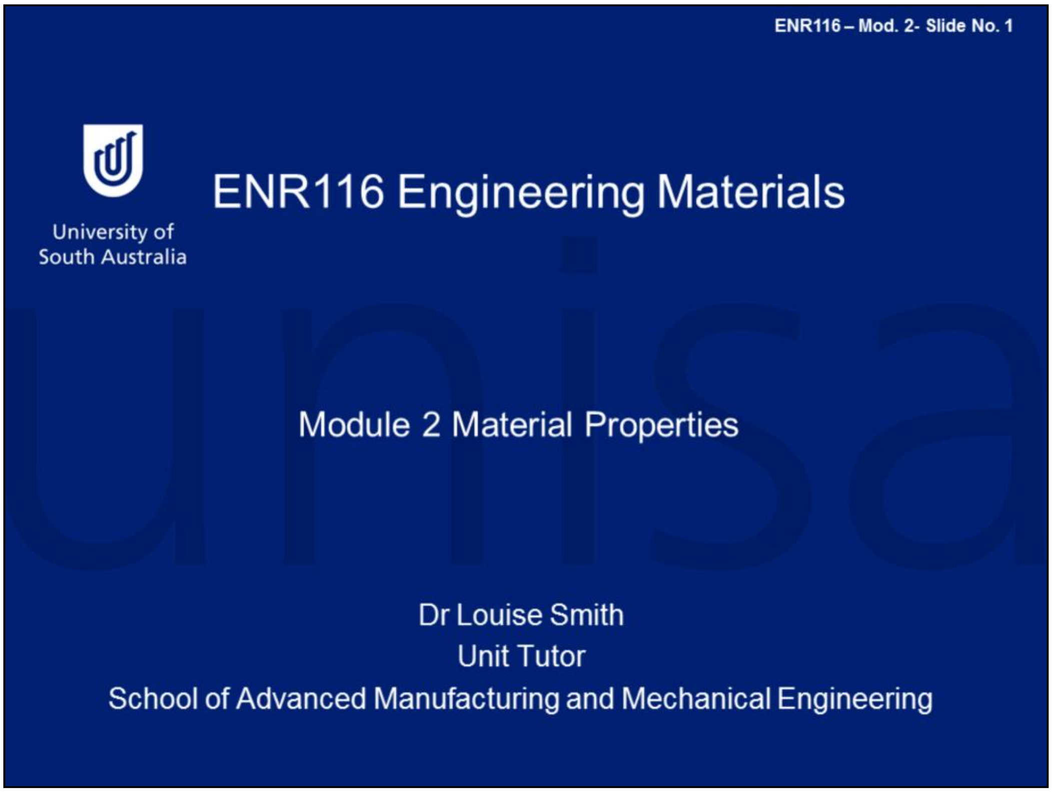

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ENR116 Engineering Materials

Module 2 Material Properties

Dr Louise Smith
Unit Tutor
School of Advanced Manufacturing and Mechanical Engineering

Welcome to ENR116 Engineering Materials. This lecture summary is part of module 2, Material Properties. I’m Louise Smith and I will be presenting this lecture summary.

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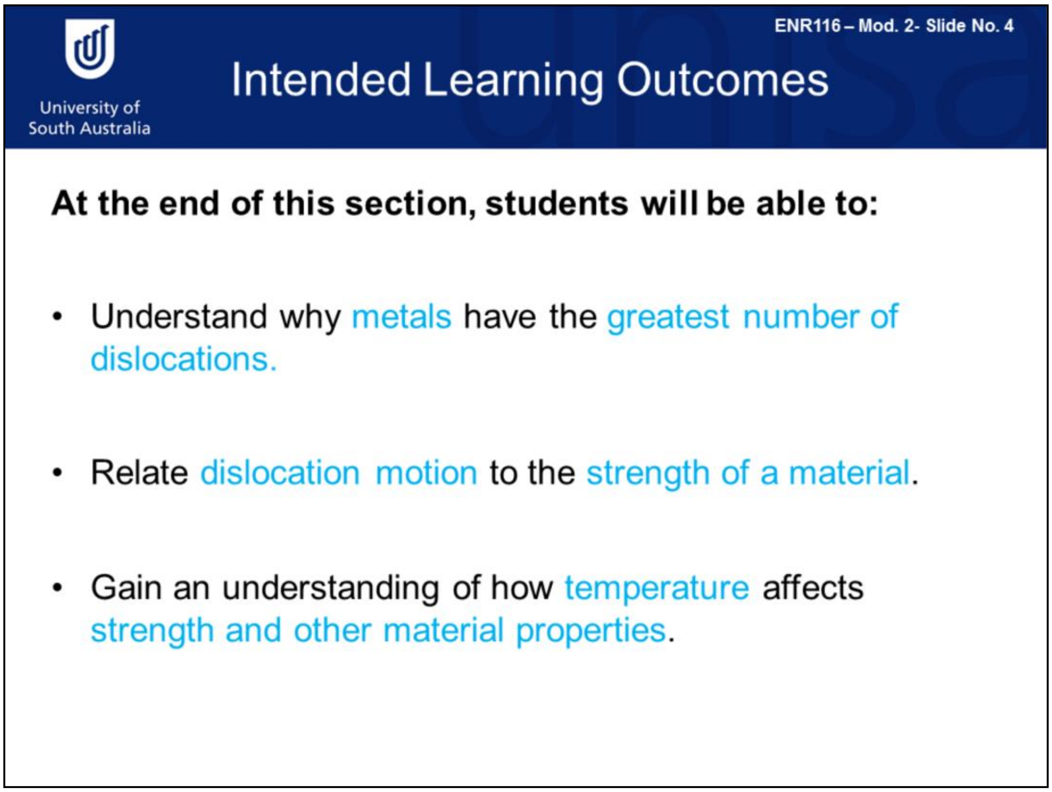
Dislocations

This lecture summary is on dislocations.



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Intended Learning Outcomes

At the end of this section, students will be able to:

- Understand why metals have the greatest number of dislocations.
- Relate dislocation motion to the strength of a material.
- Gain an understanding of how temperature affects strength and other material properties.

The intended learning outcomes from this lecture summary are that you will understand why metals have the greatest number of dislocations. You will also be able to relate how the movement of dislocations affects the strength of a material. You will also understand how temperature affects the strength of a material and its other material properties.

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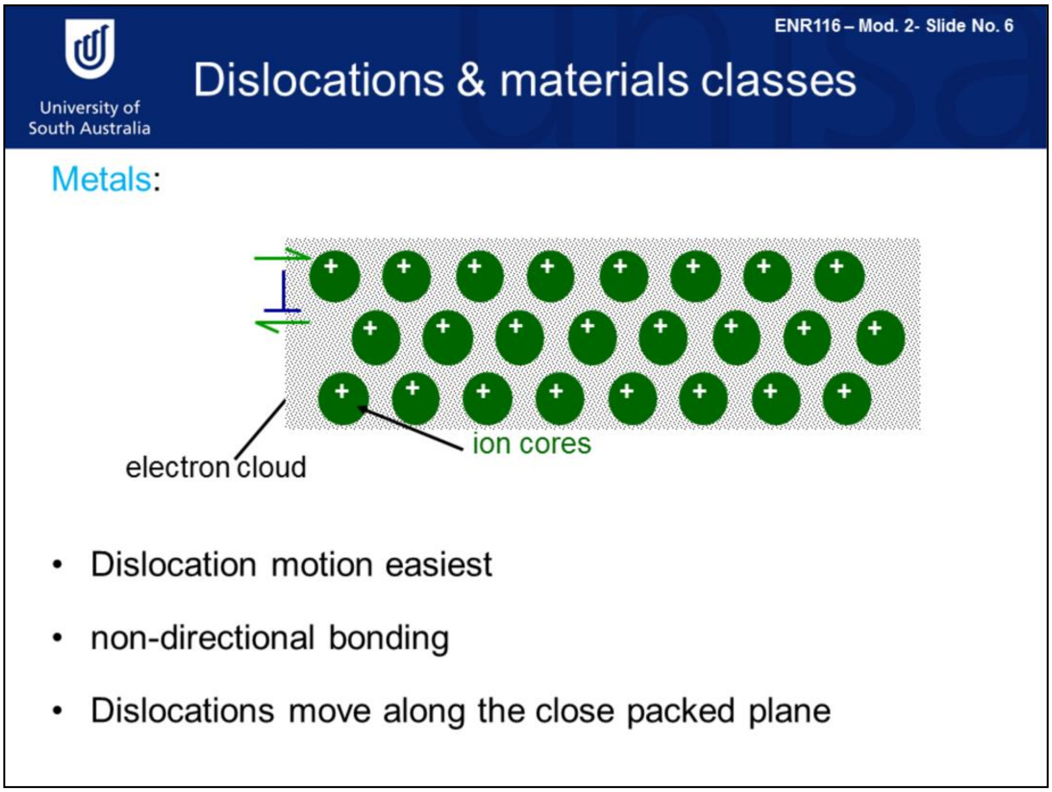
Dislocations & strengthening mechanisms

Issues to address…

- Why are the number of dislocations present greatest in metals?
- How are strength and dislocation motion related?
- Why does heating alter strength and other properties?

To do this we will discuss why metals have the greatest number of dislocations, how material strength and dislocation movement are relayed and why heating a material will alter its strength and other material properties.



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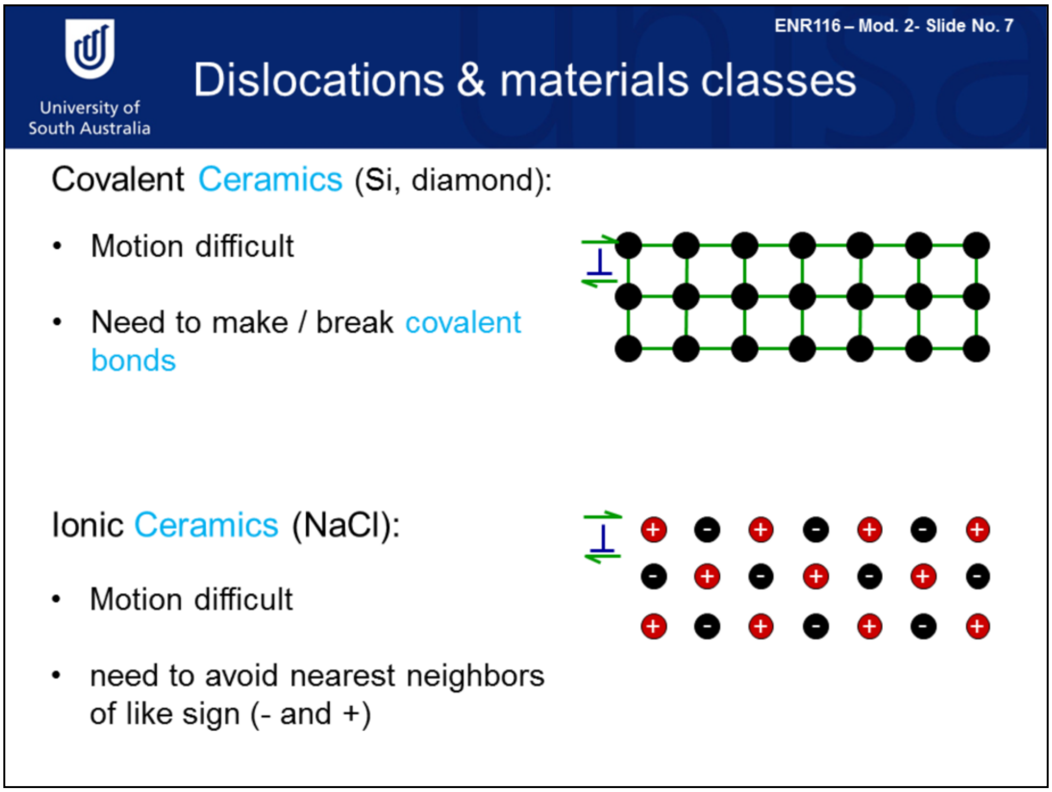
Dislocations & materials classes

Metals:

- Dislocation motion easiest
- non-directional bonding
- Dislocations move along the close packed plane

Early materials scientists calculated the strength of materials assuming that they were perfect crystals. The calculated strengths were therefore many times that of those measured. During the 1930’s dislocation theory was used to explain this discrepancy; however it was not until the invention of the electron microscope that these dislocations were seen. Dislocations in metals find it relatively easy to move due to the non-directional nature of metallic bonding. They move along the close packed plane in the crystal structure.



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Dislocations & materials classes

Covalent Ceramics (Si, diamond):

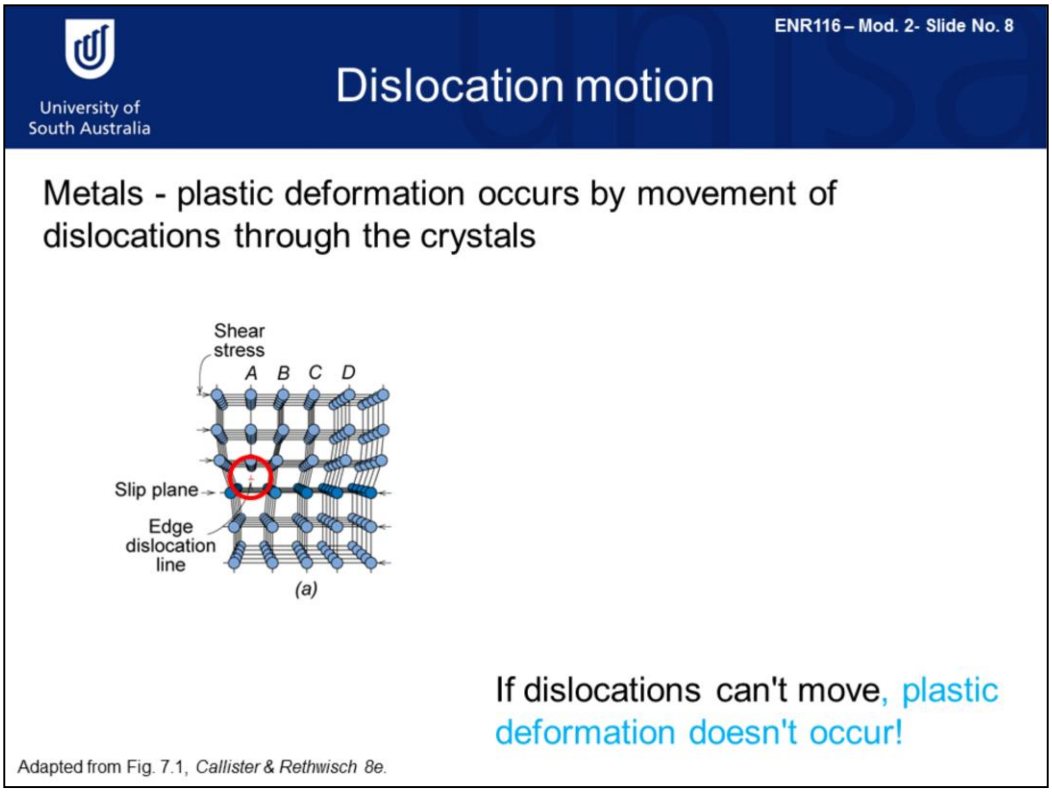
- Motion difficult
- Need to make / break covalent bonds

Ionic Ceramics (NaCl):

- Motion difficult
- need to avoid nearest neighbors of like sign (- and +)

In covalently bonded materials such as covalent ceramics, silicon and diamond it is very difficult for the dislocation to move. This is because of the energy needed to break and make covalent bonds.

In ionic ceramic materials such as sodium chloride again motion is difficult. In this case the moving atoms have to avoid other atoms of the same charge.



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Dislocation motion

Metals - plastic deformation occurs by movement of dislocations through the crystals

If dislocations can't move, plastic deformation doesn't occur!

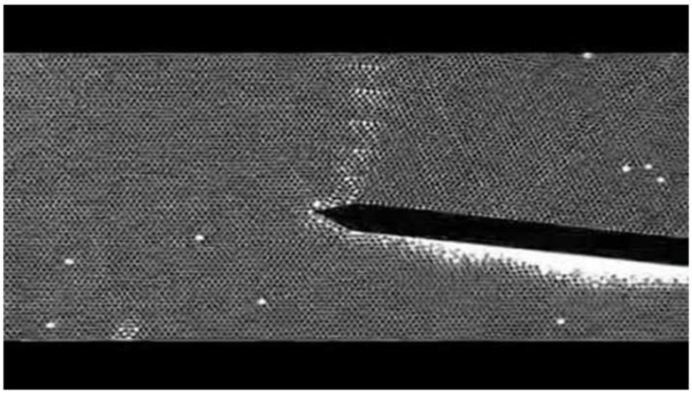
Adapted from Fig. 7.1, *Callister & Rethwisch 8e.*

There are two types of dislocation: an edge dislocation and a screw dislocation.

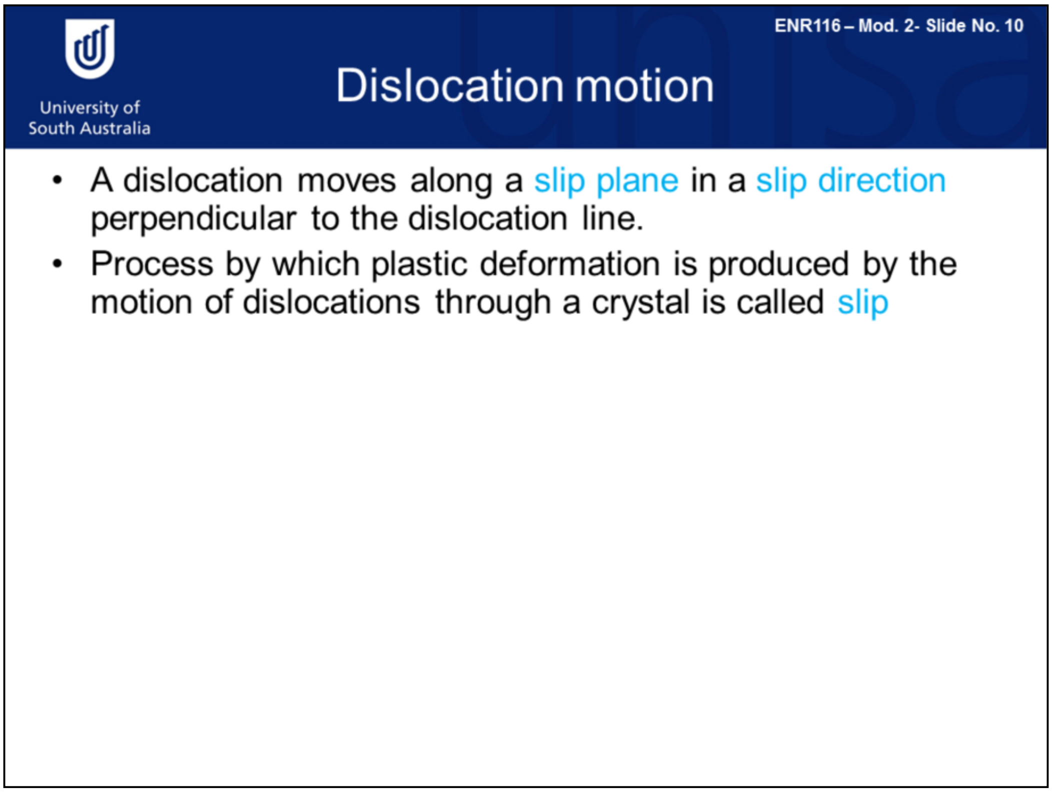
In an edge dislocation a lattice distortion is formed around an extra half plane of atoms. This extra half plane of atoms defines the dislocation line and is denoted by the small red upside down T in the crystal lattice. Plastic deformation is a result of the motion of a large number of dislocations moving through the crystals. An edge dislocation moves in response to a shear stress applied at an angle perpendicular to its line. When the shear force is applied the extra half plane of atoms is moved one atomic space to the right. This causes the rest of the atoms to move across one extra atomic space. If the applied force is strong enough the atomic bonds are broken along the slip plane, and the extra half plane moves along as the atoms in the half plane A join to the atoms in the bottom half of plane B making plane B the new half plane of atoms. The dislocation moves in discrete steps by the repeated breaking of bonds and the repeated shifting of the extra half plane of atoms. Around the dislocation the crystal structure is perfect. It is only in the immediate vicinity of the dislocation that the crystal structure is disrupted. Eventually the dislocation will erupt from the side of the crystal forming a ledge that is 1 atomic unit wide. A screw dislocation can be thought of as resulting from shear distortion. The line of the dislocation passes through the centre of a spiral. Whilst these two types of dislocation are the two fundamental types, it is extremely unusual to find either a pure screw dislocation or a pure edge dislocation. Most dislocations are hybrids of the two.

Dislocations demonstration

In this online video, you can see a demonstration of how dislocations move in response to an applied stress



https://www.youtube.com/watch?v=VLsLS74AM9o
(video plays for 1 min 25 s)



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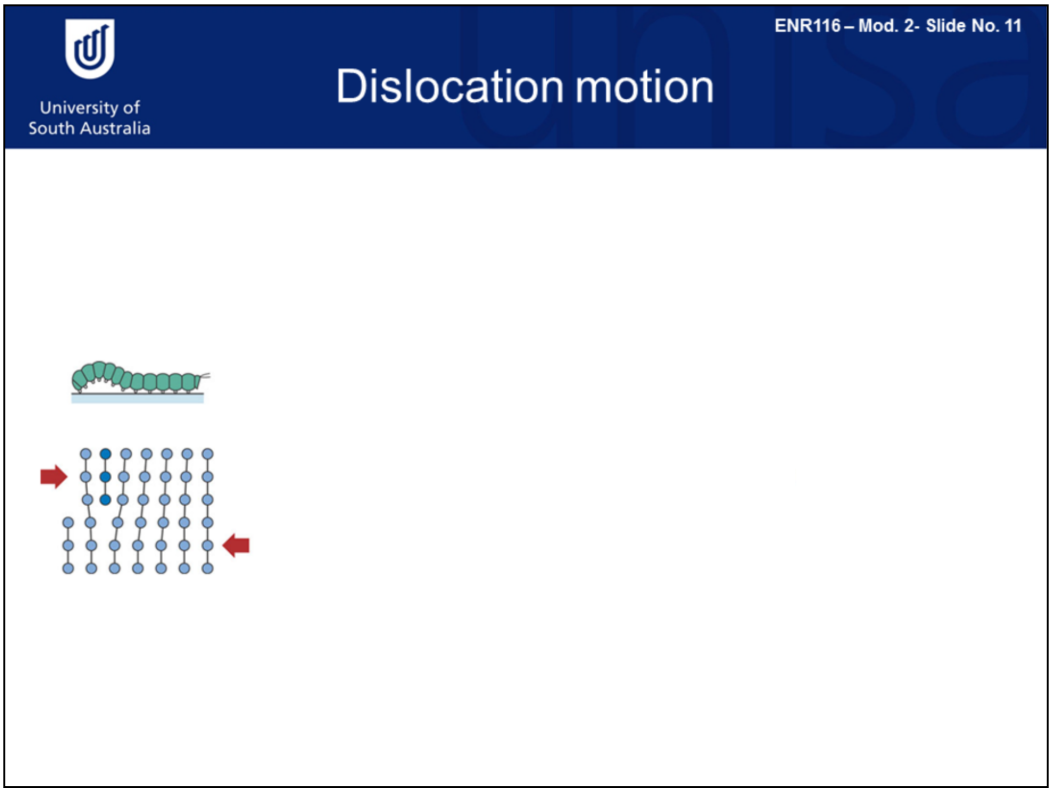
Dislocation motion

- A dislocation moves along a slip plane in a slip direction perpendicular to the dislocation line.
- Process by which plastic deformation is produced by the motion of dislocations through a crystal is called slip

Regardless of the type of dislocation, a dislocation moves along a slip plane and in a slip direction which is perpendicular to the dislocation line. The process by which plastic deformation is produced by the motion of dislocations through a crystal is called slip. You can see with the edge dislocation that the applied shear stress forces the extra plane of atoms forward in the direction of the applied force. When the same force is applied to a screw dislocation the dislocation actually moves in a direction perpendicular to the applied force as the extra plane of atoms almost unzips. However the net result is the same extra half plane of atoms appearing at the edge of the crystal in the direction of the applied force.



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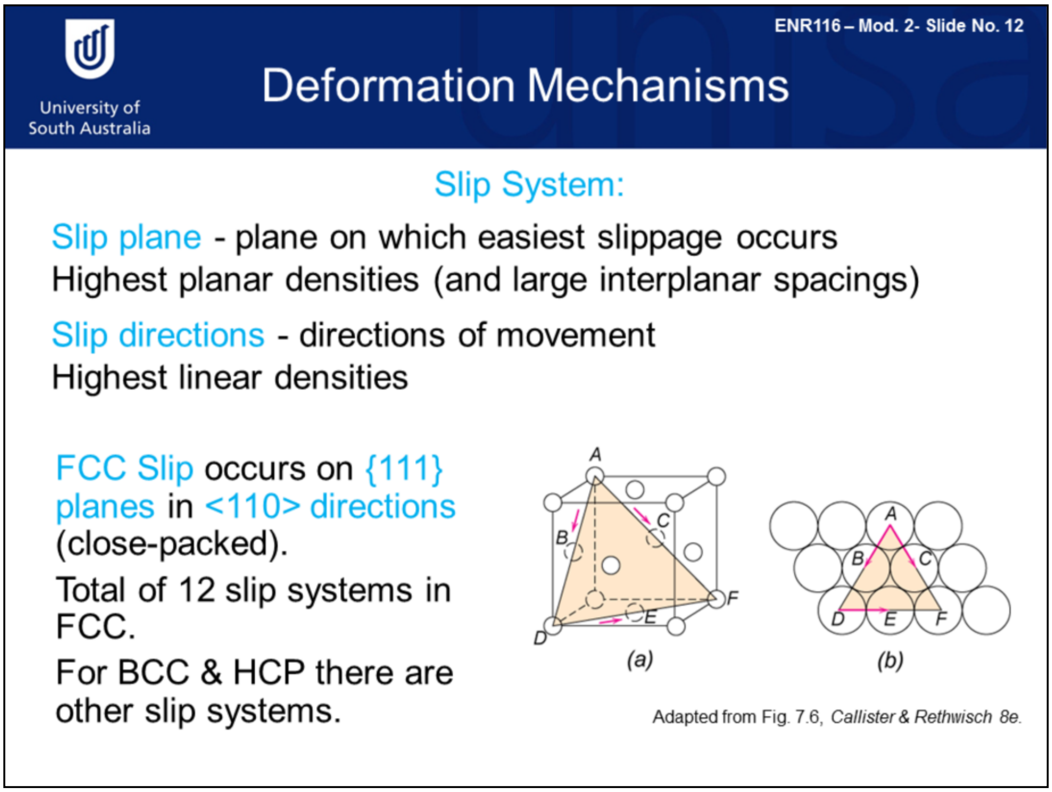
Dislocation motion

The motion of a dislocation through a crystal lattice is somewhat analogous to that of a caterpillar crawling along. The caterpillar forms a hump at the posterior end by bringing in its last pair of legs. The hump is moved forward by the sequential lifting and replacing of the rest of the pairs of legs. The result is that at the end of this process, the caterpillar has moved forward by the same distance that it originally moved the back pair of legs forward by. The hump in the caterpillar can be thought of as the extra half plane of atoms in the crystal lattice.



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Deformation Mechanisms

Slip System:

Slip plane - plane on which easiest slippage occurs
Highest planar densities (and large interplanar spacings)

Slip directions - directions of movement
Highest linear densities

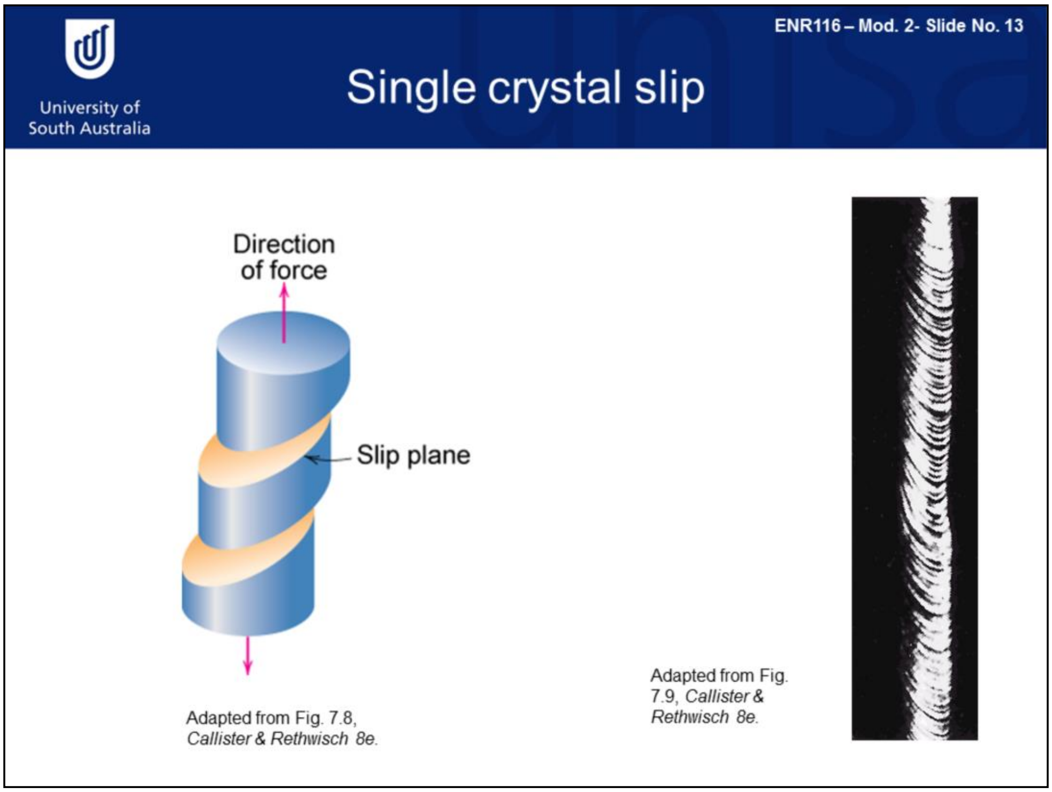
FCC Slip occurs on {111} planes in <110> directions (close-packed).

Total of 12 slip systems in FCC.

For BCC & HCP there are other slip systems.

Adapted from Fig. 7.6, *Callister & Rethwisch 8e.*

Dislocations move differently in different crystallographic directions. Ordinarily there is a preferred plane, and on that plane there are preferred directions. The preferred plane is called the slip plane it is usually the plane that has the densest atomic packing. The direction of movement is called the slip direction and is the most densely packed direction of the plane. The combination of the slip plane and the slip direction is a slip system. If you consider the face centred cubic system shown here the 111 family of planes (note the curly brackets denoting a family of planes) slip will occur along 110 type directions. Again please note the chevron brackets denoting a family of directions. As you can see in figure b more than one slip direction may occur in a slip plane. It is therefore possible that several slip systems may exist for a given crystallographic structure. In a face centred cubic system there are 12 slip systems. Four planes and each plane contains three directions.



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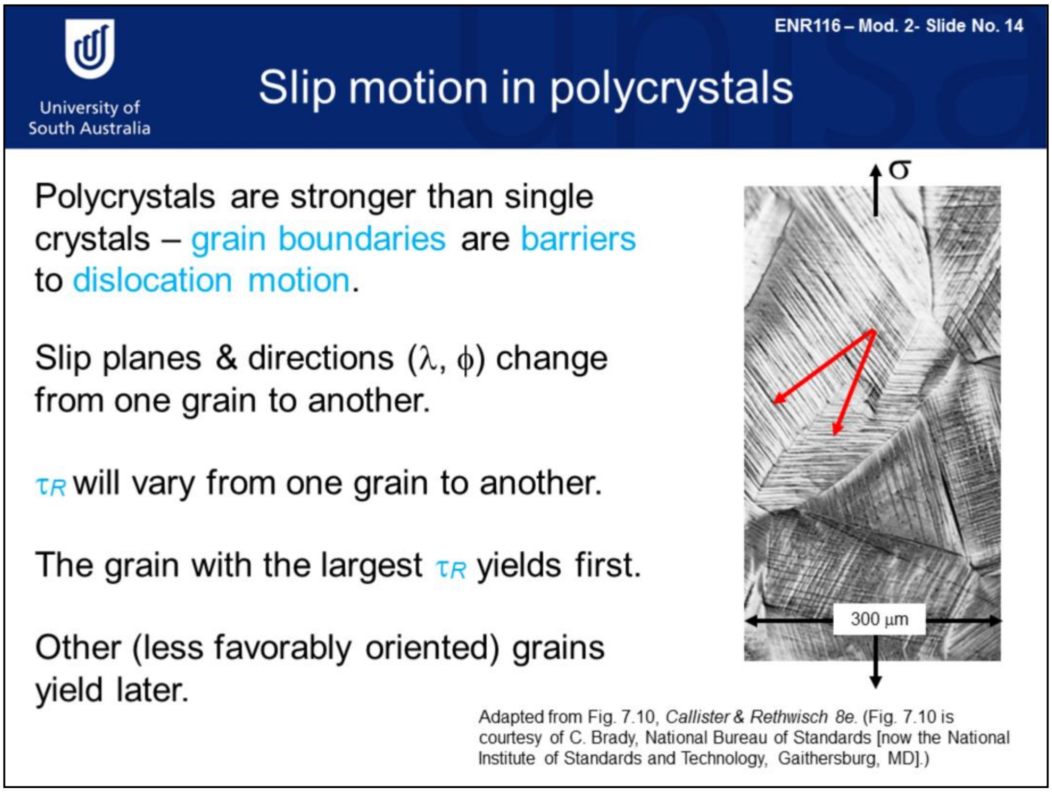
Single crystal slip

Adapted from Fig. 7.8, *Callister & Rethwisch 8e.*

Adapted from Fig. 7.9, *Callister & Rethwisch 8e.*

For a single crystal experiencing a tensile load the slip will occur along a number of equivalent and favourably oriented crystal planes along the sample. This results in small steps being visible as slip lines on the surface of the crystal as shown in this single crystal of zinc. Each step is the result of the movement of a large number of dislocations in the same slip plane.



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Slip motion in polycrystals

Polycrystals are stronger than single crystals – grain boundaries are barriers to dislocation motion.

Slip planes & directions (λ, ϕ) change from one grain to another.

τ_R will vary from one grain to another.

The grain with the largest τ_R yields first.

Other (less favorably oriented) grains yield later.

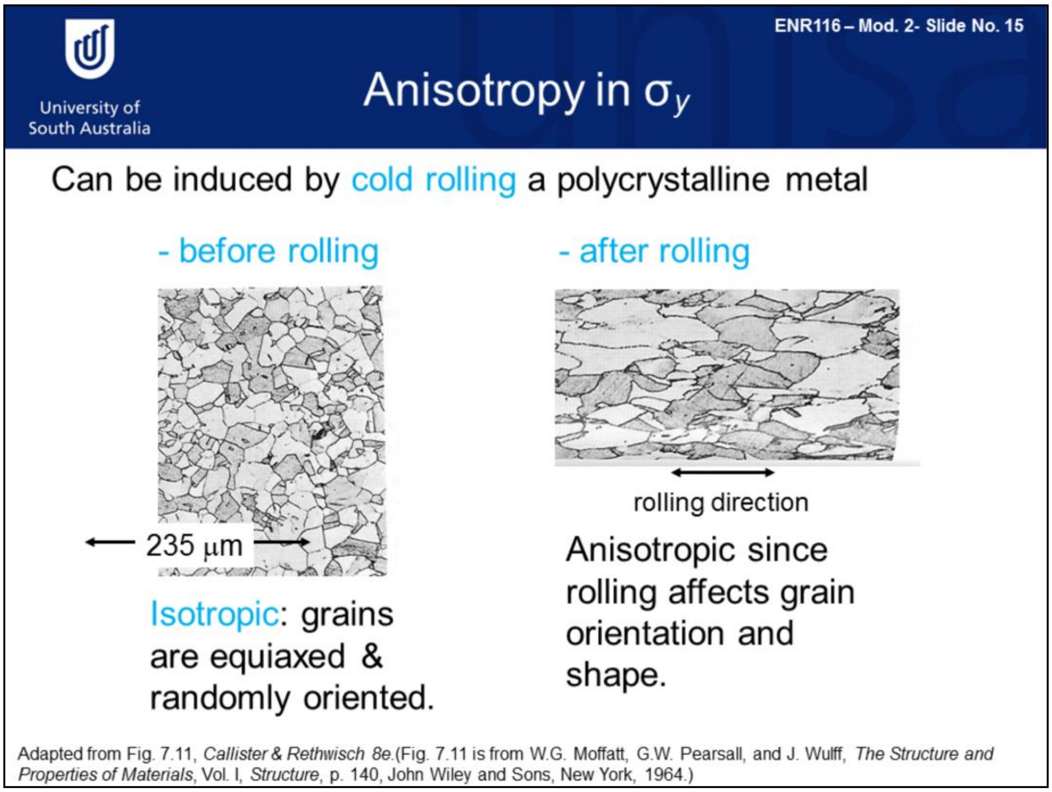
Adapted from Fig. 7.10, *Callister & Rethwisch 8e.* (Fig. 7.10 is courtesy of C. Brady, National Bureau of Standards [now the National Institute of Standards and Technology, Gaithersburg, MD].)

Deformation and slip in a polycrystalline material is a more complex situation than that in a single crystal.

Polycrystalline materials are stronger than single crystals. This is because the grain boundaries between crystals act as a barrier to the movement of dislocations.

As the crystals are randomly oriented the direction of slip varies from grain to grain. The most favourable slip system in one grain will be different to that in the grain next door. This means that the resolved shear stress will also be different from one grain to another. The grain with the highest resolved shear stress will yield first and then other less favourably oriented grains will yield later.

The photomicrograph shows a picture of slip lines on the surface of a piece of polycrystalline copper. The slip lines show that for most of the grains two slip systems operated as evidenced by the chevron like markings in the crystals.



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Anisotropy in σ_y

Can be induced by cold rolling a polycrystalline metal

- before rolling

235 μm

Isotropic: grains are equiaxed & randomly oriented.

- after rolling

rolling direction

Anisotropic since rolling affects grain orientation and shape.

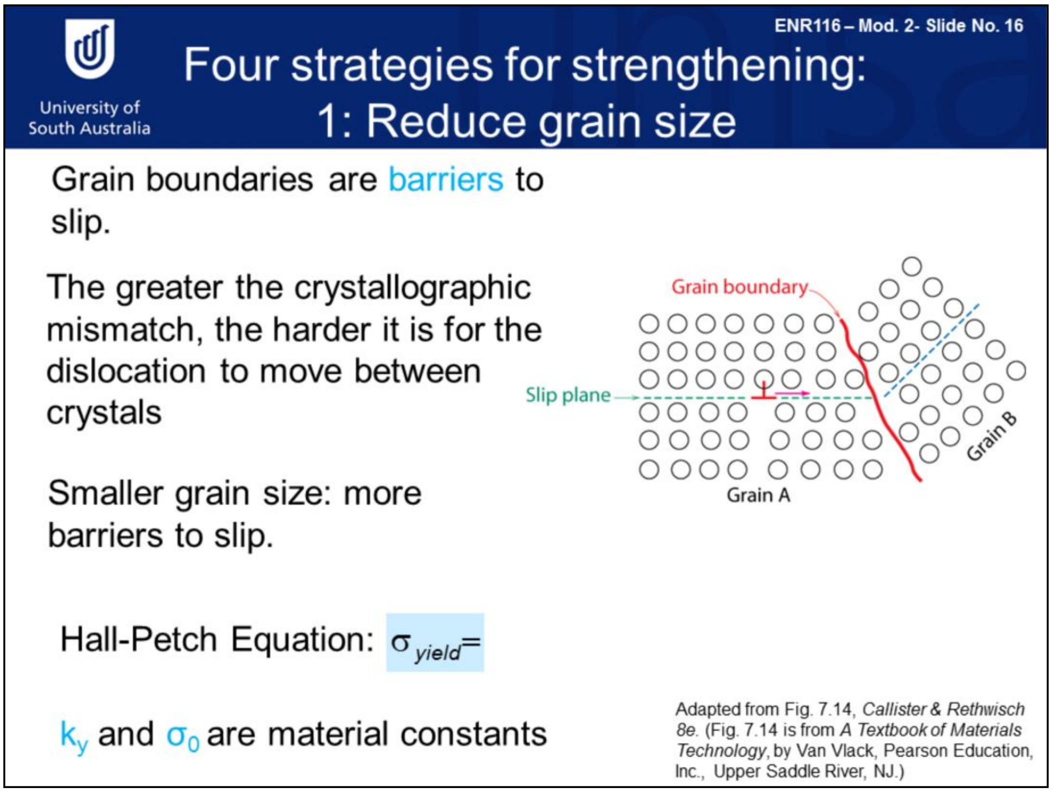
Adapted from Fig. 7.11, *Callister & Rethwisch 8e.*(Fig. 7.11 is from W.G. Moffatt, G.W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, *Structure*, p. 140, John Wiley and Sons, New York, 1964.)

Anisotropy or the ability of a material to exhibit different properties in different crystallographic directions can be induced in polycrystalline materials by cold rolling the metal.

The plastic deformation seen in polycrystalline materials is a result of the distortion of the individual grains due to slip.

Dislocations cannot pass through grain boundaries and therefore the amount of plastic deformation experienced by an individual grain is somewhat constrained by the grains surrounding it.

In an isotropic material, the grains are eqiaxial and randomly orientated. After cold rolling the grains are oriented along the direction of the rolling.



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Four strategies for strengthening: 1: Reduce grain size

Grain boundaries are barriers to slip.

The greater the crystallographic mismatch, the harder it is for the dislocation to move between crystals

Smaller grain size: more barriers to slip.

Hall-Petch Equation: $\sigma_{yield} =$

k_y and σ_0 are material constants

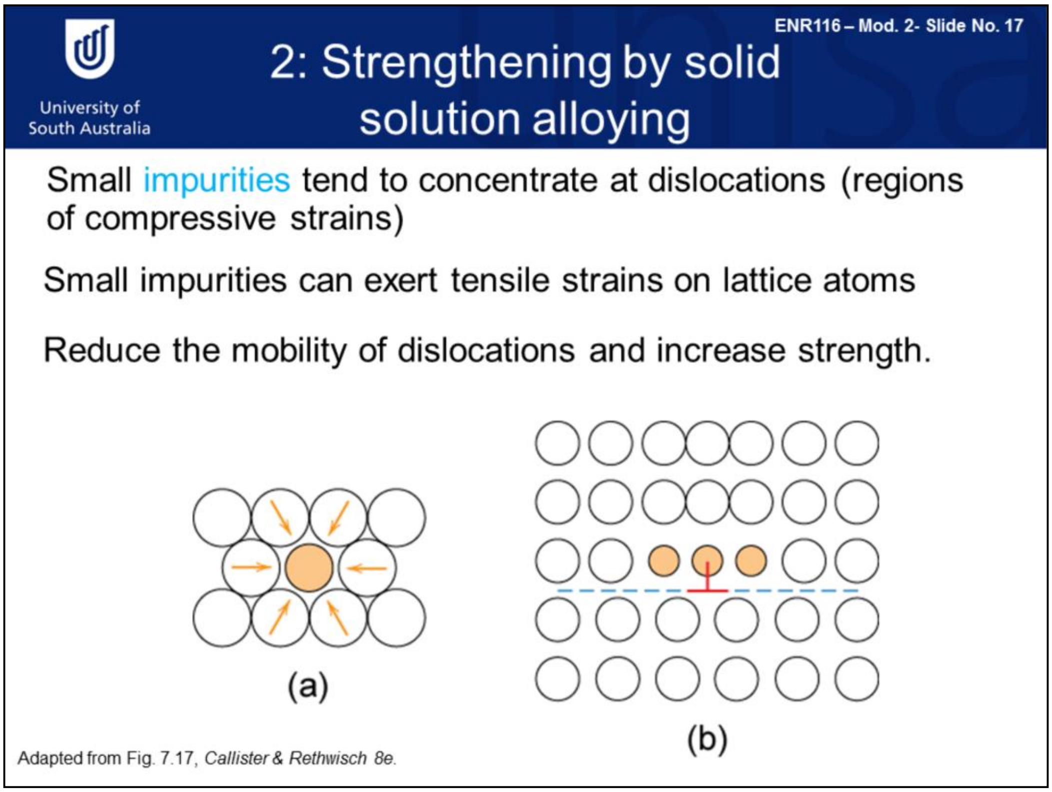
Adapted from Fig. 7.14, *Callister & Rethwisch 8e.* (Fig. 7.14 is from *A Textbook of Materials Technology*, by Van Vlack, Pearson Education, Inc., Upper Saddle River, NJ.)

There are four ways to strengthen a material.

These are to reduce the grain size, strengthen the solid by the addition of impurities, strengthen the solid by the inclusion of precipitates and strengthen the material by cold working it.

As mentioned previously dislocations cannot easily move through grain boundaries. Therefore grain boundaries are barriers to slip. Adjacent grains normally have different crystallographic orientations but share a grain boundary. During plastic deformation the dislocation must move from one grain to another. This means that it will have to change direction. The greater the crystallographic mismatch the harder it is for the dislocation to move between crystals. If the size of the crystals in the material is reduced then there are more obstacles in the path of the dislocation. A material with smaller grains is therefore harder and stronger, and usually tougher, than one that has larger grains.

For many materials the yield strength of the material varies with the grain size according to the Hall Petch equation where the yield stress is equal to sigma zero plus k y times the average grain diameter to the power of minus one half. Sigma zero and ky are material constants.



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2: Strengthening by solid solution alloying

Small impurities tend to concentrate at dislocations (regions of compressive strains)

Small impurities can exert tensile strains on lattice atoms

Reduce the mobility of dislocations and increase strength.

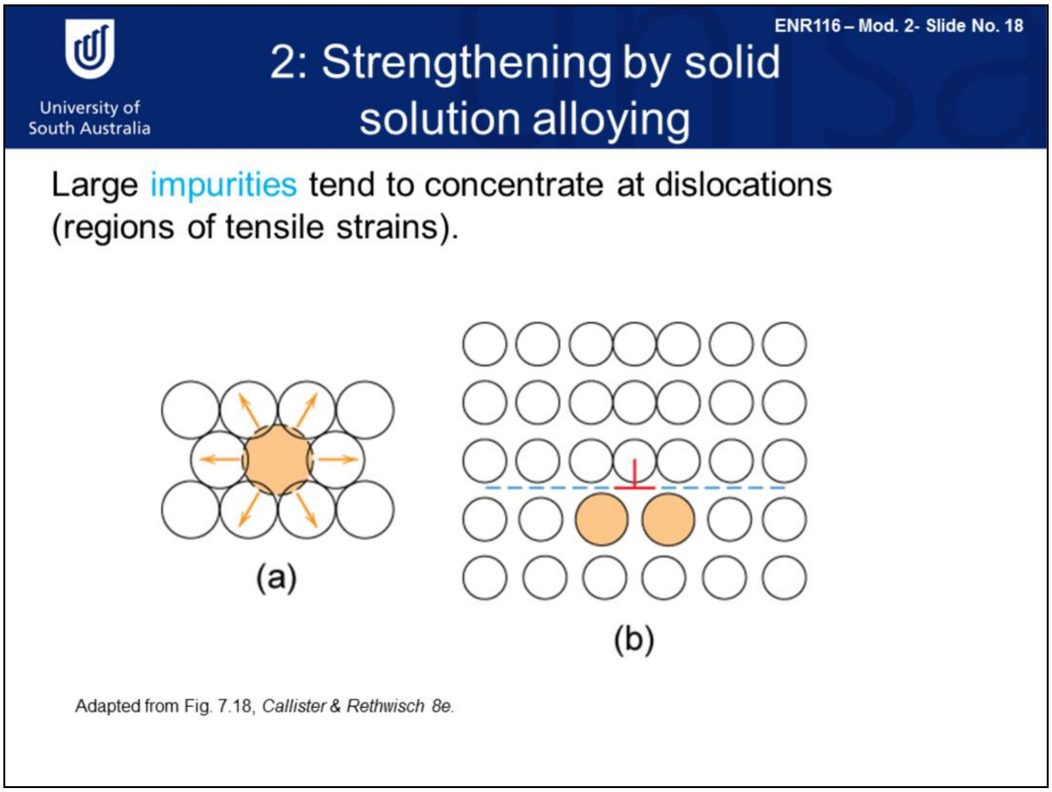
Adapted from Fig. 7.17, *Callister & Rethwisch 8e.*

Another method to strengthen and harden metals is to introduce small impurities into the metal alloy.

An example of this is the introduction of carbon into iron. The small impurities converge at dislocations.

High purity metals are nearly always softer than they're alloyed counterparts. You just have to think about the difference between high purity or 24 carat gold and 9 carat gold. I'm not only talking about the price!

Increasing the amount of the impurity strengthens the metal, it increases the tensile and yield strengths, however it often makes the metal stiffer increasing the elastic modulus but less ductile. Impurity atoms that are smaller than the atoms that they are substituting for tend to exert a tensile strain on the surrounding atoms in the crystal lattice. The presence of the impurity atoms, altering the structure of the crystal lattice, works to reduce the mobility of dislocations trying to move.



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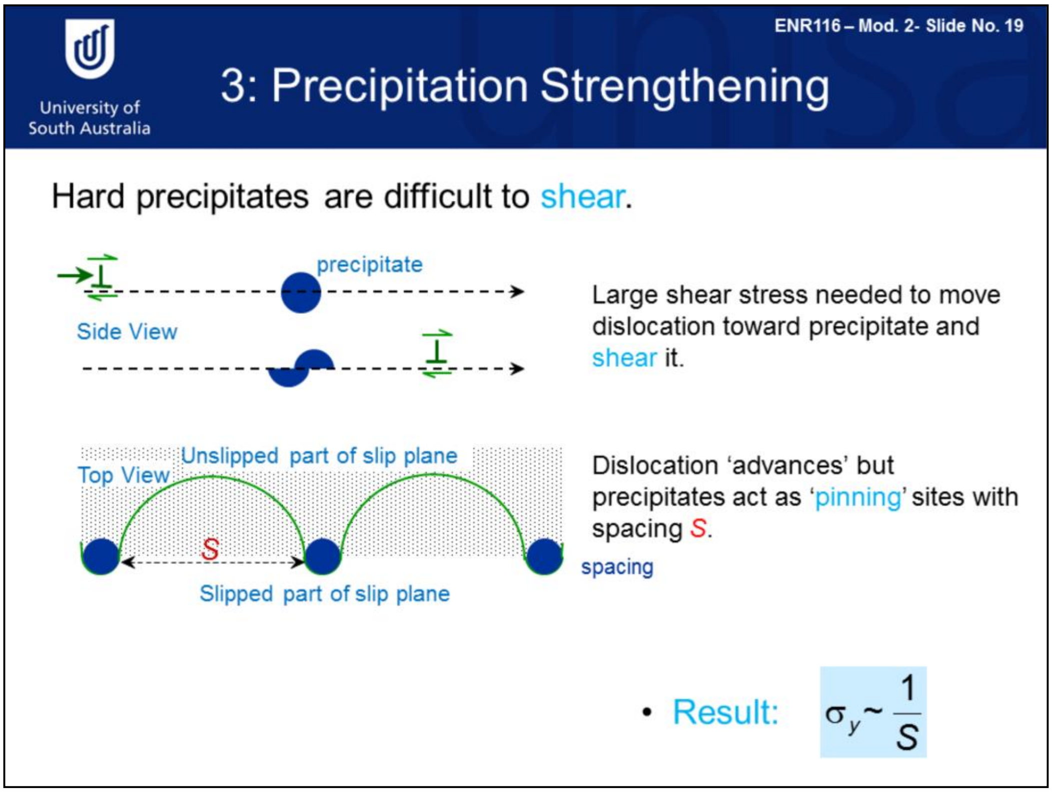
2: Strengthening by solid solution alloying

Large impurities tend to concentrate at dislocations (regions of tensile strains).

Adapted from Fig. 7.18, *Callister & Rethwisch 8e.*

Atoms that are larger than those of the base metal can also be used for solid solution alloying. Examples of this are the addition of nickel into copper and tin into lead. The addition of the larger impurities produces a tensile strain on the atoms in the surrounding crystal lattice.



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3: Precipitation Strengthening

Hard precipitates are difficult to shear.

precipitate

Side View

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

Top View

Unslipped part of slip plane

S

Slipped part of slip plane

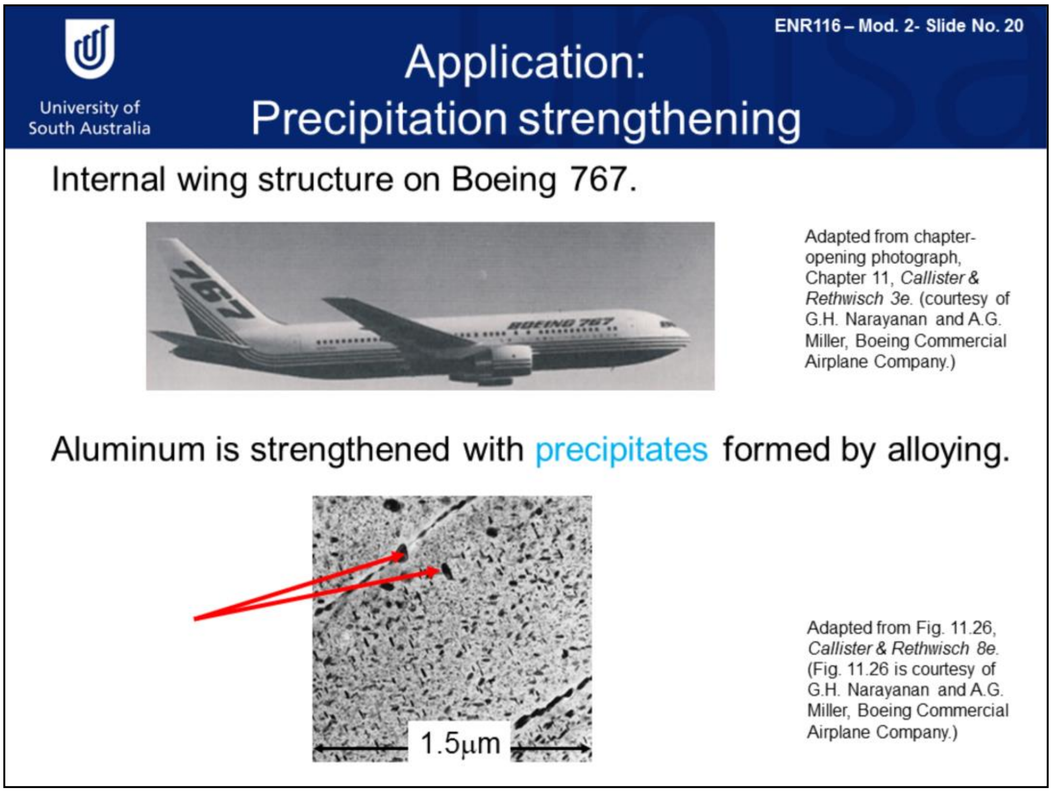
spacing

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

- Result: $\sigma_y \sim \frac{1}{S}$

Another way to harden metals is by the addition of precipitates into the metal solution. These are very small particles that have been dispersed uniformly throughout the bulk material, sometimes called a matrix.

The precipitates formed within the matrix materials are very difficult to shear. The precipitate also imposes stresses upon the surrounding crystals in the matrix. Therefore the stresses needed to move the dislocations towards the precipitate are larger; additionally to shear the precipitate even larger stresses are needed. The dislocation will be able to advance through the material but the precipitate will to a point act as a pin and stop the dislocation in its tracks. The result is that for precipitates dispersed a distance s apart within a matrix the yield stress is approximately equal to 1 divided by the distance S.



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Application: Precipitation strengthening

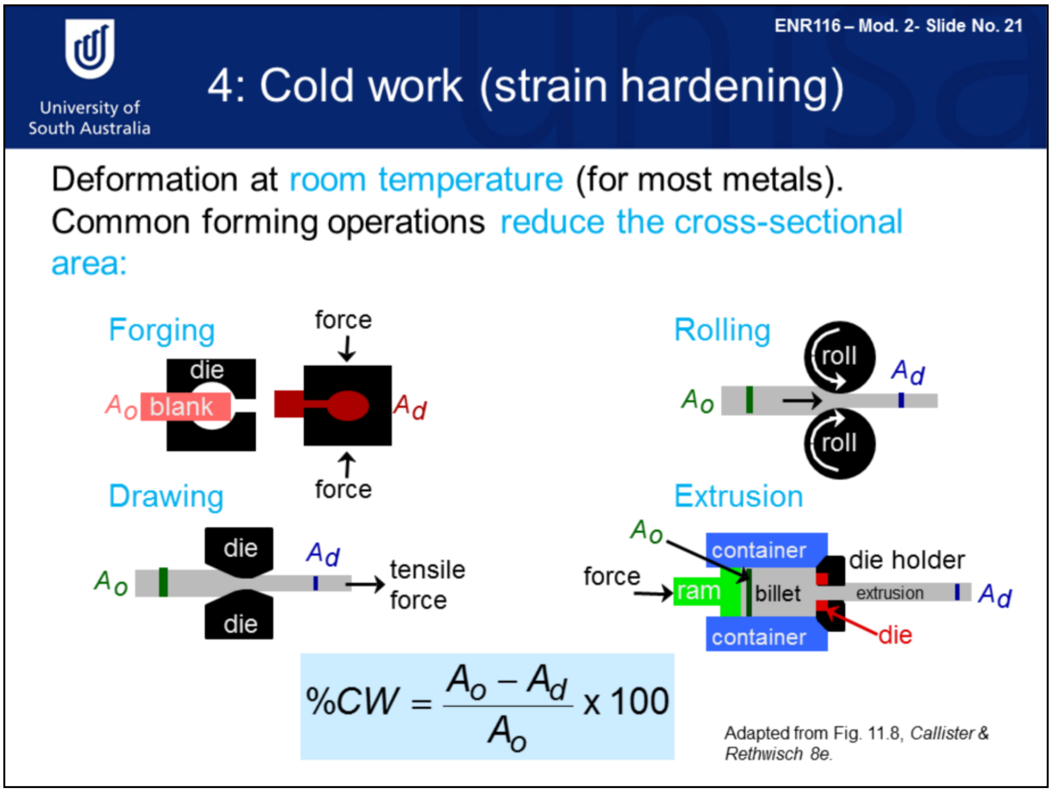
Internal wing structure on Boeing 767.

Adapted from chapter-opening photograph, Chapter 11, *Callister & Rethwisch 3e.* (courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

Aluminum is strengthened with precipitates formed by alloying.

Adapted from Fig. 11.26, *Callister & Rethwisch 8e.* (Fig. 11.26 is courtesy of G.H. Narayanan and A.G. Miller, Boeing Commercial Airplane Company.)

Precipitation strengthening is used in a variety of applications. Here we see the use of precipitation hardening used to strengthen the aluminium used in the internal wing structure of the Boeing 767. You can see the dark precipitate formed in the lighter aluminium matrix. Other alloys that are hardened using precipitation hardening are aluminium copper alloys, copper beryllium alloys, copper tin alloys and magnesium aluminium alloys.



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4: Cold work (strain hardening)

Deformation at room temperature (for most metals).
Common forming operations reduce the cross-sectional area:

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

Adapted from Fig. 11.8, *Callister & Rethwisch 8e.*

Another term for strain hardening is work hardening or cold work. It is called cold work because it is performed at relatively low temperatures, for metals!

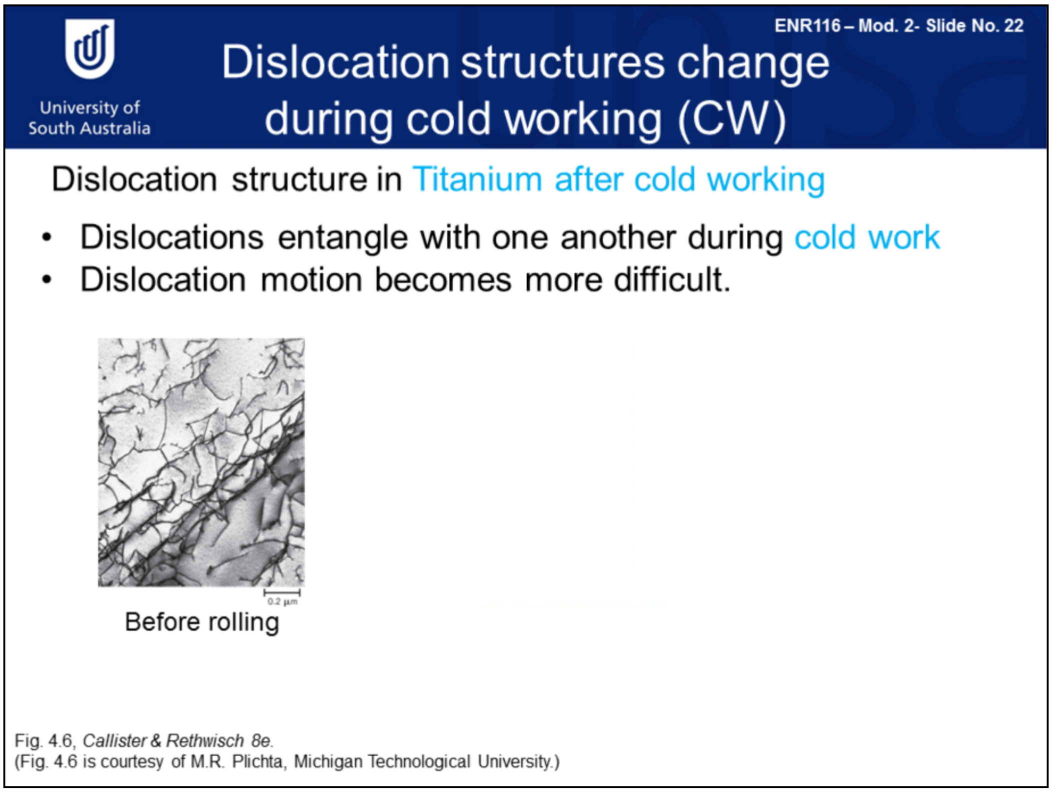
Cold work is a method of deforming the metal i.e. introducing plastic deformation which results in the metal becoming harder and stronger. Four common methods used to do this involve reducing the cross sectional area of the metal specimen. These methods are Forging which is the mechanical working or deforming of a single piece of metal. The classic example of this is the blacksmith, standing over his forge pounding a bit of metal into shape with a hammer to form a horse shoe, sword or a farm implement. Forging can be classed as either closed die or open die. In a closed die system a force is brought to bear on multiple die parts having the final shape. This results in the metal being deformed between them. An example of this is the production of coins. An open die system is used for larger pieces.

Drawing is the pulling of the piece of metal through a die that has a tapered bore by means of a force being applied on the exit side. The reduction in the cross sectional area is proportional to its change in length. This is how wire is produced.

Rolling is the most widely used cold work process. Basically the bar of metal is passed between two rollers and the resulting compressive stress applied to the bar reduces its thickness. Sheet metal and foil is produced in this manner.

Extrusion is similar to drawing except that the force applied is a compressive force. This is transferred to the metal via a ram which forces the metal through a hole in the die. Metal tubing can be formed this way.

Sometimes the percentage cold work is expressed using the equation, where the percentage cold work is equal to the original area of the specimen before cold work minus the cross section of the specimen after cold work divided by the original cross section area multiplied by 100.



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Dislocation structures change during cold working (CW)

Dislocation structure in Titanium after cold working

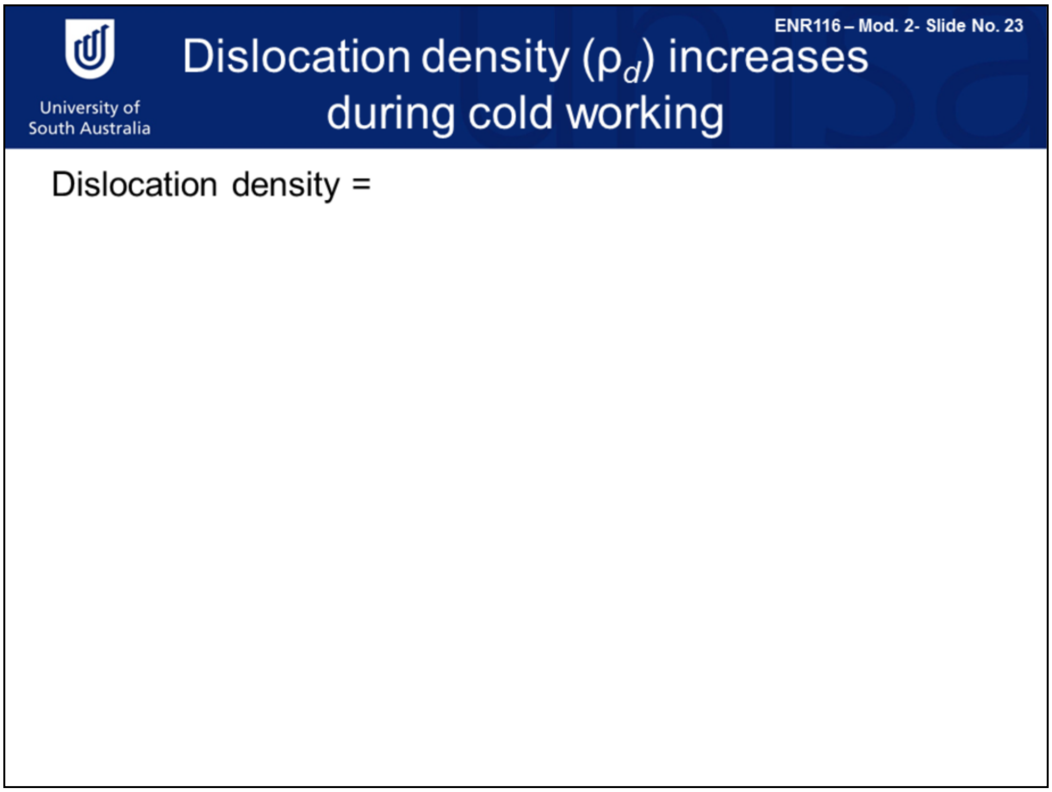
- Dislocations entangle with one another during cold work
- Dislocation motion becomes more difficult.

Before rolling

Fig. 4.6, *Callister & Rethwisch 8e.*
(Fig. 4.6 is courtesy of M.R. Plichta, Michigan Technological University.)

The phenomenon of strain hardening is explained by the movement of dislocations during plastic deformation. The dislocations start to interact with each other and entangle effectively trying to pin each other in place. This makes it more difficult for subsequent dislocations to move which means that additional slip systems become activated in less well orientated crystals.

The electron micrographs show the density of the dislocations in titanium before cold working and after 5 per cent cold work and finally after 20% cold work.



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Dislocation density (ρ_d) increases during cold working

Dislocation density =

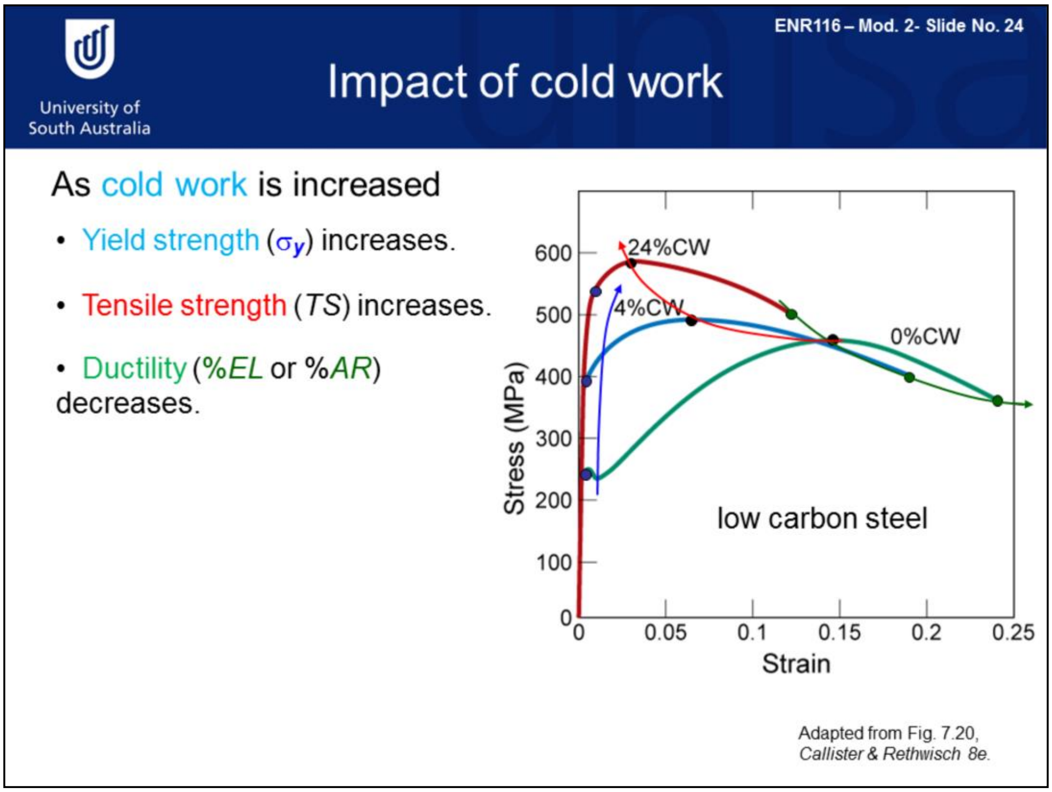
The dislocation density of a material is calculated by dividing the total dislocation length by the unit volume.

Because in essence dislocations are lines and one dimensional running through a three dimensional volume the units of dislocation density are meters per meter cubed or meters to the power of -2.

In carefully grown single crystals the dislocation density can be around ten thousand millimetres to the minus 2.

If you deform, or cold work the sample the density increases.

If the sample is then heat treated the dislocation reduces again. As the dislocation density increases the yield stress increases.



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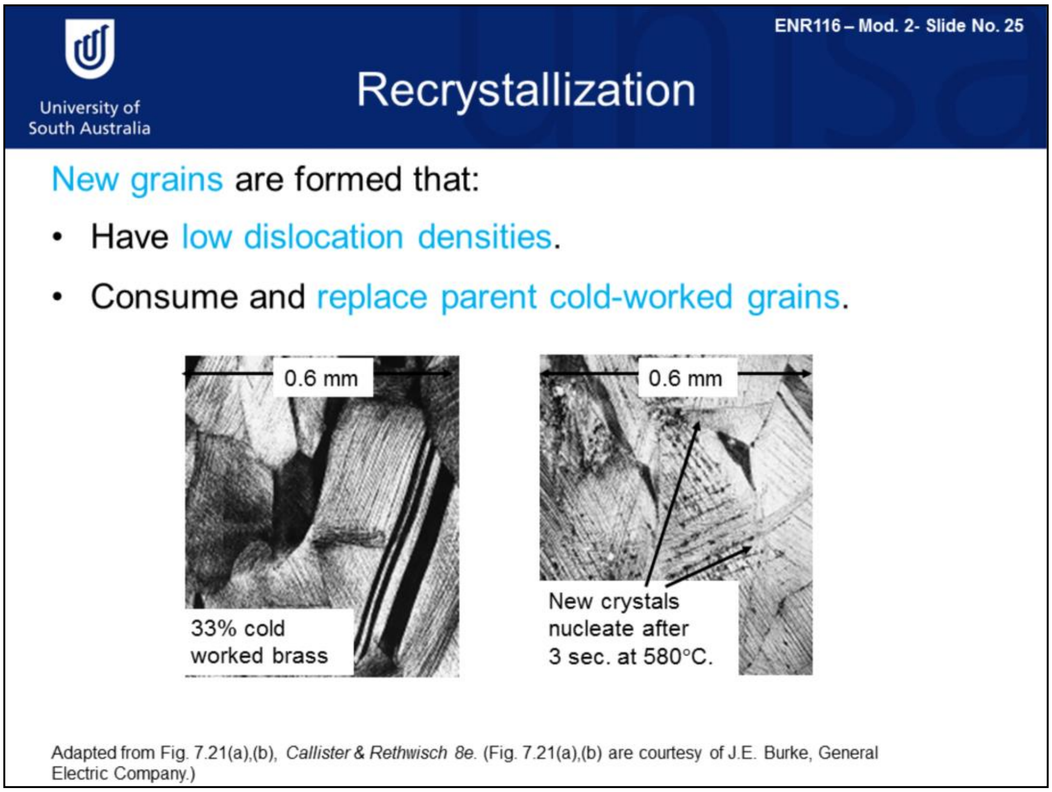
Impact of cold work

As cold work is increased

- Yield strength (σ_y) increases.
- Tensile strength (*TS*) increases.
- Ductility (%*EL* or %*AR*) decreases.

Adapted from Fig. 7.20, *Callister & Rethwisch 8e.*

This is summarised in this slide. You can see that as the amount of cold work introduced into this sample of low carbon steel is increased, the yield strength increases. This is accompanied by an increase in the tensile strength of the material. However the ductility is reduced.



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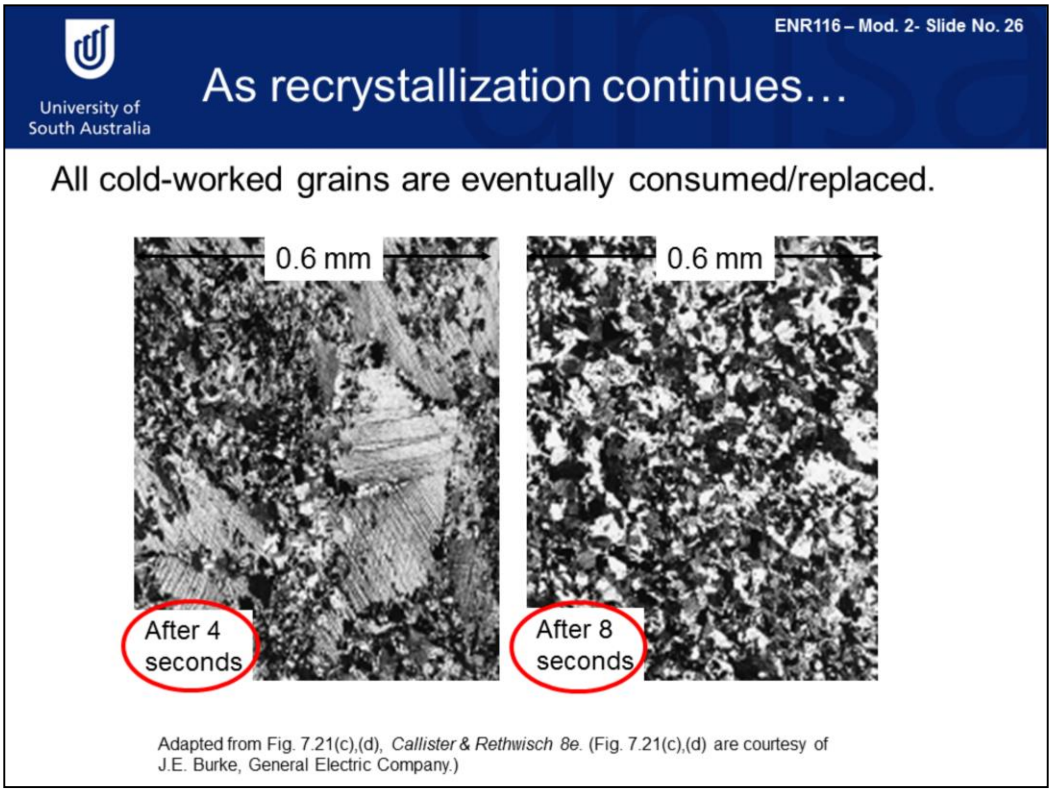
Recrystallization

New grains are formed that:

- Have low dislocation densities.
- Consume and replace parent cold-worked grains.

Adapted from Fig. 7.21(a),(b), *Callister & Rethwisch 8e.* (Fig. 7.21(a),(b) are courtesy of J.E. Burke, General Electric Company.)

As I just mentioned if you heat treat a sample the dislocation density decreases. This is due to a process called recrystallisation. This is the process by which new grains are formed that are strain free and are eqiaxed. These new grains have low dislocation densities. The new grains form as small nuclei and grow until they consume the parent cold worked grains. You can see the difference in the grain size and dislocation density by looking at these electron micrographs. In the cold worked specimen the grains are different shapes and the lines of dislocations are very visible. In the recrystallised grains the grains are much more regular in shape and have fewer dislocation lines.



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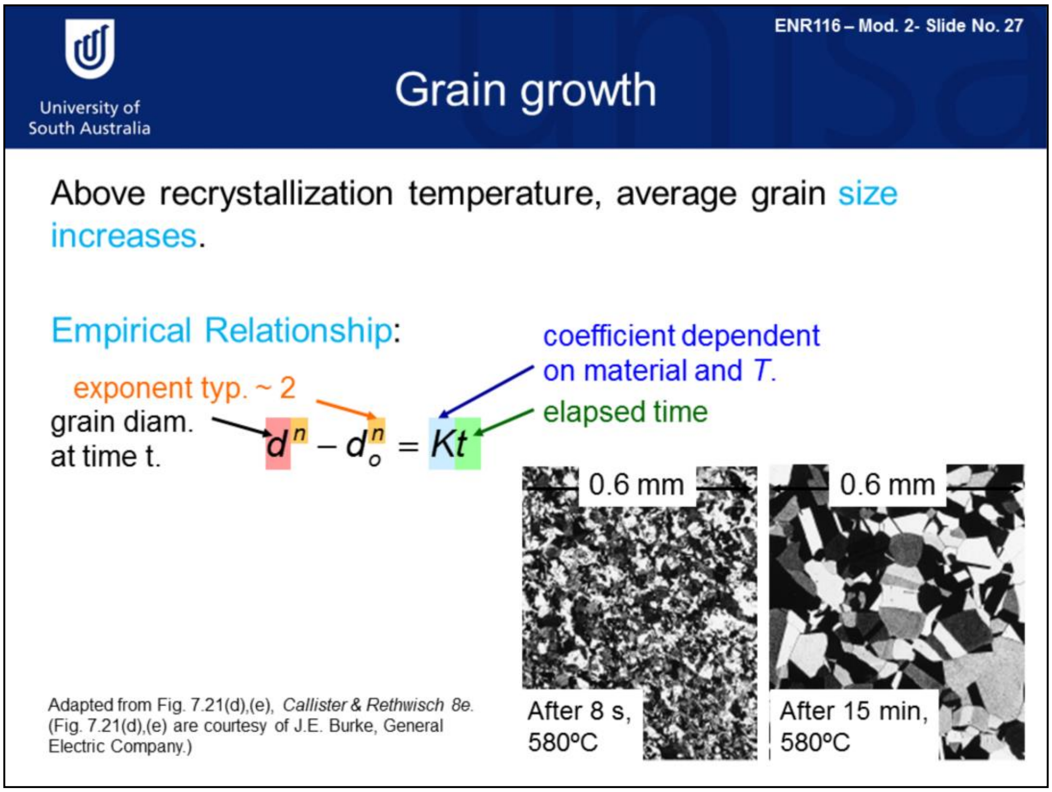
As recrystallization continues…

All cold-worked grains are eventually consumed/replaced.

Adapted from Fig. 7.21(c),(d), *Callister & Rethwisch 8e.* (Fig. 7.21(c),(d) are courtesy of J.E. Burke, General Electric Company.)

In this slide you can see the process of recrystallisation occurring. After 4 seconds you can see the new grains starting to encroach on the larger cold worked grains. After 8 seconds the larger cold worked grains have more or less disappeared having being consumed by the new grains.

The temperature of recrystallisation is much lower than the melting temperature of the metal. It is usually between one third and one half of the melting temperature of the metal.



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Grain growth

Above recrystallization temperature, average grain size increases.

Empirical Relationship:

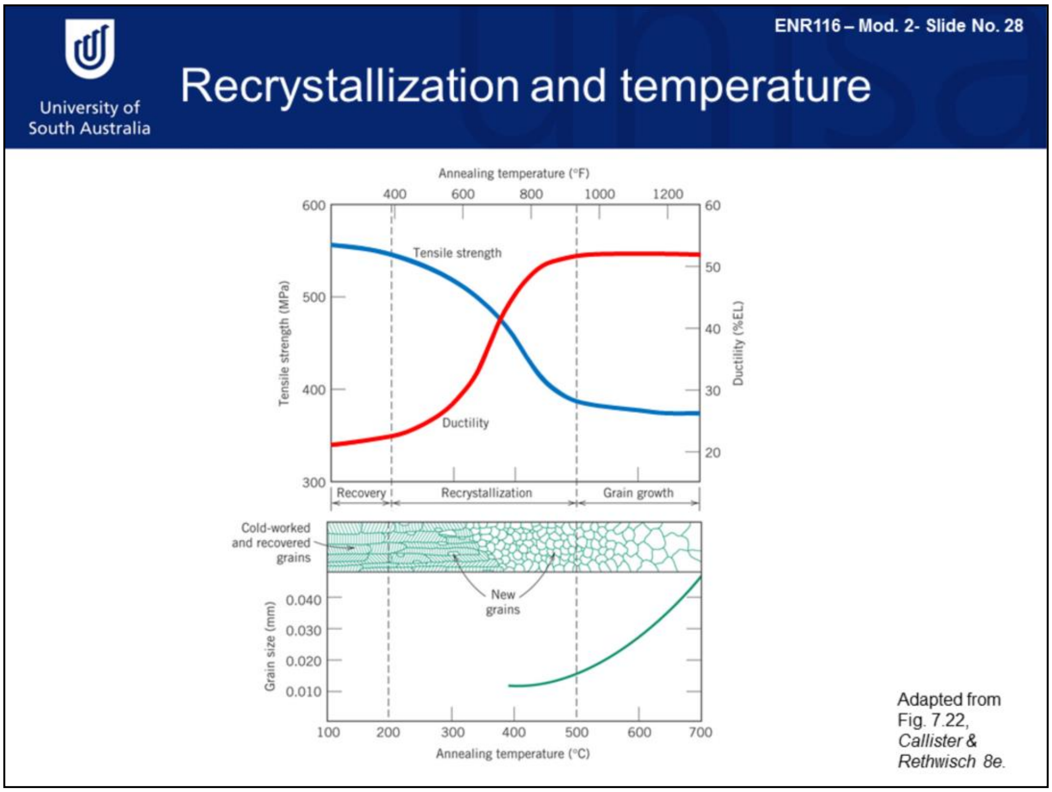
$$d^n - d_o^n = Kt$$

After 8 s, 580ºC

After 15 min, 580ºC

Adapted from Fig. 7.21(d),(e), *Callister & Rethwisch 8e.* (Fig. 7.21(d),(e) are courtesy of J.E. Burke, General Electric Company.)

After the process of recrystallisation has finished if the temperature of the metal is not reduced back to below its recrystallisation temperature the grains will continue to grow and merge with smaller grains merging to form larger and larger grains. For many polycrystalline materials the grain diameter d varies with time. This is described by the relationship whereby the grain dimension at time t to the power n minus the initial grain diameter to the power n is equal to the material constant K multiplied by the time. K and n are material properties and are time independent. N is usually greater than or equal to 2.



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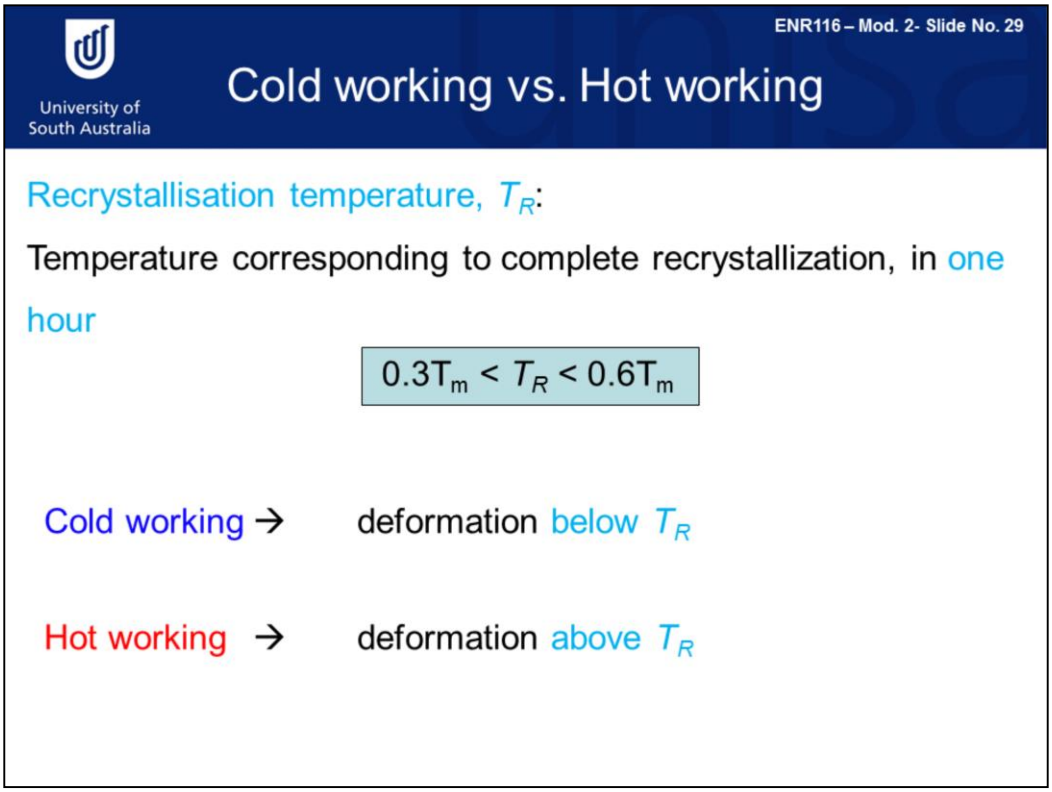
Recrystallization and temperature

Adapted from Fig. 7.22, *Callister & Rethwisch 8e*.

You can see how as the temperature increases the structure of the material changes and how this results in a decrease in the tensile strength of the material with a corresponding increase in ductility. This process is called annealing and is used as a way to reduce the brittleness of materials after cold working.



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Cold working vs. Hot working

Recrystallisation temperature, T_R:

Temperature corresponding to complete recrystallization, in one hour

$$0.3T_m < T_R < 0.6T_m$$

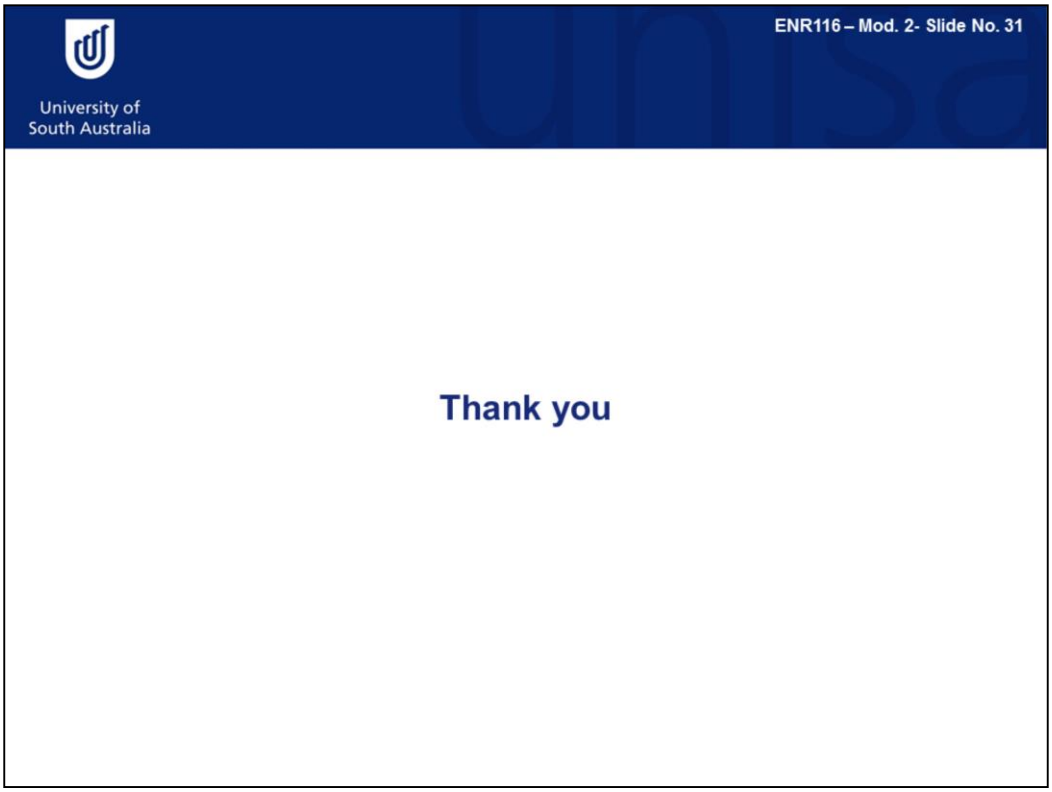
Cold working → deformation below T_R

Hot working → deformation above T_R

When working with a material it is useful to know whether you are hot working or cold working. Cold working is work done to the material at a temperature below its recrystallisation temperature. Hot working is work done to a material above its recrystallisation temperature. So whilst the process might feel hot i.e. work at 200 degrees centigrade, if this is below the recrystallisation temperature of the material then it is cold working. It does not necessarily have to occur at room temperature.

Summary

- Dislocation motion occurs along the slip planes present in crystallographic structures.
- The strength of metals is increased by making dislocation motion difficult.
- Methods to increase strength are: decreasing grain size, solid solution strengthening, precipitate hardening and/or cold working.



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Thank you

Thank you for your attention during this lecture summary. The concepts covered in this lecture summary are covered in chapter seven of the course text book. With additional information in chapter eleven. If you have any questions please post them on the message board.