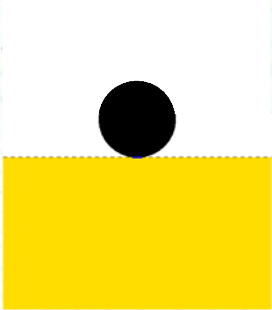
Chapter 8

Strain Hardening and Annealing

This is a further application of our knowledge of plastic deformation and is an introduction to heat treatment.

Part of this lecture is covered by Chapter 4 of the textbook

The Main Purpose is…

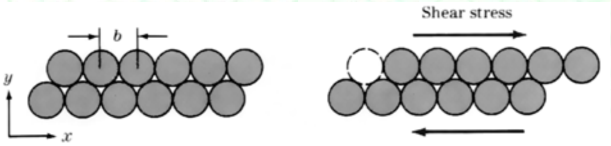


- To study mechanisms of plastic deformation in order to:
  - Predict how easy a material can be permanently deformed
  - Design process to <u>prevent</u> that deformation (if strengthening is required.

Plastic Deformation

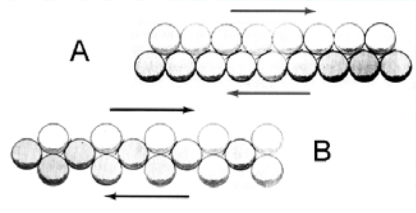
- Role of shear stresses
- First in single crystals to understand the deformation mechanisms
- Then in polycrystalline materials to understand the behavior of materials when they work in the plastic region.

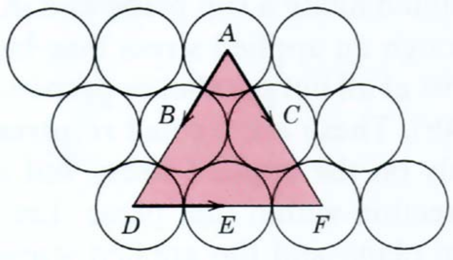
Plastic Deformations and Shear Stresses



- Movement of atoms as a result of an applied shear stress.
- The slippage occurs on a high-density (compact) plane and along a high-density (compact) crystallographic direction.
- Examples of compact planes and compact directions in FCC, BCC and HCP crystals?

On which plane is it easier to move atoms? A or B?





On a (111) plane of an FCC metal the slip directions are indicated

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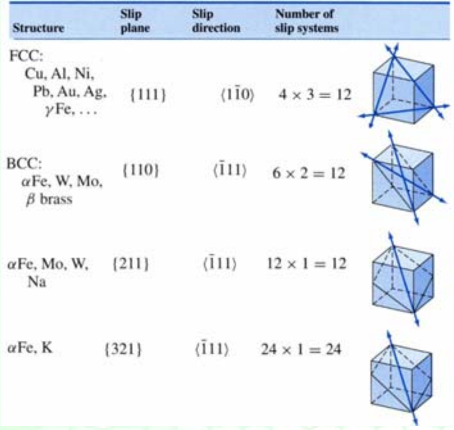
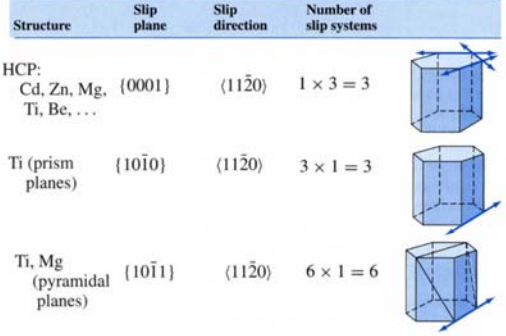
Slip Systems

A slip system is conformed by a slip plane (dense plane) and a slip direction (compact direction). Examples:

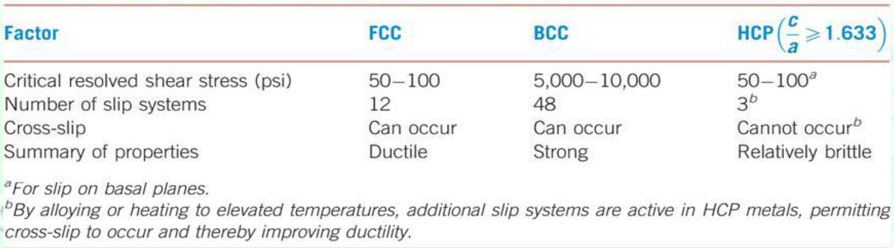


Structure	Slip plane	Slip direction	Number of slip systems
FCC: Cu, Al, Ni, Pb, Au, Ag, γFe, …	$\{111\}$	$\langle 1\bar{1}0\rangle$	$4 \times 3 = 12$
BCC: αFe, W, Mo, β brass	$\{110\}$	$\langle \bar{1}11\rangle$	$6 \times 2 = 12$
αFe, Mo, W, Na	$\{211\}$	$\langle \bar{1}11\rangle$	$12 \times 1 = 12$
αFe, K	$\{321\}$	$\langle \bar{1}11\rangle$	$24 \times 1 = 24$



Structure	Slip plane	Slip direction	Number of slip systems
HCP: Cd, Zn, Mg, Ti, Be, …	$\{0001\}$	$\langle 11\bar{2}0\rangle$	$1 \times 3 = 3$
Ti (prism planes)	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	$3 \times 1 = 3$
Ti, Mg (pyramidal planes)	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	$6 \times 1 = 6$

Remember: A shear stress must align with a slip system to promote plastic deformation



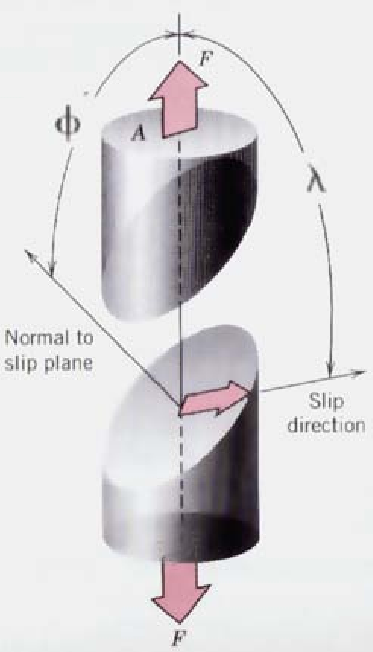
Factor	FCC	BCC	HCP $\left(\frac{c}{a} \geqslant 1.633\right)$
Critical resolved shear stress (psi)	50–100	5,000–10,000	50–100[a]
Number of slip systems	12	48	3[b]
Cross-slip	Can occur	Can occur	Cannot occur[b]
Summary of properties	Ductile	Strong	Relatively brittle

[a] *For slip on basal planes.*

[b] *By alloying or heating to elevated temperatures, additional slip systems are active in HCP metals, permitting cross-slip to occur and thereby improving ductility.*

Critical Resolved Shear Stress

The minimum measured value of a shear stress τ_{crit} that would start a plastic deformation on a specific direction. Relates to elastic limit.



$$\text{Tangential Force} = F \cdot \cos\lambda$$

$$\text{Projected Area} = \frac{A}{\cos\phi}$$

$$\tau_C = \frac{F}{A} \cdot \cos\lambda \cdot \cos\phi = \sigma \cdot \cos\lambda \cdot \cos\phi$$

Schmid’s Law

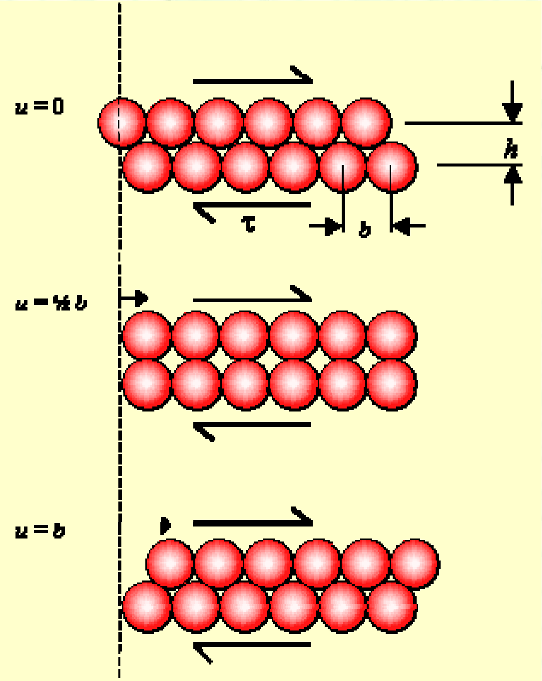
Critical Shear Stress in a Cubic System

- An approximation of the needed τ_{crit} to move the upper atomic block over the lower one on compact planes:

$$\tau_{crit} = \frac{Gb}{2\pi h} = \frac{G}{\pi\sqrt{3}}$$

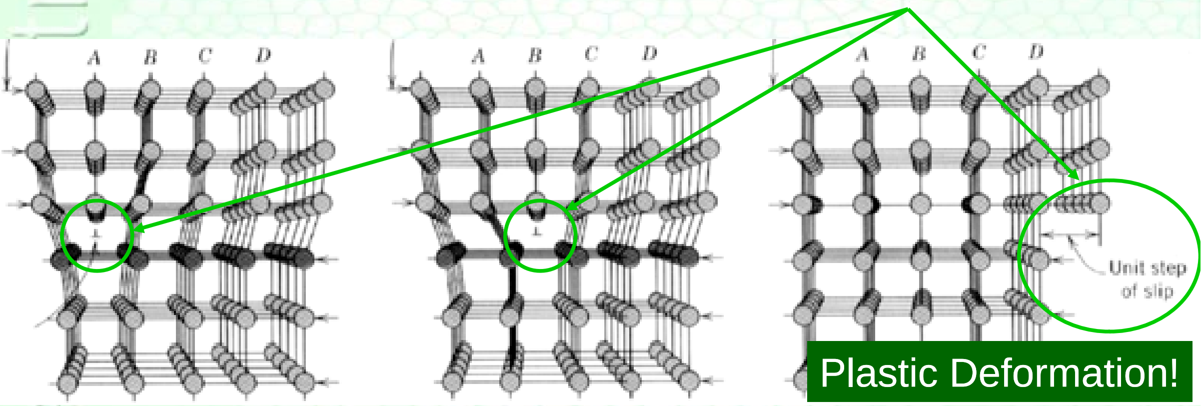
$$\tau_{crit} \cong \frac{G}{5}$$

- For Fe with low C: $\tau_{crit} \cong 16$ GPa!



The Role of Dislocations in Plastic Deformations

- Theoretical calculations of τ_c are 1,000 higher than measured values!
- There must be a different deformation mechanism.
- Dislocations are the answer. Look at the dislocation line motion.

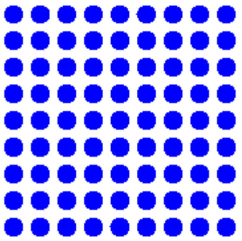


Plastic Deformation!

The Role of Dislocations in Plastic Deformations (cont.)

Things to consider:

No atom has been transported more than a fraction of the lattice parameter!



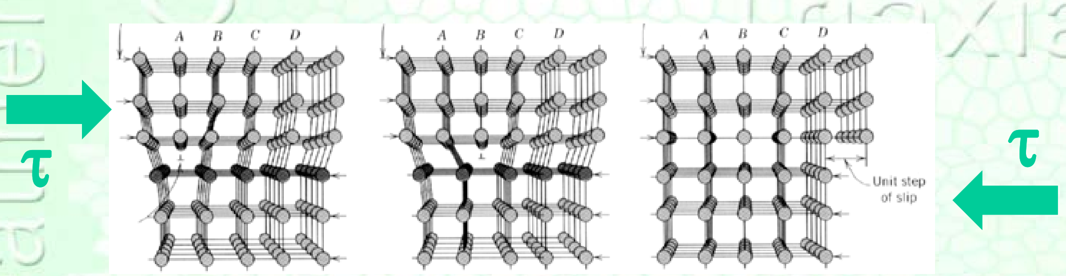
- Only the dislocation line has physically moved.
- Therefore the necessary energy to deform plastically the metal is much lower.
- Therefore the measured τ values are much smaller!
- Example for Fe with low C: $\tau_p \cong 0.145$ GPa!

Peierls-Nabarro stress

$$\tau_p = 3G \cdot e^{-2\pi}$$

$$\tau_p \cong \frac{G}{180}$$

The Role of Dislocations in Plastic Deformations (cont.)

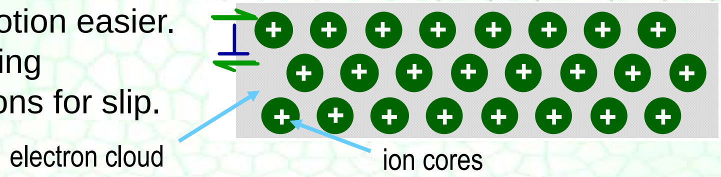


One last VERY important conclusion:

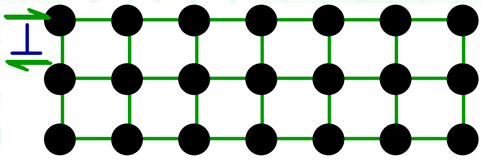
- ANYTHING that hampers, hinders, stops a dislocation movement is in fact preventing the plastic deformation of the material.
- Therefore, ANY obstacle for the dislocation motion <u>increases</u> the mechanical strength of the material: both UTS and YS, while reducing the ductility d.

Dislocation movements determine why different types of materials have very different formability

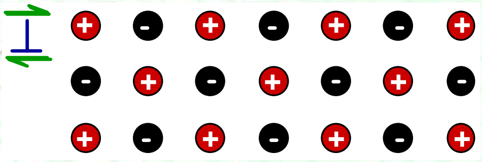
- Metals: Dislocation motion easier.
  - -non-directional bonding
  - -close-packed directions for slip.



- Covalent Ceramics (Si, diamond): Motion hard.
  - -directional (angular) bonding



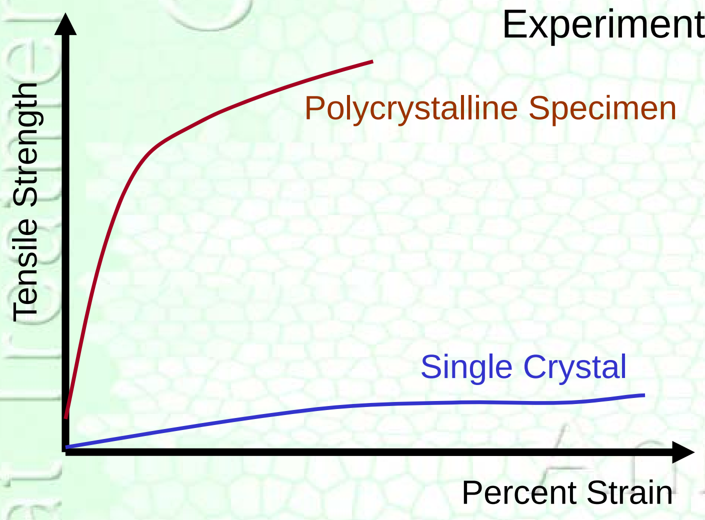
- Ionic Ceramics (NaCl): Motion hard.
  - -need to avoid + and - neighbors.



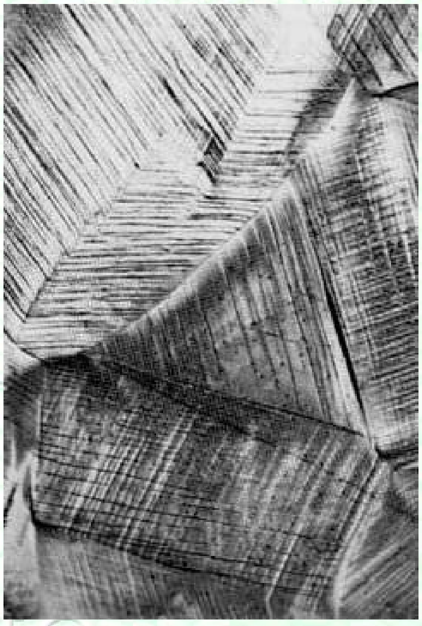
Examples of Obstacles to Dislocation Motion

- More dislocation lines → higher number of dislocation per unit volume results in stronger materials.
- Solute atoms, either substitutional or interstitial.
- Impurity particles can pinned down dislocation motion.
- Grain boundaries can stop and pile up dislocation lines → small grain sizes increase YS.

Effect of Grain Boundaries on the Strength of Metals

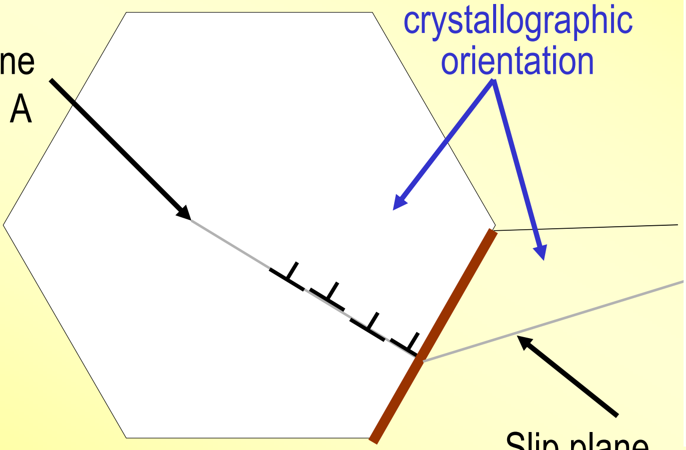


Experimental Evidence



Slip lines in a polycrystalline copper sample

Grain Boundary Effect (cont.)

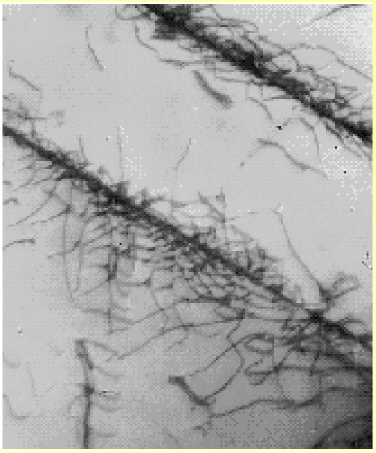


Slip plane in grain A

Neighboring grains have different crystallographic orientation

Slip plane in grain B

Grain boundary stops dislocation slippage



TEM photograph of dislocation pile-up at the grain boundaries

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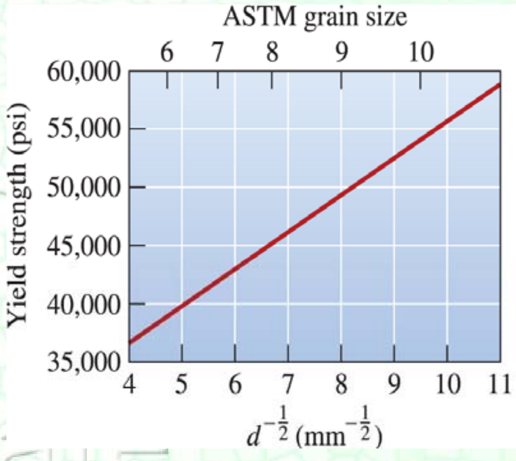
Grain Boundary Effect (cont.)

- The smaller the grain the larger the amount of grain boundaries
- The larger the amount of grain boundaries, the more hurdles the dislocation movement will find
- Therefore the smaller the grain size the higher the strength of the metallic material
- In particular the grain size affects the yield strength YS

Hall-Petch Effect

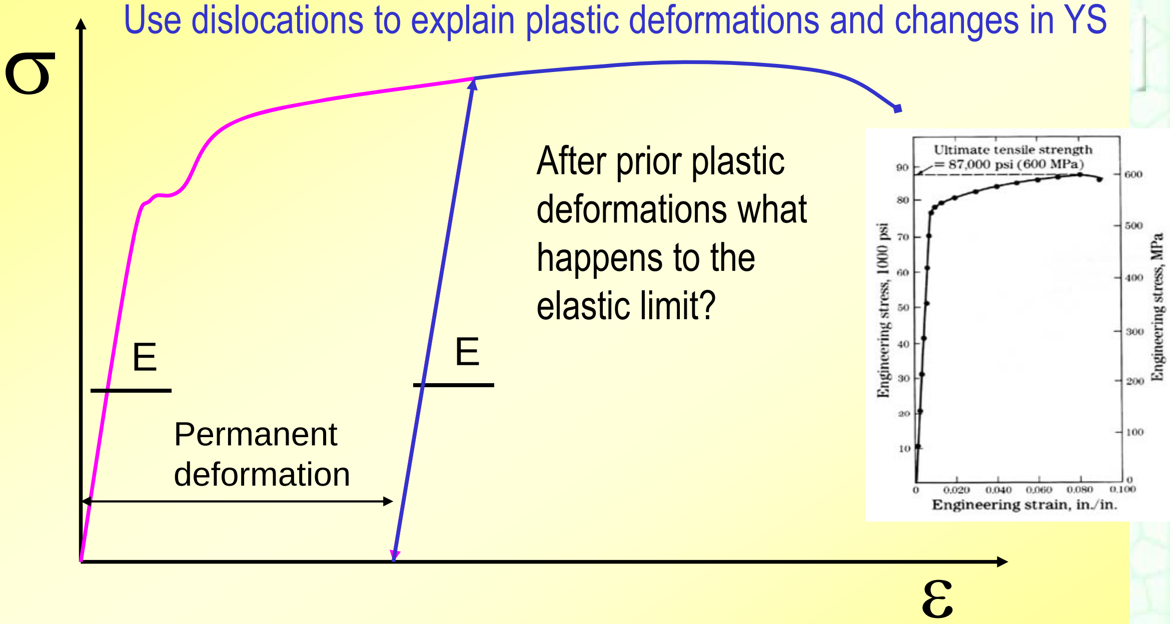
$$YS = \sigma_0 + k \cdot d^{-\frac{1}{2}}$$

YS: Yield Strength
σ_0: Basic Strength
k: Material constant
d: Grain size equivalent diameter



Cold plastic deformations effect YS and, thus, hardening

Use dislocations to explain plastic deformations and changes in YS



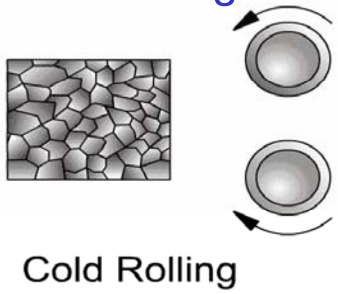
After prior plastic deformations what happens to the elastic limit?

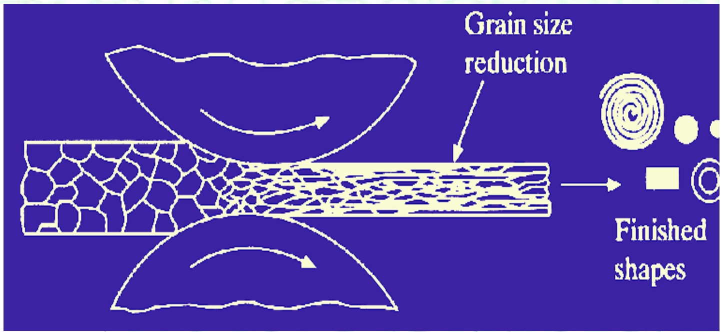
This explain the ***Strain Hardening*** phenomenon

Uniaxial vs. Tri-axial Deformations

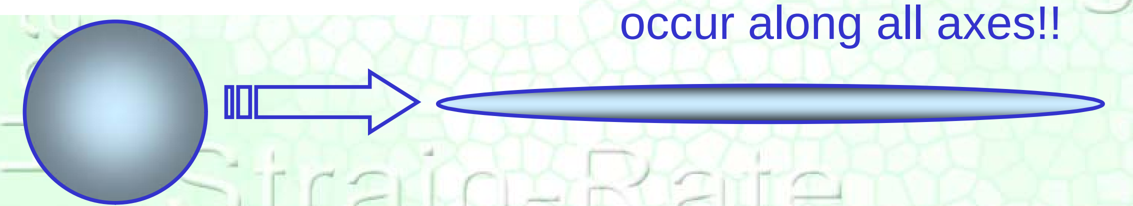
During tensile test, the materials is preferentially deformed along the vertical axis.

Cold rolling of a sheet





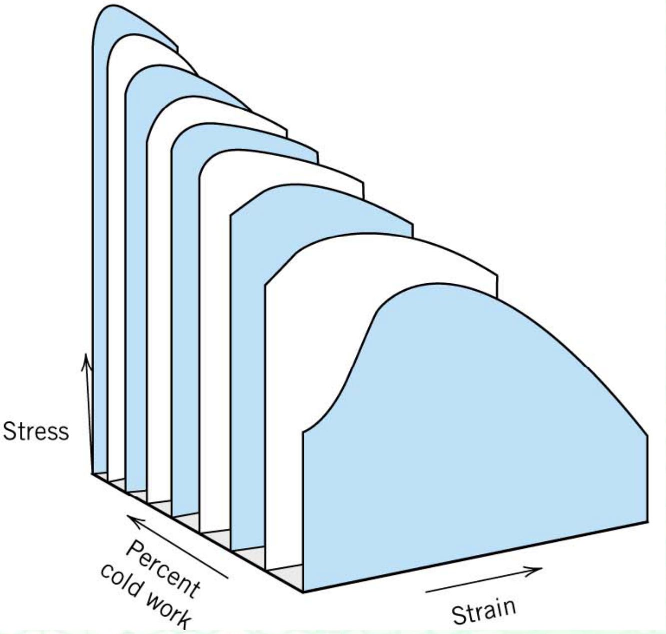
Plastic deformations occur along all axes!!



This is the effect of cold work in the tensile curves of a low carbon steel.

What is the effect of cold work on:

- UTS?
- YS or $\sigma_{0.2}$?
- Toughness?
- Elongation to fracture?
- Area reduction ψ?
- E?



Cold work is then another strengthening mechanism:

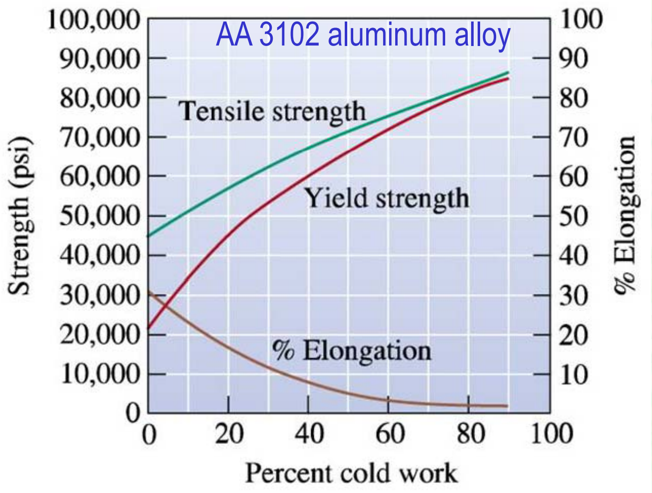
Examples of cold work in processing:

- Cold Rolling
- Cold Drawing

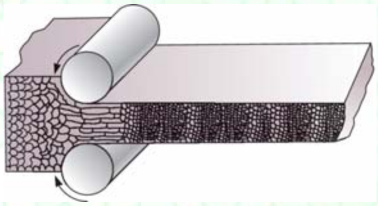
Amount or percent of cold work:

$$\%\text{Cold Work} = \frac{A_o - A_d}{A_o} \cdot 100$$

A_o: initial transverse area
A_d: deformed transverse area



Note that this definition is not that different from the area reduction upon fracture in a tensile test: ψ (%) = $(1 - A_{fracture}/A_0)\cdot 100$



So what would happen in *hot* work?

Solution hardening is less effective than cold work

Solute atoms, either substitutional or interstitial

Relative size factor: Effect of solute atoms having a different size than solvent atoms

Short range order: Clustering of atoms that follow certain ordering

Alloys are in general harder than pure metals

Thermomechanical Treatment of Materials

What is heat treatment?

Application of a process under controlled heating and cooling steps to obtain specific mechanical properties.

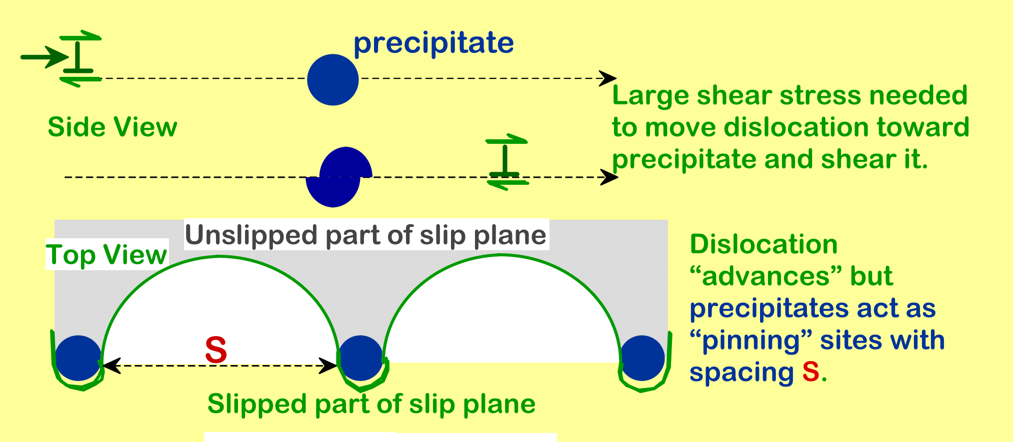
Examples:

- Annealing
- Normalizing
- Quenching and Tempering
- Solution and Precipitation Hardening (or Aging)

Precipitation/dispersion strengthening

Hard precipitates are difficult to shear.

Example: Ceramics in metals (SiC in Iron or Aluminum).



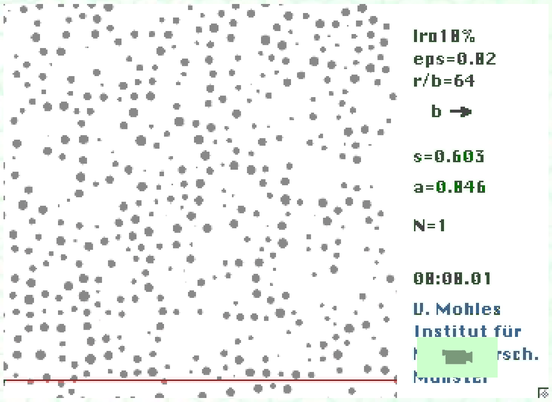
Large shear stress needed to move dislocation toward precipitate and shear it.

Dislocation "advances" but precipitates act as "pinning" sites with spacing **S**.

- Result:

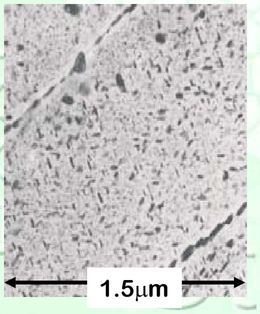
$$\sigma_y \sim \frac{1}{S}$$

This is a simulation of the strengthening mechanism due to the presence of precipitates



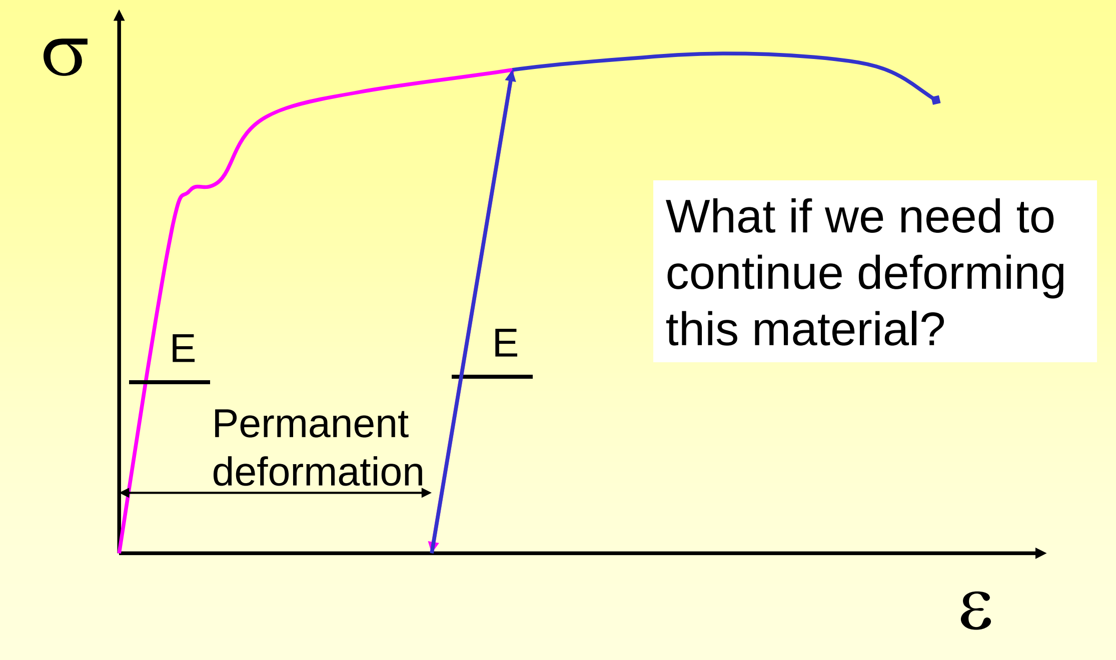
- View onto slip plane of Nimonic PE16 (Ni-Cr superalloy)
- Precipitate volume fraction: 10%
- Average precipitate size: 64 b (b = 1 atomic slip distance)

Application: precipitation strengthening plays a major role in aerospace materials



Aluminum alloys containing Zn, Cu, Mg, Si, such as AA7075, 6061, 2024, 2014, etc. are strengthened with precipitates formed by alloying elements.

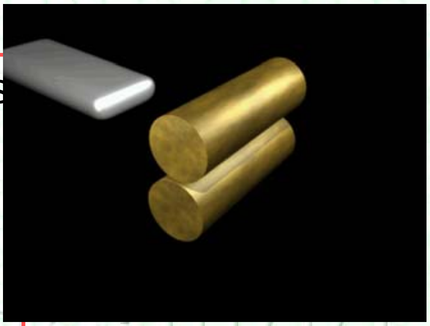
Recovery and Recrystallization of Deformed Materials



What if we need to continue deforming this material?

Recovery and Recrystallization of Deformed Metals (cont.)

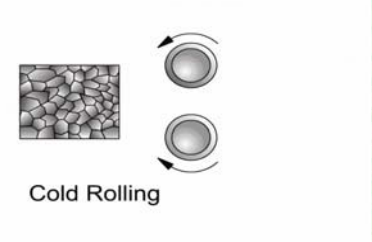
- What if we need to soften the material?
- One choice is by heating it.



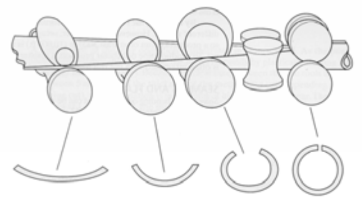
For cold worked metals the process involves the following stages:

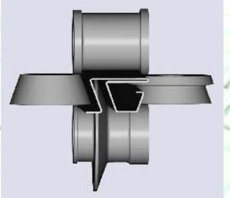
- Recovery
- Recrystallization
- Grain Growth

The Initial Stage



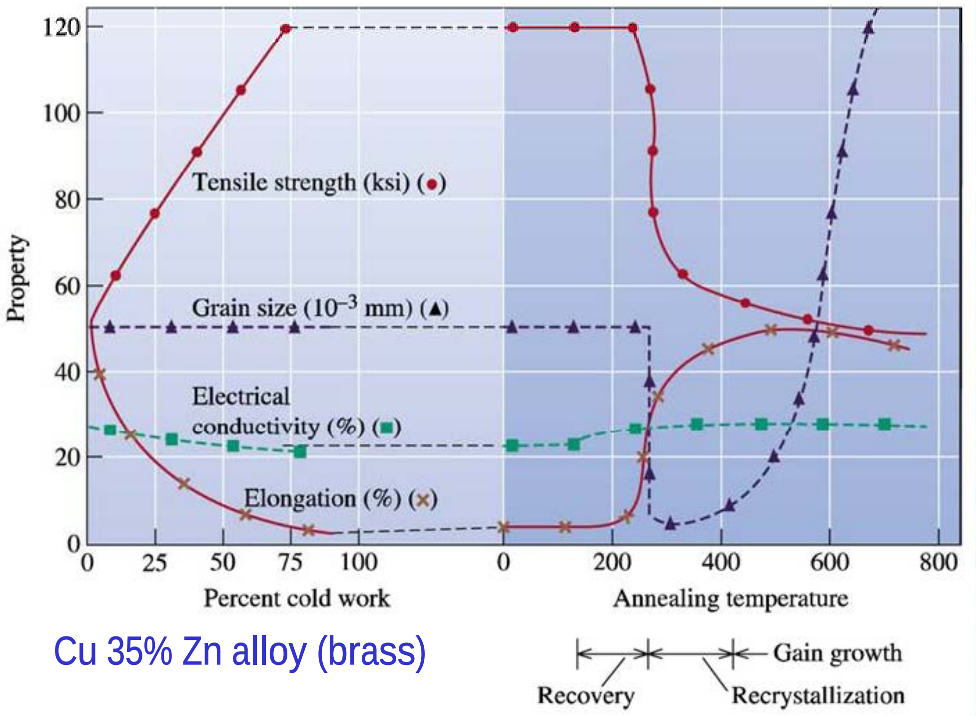
- Cold Worked Metallic Materials:
  - –Higher dislocation density
  - –*A lot* of stored energy as plastic deformation





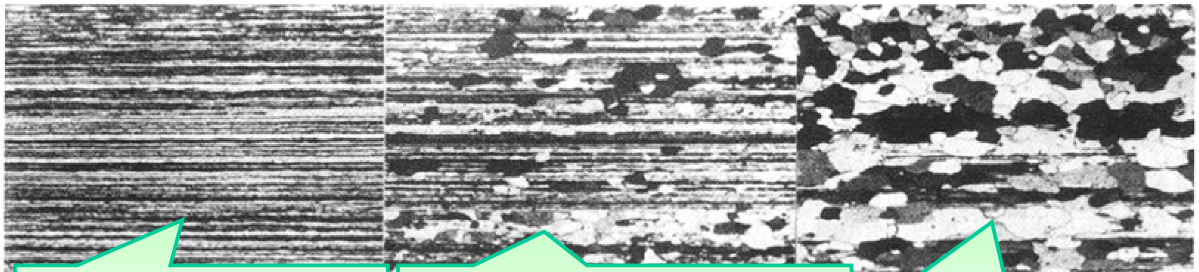
- Heating up to the "recovery temperature"

Summary of the Thermomechanical Processing



Cu 35% Zn alloy (brass)

Evolution of the Microstructure with Temperature



Recovery (no microscopic evidence)

Recrystallization (small equiaxed grains form)

Grain Growth (larger grains)

Large dislocation density

Recrystallized Metal: Small dislocation density

Grain Growth Onset: No major dislocation lines are observable

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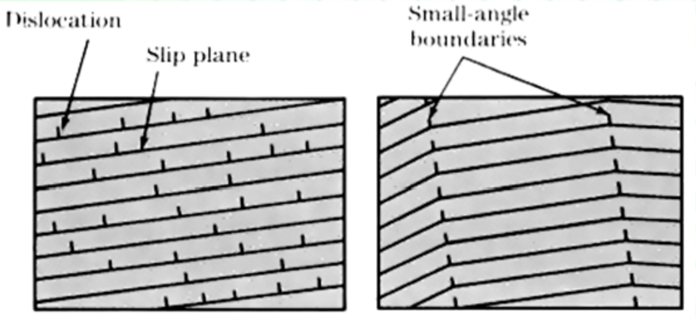
Let's analyze each stage individually

Recovery



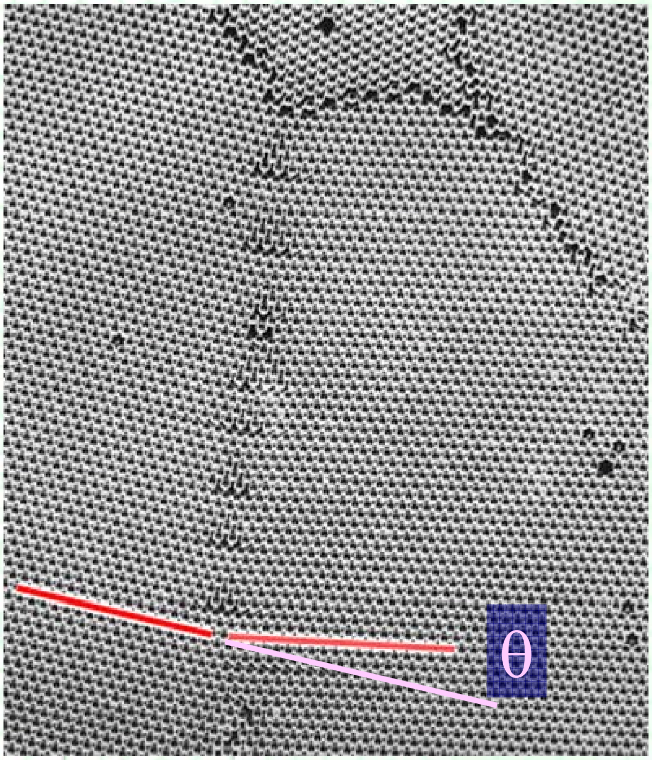
Start with a large dislocation density shown on slip planes

Increase of internal energy (high temperature) provides energy to "align" dislocations along "low angle grain boundaries"

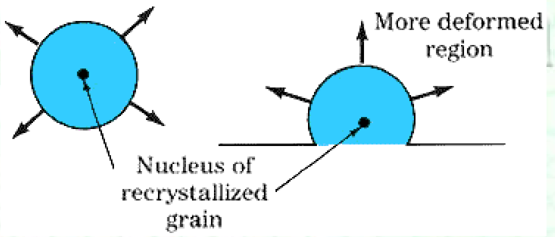
Recovery (cont.)

Low angle grain boundary in the bubble raft forming a θ angle.

Low angle grain boundary are not effective stoppers for dislocations.



Recrystallization



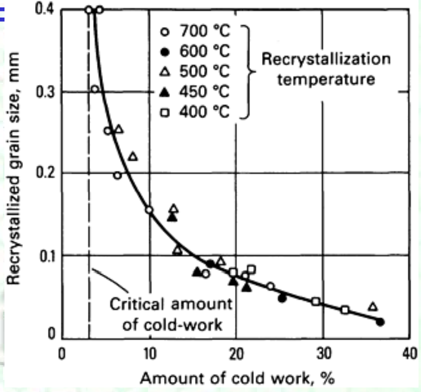
Nucleus formation follows same basic principles studied before.

In this case all phases are solid.

Need a substrate for heterogeneous nucleation → a place with high stored energy. → Grain Boundaries

There is an alternative also: → Dislocations

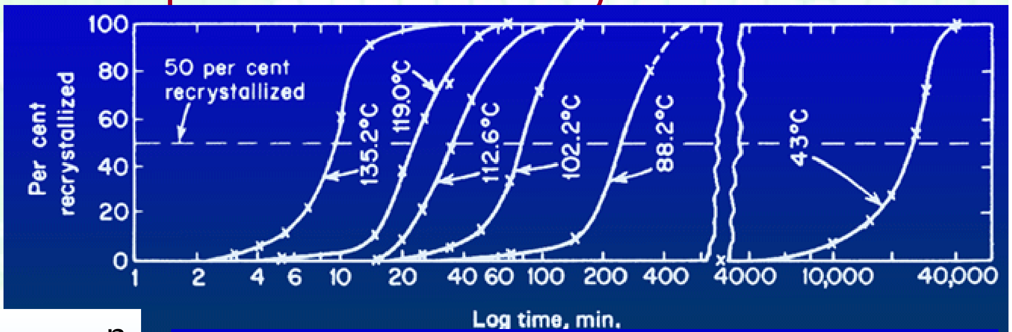
Both are abundant in the cold worked material. Therefore recrystallization is favored in highly deformed metals.



The effect of prior cold work on recrystallized grain size

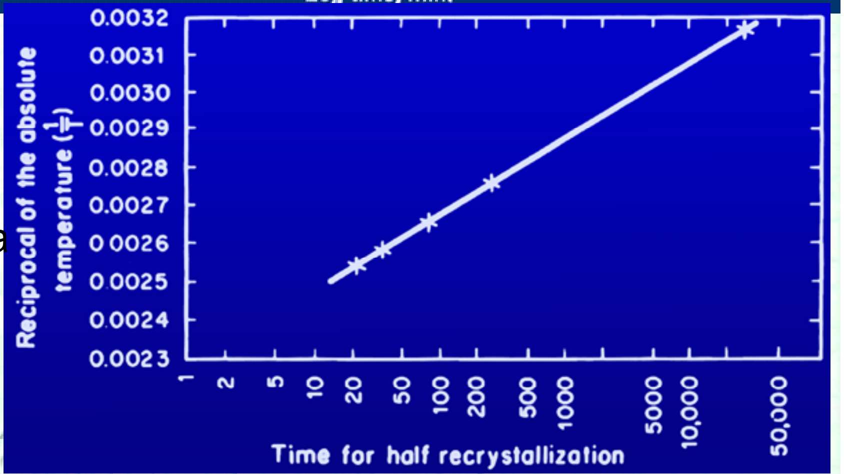
Effect of temperature on the recrystallization time

If X is the re-crystallized fraction by Avrami's equation:



$$X = 1 - e^{-k \cdot t^n}$$

The "re-crystallization time" t_R is then measured at 50% or X=0.5 and plotted as a function of 1/T



Recrystallization (cont.)

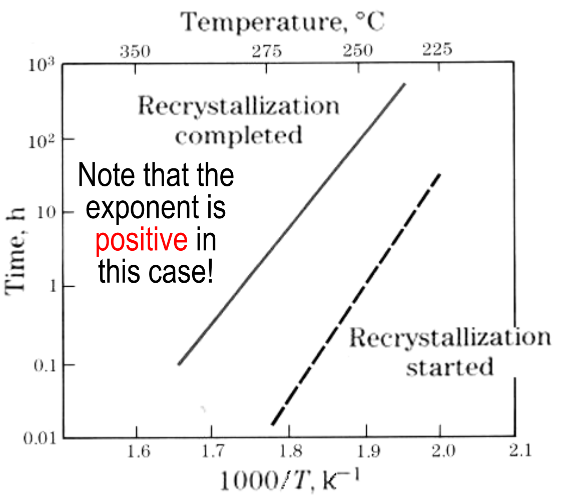
The recrystallization time t_R also obeys an Arrhenius rate equation:

$$t_R = C \cdot e^{+\frac{Q}{RT}}$$

where: t_R is the time for full recrystallization at a temperature T (in degrees Kelvin)

Q is the activation energy for recrystallization

C is a constant

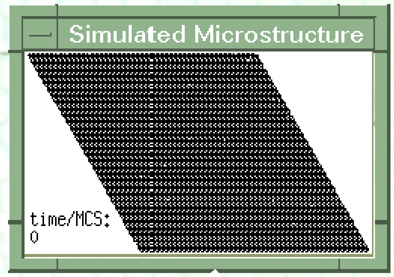


Note that the exponent is positive in this case!

For instance, in γFe measured values of Q (~125 kJ/mol) are very close to the values of Q for self-diffusion. Why?

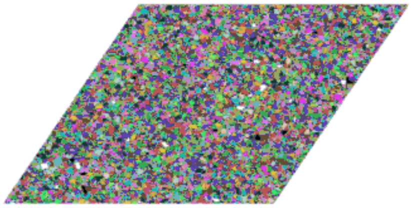
Grain Growth

Once most grains recrystallize they promptly start to grow. We need to control this growth!

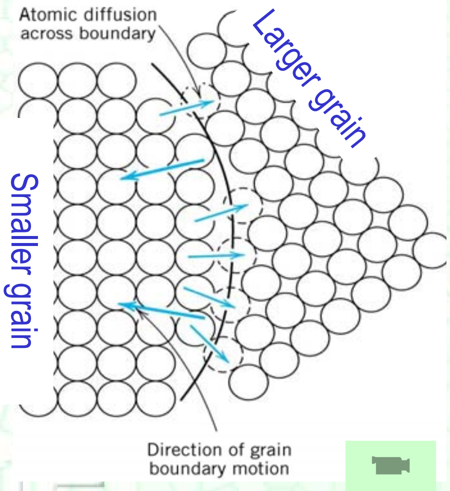


- Large grains grow at the expense of small grains.
- Large grains possess a larger surface area to attach neighbor atoms.
- Those grains seem to "eat" the small ones.

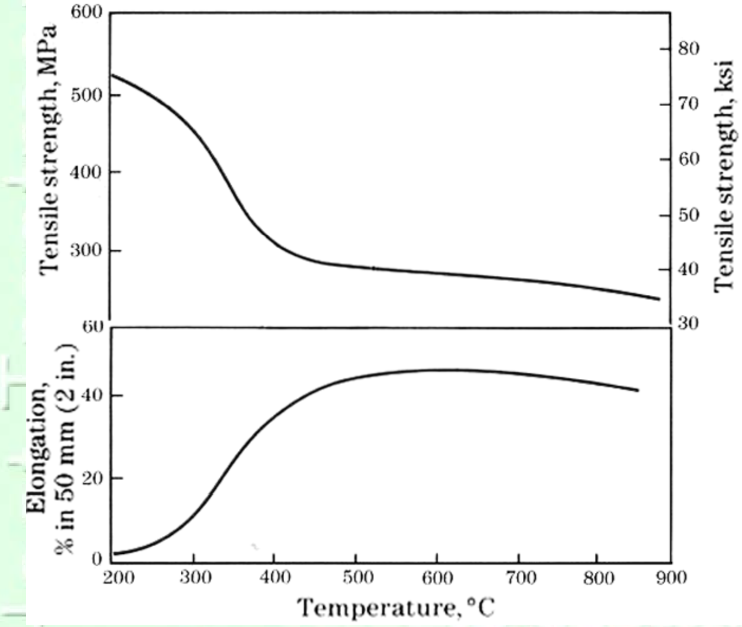
It is evident that grain growth is a diffusion-controlled phenomenon. By the way, what type of diffusion?



Note the relation between concave and convex surfaces in the grains. Any thoughts?



Effect of Annealing Temperature on Mechanical Properties



85wt.%Cu- 15wt.%Zn alloy originally with a 50% cold-rolled section

Given these curves you should be able to indicate the three stages of annealing and recommend the proper treating temperature