Dislocation Motion

Plastic Deformation in Crystalline Materials

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Lecture 8

Slip and Climb

- Dislocations can either slip (or glide) or climb

Dislocation Glide (Slip)

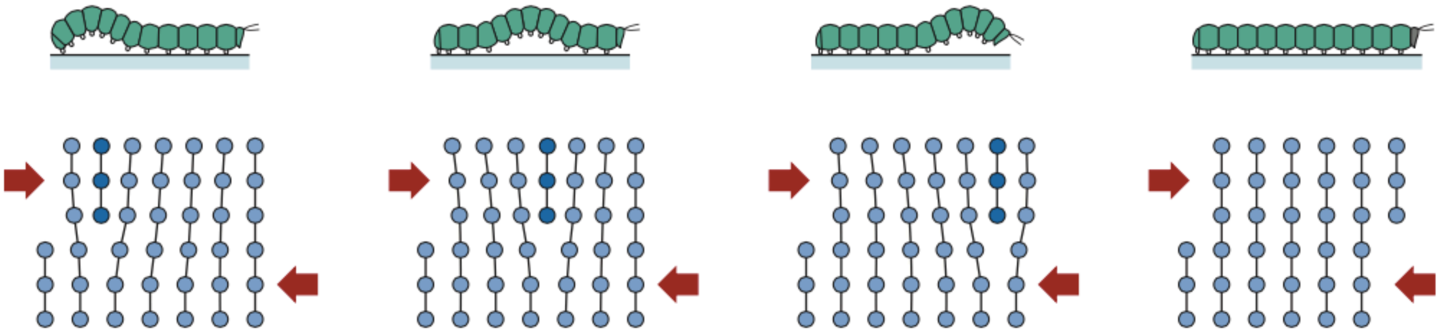
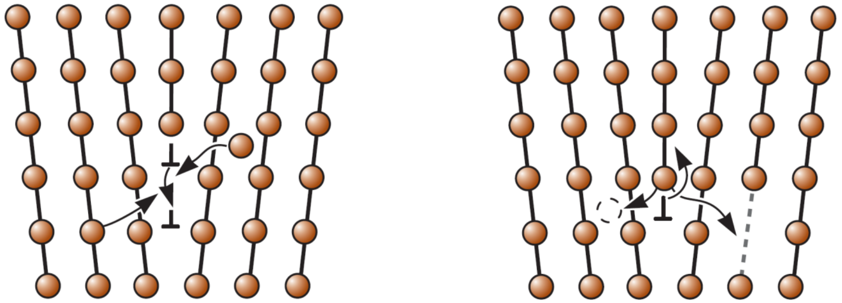


Figure 7.3 Representation of the analogy between caterpillar and dislocation motion.

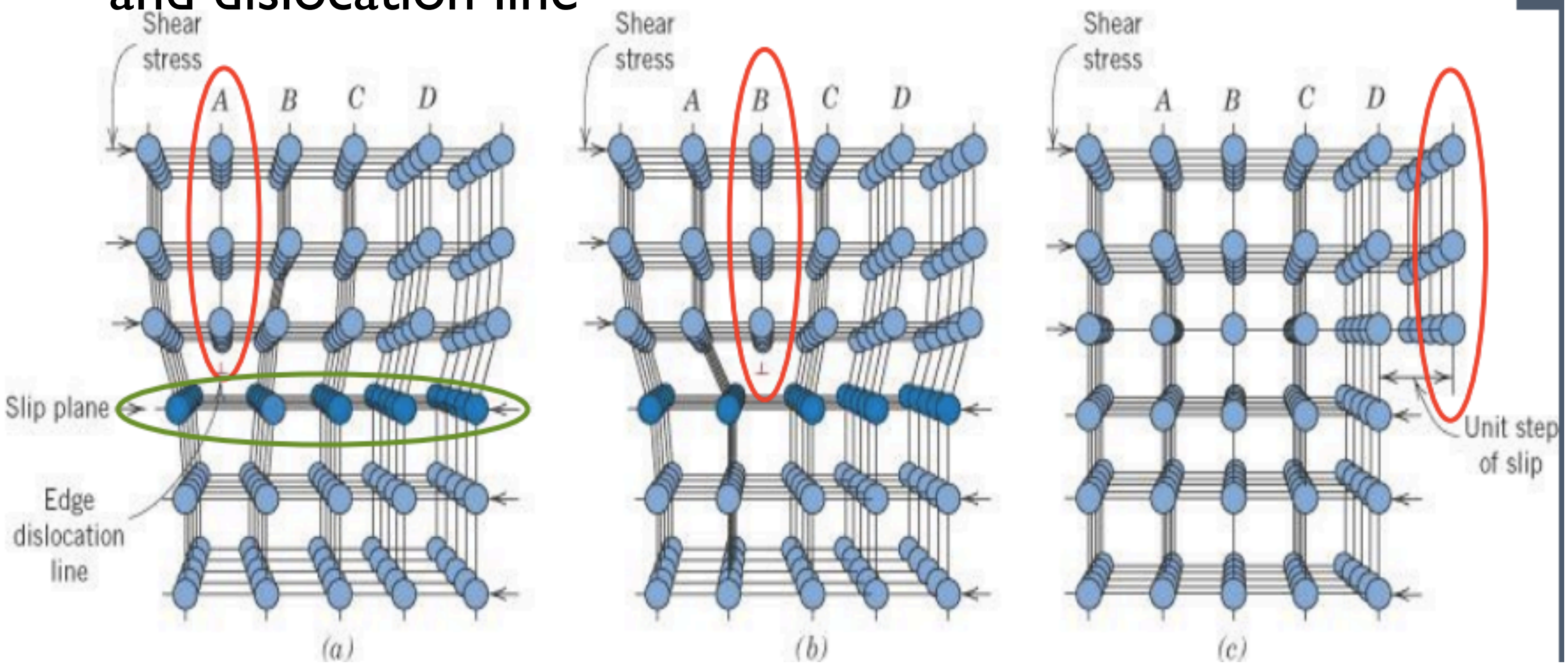
Dislocation climb



[Askland & Fulay, Essentials of materials science and engineering]

Slip Plane

- Slip plane is a plane that contains both the Burgers vector and dislocation line



- Glide= motion in the slip plane
- Climb = motion out of the slip plane
- A screw dislocation can slip on any plane!

Slip System

- The slip planes and slip directions are specific crystallographic planes and directions.
- The slip planes are normally the crystallographic planes which have the highest density of atoms.
- the direction of slip = shortest lattice translation vectors in the slip plane, often the direction in which the atoms are most closely spaced.
- Slip system = slip plane +slip direction

Slip System - II

- Shortest lattice vector:
  bcc: <111>/2
  fcc: <110>/2
  hcp: $\frac{1}{3}\langle 11\bar{2}0 \rangle$

- Slip plane:
  bcc: not well defined
  fcc: {111}
  hcp: (0001)

- In bcc, microscopic evidence: {112} and {110} ({110} is preferred at low temperaute}

- An fcc has twelve {111}<110> slip systems.

Slip Systems - III

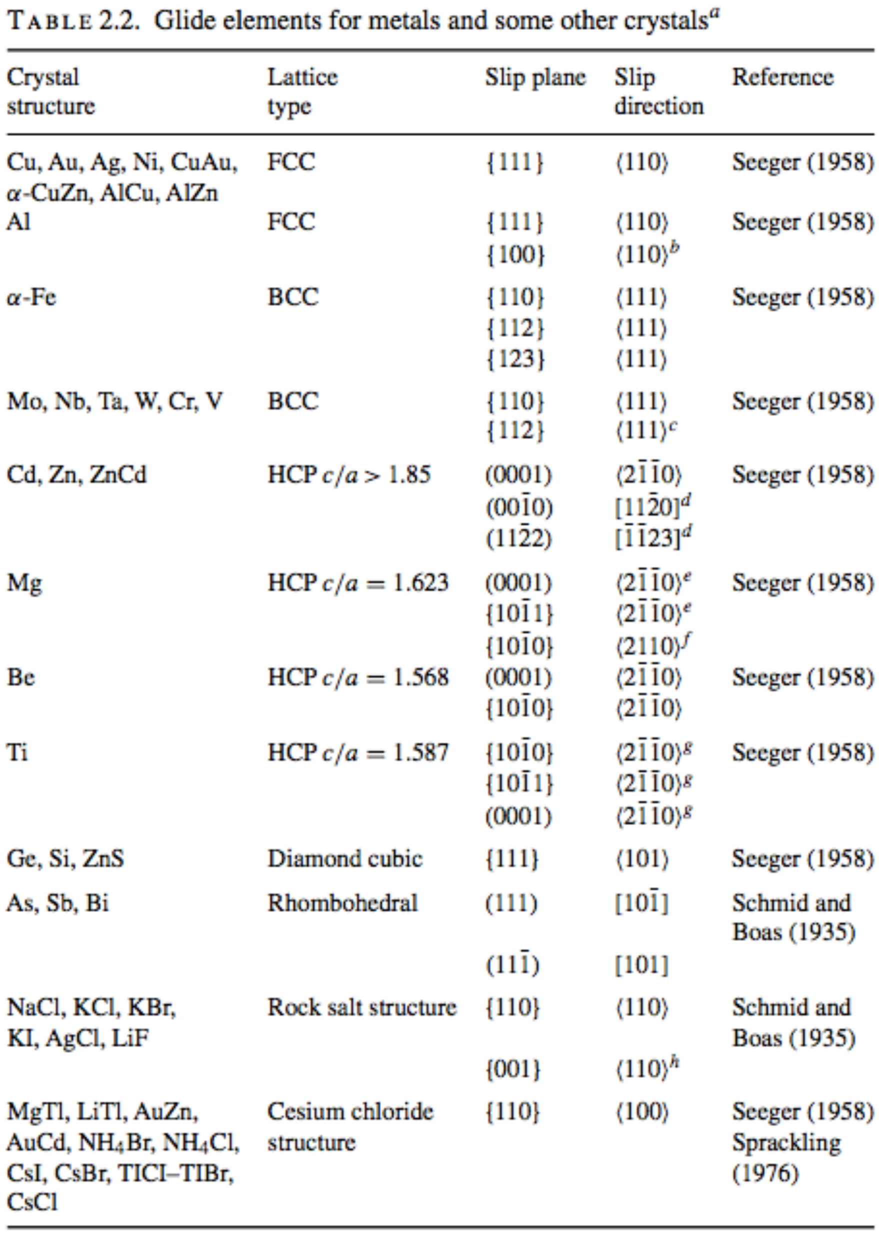


TABLE 2.2. Glide elements for metals and some other crystals[a]

Crystal structure	Lattice type	Slip plane	Slip direction	Reference
Cu, Au, Ag, Ni, CuAu, α-CuZn, AlCu, AlZn	FCC	$\{111\}$	$\langle 110\rangle$	Seeger (1958)
Al	FCC	$\{111\}$ $\{100\}$	$\langle 110\rangle$ $\langle 110\rangle^b$	Seeger (1958)
α-Fe	BCC	$\{110\}$ $\{112\}$ $\{123\}$	$\langle 111\rangle$ $\langle 111\rangle$ $\langle 111\rangle$	Seeger (1958)
Mo, Nb, Ta, W, Cr, V	BCC	$\{110\}$ $\{112\}$	$\langle 111\rangle$ $\langle 111\rangle^c$	Seeger (1958)
Cd, Zn, ZnCd	HCP $c/a > 1.85$	(0001) $(00\bar{1}0)$ $(11\bar{2}2)$	$\langle 2\bar{1}\bar{1}0\rangle$ $[11\bar{2}0]^d$ $[\bar{1}\bar{1}23]^d$	Seeger (1958)
Mg	HCP $c/a = 1.623$	(0001) $\{10\bar{1}1\}$ $\{10\bar{1}0\}$	$\langle 2\bar{1}\bar{1}0\rangle^e$ $\langle 2\bar{1}\bar{1}0\rangle^e$ $\langle 2110\rangle^f$	Seeger (1958)
Be	HCP $c/a = 1.568$	(0001) $\{10\bar{1}0\}$	$\langle 2\bar{1}\bar{1}0\rangle$ $\langle 2\bar{1}\bar{1}0\rangle$	Seeger (1958)
Ti	HCP $c/a = 1.587$	$\{10\bar{1}0\}$ $\{10\bar{1}1\}$ (0001)	$\langle 2\bar{1}\bar{1}0\rangle^g$ $\langle 2\bar{1}\bar{1}0\rangle^g$ $\langle 2\bar{1}\bar{1}0\rangle^g$	Seeger (1958)
Ge, Si, ZnS	Diamond cubic	$\{111\}$	$\langle 101\rangle$	Seeger (1958)
As, Sb, Bi	Rhombohedral	(111)	$[10\bar{1}]$	Schmid and Boas (1935)
		$(11\bar{1})$	$[101]$	
NaCl, KCl, KBr, KI, AgCl, LiF	Rock salt structure	$\{110\}$	$\langle 110\rangle$	Schmid and Boas (1935)
		$\{001\}$	$\langle 110\rangle^h$	
MgTl, LiTl, AuZn, AuCd, NH_4Br, NH_4Cl, CsI, CsBr, TlCl–TlBr, CsCl	Cesium chloride structure	$\{110\}$	$\langle 100\rangle$	Seeger (1958) Sprackling (1976)

Argon, A., *Strengthening Mechanism in Crystal Plasticity*, Oxford University Press, 2008.

Remarks

- Because interstitials have very high formation energy and low migration energy, their concentration is much lower than vacancy concentration (unless there are excess interstitials due to irradiation). This means climb usually takes place via vacancy absorption and emission.
- Glide is a conservative motion (does not change volume), but climb is not because climb requires vacancy emission or absorptions. (exceptions)
- Because screw dislocation can slip on any plane containing its unit direction, it technically cannot climb. That is climb is defined only for edge and mixed dislocations. (exception)
- Because climb requires diffusion, it occurs only when the temperature is higher than 0.3 T_m where T_m is the melting point or where is stresses are very high. Therefore except for special cases, glide is the dominant mechanism of motion.

Conservative Climb

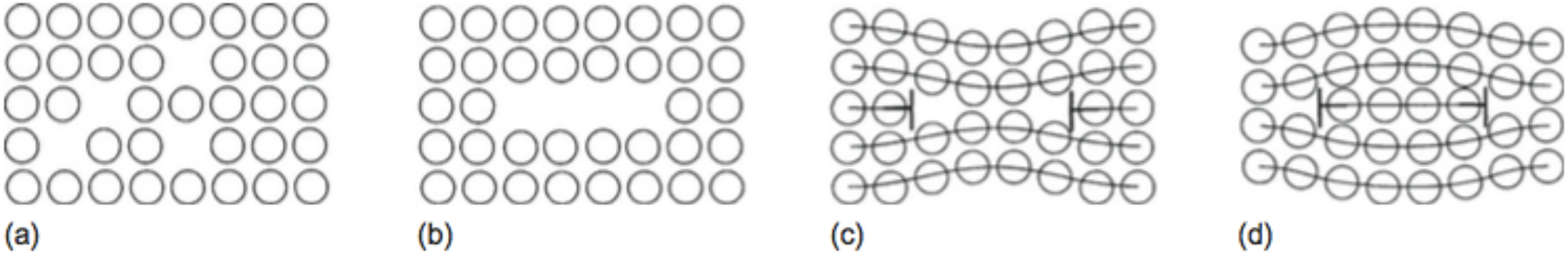


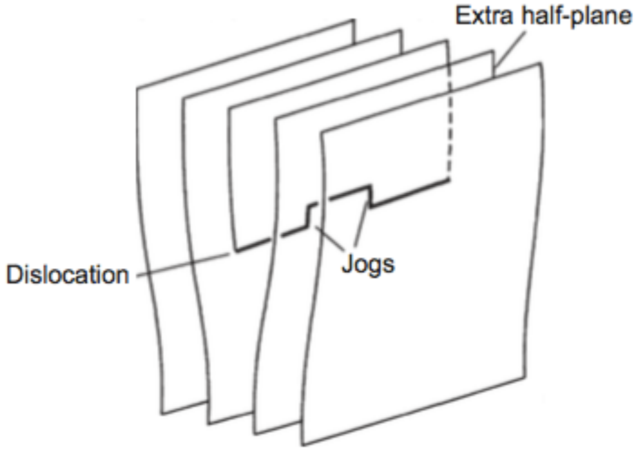
FIGURE 3.19
Formation of a prismatic dislocation loop. (a) Represents a crystal with a large non-equilibrium concentration of vacancies. In (b) the vacancies have collected on a close-packed plane and in (c) the disc has collapsed to form an edge dislocation loop. (d) Loop formed by a platelet of self-interstitial atoms.

[Hull & Bacon, Introduction to Dislocations, 5th ed., Elsevier, 2011]

- If the prismatic loop is transferred in its plane, i.e. it does not expand or shrink at the temperature is too low for bulk diffusion, climb dislocation produced as a result of this mechanism can conservatively climb.

Jogs

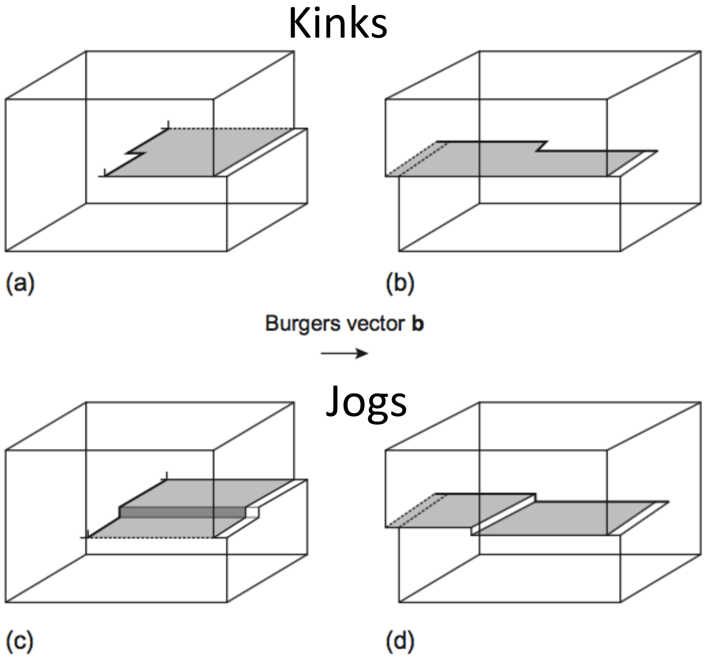
- It looks like that dislocation climb occurs by removing or adding a complete row of atoms. But in practice, climb takes place by formation of jogs.
- Individual vacancies or small cluster of them diffuse to or away the dislocation line and form two small steps, called jogs.
- Jogs are sources and sinks for vacancies.
- Jogs do not impede dislocation glide .



[figure from Hull & Bacon, Introduction to Dislocations, 5th ed., Elsevier, 2011]

Kinks

- Steps which displace on the same slip plane are called kinks.
- Kinks do not leave the original glide.
- Not only does kinks impede dislocation glide, in fact they facilitate glide.



[figure from Hull & Bacon, Introduction to Dislocations, 5th ed., Elsevier, 2011]

Plastic Deformation due to Dislocation Motion

Orowan vs Taylor

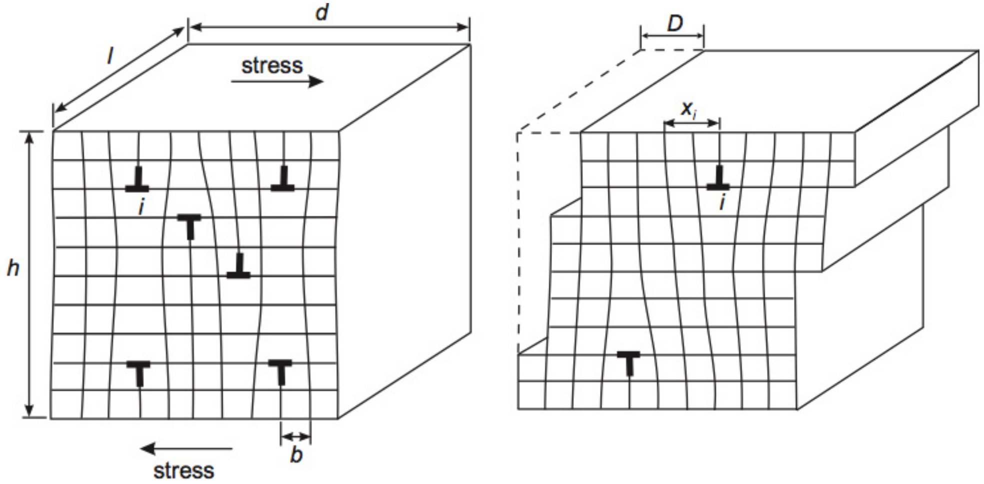
- Orowan: If there are more dislocations, the solid will be softer

- Taylor: If there are more dislocations, the solid will be harder

- Which one is correct?

- Both are correct!

Orowan’s equation - 1



macroscopic shear strain

$$\gamma^{(p)} = \frac{D}{h}$$

[figure from Hull & Bacon, Introduction to Dislocations, 5th ed., Elsevier, 2011]

$$D = \sum_{i=1}^{N} \frac{b}{d}\delta x_i = \frac{b}{d}\; N\,\overline{x} \quad \text{where} \quad \overline{x} = \left(\sum_{i=1}^{N} \delta x_i\right)/N$$

$$\gamma^{(p)} = \rho b\,\overline{x} = b\frac{\delta A}{V} \quad \text{where} \quad \rho = N/V$$

δA is the total area swept by all dislocations

Orowan’s equation - II

$$\dot{\gamma}^{(p)} \equiv \frac{\mathrm{d}\gamma^{(p)}}{\mathrm{d}t} = b\frac{\mathrm{d}\rho}{\mathrm{d}t}\,\bar{x} + b\rho\frac{\mathrm{d}\bar{x}}{\mathrm{d}t}$$

Except under extreme conditions where dislocations move very quickly, it is reasonable to neglect the first term on the right hand side of the above, to arrive at what is called Orowan's equation:

$$\dot{\gamma}^{(p)} = \rho b \bar{v}$$

where $\overline{v}$ is the average velocity of dislocations.
Because

$$\rho\bar{v} = \rho_m \bar{v}_m$$

where subscript *m* refers to mobile dislocations, Orowan’s equation is often written as:

$$\dot{\gamma}^{(p)} = \rho_m b \bar{v}_m$$

Orowan's equation: Micormechanics Approach

- the plastic strain due to an edge dislocation is given by $\varepsilon_{xy}^{*}=\frac{b}{2}\delta(y)H(-x)$
- for a dipole of a distance *d*: $\varepsilon_{xy}^{*}=\frac{b}{2}\delta(y)\left[H(-x)-H(-x+d)\right]$
- If one of them travels by Δx

$$\Delta\varepsilon_{xy}^{*}=\frac{b}{2}\delta(y)H(-x-\Delta x)-\frac{b}{2}\delta(y)H(-x)=\frac{b}{2}\delta(y)\left[H(-x-\Delta x)-H(-x)\right]$$

- The above formula is the change in the local plastic strain. The average plastic strain can is given by

$$\Delta\bar{\varepsilon}_{xy}^{*}=\frac{1}{V}\int_{V}\Delta\varepsilon_{xy}^{*(LOC)}dV$$

- If we consider a body of thickness *t*, we will have

$$\Delta\bar{\varepsilon}_{xy}^{*}=\frac{t}{tA}\int_{A}\frac{b}{2}\delta(y)\left[H(-x-\Delta x)-H(-x)\right]dydx=\frac{b}{2}\frac{t}{tA}(1\times\Delta x\times 1)=\frac{1}{2}\frac{b\Delta x}{A}$$

- It can also be written as

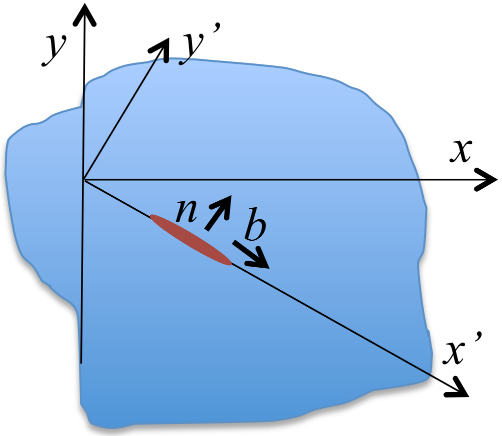
$$\Delta\bar{\varepsilon}_{xy}^{*}=\frac{b\delta A}{2V}$$

where δA is the area swept by the dislocations.

Shear - I

- Changing coordination system:

$$\varepsilon_{ij}^{(p)} = a_{i\alpha}a_{j\beta}\varepsilon_{\alpha\beta}^{(p)} = a_{ix'}a_{jy'}\varepsilon_{x'y'}^{(p)} + a_{iy'}a_{jx'}\varepsilon_{y'x'}^{(p)}$$



where

$$a_{ix'} = \hat{i}\bullet\hat{x}' = \hat{i}\bullet\hat{b}^0 = b_i^0$$

$$a_{jy'} = \hat{j}\bullet\hat{y}' = \hat{j}\bullet\hat{n} = n_j^0$$

with $\boldsymbol{b}^0=\boldsymbol{b}/|\boldsymbol{b}|$, and so on. Thus $\varepsilon_{ij}^{(p)} = \left(b_i^0 n_j + b_j^0 n_i\right)\varepsilon_{x'y'}^{(p)}$

- In general, the average strain $\Delta\bar{\varepsilon}_{ij}^{(p)}$ produced by an increase δA in the slipped area is:

$$\Delta\bar{\varepsilon}_{ij}^{(p)} = \frac{b\ \delta A}{2V}\left(b_i^0 n_j + b_j^0 n_i\right) = \frac{\delta A}{2V}\left(b_i n_j + b_j n_i\right)$$

where $b=|\boldsymbol{b}|$ and.

Shear - II

- $\alpha_{ij} = \frac{\left(b_i^0 n_j + b_j^0 n_i\right)}{2}$ is called the Schmid strain resolution tensor

- If the shear is produced by a set of *m* separate slip systems, then

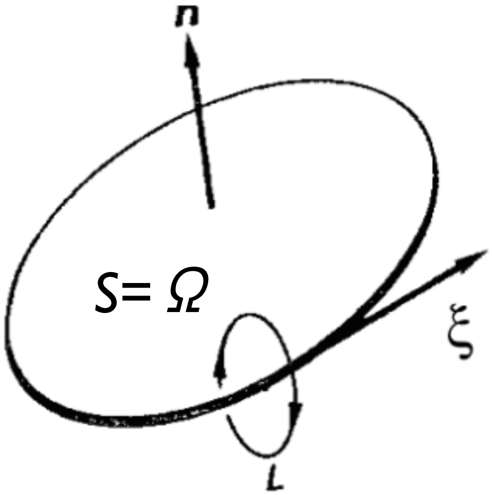
$$\Delta\bar{\varepsilon}_{ij}^{(p)} = \sum_m b_m \frac{\alpha_{ij}^{(m)} \delta A_m}{V}$$

Shear - III

- The plastic distortion $\boldsymbol{\beta}^{(p)}$ is caused by the slip b_i , can be written as:

$$\beta^{*}_{ji}(\vec{r}) = -b_i n_j \delta(\vec{S} - \vec{r})$$

where $\delta(\boldsymbol{S}\text{-}\boldsymbol{r})$ is the 1-dimensional Dirac delta function in the normal direction of S. $\delta(\boldsymbol{S}\text{-}\boldsymbol{r})$ is infinite when $\boldsymbol{r}$ is on $\boldsymbol{S}$ and zero everywhere else.



- And

$$\varepsilon^{*}_{ij}(\vec{r}) = -\frac{1}{2}(b_i n_j + b_j n_i)\delta(\vec{S} - \vec{r})$$

Orowan’s Equation when Dislocations Climb

- When edge dislocations climb, the volume of the crystal changes, and the sample experiences (normal) plastic strain

$$\varepsilon^{(p)} = D/d$$

With the same method that we used for glide, we can show that the normal plastic strain is

$$\varepsilon^{(p)} = \rho b \bar{y}$$

where $\bar{y}$ is the average climb distance.

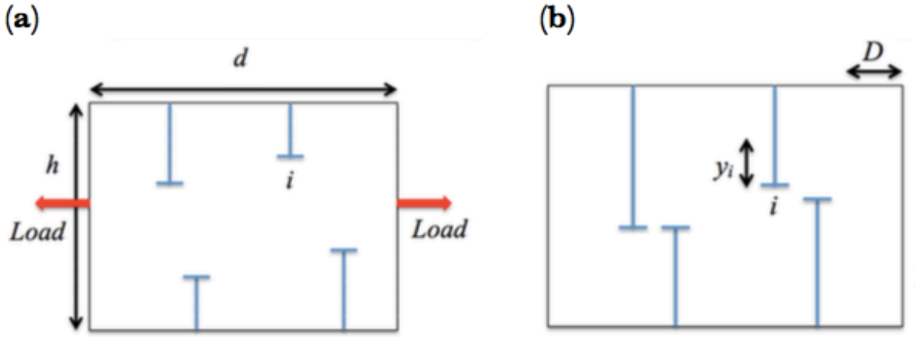


Figure 2.2.2: (a) A crystal containing some straight edge dislocations is subjected to tension. (b) Macroscopic tensile plastic shear strain $\varepsilon^{(p)}$ arises from the climb of individual dislocations. If each dislocation climb a distance y_i and the average climb distance is $\bar{y} = \sum y_i/N$, then $\varepsilon^{(p)} = \rho b \bar{y}$. Adapted from [46].

- If changes in dislocation density are negligible

$$\dot{\varepsilon}^{(p)} = \rho b \dot{\bar{y}} = \rho b \bar{v}$$

Orowan’s view

- Based on Orowan’s equation, higher dislocation density means larger plastic strains and consequently a softer material!

Further Reading

(1) Argon, A., *Strengthening Mechanism in Crystal Plasticity*, Oxford University Press, 2008.

(2) Hull, Bacon, *Introduction to Dislocations*, 5th ed., Butterworth, 2011.

(3) Mura, T., *Micromechanics of Defects in Solids*, Kluwer Academic Publishers, 1987.