Plastic Deformation and Strengthening Mechanisms in Crystalline Materials

Updated 6 October, 2011

Slip in Polycrystalline Materials

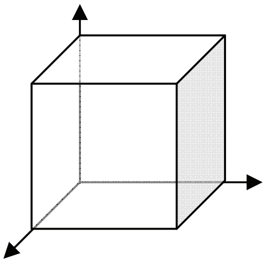
…and all you'll ever need to know about it in MSE250 and life (unless you're actually in MSE…)

Slip is the first of two plastic deformation mechanisms we will learn about (the other is twinning).

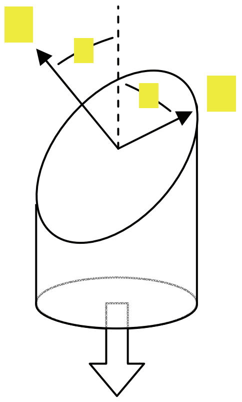
Slip is the process by which deformation occurs by .

Slip occurs on **slip systems**, which are comprised of the densest planes and - directions (i.e. LD = 1) in a crystal. Movement along these directions is energetically favorable because these movements cause the least atomic distortion.

TABLE – SLIP SYSTEMS FOR COMMON CRYSTAL STRUCTURES

Crystal structure	Diagram	Slip plane family	Slip direction family	Total # of slip systems
FCC				
BCC				
Simple cubic				

Having defined slip and slip systems, let us apply these concepts to a real material which is undergoing loading – say, a *polycrystalline metal bar*. In this sample, the grains (crystal regions) are ____ oriented. If we focus on just *one* particular slip system in *one* particular grain, we can draw a free body diagram and resolve the applied stress, $\sigma_{applied}$, into a normal component, σ_R, and a parallel (shear) component, τ_R.



A cartoon image of a slip plane in a *single grain* within a polycrystalline material

$$\tau_R = \sigma_{applied} \cos\phi \cos\lambda$$

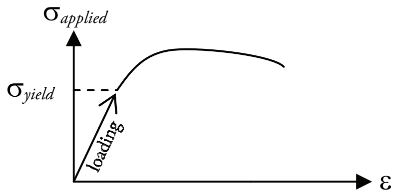
τ_R: resolved shear stress on a particular slip system in a particular grain

$\cos\phi\cos\lambda$: Schmid factor

The largest τ_R possible on a material is achieved when ____ = ____ = ____; in other words:

$$(\tau_R)_{\max} = \sigma_{applied}(\ \_\_\_\_\ )$$

Let us now gradually increase the applied stress on the sample.



When $\sigma_{applied}$ reaches σ_{yield}, ____ / ____ begins to occur, and ____ will start to move – but *only* in the grains which experience the largest ____ (i.e. those oriented with $\phi = \lambda = 45°$). Consider the resolved shear stress on one of these favorably oriented grains that is the first to deform. The resolved shear stress in this grain is actually the *minimum* τ_R required to initiate slip somewhere inside a material. It is also known as the ____, τ_{CRSS}.

We can obtain a formula for τ_{CRSS} by noting 2 things:

1) $\sigma_{applied} = \sigma_{yield}$ when slip first begins to occur
2) slip first begins to occur in the most favorably oriented grains (____ = ____ = ____)

Therefore,

$$\tau_{CRSS} = \_\_\_\_$$

But what about all the other millions of grains which are less favorably oriented and did not begin to slip/deform yet (i.e. those with ____ < ____) ? In order for slip to occur in these grains, ____ are required. In fact, this gradual "activation" of slip systems in different grains throughout the material at different loads is what causes the gradual elongation/plastic deformation of the material instead of brittle fracture of the sample.

TABLE – TYPICAL QUESTIONS ABOUT SLIP SYSTEMS

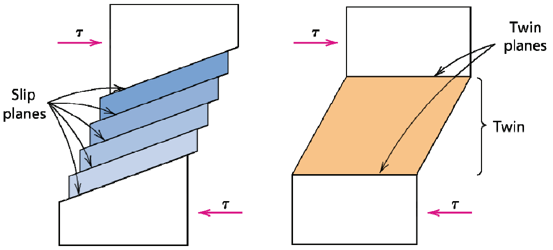
Given	Asked for
Crystal structure or slip system, $\sigma_{applied}$	Find the (maximum) τ_R on a given slip plane.
$\sigma_{applied}$, τ_{CRSS}	Will slip occur?
Crystal structure or slip system, τ_{CRSS}	What is the $\sigma_{applied}$ needed to initiate slip?

Twinning

…another plastic deformation mechanism

TABLE – COMPARISON OF 2 PLASTIC DEFORMATION MECHANISMS

	Slip	Twinning
Mechanism	Dislocation motion	Displacement of atoms within a lattice
Condition of occurrence	Sufficient $\sigma_{applied}$	High rate of loading, low temperature
Final result	Dislocation step; Same crystal direction across a slip plane	Mirror image; Reorientation of crystal direction across a twinning plane



Strengthening

Strengthening motto: "Any process that makes a material stronger!"

3 main mechanisms of making materials stronger:

1) Cold working / strain hardening / work hardening
2) Solid solution strengthening / alloying
3) Decreasing grain size

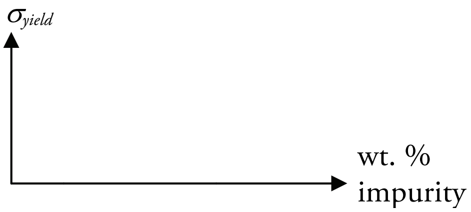
Cold working hinders dislocation motion by causing a material to undergo plastic deformation, which:

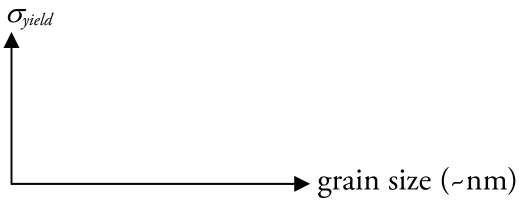
- the dislocation density, ρ_{disloc}, and causes dislocations to entangle with each other
- dislocation mobility due to repulsive interactions of neighboring dislocations
- overall, increases the stress required to move a dislocation

Types of cold working: rolling, drawing. Grains become "stretched" after cold working. Remember to consider the effects of cold working on various mechanical properties like yield strength, toughness, ductility, etc.

Solid solution strengthening hinders dislocation motion by introducing stress fields that try to hold a dislocation in place, and stress fields that increase the local stress and prevent the dislocation from moving. Be sure you understand each dislocation-impurity scenario (see class notes).

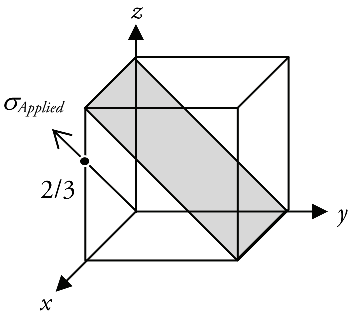
Reducing the grain size hinders dislocation motion by increasing the presence of grain boundaries, whose atomic disorder causes a discontinuity of dislocation motion. The change in across a grain boundary also forces the dislocation to change directions. occurs as dislocations are unable to move across a grain boundary.





…make sure to consult your notes for other graphs/equations!

Slip system example 1



A sample with BCC crystal structure is axially loaded with a stress of 50 MPa in the x-z plane. Calculate the maximum τ_R on the given plane.

Note: this problem looks at one of the millions of randomly oriented grains in a polycrystalline material. The maximum τ_R *you are being asked to calculate is* not *necessarily the maximum resolved shear stress that exists in the material, because there may be other grains in the sample which are oriented more favorably with respect to* $\sigma_{applied}$*. Even though this particular grain may not be favorably oriented, slip will still occur on the plane with the highest PD (verify that this is true for the given plane).*

1) Directions

$\sigma_{applied}$ (load direction) plane normal slip directions

2) Cosines: $\vec{a} \bullet \vec{b} = |\vec{a}||\vec{b}|\cos\theta$

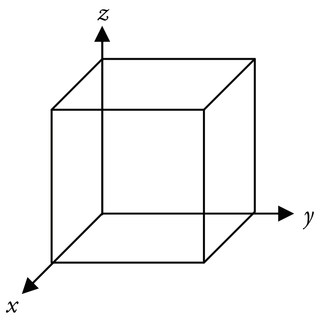
σ_R (plane normal) – $\sigma_{Applied}$ (load direction)

τ_R (slip direction) – $\sigma_{Applied}$ (load direction)

3) τ_{max} on this particular grain =

Sanity check: is the maximum $\cos\phi \cos\lambda$ on this grain < 0.5?

Slip system example 2



A sample with BCC crystal structure is axially loaded with a stress of 50 MPa along the y axis. The critically resolved shear stress of the material is 30 MPa.

a) Does slip occur somewhere in the sample, given this load?
b) What is the minimum applied stress needed to initiate slip in this particular grain?
c) What is the minimum applied stress needed to initiate slip somewhere in the sample?