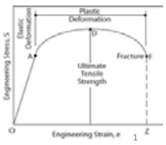
We have finished chapters 1 – 5 of Callister's book. Now we will discuss chapter 10 of Callister's book

Fundamentals of Plastic Deformation of Metals



Chapter 10 of Callister's book

Elastic Deformation vs Plastic Deformation

- Metallic materials may experience two kinds of deformation: Elastic and Plastic

1
- Nonpermanent: When the applied load is released, the piece returns to its original shape
- Permanent

2
- On an atomic scale, Small changes in the interatomic spacing and the stretching of interatomic bonds
- Net movement of large numbers of atoms in response to an applied stress. Interatomic bonds must be ruptured and then reformed.

Elastic Deformation vs Plastic Deformation

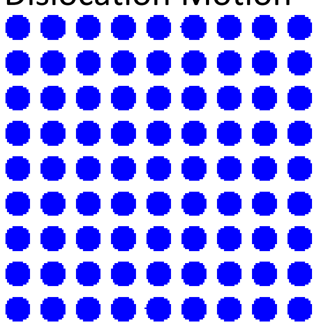
3
- Elastic modulus or stiffness is the material's resistance to elastic deformation. The greater the modulus, the stiffer the material, or the smaller the elastic strain that results from the application of a given stress.
- Strength and hardness are measures of a material's resistance to plastic deformation.

Plastic Deformation

Plastic deformation corresponds to the motion of large numbers of dislocations.

Let's see what happens when one dislocation is created and moves

Dislocation Motion

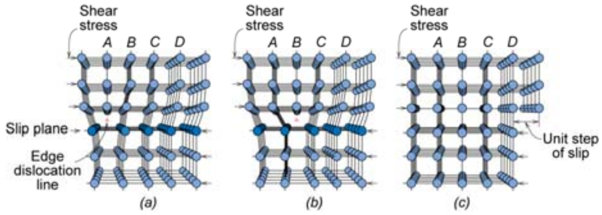


Generation of an edge dislocation by a *shear* stress	Movement of the dislocation through the crystal	Shift of the upper half of the crystal after the dislocation emerged

Dislocation Motion

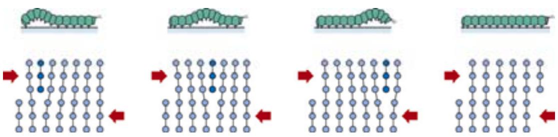
Dislocations & plastic deformation

- Plastic deformation by plastic shear or slip where one plane of atoms slides over



- If dislocations don't move, deformation doesn't occur!

Analogy between caterpillar and dislocation motion

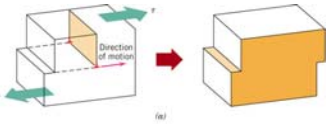


Dislocation Motion

The formation of a step on the surface of a crystal by the motion of

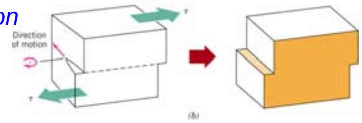
(a) an edge dislocation

The dislocation line moves in the direction of the applied shear stress



(b) a screw dislocation

The dislocation line motion is perpendicular to the stress direction.



The direction of motion of the mixed dislocation line is neither perpendicular nor parallel to the applied stress, but lies somewhere in between

Dislocation Density

Dislocations are introduced during solidification, during plastic deformation, and as a consequence of thermal stresses that result from rapid cooling.

Dislocation density is expressed as the total dislocation length per unit volume, or, equivalently, the number of dislocations that intersect a unit area of a random section.

The units of dislocation density are millimeters of dislocation per cubic millimeter or just per square millimeter.

Dislocation Density

Carefully solidified metal crystals: 10^3 mm^{-2}

Heavily deformed metals: 10^9 to 10^{10} mm^{-2}.
(Important source of these new dislocations: 1) existing dislocations, which multiply; 2) grain boundaries, 3) internal defects and surface irregularities such as scratches and nicks, which act as stress concentrations)

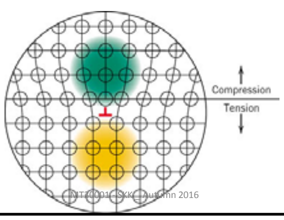
Heat treating a deformed metal specimen can diminish the density to on the order of 10^5 to 10^6 mm^{-2}.

Ceramic materials: 10^2 - 10^4 mm^{-2}

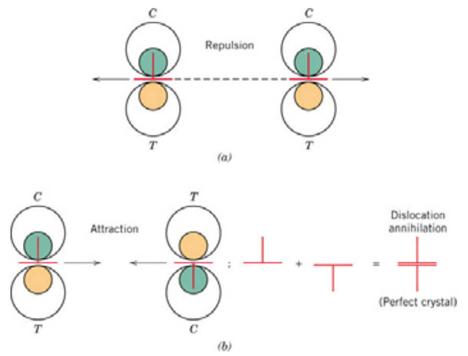
Silicon single crystals used in integrated circuits: 0.1 -1 mm^{-2}.

Strain Energy

- When metals are plastically deformed, some fraction of the deformation energy (approximately 5%) is retained internally; the remainder is dissipated as heat.
- The major portion of this stored energy is as strain energy associated with dislocations.



Strain fields and associated forces



Important in the strengthening mechanisms for metals.

Dislocation Movement and Slip

There are two basic types of dislocation movements:

- Glide: Dislocation moves in the plane which contains both its line and Burgers vector
- Climb: Dislocations moves out of the glide plane normal to the Burgers vector

Glide of many dislocations result in Slip

Slip: Most common manifestation of plastic deformation in crystalline solids

Slip System: Slip Plane + Slip Direction

- Glide of dislocations occurs not with same degree of easiness on all crystallographic planes of atoms and in all crystallographic directions.
- Preferred plane, and in that plane specific directions along which dislocation glide occurs.
- This plane is called the *slip plane;*
- *The direction of movement* is called the *slip direction.*
- *This combination of the slip plane and the slip direction* is termed the **slip system**.

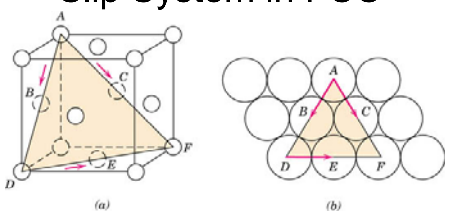
Slip System: Slip Plane + Slip Direction

•The slip system depends on the crystal structure of the metal and is such that the atomic distortion that accompanies the motion of a dislocation is a minimum.

•For a particular crystal structure, the slip plane is that plane having the most dense atomic packing

•The slip direction corresponds to the direction, in this plane, that is most closely packed with atoms, that is, has the highest linear density.

Slip System in FCC



- Slip occurs along <110>-type directions within the {111} planes
- {111}<110> represents the slip plane and direction combination, or the slip system for FCC.

There are 4 close-packed planes *{111} with 3 close-packed* directions in each plane *< 110 >* *– a total of* ***12 slip systems****.*

Slip Systems in BCC

No close-packed plane, but close-packed directions < 111 >

Three types of planes which are nearly tied for the highest packing density.

near close - packed planes in BCC : {110} {321} {211}

All these planes have been observed to be slip planes.
Thus we have the following slip systems in BCC crystals:

- *6 {110} planes each with 2 < 111 > directions = 12 slip systems*
- *24 {321} planes each with 1 < 111 > direction = 24 slip systems*
- *12 {211} planes each with 1 < 111 > direction = 12 slip systems*

Slip Systems in HCP

The basal plane (0001) is the close-packed plane and there are 3 close-packed directions $< 11\bar{2}0 >$

There can be other slip systems in HCP called Prism slip $\{10\bar{1}0\}$ *and Pyramid slip* $\{10\bar{1}1\}$*. Slip direction will remain the close packed* $<11\bar{2}0>$ *direction*

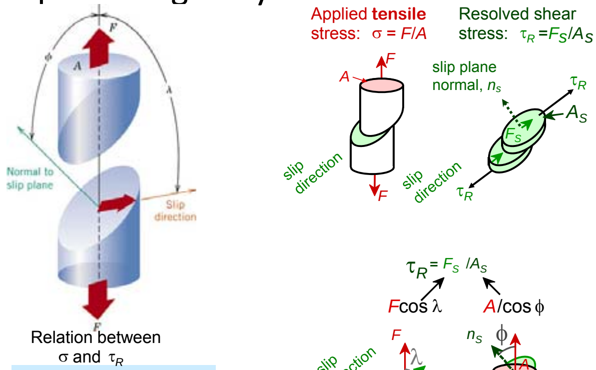
Slip System for FCC, BCC and HCP Metals

Metals	*Slip Plane*	*Slip Direction*	*Number of Slip Systems*
	Face-Centered Cubic		
Cu, Al, Ni, Ag, Au	{111}	$\langle 1\bar{1}0\rangle$	12
	Body-Centered Cubic		
α-Fe, W, Mo	{110}	$\langle \bar{1}11\rangle$	12
α-Fe, W	{211}	$\langle \bar{1}11\rangle$	12
α-Fe, K	{321}	$\langle \bar{1}11\rangle$	24
	Hexagonal Close-Packed		
Cd, Zn, Mg, Ti, Be	{0001}	$\langle 11\bar{2}0\rangle$	3
Ti, Mg, Zr	$\{10\bar{1}0\}$	$\langle 11\bar{2}0\rangle$	3
Ti, Mg	$\{10\bar{1}1\}$	$\langle 11\bar{2}0\rangle$	6

FCC or BCC: Relatively large number of slip systems (at least 12). These metals are quite ductile because extensive plastic deformation is normally possible along the various systems.

HCP metals, having few active slip systems, are normally quite brittle.

Slip in a single crystal



$\tau_R = \sigma \cos\lambda \cos\phi$

Deformation in Single Crystal

- A metal single crystal has a number of different slip systems that are capable of operating. The resolved shear stress normally differs for each one because the orientation of each relative to the stress axis (ϕ and λ angles) also differs.
- However, one slip system is generally oriented most favorably, that is, has the largest resolved shear stress, $\tau_R(max)$: $\tau_R(max) = \sigma(\cos\phi \cos\lambda)_{max}$

Slip in Single Crystal

- In response to an applied tensile or compressive stress, slip in a single crystal commences on the most favorably oriented slip system when the resolved shear stress reaches some critical value, termed the **critical resolved shear stress τ_{crss}**
- τ_{crss} represents the minimum shear stress required to initiate slip
- τ_{crss} is a property of the material that determines when yielding occurs.
- The single crystal plastically deforms or yields when $\tau_R(max) = \tau_{crss}$

Slip in single crystal

- The single crystal plastically deforms or yields when $\tau_R(max) = \tau_{crss}$
- The magnitude of the applied stress required to initiate yielding (i.e., the yield strength σ_y) is

$$\sigma_y = \frac{\tau_{crss}}{(\cos\phi \cos\lambda)_{max}}$$

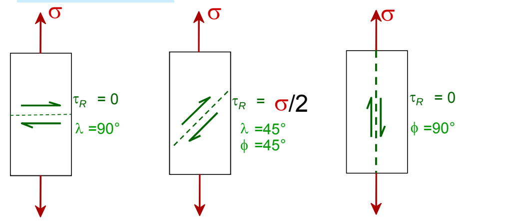
- The minimum stress necessary to introduce yielding occurs when a single crystal is oriented such that ϕ=λ=45⁰; under these conditions, $\sigma_y = 2\ \tau_{crss}$

Critical Resolved Shear Stress

- Condition for dislocation motion: $\tau_R > \tau_{CRSS}$
- Crystal orientation can make it easy or hard to move dislocation

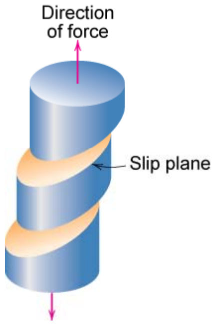
typically 10^{-4} GPa to 10^{-2} GPa

$\tau_R = \sigma \cos\lambda \cos\phi$



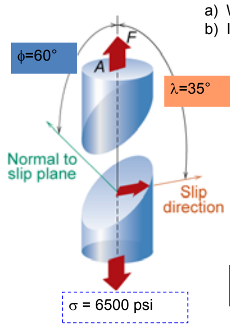
τ maximum at λ = ϕ = 45º

Single Crystal Slip



Ex: Deformation of single crystal

a) Will the single crystal yield?
b) If not, what stress is needed?



τ_{crss} = 3000 psi

$\tau = \sigma \cos\lambda \cos\phi$

σ = 6500 psi

$\tau = (6500 \text{ psi})(\cos 35°)(\cos 60°)$

$= (6500 \text{ psi})(0.41)$

$\tau = 2662 \text{ psi} < \tau_{crss} = 3000 \text{ psi}$

So the applied stress of 6500 psi will not cause the crystal to yield.

Ex: Deformation of single crystal

What stress *is* necessary (i.e., what is the yield stress, σ_y)?

$$\tau_{crss} = 3000 \text{ psi} = \sigma_y \cos\lambda \cos\phi = \sigma_y (0.41)$$

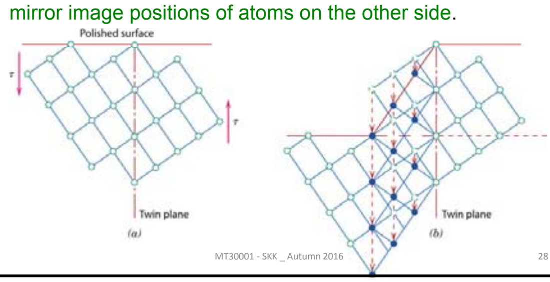
$$\therefore \sigma_y = \frac{\tau_{crss}}{\cos\lambda \cos\phi} = \frac{3000 \text{ psi}}{0.41} = \underline{\underline{7325 \text{ psi}}}$$

So for deformation to occur the applied stress must be greater than or equal to the yield stress

$$\sigma \geq \sigma_y = 7325 \text{ psi}$$

Deformation by Twining

- Plastic deformation in some metallic materials can occur by the formation of mechanical twins, or *twinning*
- A shear force can produce atomic displacements such that on one side of a plane (the twin boundary), atoms are located in mirror image positions of atoms on the other side.



Deformation by Twining

- The displacement magnitude within the twin region (indicated by arrows) is proportional to the distance from the twin plane.
- Twinning occurs on a definite crystallographic plane and in a specific direction that depend on crystal structure.
- For BCC metals, the twin plane and direction are (112) and [111], respectively

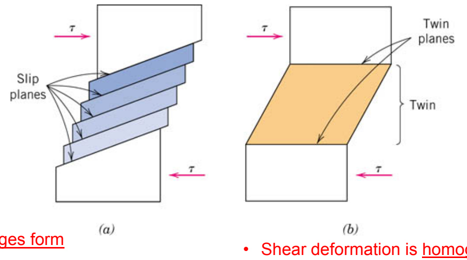
Deformation by Twining

Mechanical twinning occurs in metals that have BCC and HCP crystal structures, at low temperatures, and at high rates of loading (shock loading), conditions under which the slip process is restricted; that is, there are few operable slip systems.

The amount of bulk plastic deformation from twinning is normally small relative to that resulting from slip.

The real importance of twinning lies with the accompanying crystallographic reorientations; twinning may place new slip systems in orientations that are favorable relative to the stress axis such that the slip process can now take place.

Comparison between Slip and Twin



- Slip Ledges form
- The crystallographic orientation above and below the slip plane is the same both before and after the deformation
- Occurs in distinct atomic spacing multiples

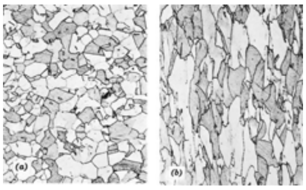
- Shear deformation is homogeneous
- A reorientation across the twin plane
- The atomic displacement for twinning is less than the interatomic separation

Slip Motion in Polycrystals

- Random crystallographic orientations of the numerous grains
- The direction of slip varies from one grain to another
- For each grain, dislocation motion occurs along the slip system that has the most favorable orientation (i.e., the highest shear stress)

Deformation in polycrystals

During deformation, mechanical integrity and coherency are maintained along the grain boundaries → the grain boundaries usually do not come apart or open up. → each individual grain is constrained, to some degree, in the shape it may assume by its neighboring grains.



Equiaxed grains ⟶ Elongated grains

Even though a single grain may be favorably oriented with the applied stress for slip, it cannot deform until the adjacent and less favorably oriented grains are capable of slip also; this requires **a higher applied stress level**.

Strengthening Mechanisms

ISSUES TO ADDRESS...

- How do we increase strength?
- Strength is increased by making dislocation motion difficult.
- Particular ways to increase strength are to:
  --solid solution strengthening
  --Strain hardening/ Work hardening/ Cold work
  --precipitation hardening
  --decrease grain size

Strengthening Mechanisms

Strengthening Mechanisms :

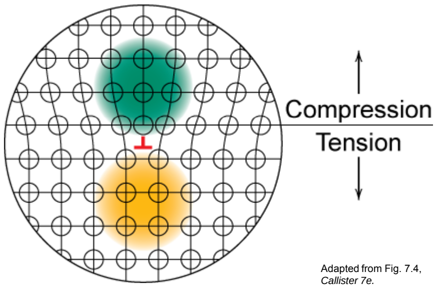
1. Solid Solution Strengthening
2. Strain Hardening
3. Precipitation Hardening
4. Grain Boundary Strengthening

Strengthening Mechanisms :

1. Solid Solution Strengthening
2. Strain Hardening
3. Precipitation Hardening
4. Grain Boundary Strengthening

Strengthening by Alloying

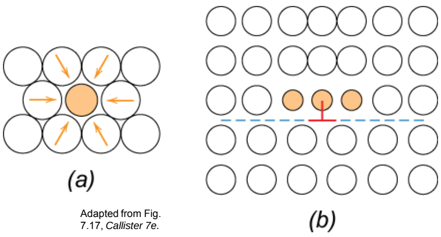
Stress Concentration at Dislocations



Adapted from Fig. 7.4, *Callister 7e.*

Strengthening by Alloying

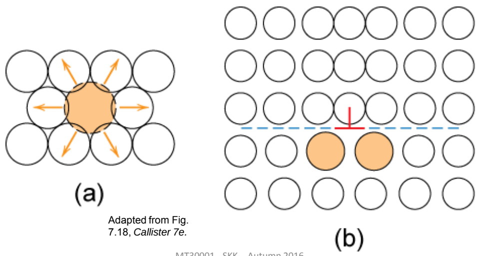
- **small impurities tend to concentrate at dislocations on the "Compressive stress side"**
- **reduce mobility of dislocation ∴ increase strength**



Adapted from Fig. 7.17, *Callister 7e.*

Strengthening by alloying

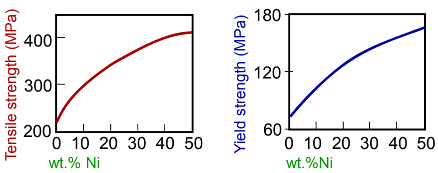
- Large impurities concentrate at dislocations on "Tensile Stress" side – pinning dislocation



Adapted from Fig. 7.18, *Callister 7e.*

Example: Solid Solution Strengthening in Copper

- Tensile strength & yield strength increase with wt% Ni.



- Empirical relation: $\sigma_y \sim C^{1/2}$
- Alloying increases σ_y and *TS*.

Strengthening Mechanisms :

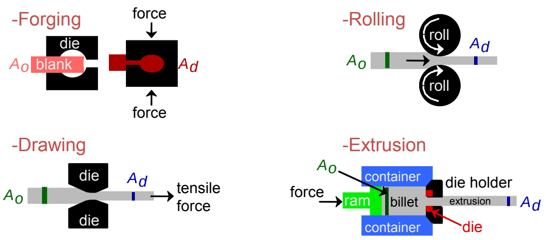
1. Solid Solution Strengthening
2. Strain Hardening
3. Precipitation Hardening
4. Grain Boundary Strengthening

Strengthening through Strain hardening

- Phenomenon whereby a ductile metal becomes harder and stronger as it is plastically deformed
- Also called Work hardening
- Also termed as Cold working: Because, the temperature at which deformation takes place is "cold" relative to the absolute melting temperature of the metal
- Most metals strain harden at room temperature
- Often utilized commercially to enhance the mechanical properties of metals during fabrication procedures.

Strengthening through Strain hardening

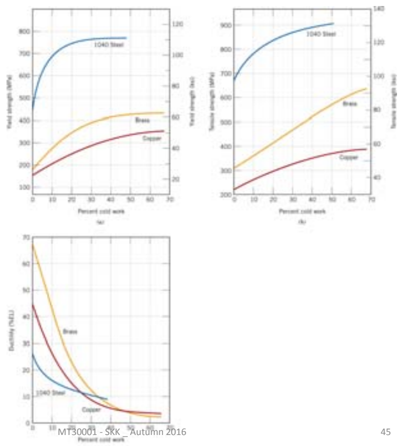
Common forming operations change the cross sectional area:



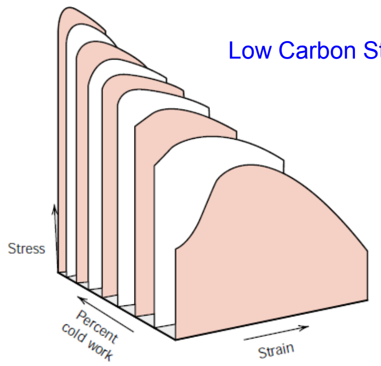
Percentage Cold Work

$$\%CW = \frac{A_o - A_d}{A_o} \times 100$$

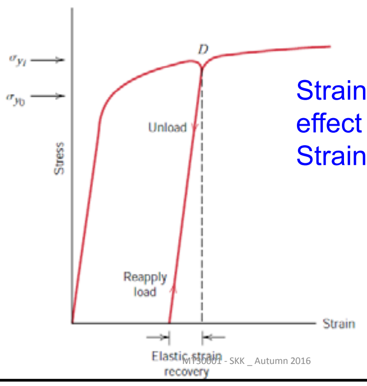
Examples



Example: Strain hardening



Example:



Strain hardening effect on Stress-Strain Diagram

Why materials strain harden?

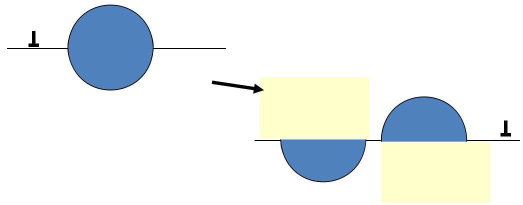
- Dislocation–dislocation strain field
- On the average, dislocation–dislocation strain interactions are repulsive → The motion of a dislocation is hindered by the presence of other dislocations.
- Cold work → Formation of new dislocations → The dislocation density in a metal increases
- As the dislocation density increases, the resistance to dislocation motion by other dislocations becomes more pronounced.
- Thus, the imposed stress necessary to deform a metal increases with increasing cold work.

Strengthening Mechanisms :

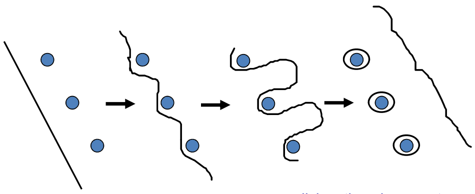
1. Solid Solution Strengthening
2. Strain Hardening
3. Precipitation Hardening
4. Grain Boundary Strengthening

Cutting precipitates:

When too small - dislocations can cut them:

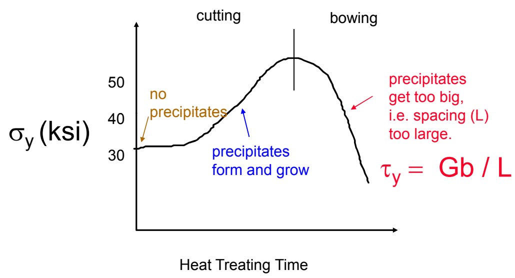


Bowing:



$$\tau_y = Gb / L$$

Precipitation strengthening:

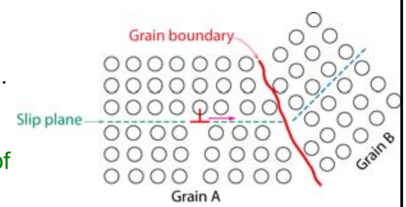


Strengthening Mechanisms :

1. Solid Solution Strengthening
2. Strain Hardening
3. Precipitation Hardening
4. Grain Boundary Strengthening

Strengthening through Grain Size Reduction

- Grain boundaries are barriers to slip.
- Barrier "strength" increases with increasing angle of misorientation



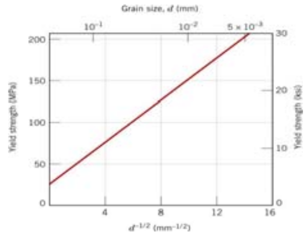
- For high-angle grain boundaries, dislocations cannot traverse grain boundaries during deformation;
  - A stress concentration ahead of a slip plane in one grain may activate sources of new dislocations in an adjacent grain.

Effectiveness of different grain boundaries on strengthening

- Small-angle grain boundaries are not very effective in interfering with the slip process because of the slight crystallographic misalignment across the boundary.
- Twin will effectively block slip and increase the strength of the material.

Strengthening through Grain Size Reduction

- Smaller grain size: more barriers to slip
  - a greater total grain boundary area to impede dislocation motion



- Hall-Petch Equation: $\sigma_{yield} = \sigma_o + k_y d^{-1/2}$

Not valid for both very large grain and extremely fine grain polycrystalline materials

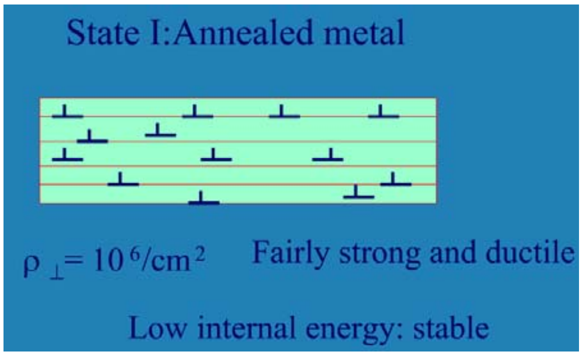
How is grain size regulated?

Grain size may be regulated

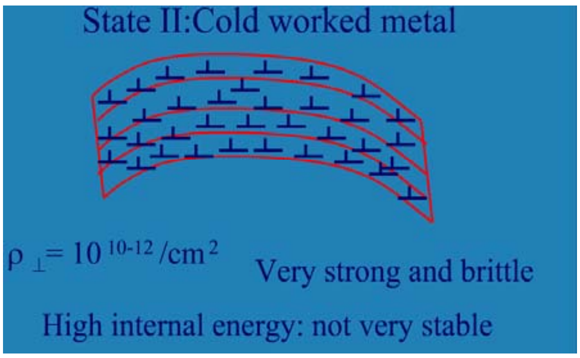
- by the **rate of solidification** from the liquid phase, and also
- by **plastic deformation followed by an appropriate heat treatment**

What happens during plastic deformation followed by an appropriate heat treatment?

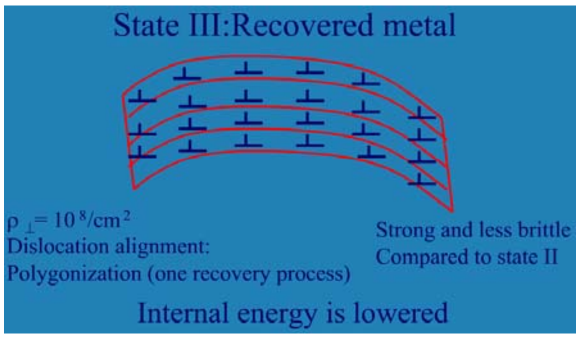
Starting Material



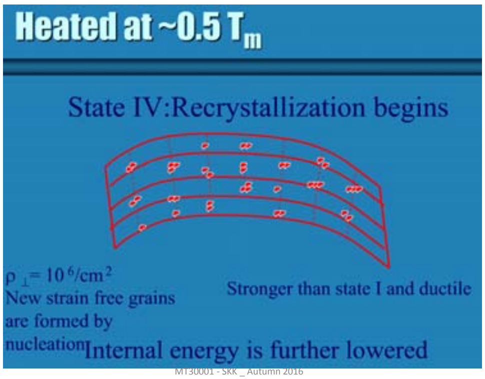
Cold Worked



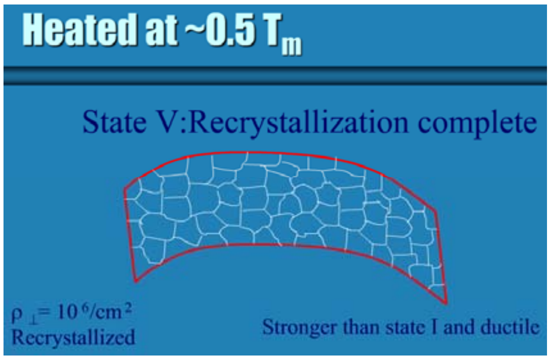
Heated at ~ 0.5 T_m



Recrystallization



Recrystallization



Effects of cold work

Cold Work →

(1) A change in grain shape

(2) Strain hardening

(3) An increase in dislocation density

(4) Electrical conductivity and corrosion resistance may be modified

Restoration of pre cold-worked state

Properties and structures may revert back to the precold-worked states by appropriate heat treatment (sometimes termed an annealing treatment).

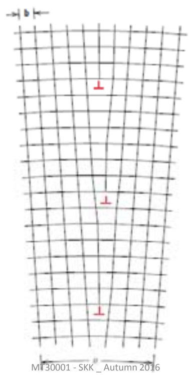
Such restoration results from two different processes that occur at elevated temperatures:
Recovery and
Recrystallization,
which may be followed by grain growth.

Recovery

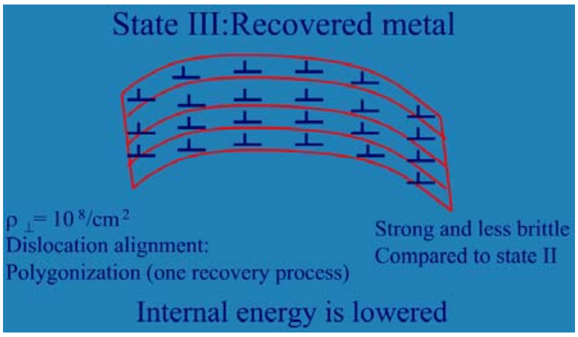
During recovery,
Reduction in some of the stored internal strain energy by virtue of dislocation motion (in the absence of an externally applied stress), as a result of enhanced atomic diffusion at the elevated temperature.

- Some reduction in the number of dislocations,
- Dislocation configurations are produced having low strain energies.

Low energy configuration of dislocations



Heated at ~ 0.5 T_m



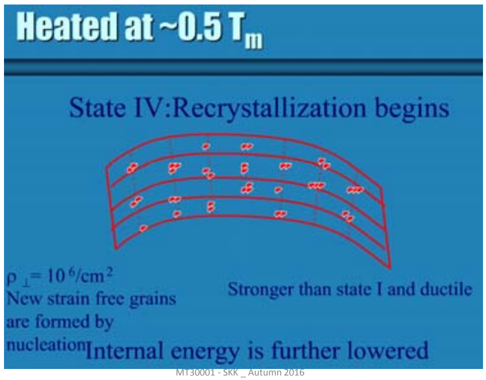
Recrystallization

- Even after recovery is complete, the grains are still in a relatively high strain energy state.
- Recrystallization is the formation of a new set of strain-free and equiaxed grains that have low dislocation densities and are characteristic of the precold-worked condition.
- The driving force to produce this new grain structure is the difference in internal energy between the strained and unstrained material.

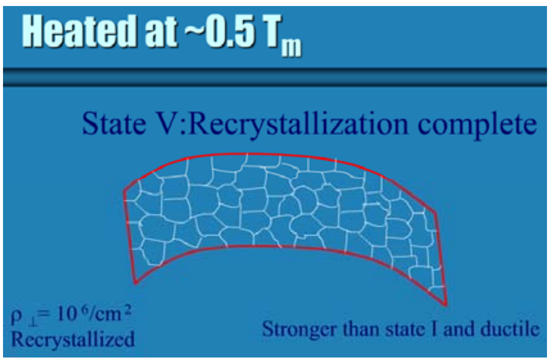
Recrystallization

- The new grains form as very small nuclei and grow until they completely replace the parent deformed material.
- Recrystallization of cold-worked metals may be used to refine the grain structure
- The mechanical properties that were changed as a result of cold working are restored to their precold-worked values.

Recrystallization

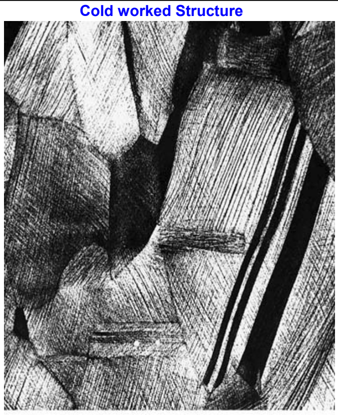


Recrystallization



Several Stages of Recrystallization and grain growth of brass

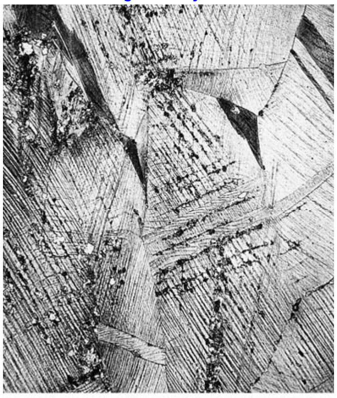
Cold worked Structure



(a)

Several Stages of Recrystallization and grain growth of brass

Initial stage of recrystallization



(b)

Degree of recrystallization increases with time

Several Stages of Recrystallization and grain growth of brass

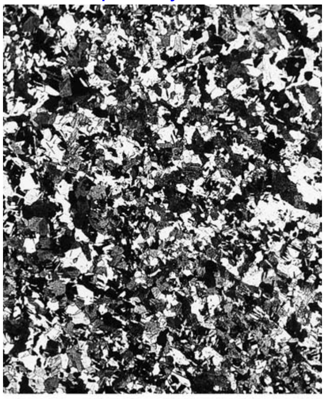
Partial replacement of cold worked grains by recrystallized ones

(c)

Degree of recrystallization increases with time

Several Stages of Recrystallization and grain growth of brass

Complete recrystallization



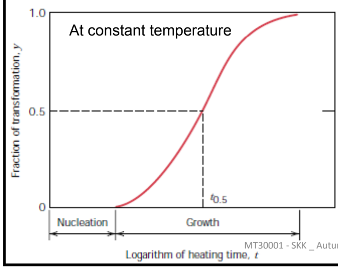
(d)

Degree of recrystallization increases with time

Kinetics of recrystallization

Extent of Recrystallization depends on both time and temperature.

The degree (or fraction) of recrystallization increases with time

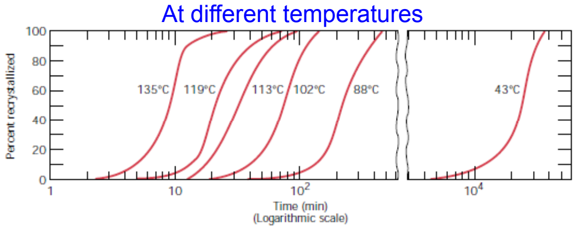


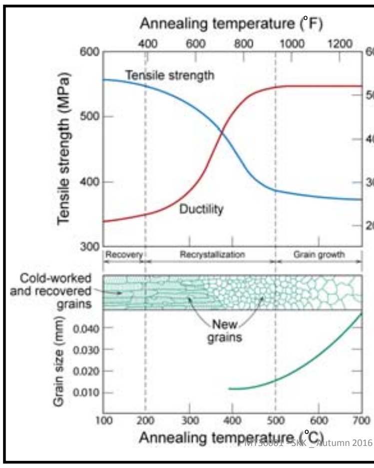
Avrami Equation

$$y = 1 - \exp(-kt^n)$$

Kinetics of recrystallization: Example for pure Copper

At different temperatures





Tensile strength and ductility (at room temperature) of a brass alloy as a function of the temperature and for a constant heat treatment time of 1 h

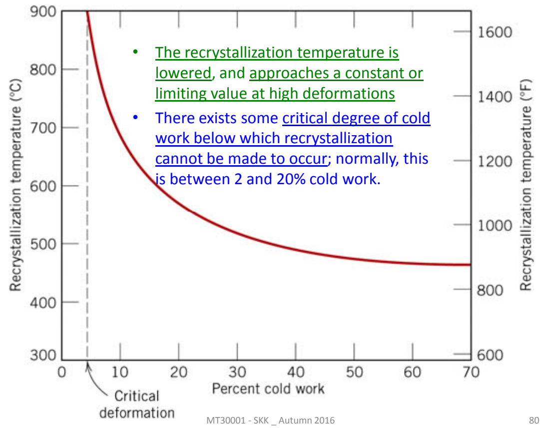
Schematic grain structure

T_R = recrystallization temperature

The temperature at which recrystallization just reaches completion in 1 h.

Recrystallization temperature

- Typically, it is between 0.3 T_m and 0.5 T_m
- Depends on several factors:
  - The amount of prior cold work
    - T_R is lowered as %CW increases
  - The purity of the alloy.
    - Recrystallization proceeds more rapidly in pure metals than in alloys. Thus, alloying raises the recrystallization temperature, sometimes quite substantially.
      - For pure metals, the recrystallization temperature is normally 0.3Tm
      - For some commercial alloys it may run as high as 0.7Tm.



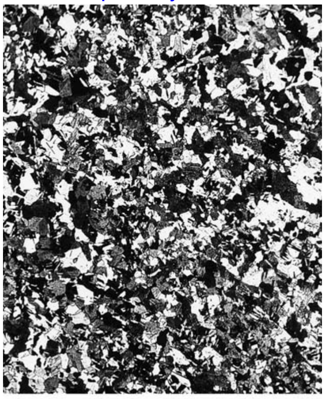
Grain Growth

After recrystallization is complete, the strain-free grains will continue to grow if the metal specimen is left at the elevated temperature

Driving force: An energy is associated with grain boundaries. As grains increase in size, the total boundary area decreases, yielding an attendant reduction in the total energy.

Several Stages of Recrystallization and grain growth of brass

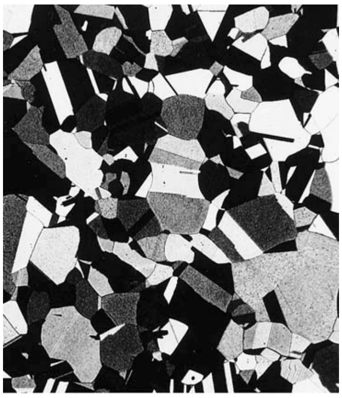
Complete recrystallization



(d)

Degree of recrystallization increases with time

Grain growth of brass at 580 deg C



(e)

Grain growth at low temperature

Grain growth of brass at 700 deg C

(f)

Further grain growth at higher temperature

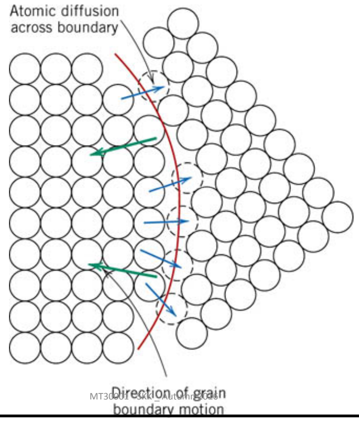
Grain Growth

Grain growth occurs by the migration of grain boundaries.

Not all grains can enlarge, but large ones grow at the expense of small ones that shrink. Thus, the average grain size increases with time.

Boundary motion is just the short-range diffusion of atoms from one side of the boundary to the other. The directions of boundary movement and atomic motion are opposite to each other

Grain Growth



Grain Growth Equation

For many polycrystalline materials, the grain diameter *d varies with time t* according to the relationship

$$d^n - d_0^n = Kt$$

- d_0 *is the initial grain diameter at t 0,*
- *K and n are time-independent* constants
- The value of *n is generally equal to or greater than 2.*

Characteristic differences between Recovery, Recrystallization, and Grain Growth

Recrystallization & Recovery:

- Recrystallization: High angle grain boundaries migrate
- Recovery: High angle grain boundaries do not migrate

Recrystallization and grain growth

- Recrystallization: Driving force is due to reduction in strain energy
- Grain Growth: Driving force is only due to the reduction in boundary area

Hot Working

- Deforming at high enough temperature for immediate (dynamic) recrystallization
- Working and annealing at the same time
- No increase in strength
- Used for large deformation
- Poor surface finish - oxidation