Chapter Outline

Dislocations and Strengthening Mechanisms

What is happening in material during plastic deformation?

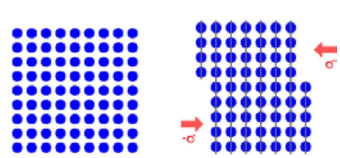
- **Dislocations and Plastic Deformation**
  - ✓ Motion of dislocations in response to stress
  - ✓ Slip Systems
  - ✓ Plastic deformation in
    - single crystals
    - polycrystalline materials
- **Strengthening mechanisms**
  - ✓ Grain Size Reduction
  - ✓ Solid Solution Strengthening
  - ✓ Strain Hardening
- **Recovery, Recrystallization, and Grain Growth**

Introduction

Why metals could be plastically deformed?

Why the plastic deformation properties could be changed to a very large degree by forging without changing the chemical composition?

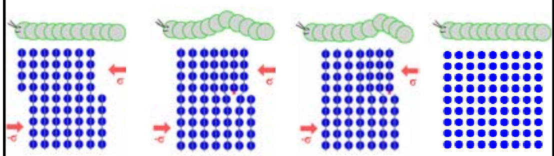
Why plastic deformation occurs at stresses that are much smaller than the theoretical strength of perfect crystals?



Plastic deformation – the force to break all bonds in the slip plane is much higher than the force needed to cause the deformation. Why?

These questions can be answered based on the idea proposed in 1934 by Taylor, Orowan and Polyani: **Plastic deformation is due to the motion of a large number of dislocations.**

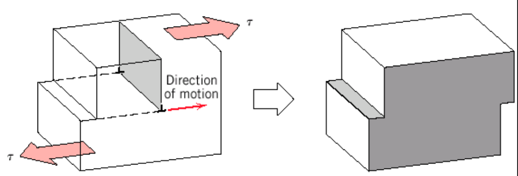
Dislocations allow deformation at much lower stress than in a perfect crystal



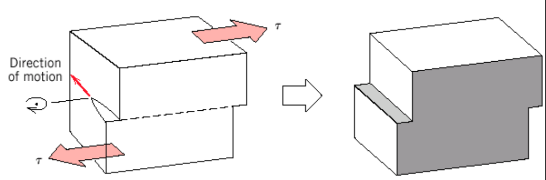
If the top half of the crystal is slipping one plane at a time then only a small fraction of the bonds are broken at any given time and this would require a much smaller force.
The propagation of one dislocation across the plane causes the top half of the crystal to move (**to slip**) with respect to the bottom half but we do not have to break all the bonds across the middle plane simultaneously (which would require a very large force).

The slip plane – the crystallographic plane of dislocation motion.

Direction of the dislocation motion



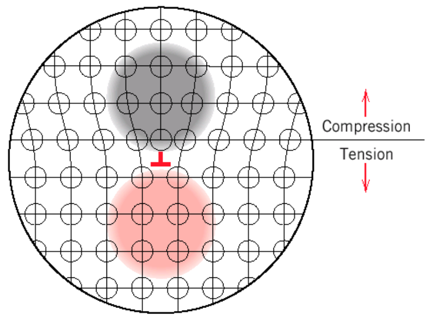
Edge dislocation line moves parallel to applied stress



Screw dislocation line moves perpendicular to applied stress

For mixed dislocations, direction of motion is in between parallel and perpendicular to the applied shear stress

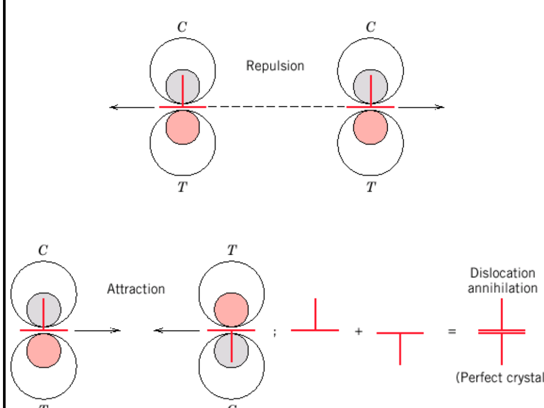
Strain field around dislocations



Dislocations have strain fields arising from distortions at their cores - strain drops radially with distance from dislocation core

Edge dislocations introduce compressive, tensile, and shear lattice strains, screw dislocations introduce shear strain only.

Interactions between Dislocations



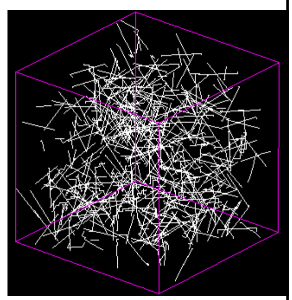
The strain fields around dislocations cause them to interact (exert force on each other). When they are in the same plane, they repel if they have the same sign (direction of the Burgers vector) and attract/annihilate if they have opposite signs.

Where do Dislocations Come From ?

The number of dislocations in a material is expressed as the **dislocation density** - the total dislocation length per unit volume or the number of dislocations intersecting a unit area. Dislocation densities can vary from 10^5 cm^{-2} in carefully solidified metal crystals to 10^{12} cm^{-2} in heavily deformed metals.

Most crystalline materials, especially metals, have dislocations in their as-formed state, mainly as a result of stresses (mechanical, thermal...) associated with the forming process.

The number of dislocations increases dramatically during plastic deformation. Dislocations spawn from existing dislocations, grain boundaries and surfaces.



This picture is a snapshot from simulation of plastic deformation in a fcc single crystal (Cu) of linear dimension 15 micrometers.

See animation at http://zig.onera.fr/lem/DisGallery/3D.html

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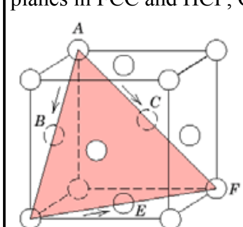
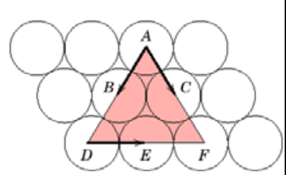
Slip Systems

In single crystals there are preferred planes where dislocations move (**slip planes**). Within the slip planes there are preferred crystallographic directions for dislocation movement (**slip directions**). The set of slip planes and directions constitute **slip systems**.

The slip planes and directions are those of highest packing density. Since the distance between atoms is shorter than the average, the distance perpendicular to the plane has to be longer than average. Being relatively far apart, the planes can slip more easily relatively to each other.

BCC and FCC crystals have more slip systems as compared to HCP, there are more ways for dislocation to propagate ⇒ FCC and BCC crystals are more ductile than HCP crystals. Remember our discussion of close packed planes in FCC and HCP, Chapter 3.



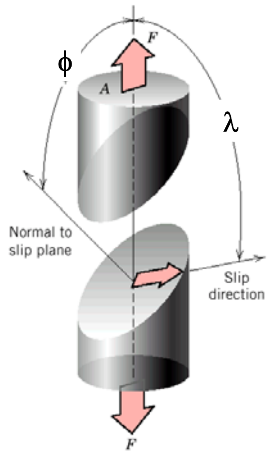


Slip in Single Crystals - Resolving the Applied Stress onto the Slip System

Dislocations move in particular directions on particular planes (the slip system) in response to shear stresses applied along these planes and directions ⇒ we need to determine how the applied stress is **resolved** onto the slip systems.

Let us define the **resolved shear stress, τ_R,** (which produces plastic deformation) that result from application of a simple tensile stress, σ.

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



Slip in Single Crystals - Critical Resolved Shear Stress

When the resolved shear stress becomes sufficiently large, the crystal will start to yield (dislocations start to move along the most favorably oriented slip system). The onset of yielding corresponds to the yield stress, σ_y (Chapter 6). The minimum shear stress required to initiate slip is termed **the critical resolved shear stress**:

$$\tau_{CRSS} = \sigma_y (\cos\phi \cos\lambda)_{MAX}$$

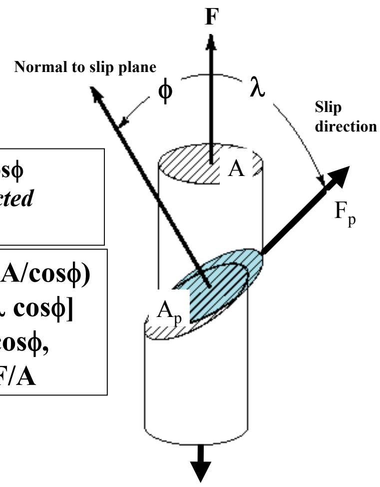
$$\sigma_y = \frac{\tau_{CRSS}}{(\cos\phi \cos\lambda)_{MAX}}$$

Maximum value of (cosϕ cosλ) corresponds to

$\phi = \lambda = 45^o \Rightarrow \cos\phi \cos\lambda = 0.5 \Rightarrow \sigma_y = 2\tau_{CRSS}$

Slip will occur first in slip systems oriented close to this angle ($\phi = \lambda = 45^o$) with respect to the applied stress

Resolved Shear Stress

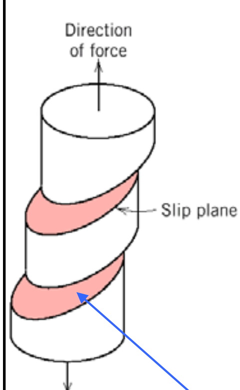


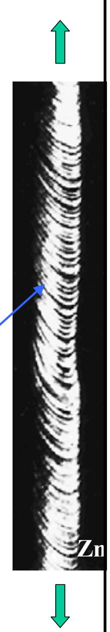
F cosλ, A / cosϕ are the *projected* components

τ = F cosλ/(A/cosϕ) =(F/A)[cosλ cosϕ]
$\tau = \sigma \cos\lambda \cos\phi$,
where σ = F/A

Definition of the resolved shear stress, τ, which directly produces plastic deformation (a shearing action) as a result of the external application of a simple tensile stress, σ.

Slip in a Single Crystal





Each step (shear band) result from the generation of a large number of dislocations and their propagation in the slip system with maximum resolved shear stress.

Plastic Deformation of Polycrystalline Materials

Grain orientations with respect to applied stress are random.

The dislocation motion occurs along the slip systems with favorable orientation (i.e. that with highest resolved shear stress).

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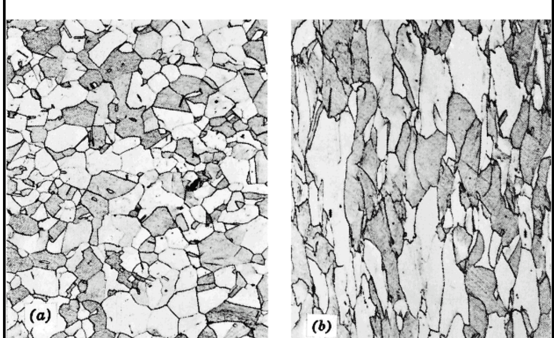
Plastic Deformation of Polycrystalline Materials

Larger plastic deformation corresponds to elongation of grains along direction of applied stress.



Before ***After***

Plastic Deformation of Polycrystalline Materials

- Slip directions vary from crystal to crystal ⇒ Some grains are unfavorably oriented with respect to the applied stress (i.e. $\cos\phi \cos\lambda$ low)
- Even those grains for which $\cos\phi \cos\lambda$ is high may be limited in deformation by adjacent grains which cannot deform so easily
- Dislocations cannot easily cross grain boundaries because of changes in direction of slip plane and disorder at grain boundary
- **As a result, polycrystalline metals are stronger than single crystals** (the exception is the perfect single crystal without any defects, as in whiskers)

Strengthening

The ability of a metal to deform depends on the ability of dislocations to move

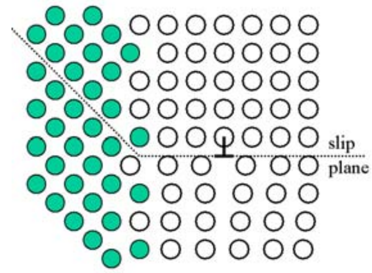
Restricting dislocation motion makes the material stronger

Mechanisms of strengthening in single-phase metals:

- grain-size reduction
- solid-solution alloying
- strain hardening

Ordinarily, strengthening reduces ductility

Strengthening by grain-size reduction (I)



Grain boundary barrier to dislocation motion: slip plane discontinues or change orientation.

Small angle grain boundaries are not very effective in blocking dislocations.

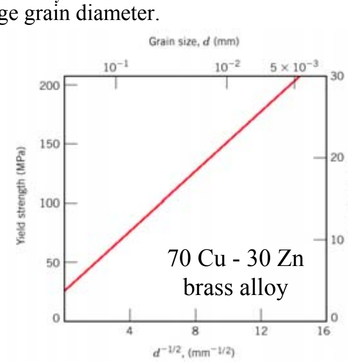
High-angle grain boundaries block slip and increase strength of the material. A stress concentration at end of a slip plane may trigger new dislocations in an adjacent grain.

Strengthening by grain-size reduction (II)

The finer the grains, the larger the area of grain boundaries that impedes dislocation motion. Grain-size reduction usually improves toughness as well. Usually, the yield strength varies with grain size d according to Hall-Petch equation:

$$\sigma_y = \sigma_0 + k_y / \sqrt{d}$$

where σ_0 and k_y are constants for a particular material, **d** is the average grain diameter.



Grain size **d** can be controlled by the rate of solidification, by plastic deformation and by appropriate heat treatment.

Solid-Solution Strengthening (I)

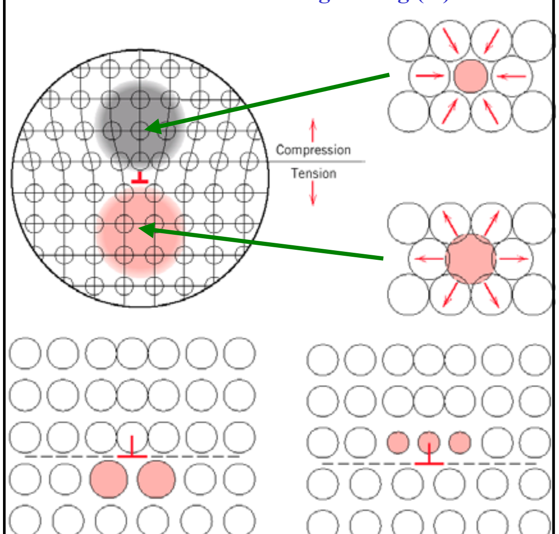
Alloys are usually stronger than pure metals of the solvent.

Interstitial or substitutional impurities in a solution cause lattice strain. As a result, these impurities interact with dislocation strain fields and **hinder dislocation motion**.

Impurities tend to diffuse and **segregate around the dislocation core** to find atomic sites more suited to their radii. This reduces the overall strain energy and "anchor" the dislocation.

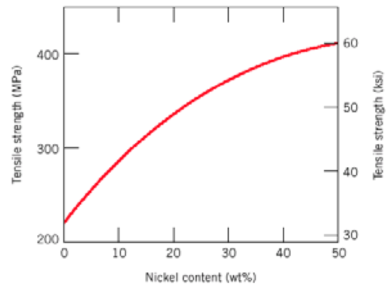
Motion of the dislocation core away from the impurities moves it to a region of lattice where the atomic strains are greater (i.e. the dislocation strains are no longer compensated by the impurity atoms).

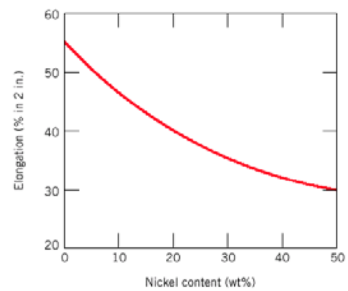
Solid-Solution Strengthening (II)



Smaller and larger substitutional impurities tend to diffuse into strained regions around the dislocation leading to partial cancellation of impurity-dislocation lattice strains.

Solid-Solution Strengthening (III)





Strengthening by increase of dislocation density (Strain Hardening = Work Hardening = Cold Working)

Ductile metals become stronger when they are deformed plastically at temperatures well below the melting point.

The reason for strain hardening is the increase of dislocation density with plastic deformation. The average distance between dislocations decreases and dislocations start blocking the motion of each other.

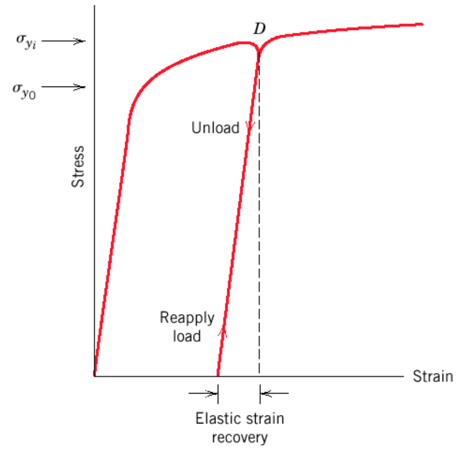
The percent cold work (%CW) is often used to express the degree of plastic deformation:

$$\%CW = \left(\frac{A_0 - A_d}{A_0}\right) \times 100$$

where A_0 is the original cross-section area, A_d is the area after deformation.

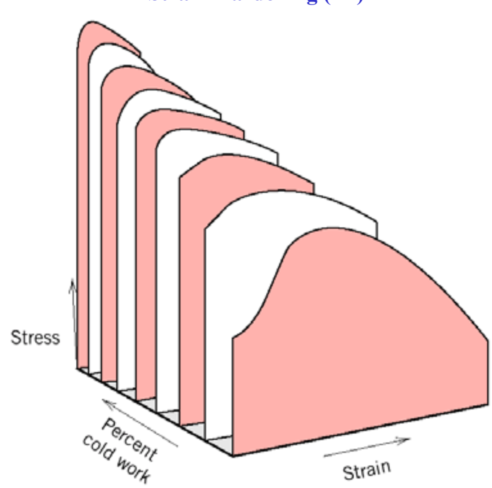
%CW is just another measure of the degree of plastic deformation, in addition to strain.

Strain Hardening (II)



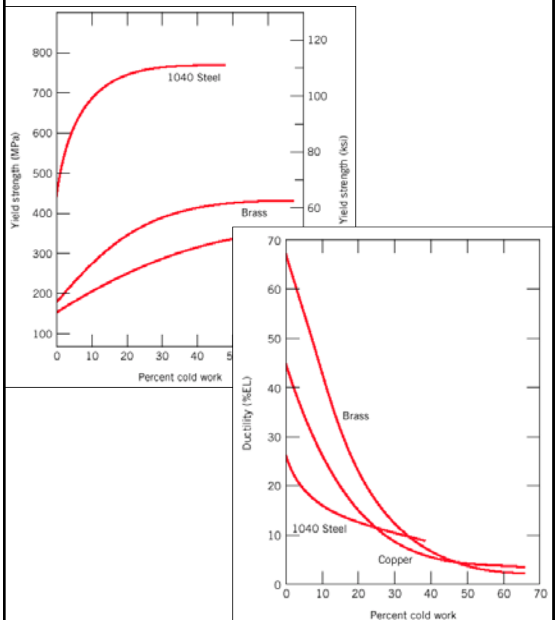
New yield strength σ_{y_0} is higher than the initial yield strength, σ_{y_i}. The reason for this effect - strain hardening.

Strain Hardening (III)



Yield strength and hardness are increasing as a result of strain hardening but **ductility is decreasing** (material becomes more brittle).

Strain Hardening (IV)



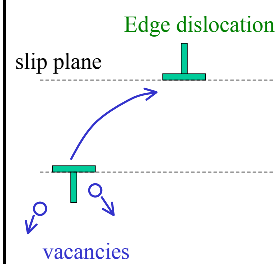
Recovery, Recrystallization, and Grain Growth

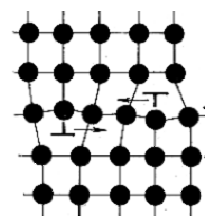
- **Plastic deformation increases dislocation density (single and polycrystalline materials) and changes grain size distributions (polycrystalline materials).**
- This corresponds to stored strain energy in the system (dislocation strain fields and grain distortions).
- When applied external stress is removed - most of the dislocations, grain distortions and associated strain energy are retained.
- Restoration to the state before cold-work can be done by heat-treatment and involves two processes: **recovery** and **recrystallization**. These may be followed by **grain growth**.

Recovery

Heating → increased diffusion → enhanced dislocation motion → decrease in dislocation density by annihilation, formation of low-energy dislocation configurations → relieve of the internal strain energy

Some of the mechanisms of dislocation annihilation:





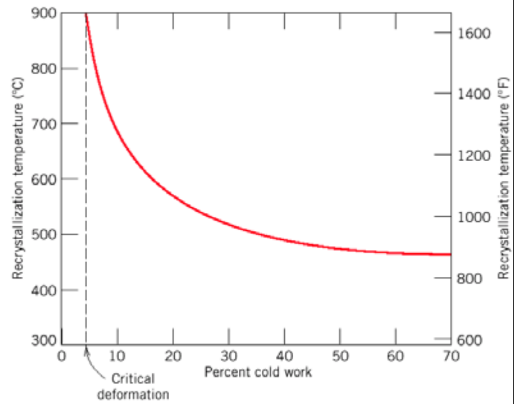
Recrystallization (I)

- Even after recovery the grains can be strained. These strained grains of cold-worked metal can be replaced, upon heating, by strain-free grains with low density of dislocations.
- This occurs through **recrystallization – nucleation and growth of new grains**.
- The *driving force* for recrystallization is the difference in internal energy between strained and unstrained material.
- Grain growth involves short-range diffusion → the extend of recrystallization depends on both temperature and time.
- Recristallization is slower in alloys as compared to pure metals

Recrystallization (II)

Recrystallization temperature: the temperature at which the process is complete in one hour. It is typically 1/3 to 1/2 of the melting temperature (can be as high as 0.7 T_m in some alloys).

Recrystallization decreases as the %CW is increased. Below a "critical deformation", recrystallization does not occur.



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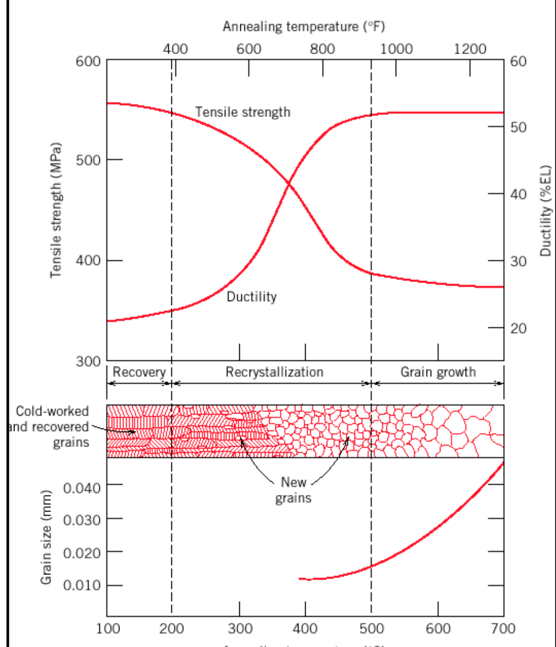
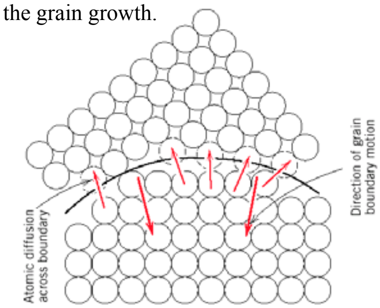
Recrystallization (III)

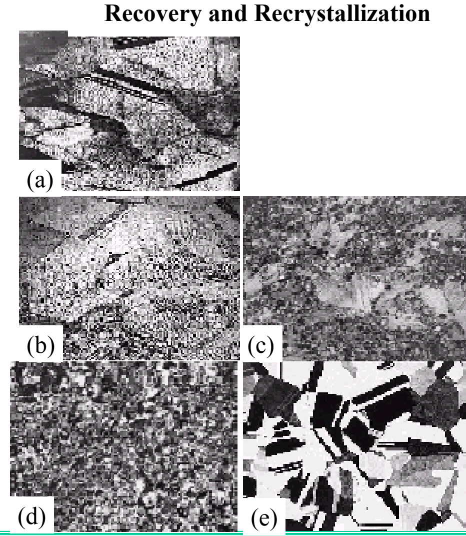


Grain Growth

- If deformed polycrystalline material is maintained at annealing temperature following complete recrystallization, then further **grain growth** occurs.
- *Driving force* is reduction of grain boundary area and hence energy Big grains grow at the expense of the small ones.
- Grain growth during annealing occurs in all polycrystalline materials (i.e. they do not have to be deformed or undergo recrystallization first).
- Boundary motion occurs by short range diffusion of atoms across the grain boundary → strong temperature dependence of the grain growth.



Recovery and Recrystallization



(a) Cold-worked brass, x-sectional area deformed by 33%
(b) After 3seconds at 580 °C, new grains appear
(c) After 4 seconds at 580 °C, many new grains are present
(d) After 8 seconds at 580 °C, complete recrystallization has occurred
(e) After 1 hour at 580 °C, substantial grain growth has occurred
The driving force for this is the reduction of high-energy grain boundaries.

Summary

Make sure you understand language and concepts:

- Cold working
- Critical resolved shear stress
- Dislocation density
- Grain growth
- Lattice strain
- Recovery
- Recrystallization
- Recrystallization temperature
- Resolved shear stress
- Slip
- Slip system
- Strain hardening
- Solid-solution strengthening

Reading for next class:

Chapter 8: Failure

- Mechanisms of brittle vs. ductile fracture
- Impact fracture testing
- Fatigue (cyclic stresses)
- Crack initiation and propagation
- Creep (time dependent deformation)