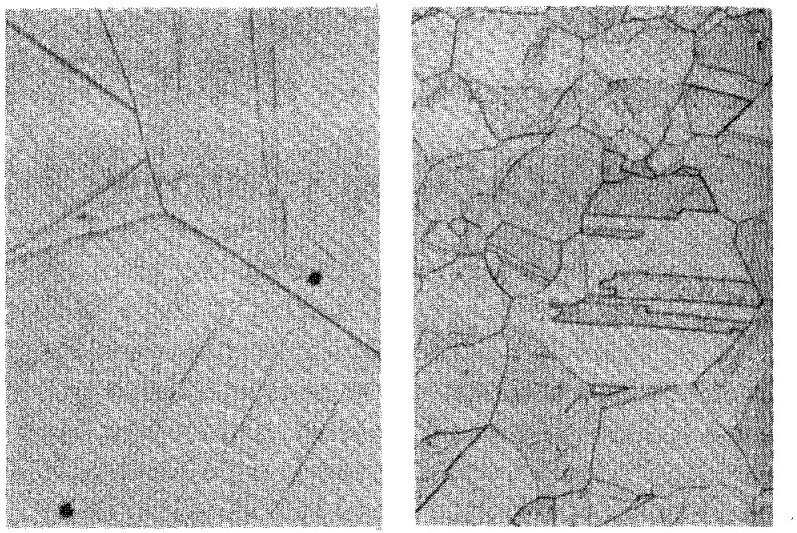
Crystal Structure	Typical examples	Twin plane	Twin Direction
BCC	Fe, W, Nb	(112)	[111]
FCC	Ag, Au, Cu	(111)	[112]
HCP	Zn, Cd, Mg, Ti	(10-12)	[-1011]

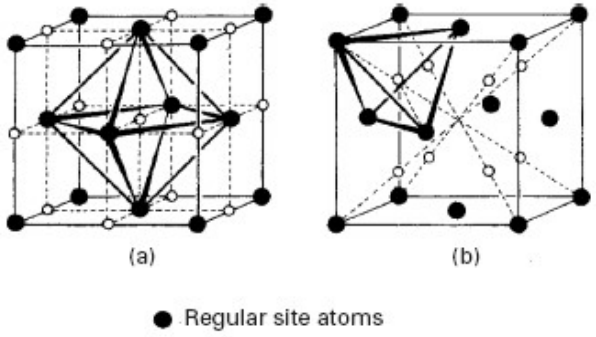
- Twinning is not a dominant deformation mechanism in metals
- Twinning generally occurs when the slip systems are restricted or critical resolved shear stress is lower than the stress for slip.

Slip	Twinning
Slip is a shear deformation that moves atoms by many inter-atomic distances relative to their initial positions.	The movement of an atom relative to its neighbours is only a fraction of an inter-atomic distance.
The crystallographic orientation above and below the slip plane is the same both before and after the deformation.	It changes the orientations of the twinned part of the crystal with respect to the untwined parts.
The slip mode of deformation is common at ambient and elevated temperatures.	It taking place in low temperatures.
It occurs in definite plane and direction for each crystal structure.	It occurs in definite plane and direction for each crystal structure.

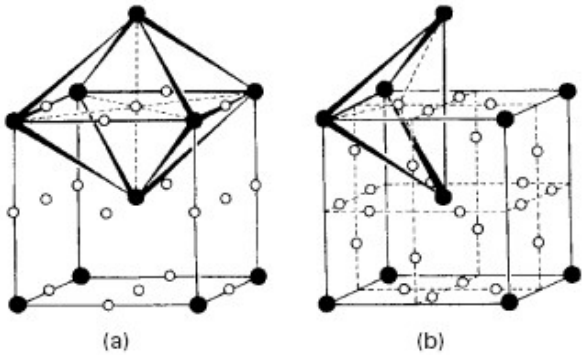
Twinning are produced by

- Mechanical deformation → mechanical twinning
- Annealing after plastic deformation → annealing twins.





Interstices in FCC structure. (a) Octahedral void. (b) Tetrahedral void.



Interstices in the BCC structure. (a) Octahedral void. (b) Tetrahedral void.

- Solubility of C in γ-Fe (Fcc) 2.11 wt.% at 1147˚C and 0.77 wt.% at 727˚C
- Solubility of C in α-Fe (Bcc) 0.02 wt.% at 727˚C and <0.00005 wt.% at 20˚C

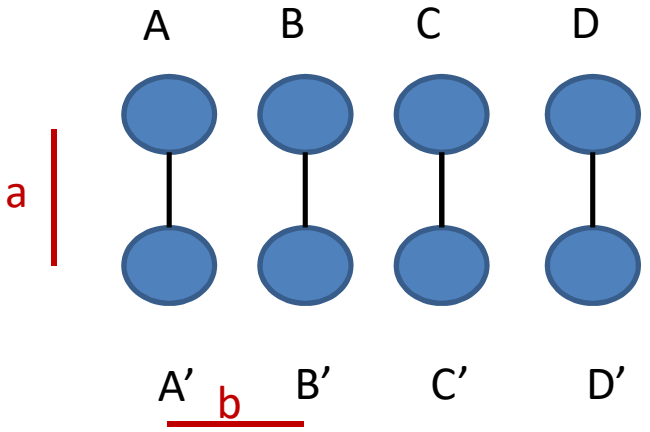
Solubility of C in Fe

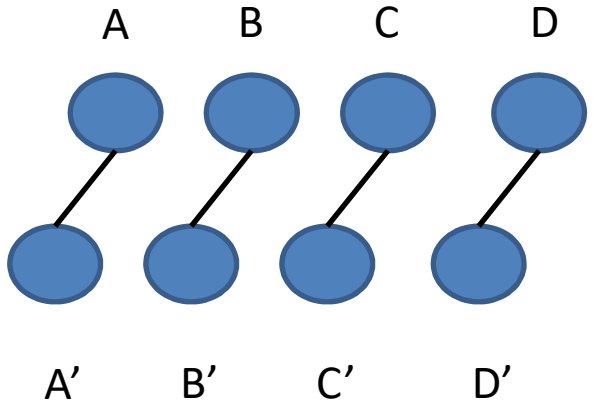
Atomic radius of α-Fe = 0.128nm and C = 0.077 nm

Crystal Structure	Type & nature of interstitial hole	Number of holes per unit cell	Radius of biggest sphere can fitting in holes in iron, nm
γ – Fe (FCC)	Octahedral, Symmetrical	4	0.052
	Tetrahedral, Symmetrical	8	0.028
α – Fe (BCC)	Octahedral, unsymmetrical	6	0.019
	Tetrahedral, Symmetrical	12	0.036

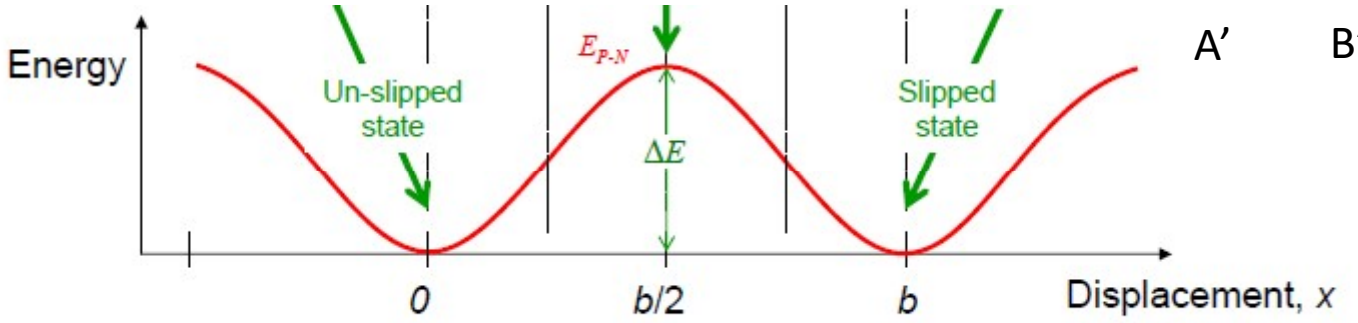
Strength of Perfect Crystal

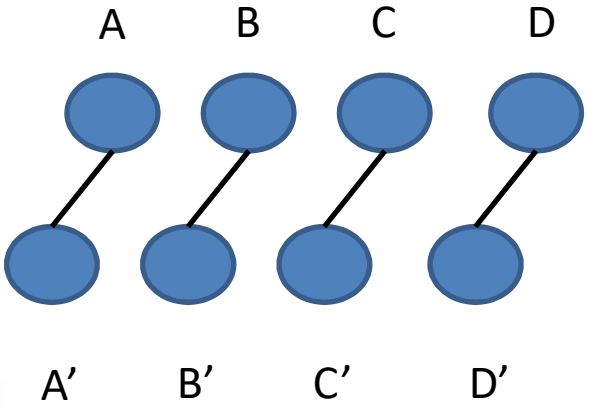
- Slip is translation of one plane of atoms over another. The shear stress required for the slip is obtained by using Hook's law.
- Consider two planes of atoms subjected to a homogeneous shear stress. The shear stress is act in these slip plane along the slip direction.

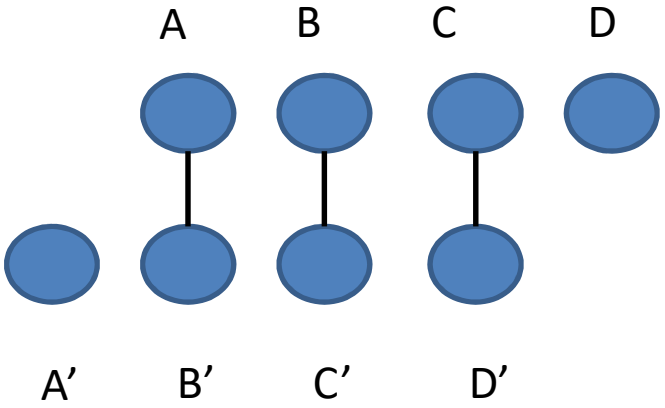




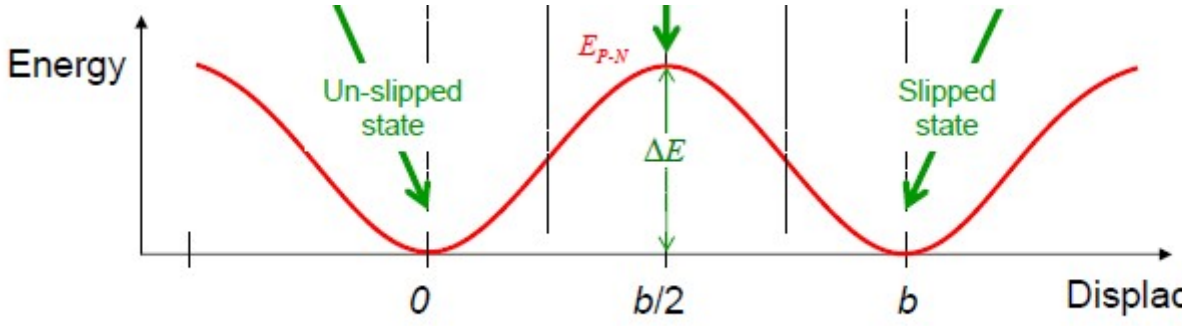
Strength of Perfect Crystal

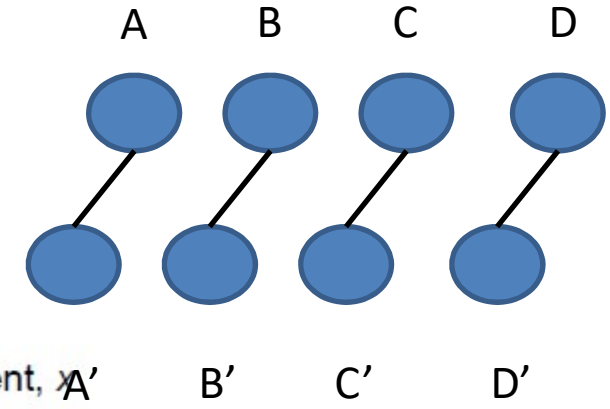


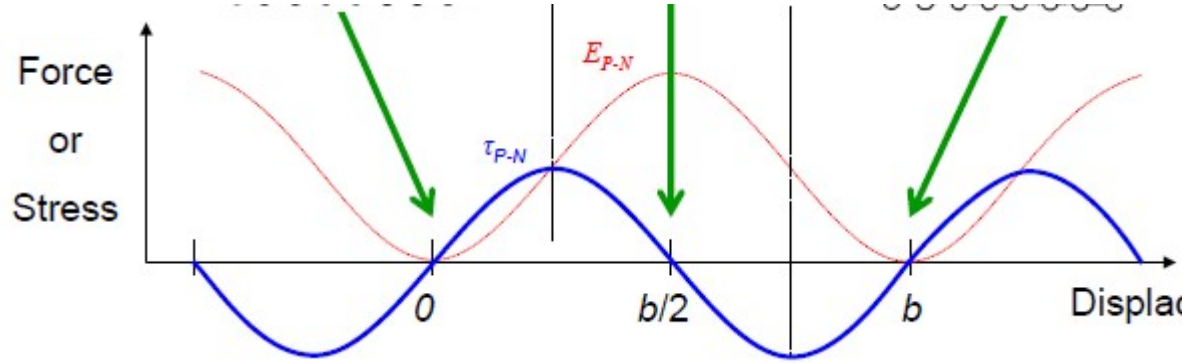


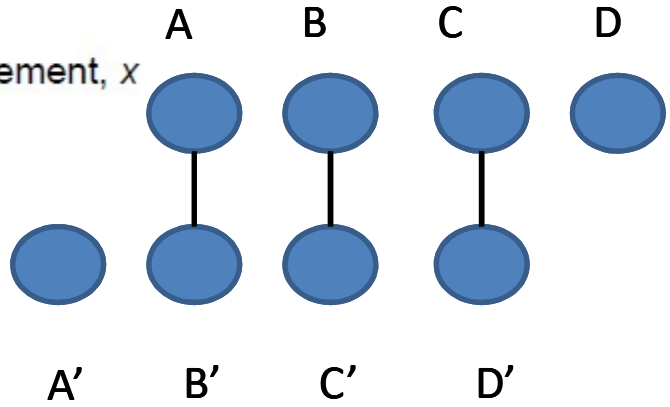


Strength of Perfect Crystal









The relation between shear stress and displacement expressed by a sine function,

$$\tau = \tau_m sin\frac{2\pi x}{b} \qquad \text{----eqn. 1}$$

where τ- applied shear stress

τ_{max}- max. theoretical strength of crystal

x - distance atoms are moved

b - distance between equilibrium positions.

For elastic strain, the shear stress defined by Hook's law.

$$\tau = G\gamma = G\frac{x}{a} \qquad \text{----eqn. 2}$$

where G - shear modulus

a - distance between lattice plane

γ - shear strain

Combining eqn. 1 and 2,

$$\tau_m sin\frac{2\pi x}{b} = G\frac{x}{a}$$

for small values of displacement, $sin\frac{2\pi x}{b} \approx \frac{2\pi x}{b}$

Therefore, $$\tau_m \frac{2\pi x}{b} = G\frac{x}{a}$$

$$\tau_m = \frac{G}{2\pi}\frac{b}{a}$$

For most crystal, a=b then the above equation can be written as

$$\tau_m = \frac{G}{2\pi}$$

Comparison of theoretical and experimental Yield strength

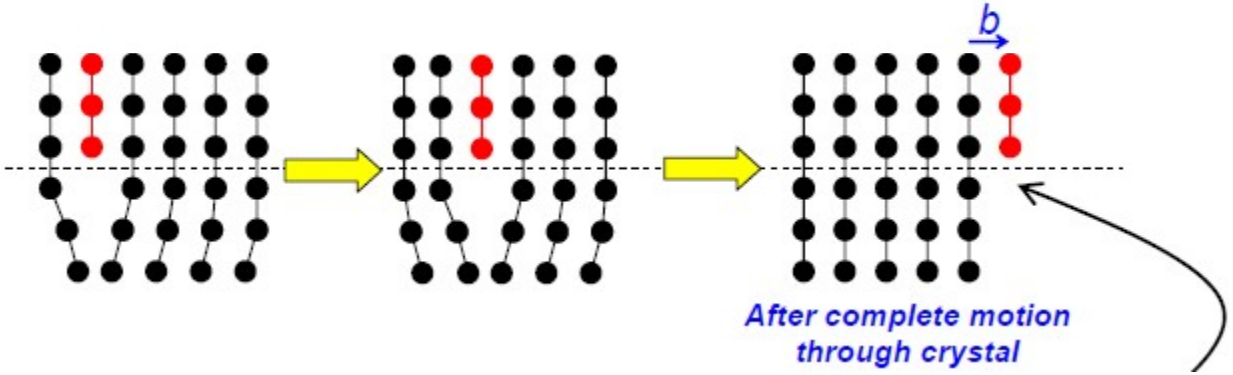
Material	Yield Strength (G/2π)	
	Theoretical (GPa)	Experimental (MPa)
Ag	4.6	0.37
Al	4.2	0.78
Cu	7.2	0.49
Ni	12.2	3.2 – 7.35
Fe	13.2	27.5

The theoretical shear strength of metal (crystals) is ~ 100 times greater than observed shear strength.

It shows that, mechanism other than shearing of planes of atoms is responsible for slip.

Slip by dislocation movement / Lattice resistance to dislocation movement/ The Peierls Stress:

- The discrepancy between the observed and theoretical shear strength of metals due to presence of dislocation.
- Slip in perfect crystal require high energy than slip in crystal having defects like dislocation .

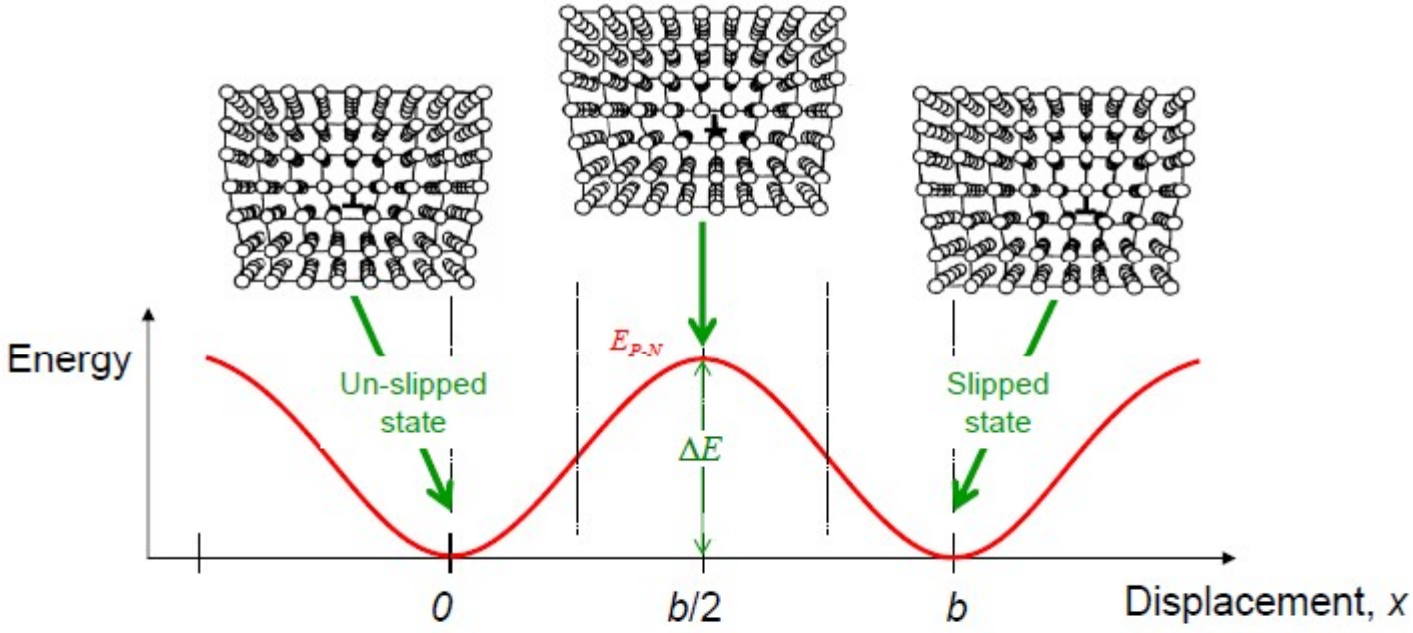


- There is also no net change in bonding. This makes the stress to move a dislocation smaller than theoretical stress to shear a perfect dislocation free crystal.

Peierls Nabarro Force

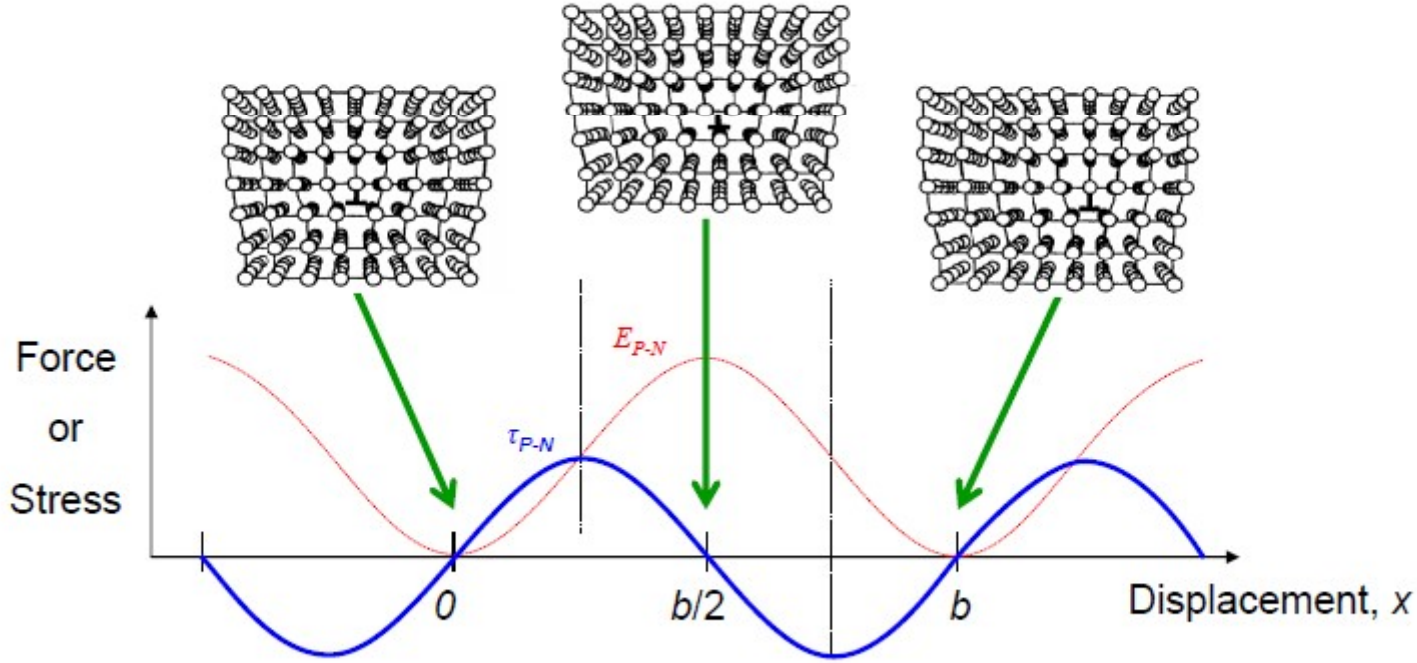
- When there is a dislocation in the crystal, it require small stress for the motion of the dislocation.
- The atoms around the dislocations are symmetrically placed, equal and opposite forces oppose and assist the motion.
- The net force on the dislocation and stress required to move the symmetrical dislocation is zero.
- For non-symmetrical dislocation, the stress is not zero.
- *The shear stress required to move a dislocation through a crystal lattice in a particular direction is called* ***Peierls Nabarro force.***
- The concept was originally developed in 1940 by Peierls, but later refined by others.

A dislocation must pass through a higher energy configuration to move.



The Peierls-Nabarro stress is the shear stress required to move an individual dislocation on its slip plane.

- The Peierls-Nabarro force depends on the form of the force acts in between the atoms and distance between atoms.



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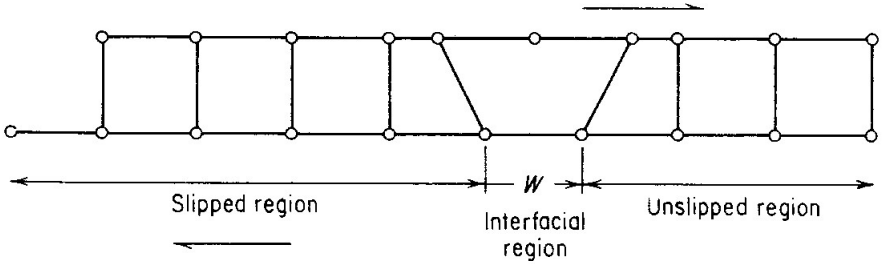
The magnitude of the Peierls force depends on

- the width of the dislocation W, which distorted distance of the lattice due to dislocation
- interplanar distance '*a*' and
- distance between atoms in equilibrium position '*b*'.

The Peierls stress is represented as

$$\tau_{p-n} \; \alpha \; Ge^{-\frac{2\pi W}{b}}$$

where, $W = a/1 - \vartheta$ (ν-Poission's ratio)



$$\tau_{p-n}\ \alpha\ Ge^{-\frac{2\pi W}{b}} \qquad\qquad W - a/1 - \vartheta$$

The above equation shows that,

- Peierls-Nabarrow stress decreases with increasing distance between slip planes.
- Peierls stress depends on the dislocation width (W) which is depends on atomic structure and nature of atomic bonding.
- Wide dislocation requires a low peierls stress to move dislocation. Wide dislocation means, dislocation is not localized on any particular atom in the crystal lattice. Ex.: FCC and HCP metals.
- Narrow dislocation requires a high Peierls stress to move dislocation. The materials which have highly directional bonds like covalent, ionic and bcc crystals have narrow dislocation. Ex.: Ceramics is brittle in nature.

Peierls Stress and Temperature Sensitivity

Peierls stress related to the temperature sensitivity of the yield strength.

- Peierls stress decreases rapidly with increasing temperature and thereby enhancing plastic deformation processes at high temperature.
- At low temperature, thermal enhancement of dislocation is limited which raises the peierls stress.

Relation between dislocation width and yield strength and temperature sensitivity.

Material	Crystal type	Dislocation width	Peierls Stress	Yield strength & temp. sensitivity
Metal	FCC	wide	very small	Negligible
Metal	BCC	narrow	moderate	strong
Ceramic	Ionic	narrow	large	strong
Ceramic	Covalent	very narrow	very large	strong

Critically Resolved Shear Stress

When a stress applied over a single crystal, it resolved into two components.

1. Normal stress (N) – acts ⊥ar to cross sectional area
2. Shear stress (τ_R) – acts on the slip plane.

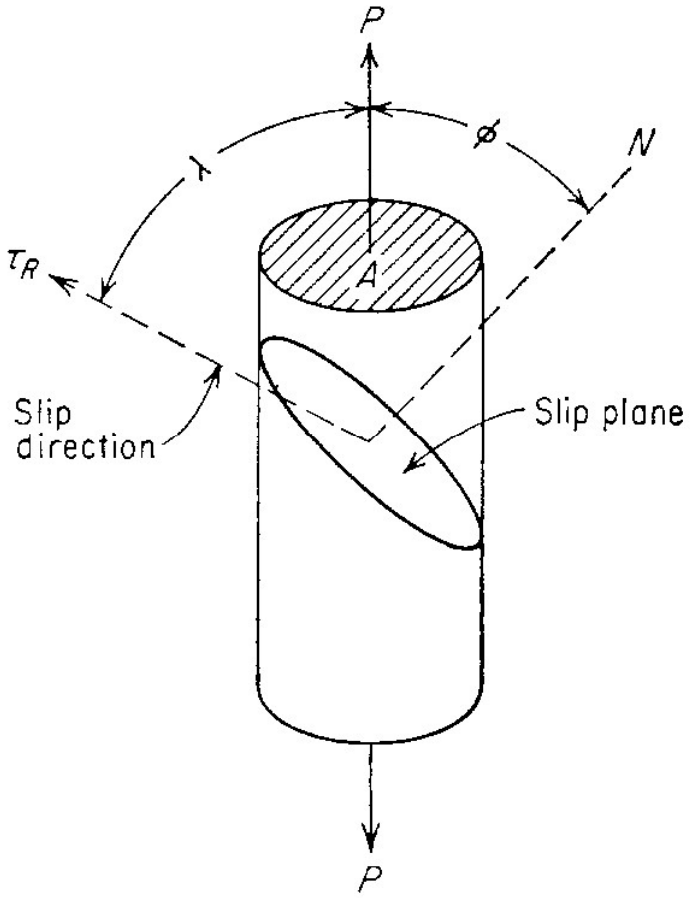
Area of the inclined plane is A/cosϕ.

Axial load acting on the slip plane is,

Pcosλ.

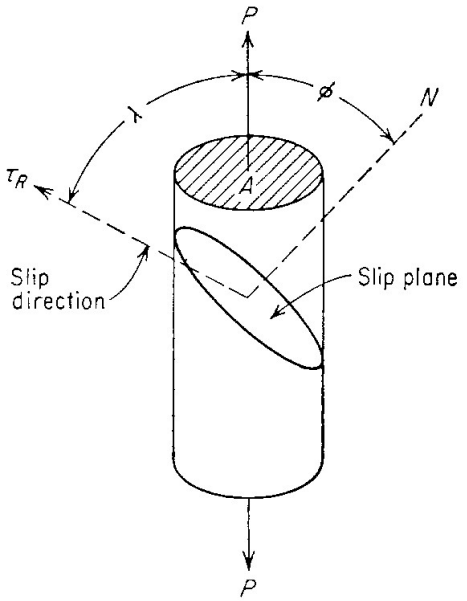
Therefore, the critical resolved shear stress is,

$$\tau_R = \frac{P\cos\lambda}{A/\cos\phi} = \frac{P}{A}\cos\phi\cos\lambda$$



$$\tau_R = \frac{P\cos\lambda}{A/\cos\phi} = \frac{P}{A}\cos\phi\cos\lambda$$

Schmid factor



- Shear stress is maximum, If $\lambda = \phi = 45^\circ$,
  Then, $\tau_R = P/2A$
- No shear occur if $\lambda = 90^\circ$ or $\phi = 90^\circ$, $\tau_R = 0$
  Instead of slip, fracture occur in the material.

Therefore, single crystal slips when the resolved shear stress reaches a critical value.

The ratio of resolved shear stress to axial stress is called as Schmid's law.

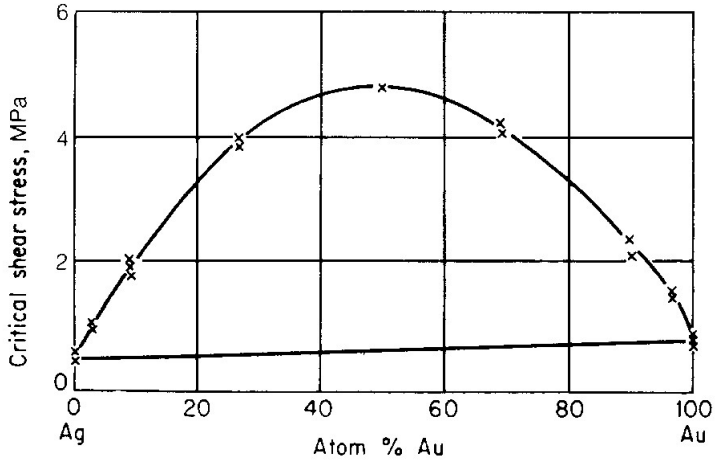
$$\frac{\tau_R}{\sigma} = m = \cos\phi\cos\lambda$$

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
Zn	hcp	99.999	(0001)	$[11\bar{2}0]$	0.18
Mg	hcp	99.996	(0001)	[1120]	0.77
Cd	hcp	99.996	(0001)	$[11\bar{2}0]$	0.58
Ti	hcp	99.99	(1010)	$[11\bar{2}0]$	13.7
		99.9	(1010)	$[11\bar{2}0]$	90.1
Ag	fcc	99.99	(111)	[110]	0.48
		99.97	(111)	[110]	0.73
		99.93	(111)	[110]	1.3
Cu	fcc	99.999	(111)	[110]	0.65
		99.98	(111)	[110]	0.94
Ni	fcc	99.8	(111)	[110]	5.7
Fe	bcc	99.96	(110) (112) (123)	[111]	27.5
Mo	bcc	...	(110)	[111]	49.0

- Crystal structure affect the τ_{CRSS}
- Impurities increases the τ_{CRSS}

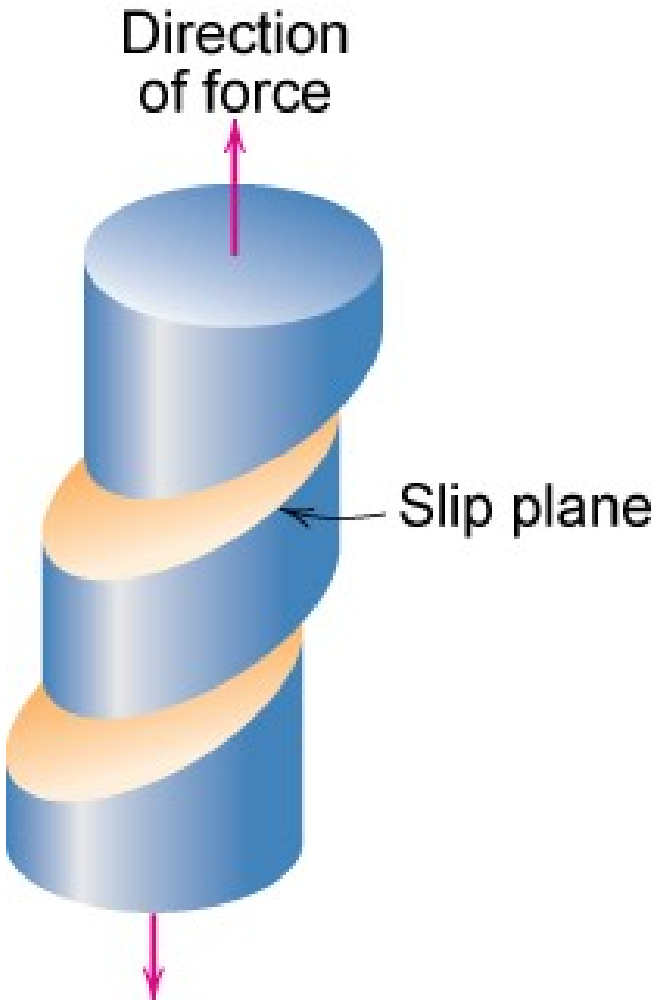
- Solid solution increases τ_{CRSS}



Therefore, Slip on the single crystal depends on ,

- Magnitude of shearing stress applied
- The geometry of the crystal structure
- Orientation of the active slip planes with respect to shearing stresses
- Presence of impurities in the system
- Solid solution of a single phase

Single Crystal Slip



Adapted from Fig. 7.8, *Callister & Rethwisch 8e.*

Adapted from Fig. 7.9, *Callister & Rethwisch 8e.*

Slip Motion in Polycrystals

- Polycrystals stronger than single crystals in terms of dislocation movement– grain boundaries are barriers to dislocation motion.
- Slip planes & directions (λ, ϕ) change from one grain to another.
- τ_R will vary from one grain to another.
- The grain with the largest τ_R yields first.
- Other (less favorably oriented) grains yield later.

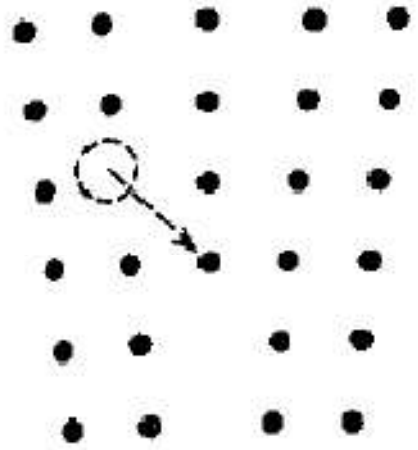
Adapted from Fig. 7.10, *Callister & Rethwisch 8e.* (Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

Dislocation Climb

- An edge dislocation can move out of the slip plane directly above or below the slip plane is called as dislocation climb.
- The dislocation climb classified in to two.
  - Positive climb
  - Negative climb.

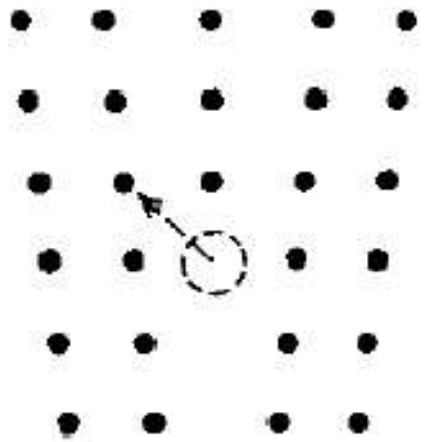
Positive Climb

- When atom is removed from the extra half plane of a positive edge dislocation, the extra half plane moves up one atom spacing.
- The existence of a compressive stress in the slip direction causes a force for positive climb.
- Mechanism:
  - Vacancy diffusion to the dislocation and extra atom moving into the vacant lattice site
  - An atom in extra half plan moves into an interstitial site



Negative Climb

- When atom is added to the extra half plane of a positive edge dislocation, the extra half plane moves down one atom spacing.
- a tensile stress to the extra half plan causes a force in the direction of negative climb
- Mechanism:
  - Atoms from the surrounding lattice joining the extra half plane
  - Interstitial atoms diffusing to the dislocation



Stress fields and energies of dislocations

- A dislocation is surrounded by an elastic stress field that produces forces on other dislocations which results in interaction between dislocations and solute atoms
- Compressive and tensile stresses are around the edge dislocation
- Shear stress is present around the screw dislocation

•The cross section of an elastic cylindrical piece (dashed line) has been distorted after an edge dislocation running through point O parallel to the z axis (blue line)

• The strain is zero in the Z axis and therefore can be treated in plane strain (X-Y)

•The stresses vary inversely with distance from the dislocation line and become infinite at r=0

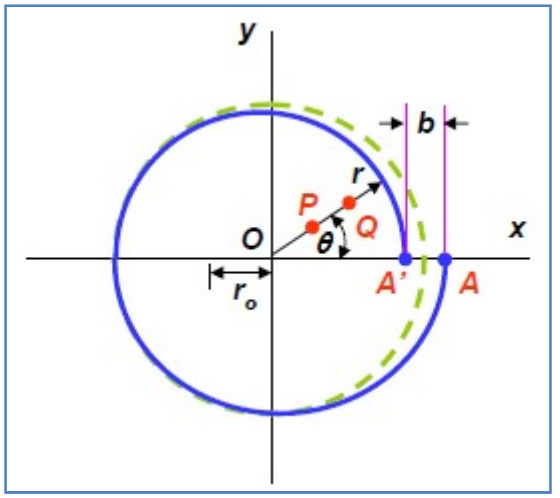
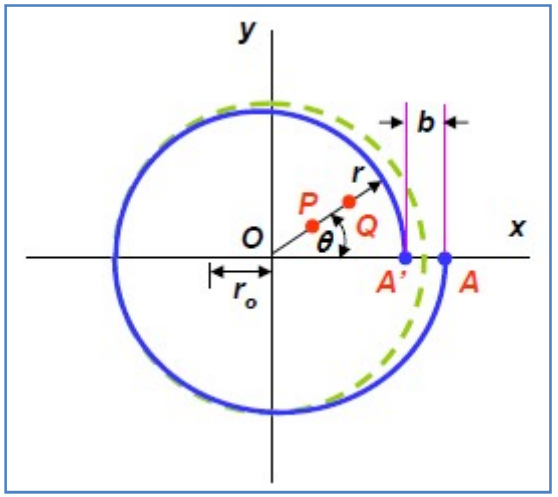


Fig: Deformation of a circle in containing edge dislocation

- The larges normal stress σ_x is along the x-axis. i.e . Compressive stress above the slip plane and tensile below the slip plane.
- In polar coordinates, the stress components are



$$\sigma_r = \sigma_\theta = -\frac{Gb}{2\pi(1-\vartheta)}\frac{bsin\theta}{r}$$

$$\tau_{r\theta} = \tau_{\theta r} = -\frac{Gb}{2\pi(1-\vartheta)}\frac{bcos\theta}{r}$$

σ_r acts in the radial direction and σ_θ acts in a plane perpendicular to r.

In the case of screw dislocation, only shear stress is involved. The Stress component in a polar-coordinate system is,

$$\tau_{\theta z} = G.\frac{b}{2\pi r}$$

The elastic strain energy for the screw dislocation is,

$$E_{screw} = \frac{1}{2}\int_{r_0}^{r_1} \tau_{\theta z} b \, dr \quad = \frac{1}{2}\int_{r_0}^{r_1} \frac{Gb^2}{2\pi}\frac{dr}{r} = \frac{Gb^2}{4\pi} ln \frac{r_1}{r_0}$$

The elastic strain energy for the edge dislocation is,

$$E_{edge} = \frac{Gb^2}{4\pi(1-\vartheta)} ln \frac{r_1}{r_0}$$

The dislocation in crystal have both edge and screw components. Since the strain energy for dislocation represented as,

$$E = \alpha G b^2$$

where E is energy of any dislocation and α is geometrical factor lies between 0.5 to 1.0