Material Strengthening Mechanisms

Academic Resource Center

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Agenda

- Definition of strengthening
- Strengthening mechanisms
- Grain size reduction
- Solid solution alloying
- Cold Working (strain hardening)
- Three steps of Annealing: Recovery, Recrystallization & Grain Growth

Strengthening

- The ability of a metal to deform plastically depends on the ability of dislocations to move.
- Hardness and strength are related to how easily a metal plastically deforms, so, by reducing dislocation movement, the mechanical strength can be improved.
- To the contrary, if dislocation movement is easy (unhindered), the metal will be soft, easy to deform.

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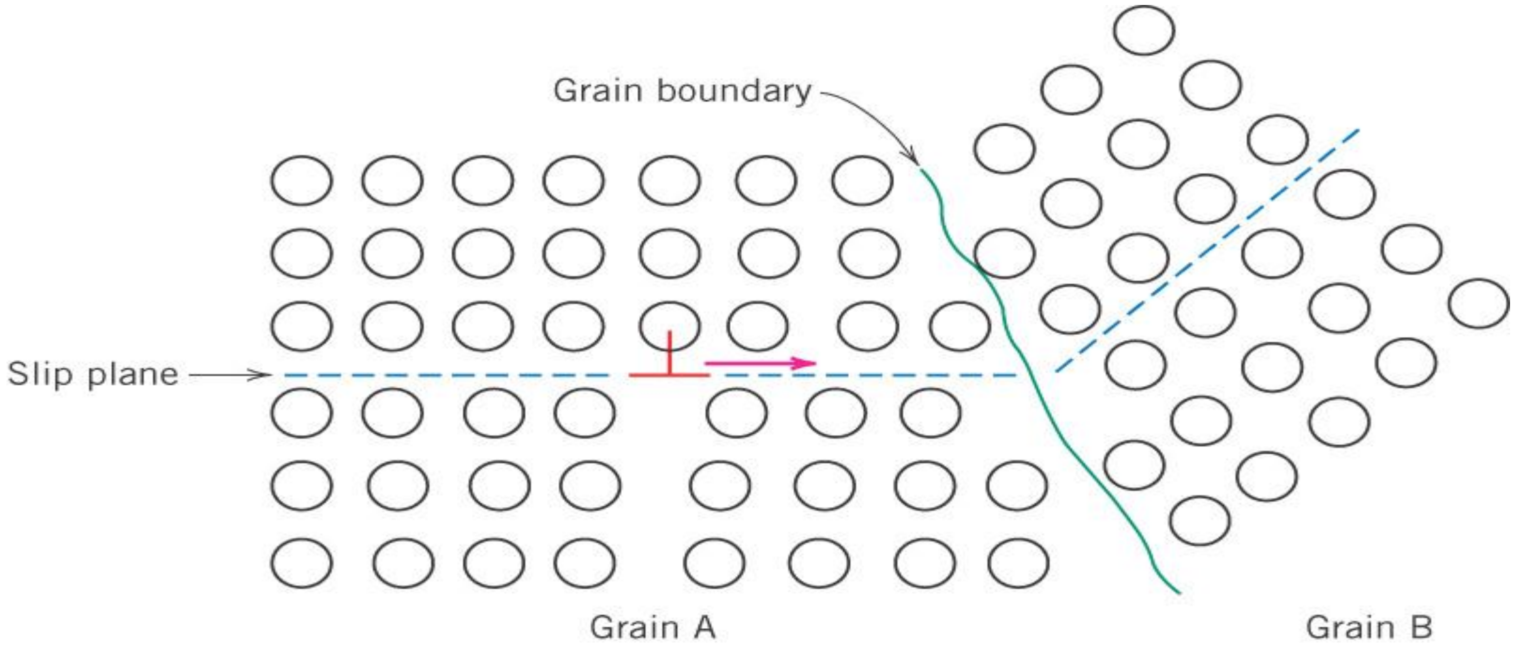
Strengthening Mechanisms

1. Grain Size Reduction
2. Solid Solution Alloying
3. Strain Hardening (Cold Working)
4. Annealing

1. Grain Size Reduction



- Grain boundaries are barriers to slip.
- Barrier "strength " increases with misorientation.
- Smaller grain size: more barriers to slip.

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Hall Petch Relation

- This equation indicates that the yield strength has an inverse square root relation with grain size (d).

- Theoretically, a … ong if the grains are made

$$s_{yield} = s_o + k_y d^{-1/2}$$

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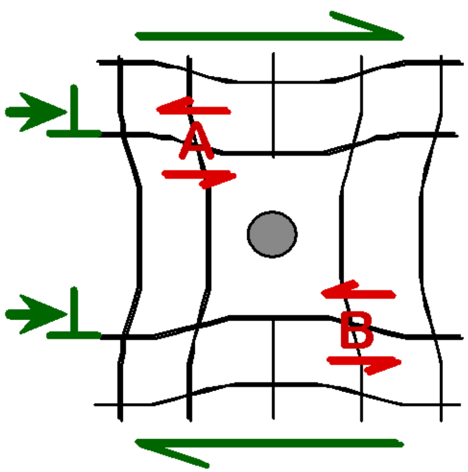
2. Solid Solutions

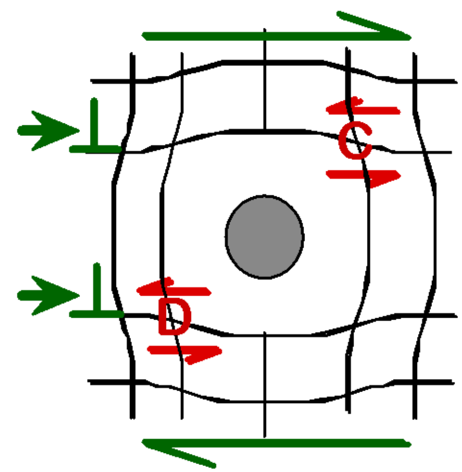
- Impurity atoms distort the lattice & generate stress.
- Stress can produce a barrier to dislocation motion.

Small substitutional impurity



Impurity generates local shear at A and B that opposes dislocation motion to the right.

Large substitutional impurity

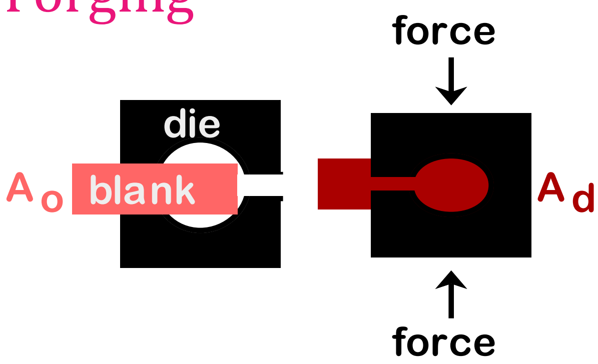


Impurity generates local shear at C and D that opposes dislocation motion to the right.

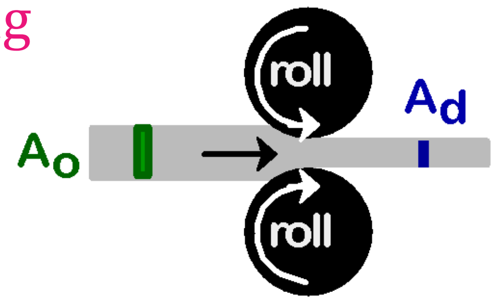
3. Strain Hardening (Cold Work)

- Room temperature deformation.
- Common forming techniques used to change the cross sectional area:

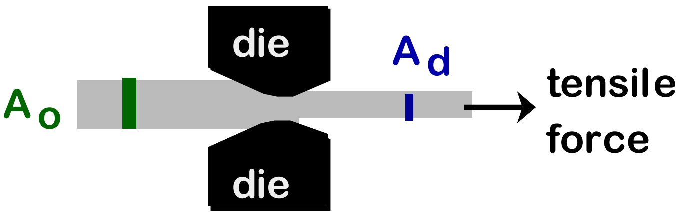
-Forging



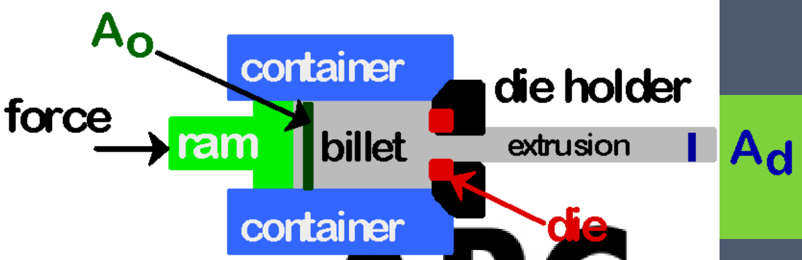
-Rolling



-Drawing



-Extrusion

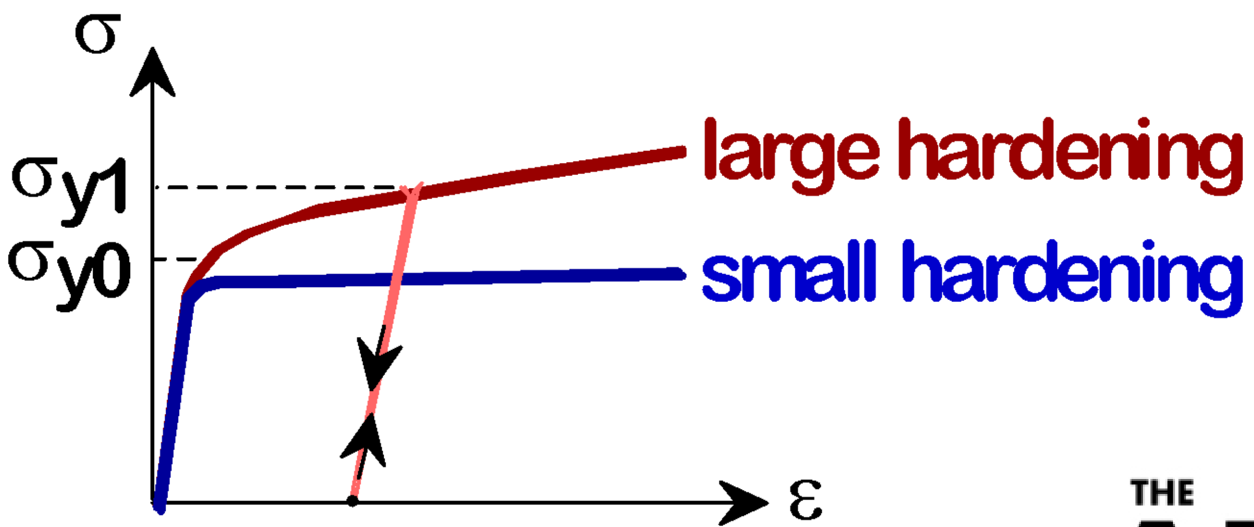


Dislocations during Cold Work

- Dislocations entangle one another during cold work.
- Dislocation motion becomes more difficult, which makes the material stronger overall.

Result of Cold Work

- Dislocation density increases, which leads to a increase in yield strength: Materials becomes harder.
- Ductility and tensile strength also increases.



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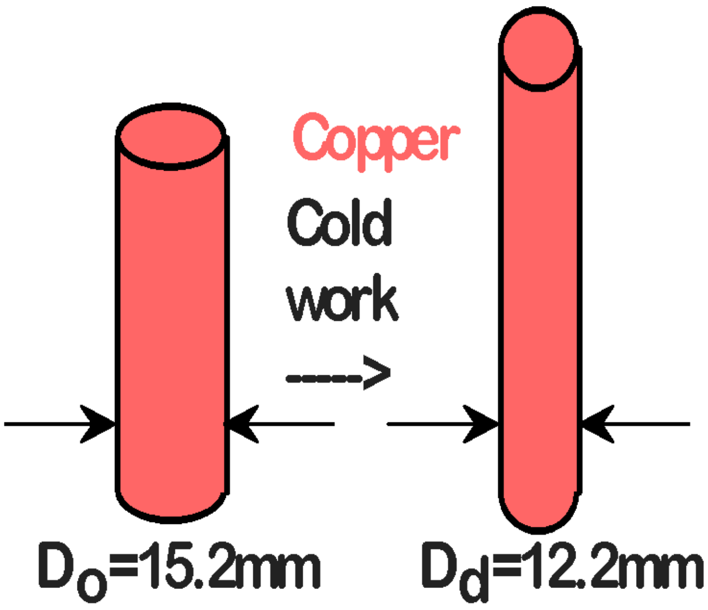
Percentage Cold Work - Definition

$$\%CW = \frac{A_o - A_d}{A_o} x100$$

$$\%CW = \frac{\pi r_o^2 - \pi r_d^2}{\pi r_o^2} x100 = 35.6\%$$



Cold Rolling Illustration

<u>Isotropic</u>

grains are approx. spherical, equiaxed & randomly oriented.

<u>Anisotropic (directional)</u>

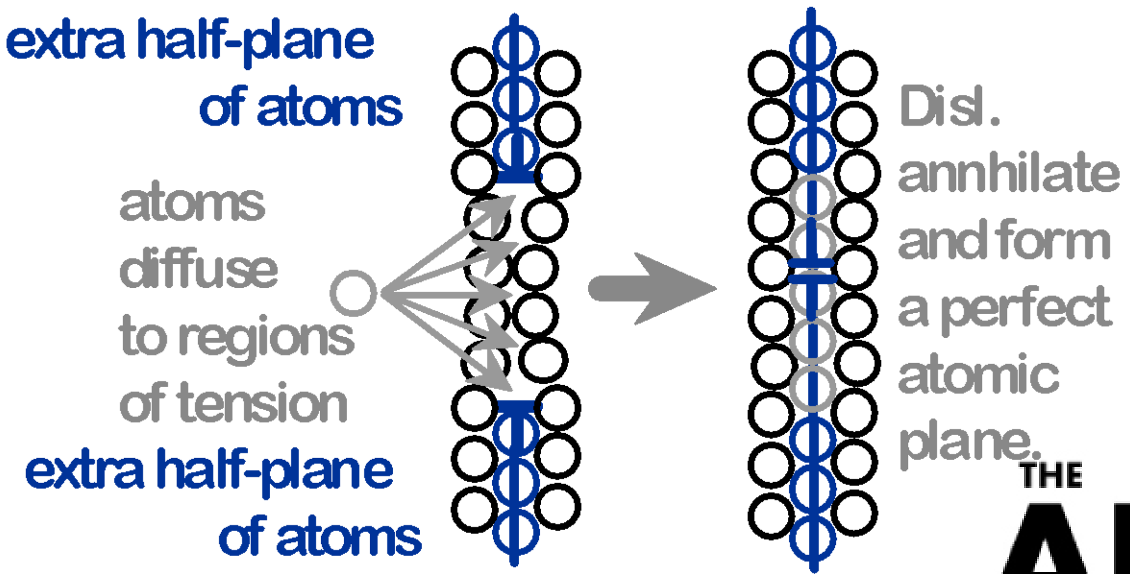
since rolling affects grain orientation and shape.

Annealing

- Process where material is heated to above the recrystallization temperature of the sample and then cooled down.
- Main purpose is to improve Cold work properties by increasing ductility and retaining most of the hardness.
- There are 3 steps involved with annealing: recovery, recrystallization and grain growth.

Recovery

- During recovery, some of the stored internal strain energy is relieved through dislocation motion due to enhanced atomic diffusion at the elevated temperatures.
- Leads to reduction in the number of dislocations.



Recrystallization

- 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 uniaxial grains that have low dislocation densities.
- The driving force to produce the new grain structure is the internal energy difference between strained and unstrained material.
- The new grains form as very small nuclei and grow until they consume the parent material.

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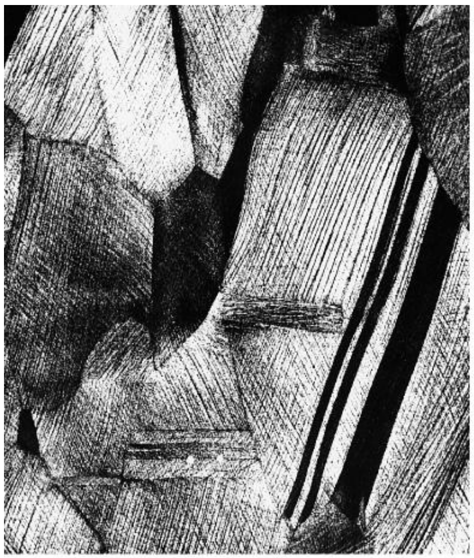
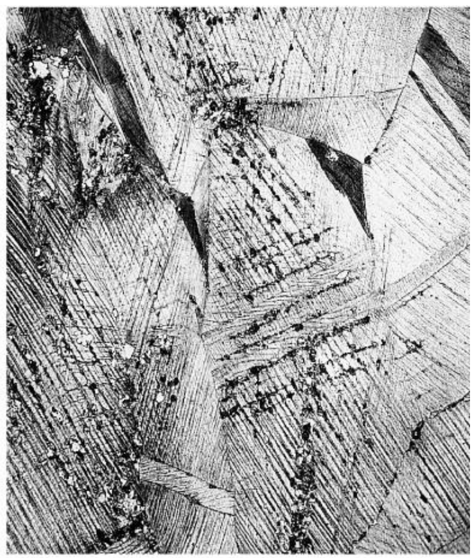
Recrystallization Illustration



Cold Worked grains. Not annealed.



Initial recrystallization after 3 seconds @ 580˚C

Partial replacement of grains, after 4 seconds

Complete recryst. after 8 seconds

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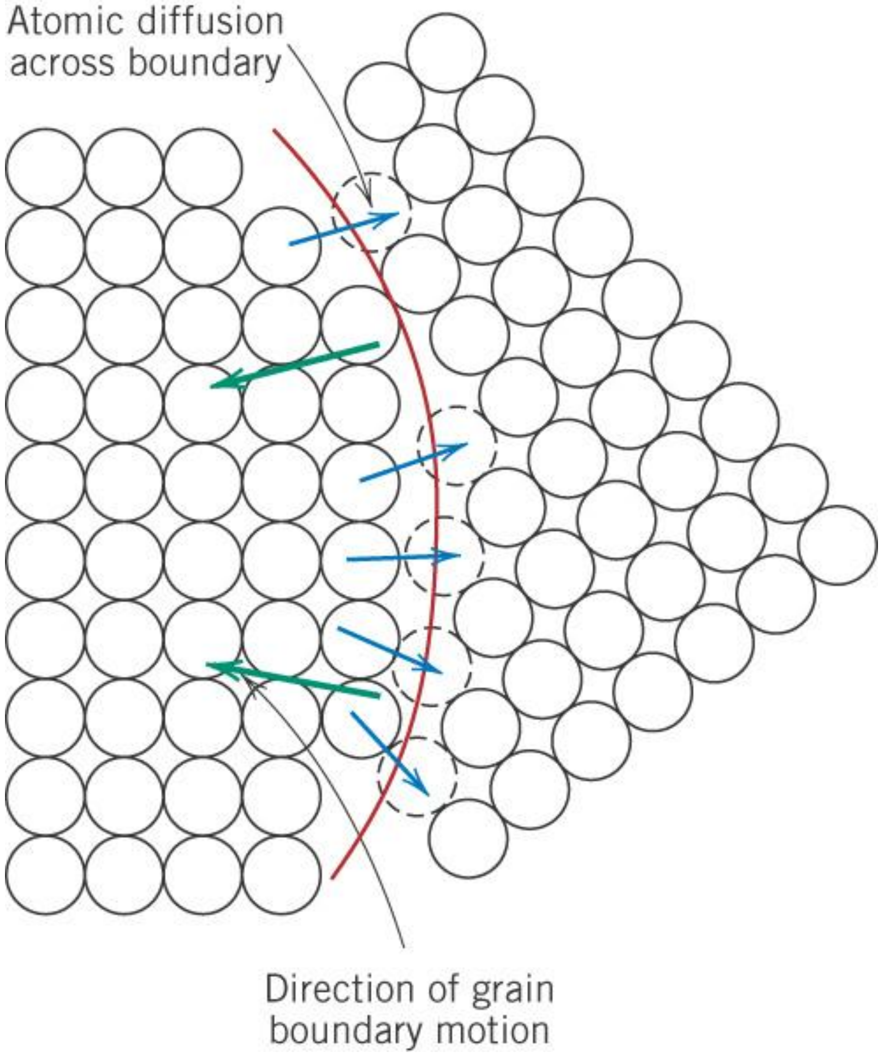
Grain Growth



- After recrystallization, the strain-free grains will continue to grow if the metal specimen is left at elevated temperatures.
- As grains increase in size, the total boundary area decreases, as does the total energy.
- Large grains grow at the expense of smaller grains.

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References

- Abbaschian, Reed-Hill. *"Physical Metallurgy Principles"*. 4th edition. 2009
- Beer & Johnston (2006). Mechanics of Materials (5th edition). McGraw Hill.