Lecture #13:

- Dislocation Climb
- Implications of Climb
- Intersection of dislocations
- Energy of dislocations
- Stress field around dislocations
- Forces on dislocations
- Forces between dislocations

References:

1- Derek Hull, David Bacon, (2001), Introduction to Dislocations, fourth edition, Butterworth-Heinemann.

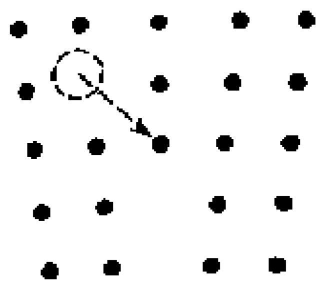
2- Hosford W.F, (2005), Mechanical Behavior of Materials, Cambridge

3- Meyers M.A. and Chawla K.K., (2009). Mechanical Behavior of Materials, Prentice- Hall.

4- Dieter G.E., (1986), Mechanical Metallurgy, McGraw-Hill

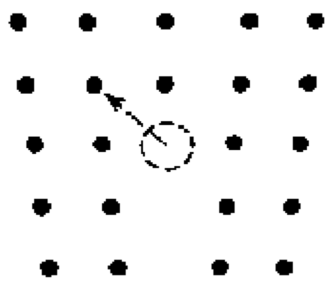
Dislocation Climb:

An edge dislocation moves out of the slip plane onto a parallel plane directly above or below the slip plane. This movement is termed nonconservative, as compared with conservative movement (glides).



(a)Diffusion of vacancy to edge dislocation

*** Positive dislocation**
*** Moving up one atom spacing**



(b)Dislocation climbs up one lattice spacing

*** Negetive dislocation**
*** Moving down one atom spacing**
*** Less probably by interstitial atoms diffusing to the dislocation.**

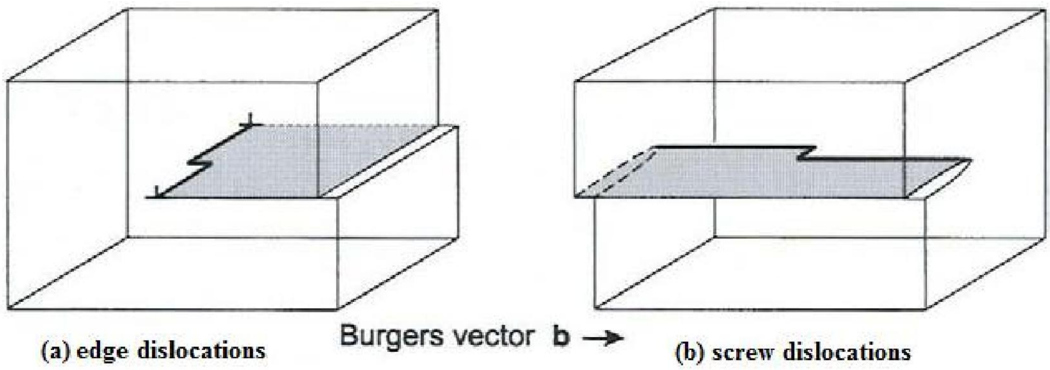
In actual fact individual vacancies or small clusters of vacancies diffuse to the dislocation and climb occurs over a short segment of the dislocation line.

This results in the formation of short steps or jogs (عتبات) along the dislocation line. Climb proceeds by the nucleation and motion of jogs.
Dislocation climb is an important mechanism in the creep of metals (as both are related to the activation energy for diffusion / **as will be discussed later**).

Climb is not possible with screw dislocations as there is no extra half plane of atoms. Because the Burgers vector is parallel to the dislocation, screw dislocation is free to slip on any plane which contains the dislocation line and the Burgers vector (no diffusion of atoms needed).

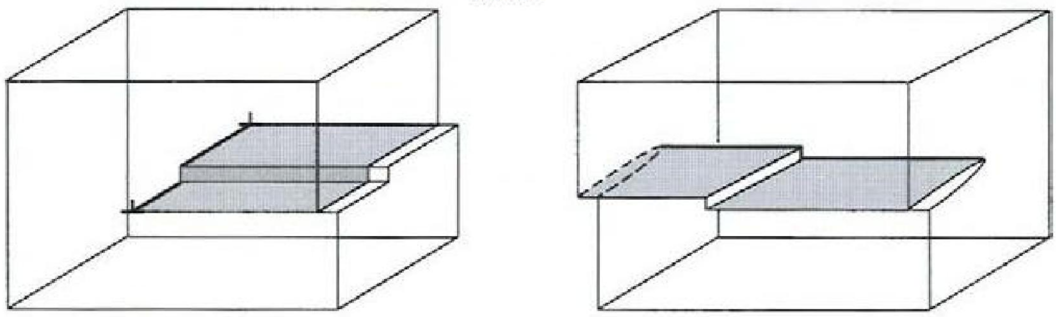
<u>Implications of Climb:</u>

• Climb of short sections of dislocation lines result in the formation of steps called *jogs*.
• *Climb* proceeds by the nucleation and motion of jogs.
• Jogs are steps (out of the slip plane) on a dislocation that move it from one atomic plane to another.
• There is also another type of dislocation step called a *kink*.
• Kinks are steps (in the slip plane) that displace the dislocation within the slip plane.



(a) edge dislocations (b) screw dislocations

Kinks



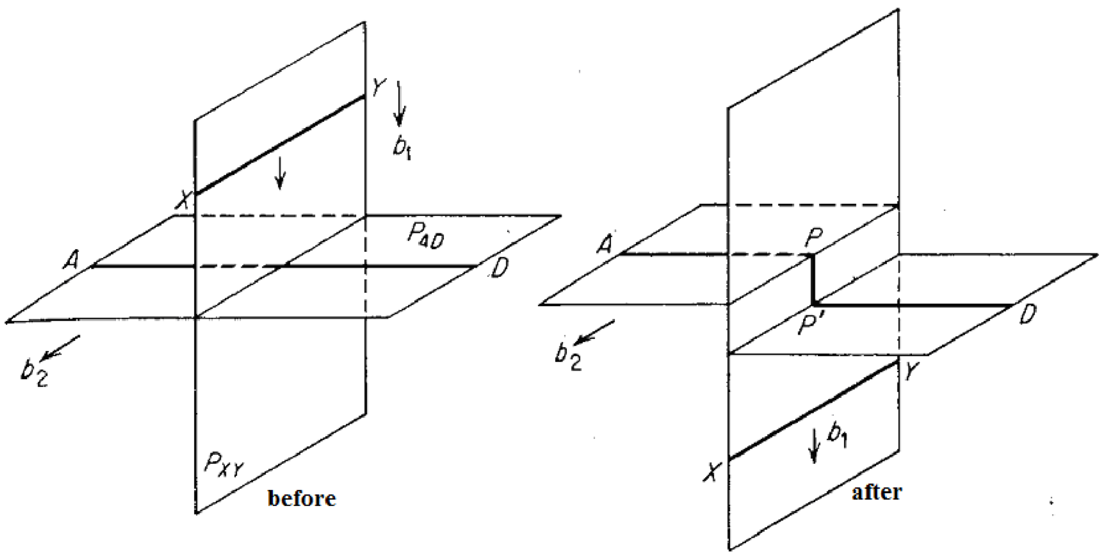
(a) edge dislocations (b) screw dislocations

Jogs

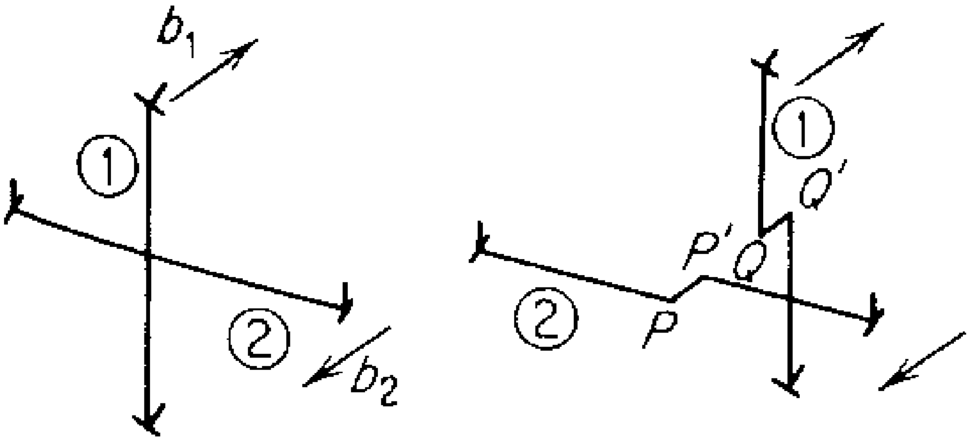
• *Jogs* and *kinks* are short segments of a dislocation that have the same Burgers vectors as the lines on which they lie.
• Both are subject to the same rules for conservative and non-conservative motion as perfect dislocations.
• Kinks, which have the same slip plane as the dislocation line, do not impede glide of the line. In fact a kink may assist glide.
• **Edge dislocations**: Jogs do not influence the glide of edge dislocations. They are able to glide readily because they lie in the slip planes of the original dislocations. Gliding will be over a stepped surface.
• **Screw dislocations**: Jogs will have "edge character" and will be restricted to the original slip plane. Thus, they do impede motion of screw dislocations. The only way that the screw dislocation can slip to a new position and take its jogs with it is by a noncoservative process such as climb which is a thermally activated process. Therefore the movement of jogged screw dislocations will be temperature dependent. This means that screw dislocations move more slowly through a crystal than edge dislocations.

Intersection of dislocations:

Crystals contain many dislocations and a dislocation moving in its slip plane will intersect other dislocations crossing the slip plane. Dislocation intersection mechanism plays an important role in the strain hardening process. The intersections of dislocations produce the two types of steps (jogs and kinks).

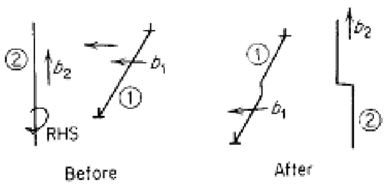


Two edge dislocations with $b_1 \perp b_2$ produce a jog pp' parallel and equal to b_1 with a Burger vector b_2. To determine which dislocation forms the jog: a jog forms when the Burger vector of the intersecting dislocation is normal to the other dislocation line (b_1 is normal to AD and b_2 is parallel to xy).

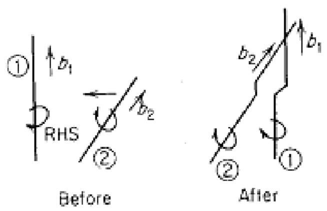


Before **After**

Intersection of edge dislocations with parallel Burger vectors.
Produced steps are called kinks in this case as they lie in the slip plane



Intersection of edge and screw



Intersection of two screw dislocations

Energy of dislocations:

The energy associated with a screw dislocation is the energy required to distort the lattice surrounding the dislocation elastically. The distortion is severe near the dislocation but decreases with distance from it. Consider an element of length L and thickness dr at a distance r from the center of a screw dislocation (see the figure).

The volume of the element = $2\pi r L dr$.

The shear strain associated with this element, $\gamma = \mathbf{b}/(2\pi r)$

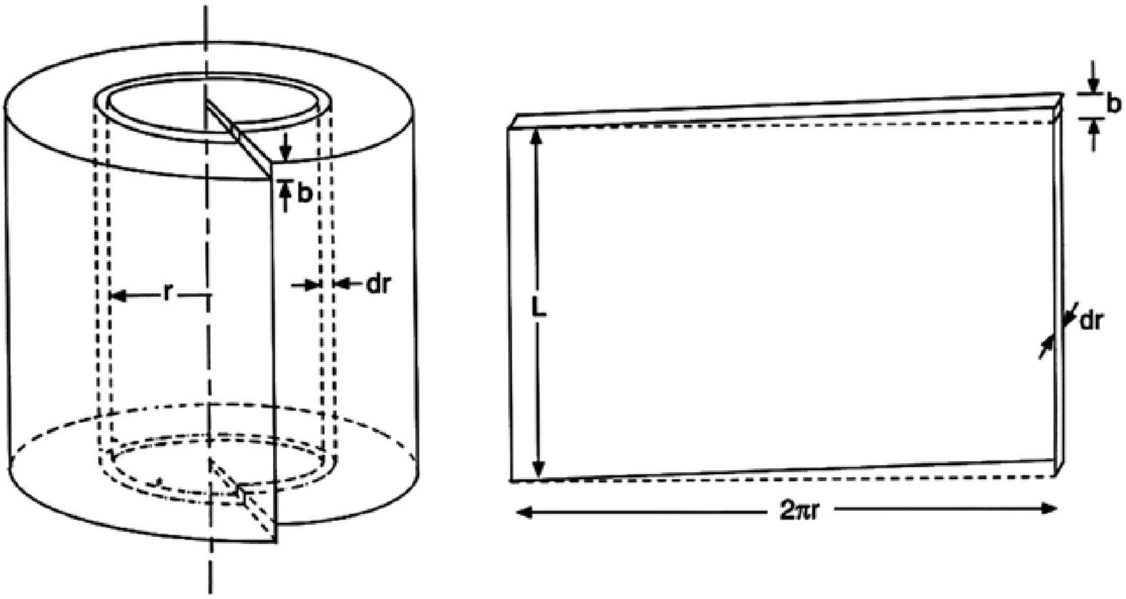
The energy/volume associated with an elastic distortion, $U_v = (1/2)\tau\gamma$

where τ is the shear stress necessary to cause the shear strain γ . But $\tau = G\gamma$

So: $\quad U_v = G\gamma^2/2 = (1/2)Gb^2/(2\pi r)^2$.

The elastic energy, dU, associated with the element is its energy/volume times its volume, so:

$$dU = [(1/2)Gb^2/(2\pi r)^2](2\pi rL\,dr) = (Gb^2L/4\pi)dr/r$$



The total energy of the dislocation per length, L, is obtained by integrating,

so: $$\frac{U}{L} = \frac{Gb^2}{4\pi}\int_{r_0}^{r_1}\frac{dr}{r} = \frac{Gb^2}{4\pi}\ln(r_1/r_0)$$

The problem, now, is to decide what are appropriate values for the lower limit, r_o, and the upper limit, r_1, of the integral. We might be tempted to let r_o be 0 and r_1 be ∞, but both would cause the value of U to be infinite.

First consider the lower limit, $r_o = 0$ which gives an infinite strain that corresponds to an infinite energy/volume at the core of the dislocation.

This is clearly unreasonable. This discrepancy is a result of the breakdown of Hooke's law at the very high strains that exist near the core of the dislocation. So a value of $\boldsymbol{r_o = b/4}$ has been suggested as reasonable.

The upper limit, r_1, can't be any larger than the radius of the crystal. A reasonable value for r_1 is half of the distance between dislocations. At greater distances, the stress field is probably neutralized by stress fields of other dislocations. The value of r_1 is often approximated by 10^5b, which corresponds to a dislocation density of 10^{10} dislocations per m^2. This is convenient because $\ln(10^5b/0.25b) = \ln(4 \times 10^5) = 12.9 \approx 4\pi$. So: $\boldsymbol{U_L \approx Gb^2}$.

For edge dislocations, $\boldsymbol{U_{\mathrm{L}} \approx Gb^2/(1-v)}$

As seen the energy of a dislocation is proportional to its length. Energy per length is equivalent to line tension, or a contractile force. The units of energy/length are J/m, which is the same as the units of force, N.

Stress field around dislocations

Dislocations are defects; hence, they introduce stresses and strains in the surrounding lattice of a material. The dislocation is therefore a source of **internal stress** in the crystal. The mathematical treatment of these stresses and strains can be **simplified by assuming a state of isotropic body**. Under conditions of isotropy, a dislocation is completely described by the line and Burgers vectors. With this in mind, and considering the simplest possible situation, dislocations are assumed to be straight, infinitely long lines. This still results in a good approximation in most cases. The elastic field produced by a dislocation is not affected by the application of stress from external sources: the total stress on an element within the body is the superposition of the internal and external stresses.

The elastic distortion around an infinitely-long, straight dislocation can be represented in terms of a cylinder of elastic material as shown in the figures on the next page.

1- Stress field of a Screw Dislocation:

First, it is noted that there are no displacements in the x and *y* directions.

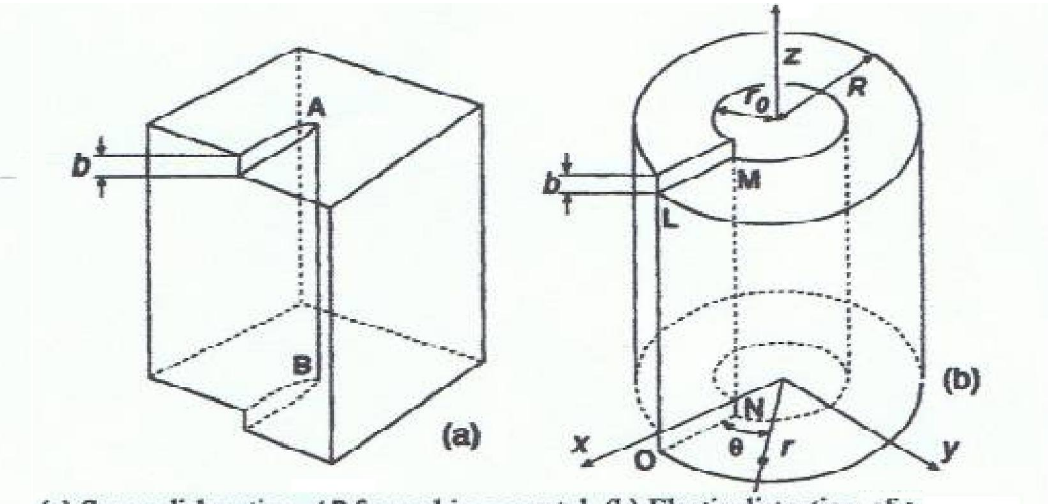
$U_x = U_y = 0$

Secondly, the displacement in the z-direction increases uniformly from zero to b, as θ increases from 0 to 2π:

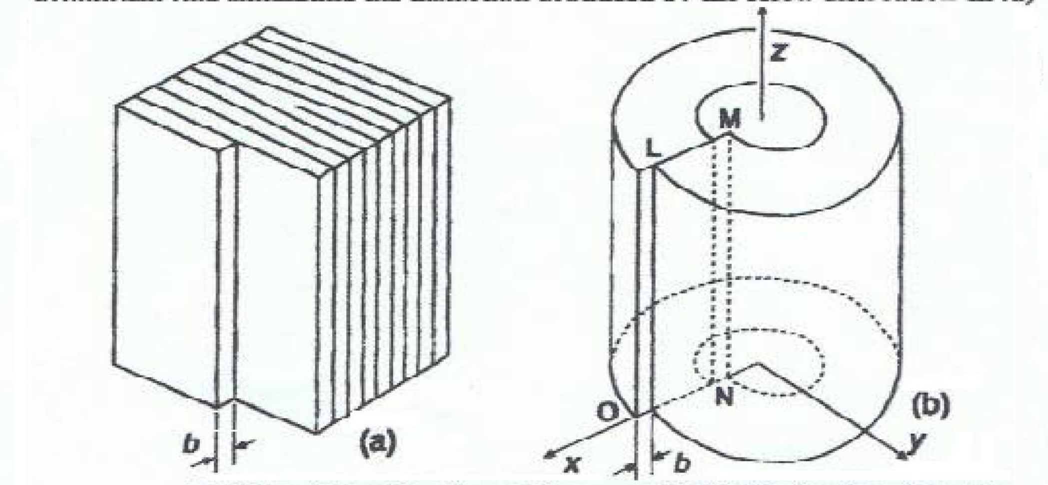
$$\sigma_{xx} = \sigma_{yy} = \sigma_{zz} = \sigma_{xy} = \sigma_{yx} = 0$$

$$\sigma_{xz} = \sigma_{zx} = -\frac{Gb}{2\pi}\frac{y}{\left(x^2+y^2\right)} = -\frac{Gb}{2\pi}\frac{\sin\theta}{r}$$

$$\sigma_{yz} = \sigma_{zy} = \frac{b}{2\pi}\frac{x}{\left(x^2+y^2\right)} = \frac{Gb}{2\pi}\frac{\cos\theta}{r}$$



(a) Screw dislocation *AB* formed in a crystal. (b) Elastic distortion of a cylindrical ring simulating the distortion produced by the screw dislocation in (a)



(a) Edge dislocation formed in a crystal. (b) Elastic distortion of a cylindrical ring simulating the distortion produced by the edge dislocation in (a).

2- Stress field of an Edge Dislocation:

The displacement and strains in the z-direction are zero and the deformation is a plane strain state

$$\sigma_{xx} = -Dy\frac{\left(3x^2 + y^2\right)}{\left(x^2 + y^2\right)^2} \qquad \sigma_{yy} = Dy\frac{\left(x^2 - y^2\right)}{\left(x^2 + y^2\right)^2}$$

$$\sigma_{xy} = \sigma_{yx} = Dx\frac{\left(x^2 - y^2\right)}{\left(x^2 + y^2\right)^2} \qquad \sigma_{zz} = \upsilon\left(\sigma_{xx} + \sigma_{yy}\right)$$

$\sigma_{xz} = \sigma_{zx} = \sigma_{yz} = \sigma_{zy} = \mathbf{0}$ **where** $D = \dfrac{Gb}{2\pi(1-\upsilon)}$

<u>Forces on dislocations:</u>

• When applied stresses are high enough, dislocations will move causing plastic strain.

• The applied load induces work on the crystal during dislocation motion.

• In turn, the dislocation responds to the applied stress as though it experiences a force. The force is given by:

Force = work done / distance moved

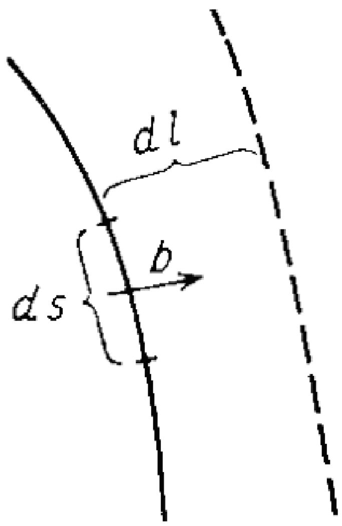
Dislocation line moving in the direction of its Burgers vector under the influence of τ.
ds-element of the dislocation line displaced by dl

The area swept out by the line element is $ds\,dl$**. This corresponds to an average displacement of the crystal above the slip plane to the crystal below the slip plane of an amount** $(ds\,dl/A)b$**, where A is the area of the slip plane. The applied force is** τA **and the work done is**

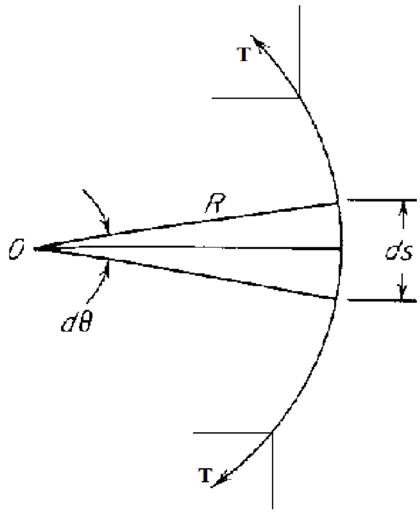
$$dW = \tau A\left(\frac{ds\,dl}{A}\right)b$$

The force on a dislocation is defined as a force per unit length of dislocation line. Since $F = dW/dl$ **and this is a force per unit length** (ds)**, so:**

$$F = \frac{dW}{dl\,ds} = \tau b$$



The strain energy of a dislocation was determined per unit length ($\boldsymbol{U_L \approx Gb^2}$ **and** for edge dislocations, $\boldsymbol{U_L \approx Gb^2/(1-\upsilon)}$**,** the energy of a dislocation is proportional to its length.), so work must be performed to increase its length. Straight dislocations are shorter and thus have less strain energy than curved dislocations. • Thus dislocations have *forces* acting on them **and** are subject to line tension (توتر خطي) that tries to straighten them out. For a curved dislocation line the line tension produces a restoring force (قوة اعادة) which tends to straighten it out.



The line tension **T** will produce a force tending to straighten the line and the line only will remain curved if there is a shear stress which produces a force on the dislocation to resist the line tension.

$$d\theta = ds/R.$$

The outward force on the dislocation line is $\tau b\,ds$. The opposing inward force due to the line tension is $2\mathbf{T}\sin(d\theta/2) \approx \mathbf{T}d\theta$ for small $d\theta$. For the dislocation line to remain in the curved configuration

$$\mathbf{T}d\theta = \tau b\,ds$$

or

$$\tau = \frac{\mathbf{T}}{bR}$$

But, **T** is an energy per unit length, and $U_L \approx Gb^2$. Thus, the shear stress required to bend a dislocation to a radius R is

$$\tau \approx \frac{Gb}{R}$$

• This equation provides an adequate approximation for most dislocations, however it does make some generally invalid assumptions.
• It assumes that edge, screw, and mixed dislocation segments have the same energy per unit length, and that the curved dislocation is the arc of a circle.
• This will only be valid if Poisson's ratio = 0.

Forces between dislocations

• The forces acting on dislocations depend on the Peierls stress, which is the intrinsic resistance to dislocation movement through a lattice, and interactions with other dislocations.
• Two **like edge dislocations** (i.e., both have parallel Burgers vectors) lying **on the same slip plane** will **repel** each other.
•Two **unlike edge dislocations** (i.e., both have opposite Burgers vectors) lying **on the same slip plane** will **attract** each other and **annihilate** out**.**
•Two **unlike edge dislocations** (i.e., both have opposite Burgers vectors) Lying on **parallel slip planes separated by a few atomic spacings** will **attract** each other and **annihilate** out leaving **vacancies.**