02D3_Plasticity: Dislocation Multiplication and the Orowan Stress

Topics:

•Generation of Dislocation Loops from a Pinned Segment of a Dislocation

•Orowan Stress: Overcoming Hard Particles in the Path of the Dislocation

•Metallurgical processing - Nanostructure and the Yield Stress

Mechanisms for Pinned Dislocations

•Cross slip into a new slip plane

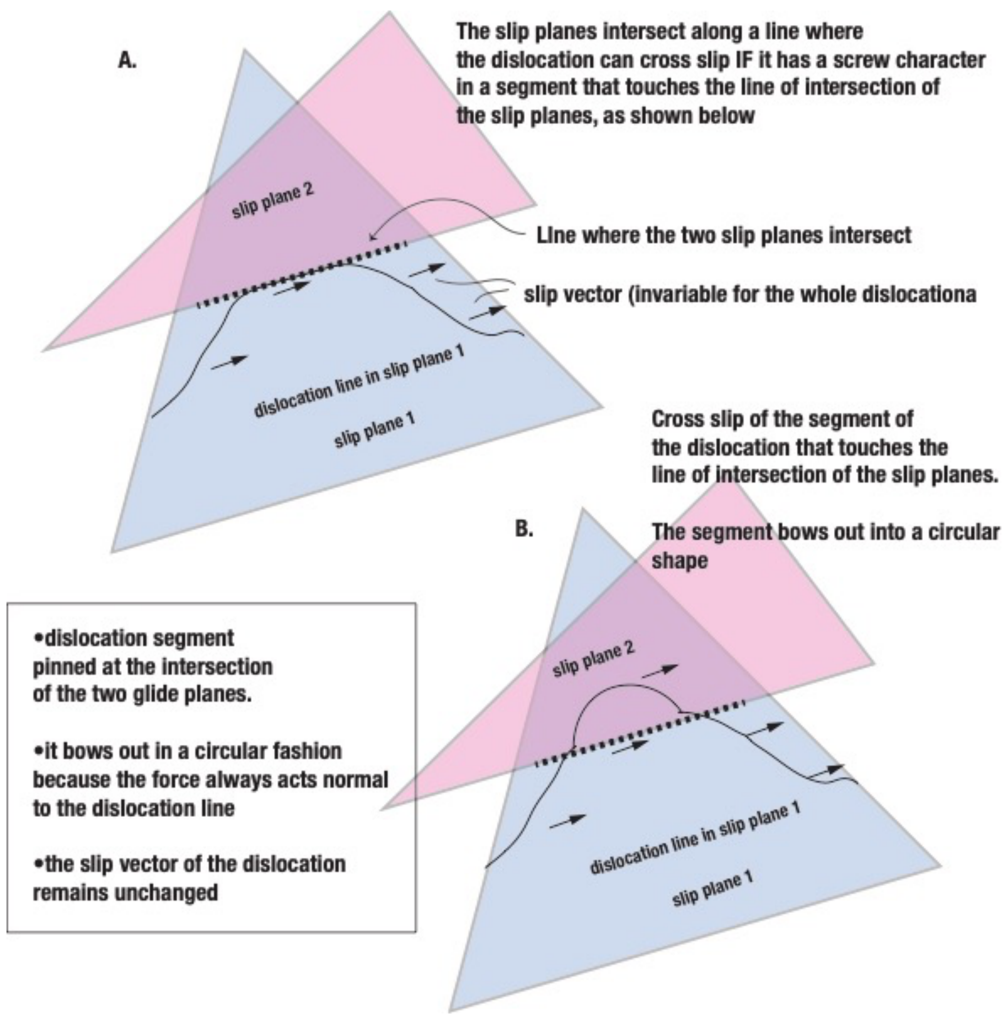
•Dislocation intersections

•Hard particles (that do not shear)

Cross Slip: Intersection of two slip (or glide) planes of the same family

The figure A on the right shows the screw section of the dislocation line touching the line of intersection of the two slip planes

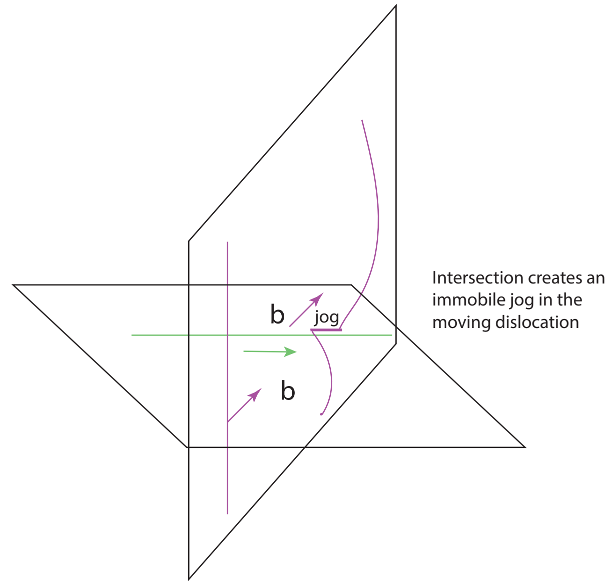
Figure B shows that the above section of the dislocation has migrated into slip plane 2



Dislocations Intersect

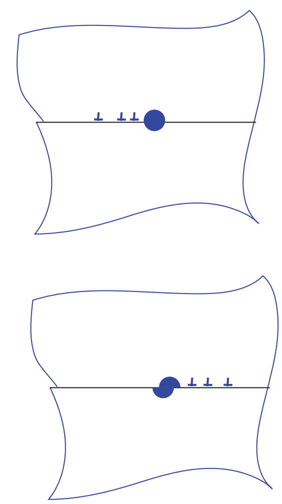
When one dislocation moves across the slip plane of another (stationary) dislocation with a different slip vector, the a jog is created in the moving dislocation. This jog is a vector that is equal to the slip vector of the stationary dislocation.

The immobile jogs are another mechanism for pinning the dislocations.

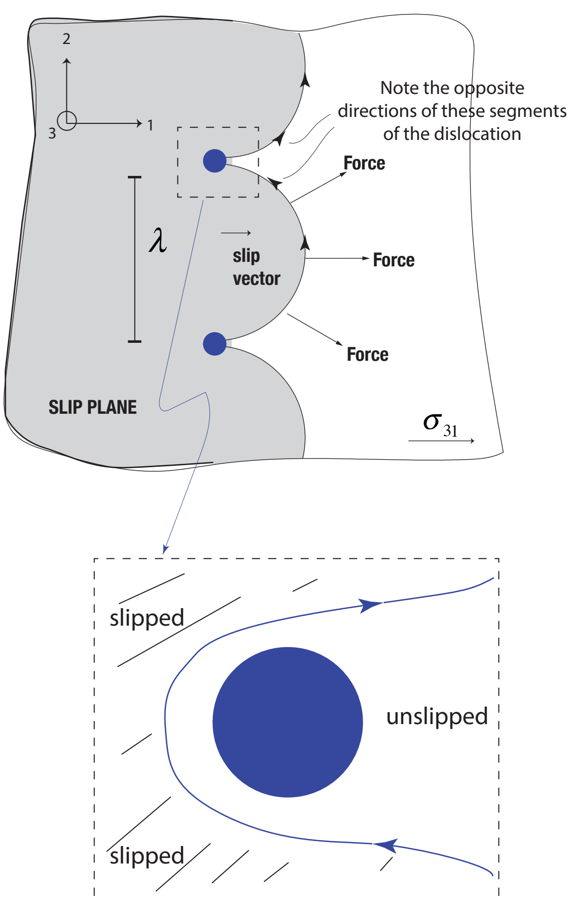


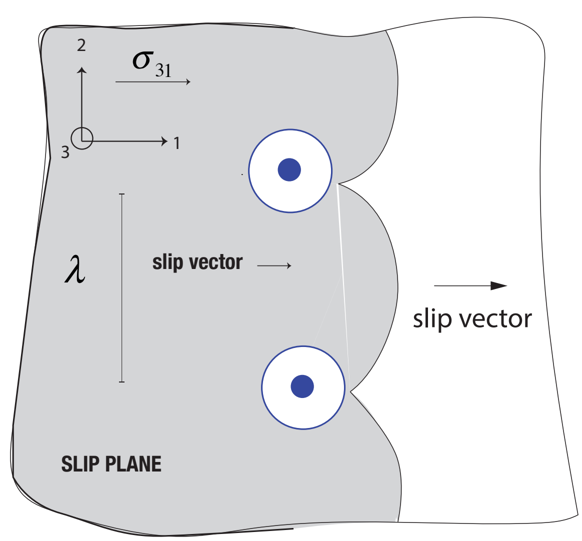
Dislocations pinned by hard particles in the slip plane that are difficult to shear and therefore the dislocations cannot go through them

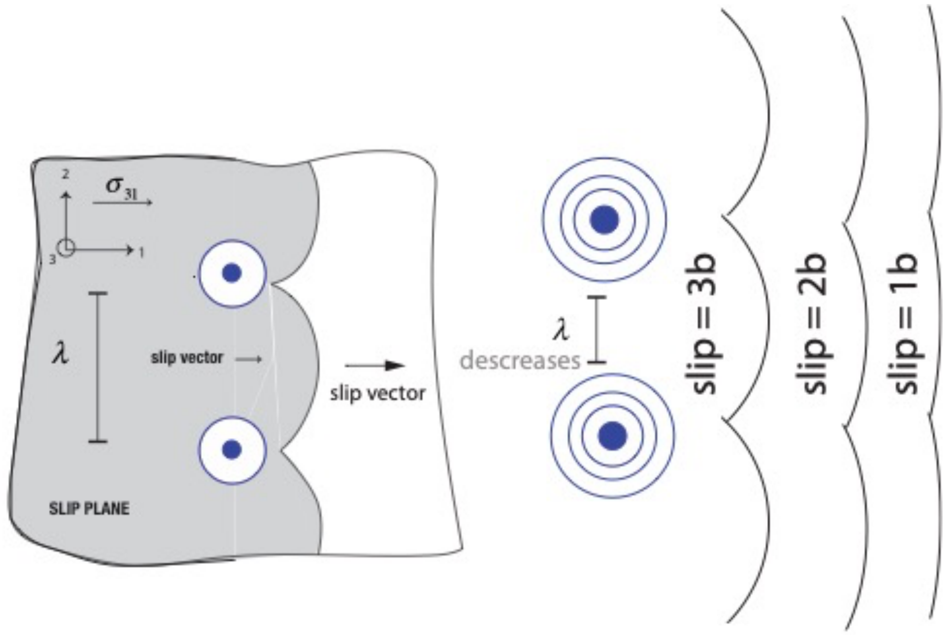
The question is what is the mechanism for the dislocations to be able to bypass the particles lying in the slip plane of the dislocation.

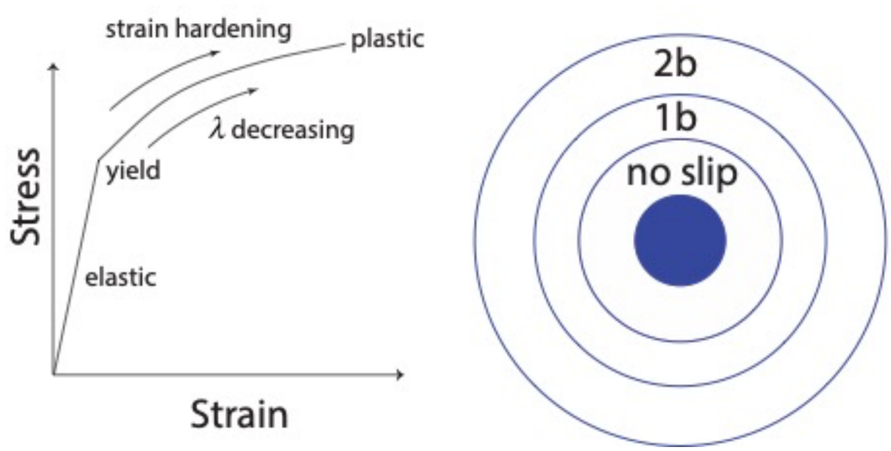


If the particle is difficult to shear line a ceramic or a hard metal, then it can completely pin the dislocation









Strain Hardening

As we shall see shortly the yield stress is determined by the applied stress required to exert enough force on a dislocation so that it can bypass the hard particles. This is also the yield stress since it sliding of the dislocation causes plastic deformation.

When dislocations bypass particles they leave behind loops around the particles. The "white space" between the loop and the particle circumference is the un-slipped area.

A large number of loops can accumulate around the particles as the dislocation move large distances to effect plastic deformation.

The loops resistance the movement of new dislocations arriving at the particle. Therefore, the effective size of the particles becomes larger with plastic strain (that is with increasing number of loops).

We shall see that the yield stress depends inversely on the pinning distance, that is the "effective" distance between the particles. Since this effective distance becomes narrower as the number of loops, or the plastic strain, increases, the yield stress continues to increase with plastic strain.

This phenomenon is called strain hardening.

Typically the yield stress increases with the square root of the plastic strain

$\sigma_{yield} = \sigma_{original} + \sigma_o \varepsilon^{1/2}$; usually $\sigma_{original} << \sigma_{yield}$, so it is often written that $\sigma_{yield} \approx \sigma_o \varepsilon^{1/2}$.

Recall that the dislocation spacing, L is related to the dislocation density by $\rho = \frac{1}{L^2}$.

Let us anticipate that since dislocations multiply with plastic strain, we may assume that $\rho \propto \varepsilon$. Inserting this into the strain hardening equation,

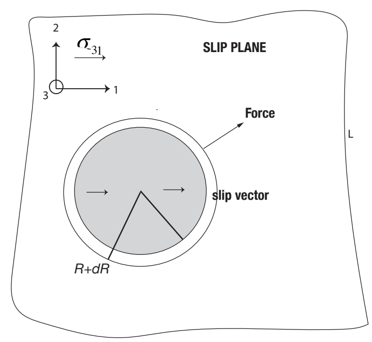
$$\sigma_{yield} \propto \sigma_o \rho^{1/2}$$

$$\sigma_{yield} \propto \frac{\sigma_o}{L}$$

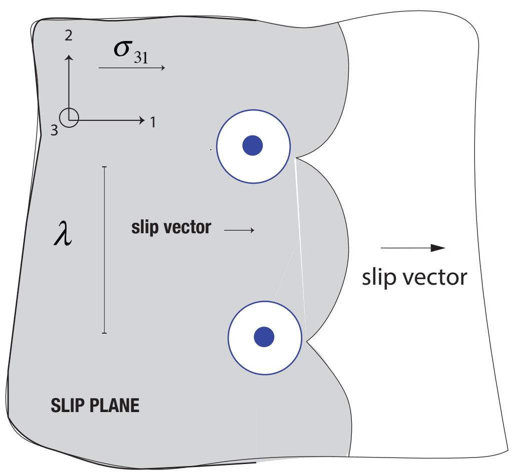
It seems that dislocation pin one another and the yield stress is depends on the spacing between the dislocations which is the effective pinning distance for plastic deformation.

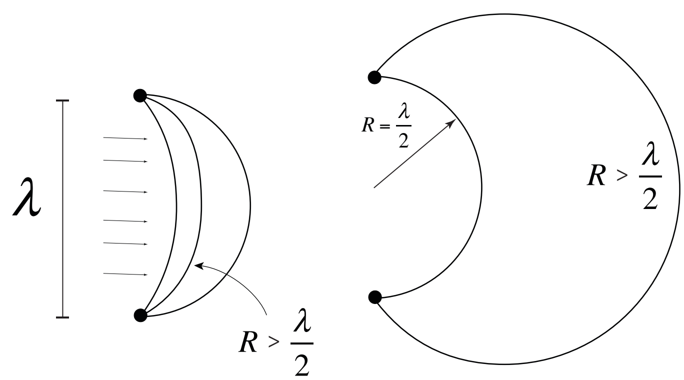
Derivation of the Orowan Stress

The Orowan stress is the stress requires for



$$\sigma = \frac{Gb}{2R}$$





therefore

$$R_{\min} = \frac{\lambda}{2} \qquad \sigma_{\max} = \sigma_{Orowan} = \frac{Gb}{\lambda}$$

The Orowan stress can be applied generally to relate the yield stress to the effective distance between the obstacles to dislocation motion.

Metallurgical Design

Say we wish to have a yield stress that is 1% of the shear modulus. That means that spacing of the particle should be

$$\frac{b}{\lambda} = \frac{1}{100}$$

So if b=0.2 nm, then λ, the spacing between the particles, would need to be 20 nm. Need to have a nanoscale dispersion of particles. Heat treatments, alloying etc. etc. are all geared to achieve such fine dispersion of hard particles, in steels, aluminum alloys and so on.

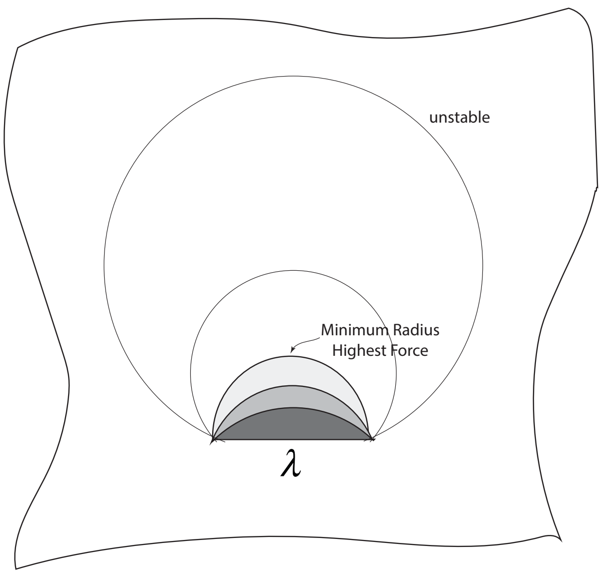
Dislocation Multiplication

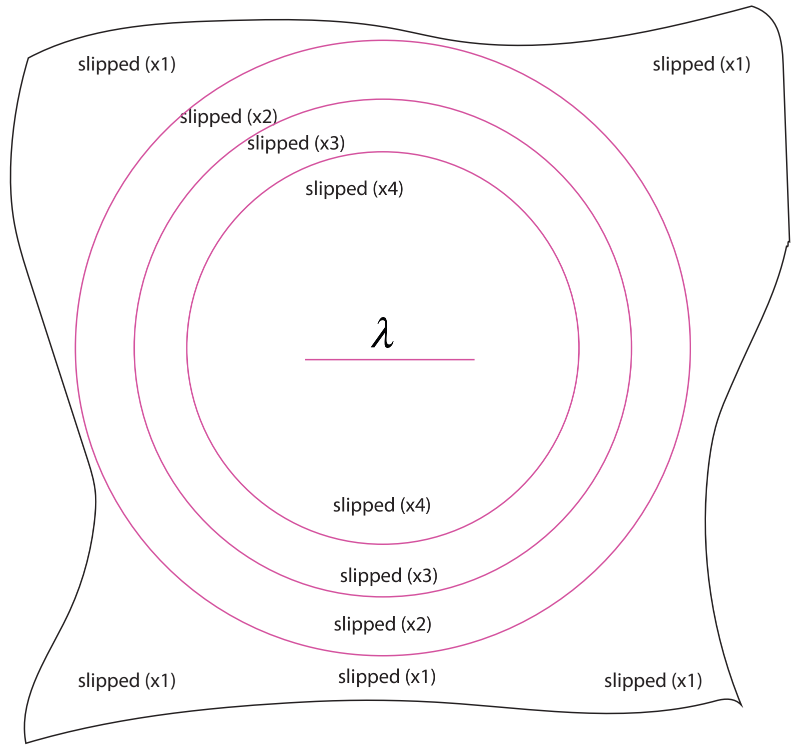
It is clear from the phenomenon of strain hardening, and from electron microscopy that the density of dislocations keeps on increasing with plastic strain.

A simple mechanism of dislocation generation, or multiplication is shown in the figure below. Here a small segment of dislocation bulges out, goes all the way around and then pinches off when the two sides meet, releasing a dislocation loop.

Note that the segment is restored to its original position. Further plastic strain then continues to generate more loops, and more loops, and so on.

In this way a small segment of a pinned dislocation can generate many many more dislocations.





HW: can you draw the full circle that creates the first loop while leaving behind the dislocation segment intact to create more and more loops as plastic deformation continues.