

ENR212 Lecture 2 Notes and Slides

Slide 1

Manufacturing Processes
Lecture 2

UniSA

THE NATURE OF MATERIALS

Dr Jun Ma

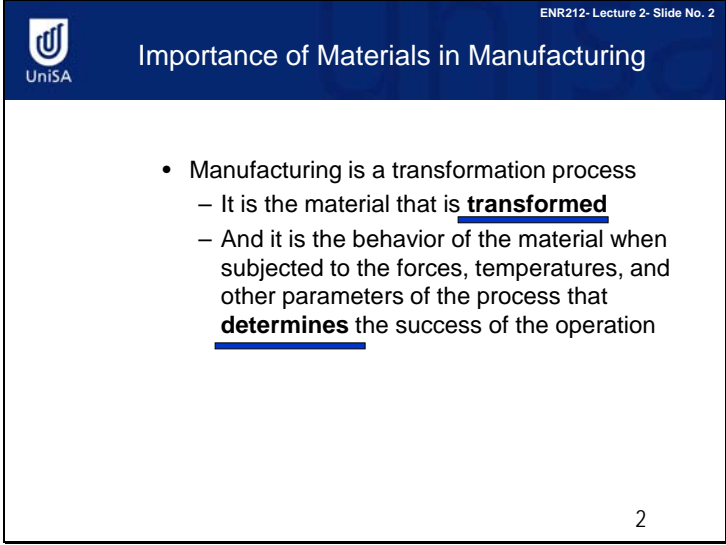
1. Atoms and bonding
2. Crystalline Structures
3. Amorphous (Noncrystalline) Structures

Hello everyone, and welcome to lecture summary two of Manufacturing Processes. (This lecture will cover content from chapter 2 of the textbook.)

In this lecture, we will introduce materials in manufacturing. We will address the following three questions: first, what is an atom, and what are the bondings between molecules, and between atoms? Second, what are crystalline structures, and how do atoms arrange themselves in a crystalline structure? Third, what are amorphous structures and what are the features of amorphous materials?

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Importance of Materials in Manufacturing

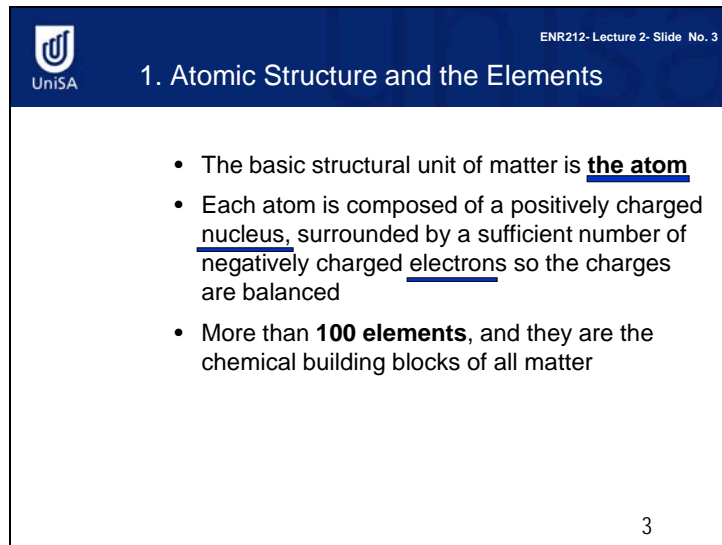
- Manufacturing is a transformation process
 - It is the material that is **transformed**
 - And it is the behavior of the material when subjected to the forces, temperatures, and other parameters of the process that **determines** the success of the operation

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Materials are of great importance in manufacturing for two reasons. First, the aim of manufacturing is to transform materials from one state to another more advanced state with increased value. Second, it is the material properties that determine the manufacturing processes, such as the set up of machines.

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1. Atomic Structure and the Elements

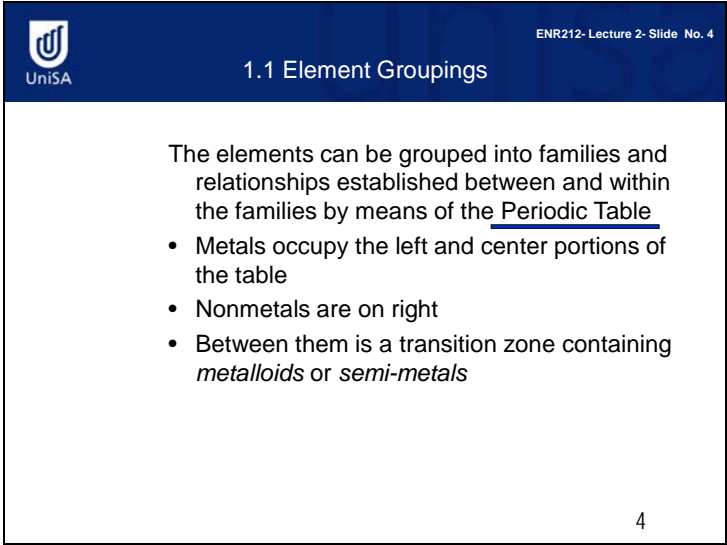
- The basic structural unit of matter is the atom
- Each atom is composed of a positively charged nucleus, surrounded by a sufficient number of negatively charged electrons so the charges are balanced
- More than **100 elements**, and they are the chemical building blocks of all matter

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There are two levels of structural unit: atom and molecule. The basic structural unit of a material is the atom. Each atom comprises a dense nucleus and electrons. The nucleus includes protons and a neutron. There are more than 100 elements in total.

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1.1 Element Groupings

The elements can be grouped into families and relationships established between and within the families by means of the Periodic Table

- Metals occupy the left and center portions of the table
- Nonmetals are on right
- Between them is a transition zone containing *metalloids* or *semi-metals*

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Based upon the atomic number and the outermost electron configuration of elements, these elements are grouped and classified in the Periodic table. Note that the atomic number of an atom is the numbers of protons in this atom.

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1.2 Periodic Table

Periodic Table of Elements. Atomic number and symbol are listed for the 103 elements.

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In the periodic table, all elements are sequenced according to their atomic number. For example, the top right element is helium. The value on the top of Helium is the atomic number of Helium.

The three types of elements are metals, non-metals and semi-metals. Non-metals are located in the right part of the table. Metals are in the left and in the middle. Between the middle and the right part of the table is the transition zone, which contains semi-metals such as silicon.

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UniSA 1.2 Bonding between Atoms and Molecules

Atoms are held together in molecules by various types of bonds

1. **Primary bonds** - generally associated with formation of molecules
2. **Secondary bonds** - generally associated with attraction between molecules

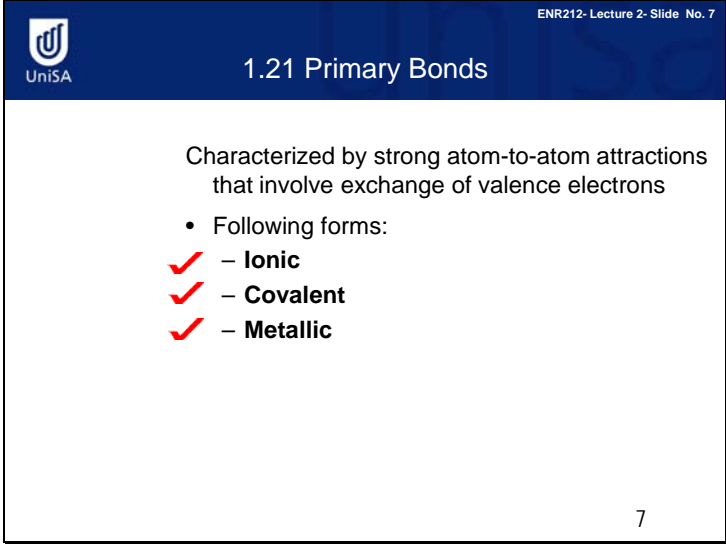
- Primary bonds are **much stronger** than secondary bonds

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There are two levels of interaction in materials. Primary bonds exist between atoms. Secondary bonds exist between molecules. In general, primary bonds are much stronger than secondary bonds. This explains why metals generally have higher absolute strength than polymers.

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1.21 Primary Bonds

Characterized by strong atom-to-atom attractions that involve exchange of valence electrons

- Following forms:
 - ✓ – **Ionic**
 - ✓ – **Covalent**
 - ✓ – **Metallic**

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Primary bonds include ionic bonds, covalent bonds and metallic bonds.

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1.211 Ionic Bonding

Atoms of one element give up their outer electron(s), which are in turn attracted to atoms of some other element to increase electron count in the outermost shell to eight

Three forms of primary bonding:
(a) Ionic

The diagram illustrates the process of ionic bonding. On the left, a 'Metal ion(+)' is shown with a central nucleus containing a '+' sign and an 'Outer orbit' containing one electron. An arrow points from this electron to the right, where a 'Nonmetal ion(-)' is shown with a central nucleus containing a '+' sign and an outer orbit containing two electrons. One of these electrons is labeled as a 'Transferred electron' with a red arrow pointing to it. Below the diagram is the label '(a) Ionic'.

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Ionic bonding involves electron transfers. As you can see in this image, electrons are transferred from the metal ion to the non-metal ion. The electrons are only transferred between these two ions, not to other atoms. This means that the ionic bonding is directional, and it explains why ionic bonding materials are not electrically and thermally conductive.

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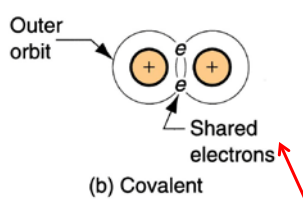
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1.212 Covalent Bonding

Electrons are shared (as opposed to transferred) between atoms in their outermost shells to achieve a stable set of eight

Three forms of primary bonding: (b) covalent



Outer orbit

Shared electrons

(b) Covalent

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The diagram illustrates two atoms, each represented by a central orange nucleus with a '+' sign and a surrounding white outer orbit. The two outer orbits overlap, and within the overlapping region, two electrons are shown, each labeled with a lowercase 'e'. A red arrow points to these two electrons, which are labeled 'Shared electrons'. A black arrow points to the outer orbit of the left atom, labeled 'Outer orbit'. Below the diagram, the text '(b) Covalent' is written.

Shared electrons are involved in covalent bonding. As you see in this figure, a pair of electrons is shared by two atoms. This means the covalent bonding is directional. Therefore, covalent bonding such as in wood is not electrically and thermally conductive.

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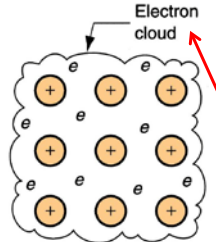
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1.213 Metallic Bonding

Sharing of outer shell electrons by all atoms to form a general electron cloud that permeates the entire block

Three forms of primary bonding: (c) metallic



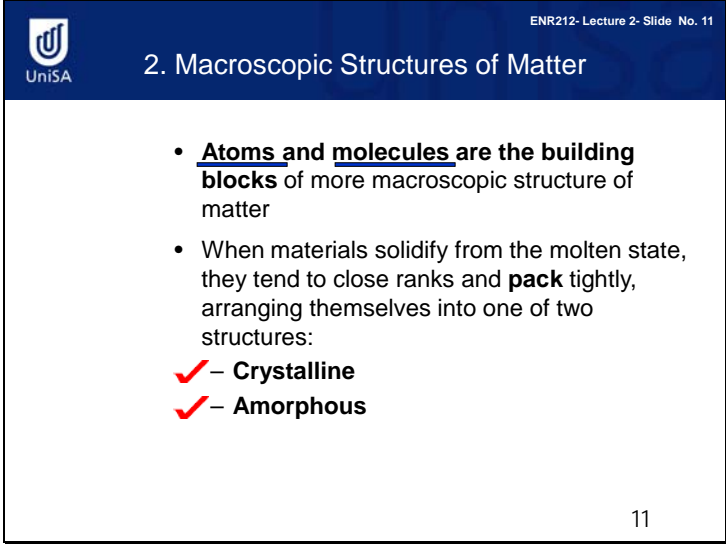
The diagram illustrates metallic bonding. It shows a 3x3 grid of nine orange circles, each containing a '+' sign, representing positive metal ions. These ions are surrounded by a cloud of small 'e' symbols, representing delocalized electrons. A red arrow points to the cloud with the label 'Electron cloud'. Below the diagram is the label '(c) Metallic'.

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In metallic materials, each atom contributes at least an electron, so there are a great many electrons in a metal. These electrons have complete freedom. That is, one electron is able to move from one atom to another. Therefore, metallic bonding is not directional. This explains why metallic materials are electrically and thermally conductive and why metals are normally stronger than organic materials such as wood, which comprises covalent bonding.

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2. Macroscopic Structures of Matter


- Atoms and molecules are the building blocks of more macroscopic structure of matter
- When materials solidify from the molten state, they tend to close ranks and **pack** tightly, arranging themselves into one of two structures:
 - ✓ – **Crystalline**
 - ✓ – **Amorphous**

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The building blocks of materials include atoms and molecules. Atoms are the building blocks of metals, while molecules are the building blocks of polymers. Materials are classified into crystalline and amorphous, according to how the atoms arrange themselves.

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2.1 Crystalline Structure

Structure in which atoms are located at **regular and recurring positions** in three dimensions

- **Unit cell** - basic geometric grouping of atoms that is repeated
- The pattern may be replicated millions of times within a given crystal
- Characteristic structure of virtually all metals, as well as many ceramics and some polymers

AtomS

↓

Unit cellS

↓

CrystalS

Grain boundaries

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In a crystalline structure, the atoms are arranged at regular and recurring positions. That is, the atoms in a crystalline structure are disordered. Atoms are combined into unit cells. Unit cells are combined to produce crystals. The size of atoms is around 0.1 to 0.13 nanometers. The average size of unit cells is around 0.4 to 0.6 nanometers. The size of crystals range from nanometers to millimeters.

The combination between atoms and the combination between unit cells is very good. However, the combination between crystals is not good at all, and produces defects. The area between crystals is called the grain boundary. Grain boundaries are defects of metals. However, grain boundaries are desirable in manufacturing, because more grain boundaries means lower yield strength and higher ductility. This reduces manufacturing costs.

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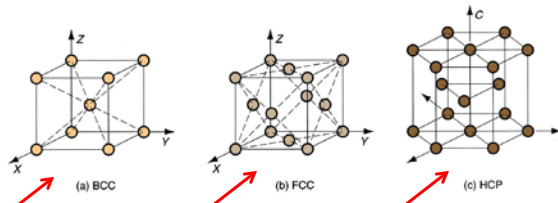
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2.11 Three Crystal Structures in Metals

1. Body-centered cubic
2. Face-centered cubic
3. Hexagonal close-packed



(a) BCC (b) FCC (c) HCP

Three types of crystal structure in metals.

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There are three crystal structures for metals: body-centered cubic structure, face-centered cubic structure and hexagonal close-packed structure.


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Crystal Structures for Common Metals




Room temperature crystal structures for some of the common metals:

- ✓ **Body-centered cubic (BCC)**
 - Chromium, **Iron**, Molybdenum, Tungsten
- ✓ **Face-centered cubic (FCC)**
 - **Aluminum**, Copper, Gold, Lead, Silver, Nickel
- **Hexagonal close-packed (HCP)**
 - Magnesium, Titanium, Zinc

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Body-centered cubic materials, such as iron, have very good strength at room temperature, but their fracture toughness at low temperature is poor. Do you remember the movie 'Titanic'. It was about a ship which sank, leading to the loss of 2000 lives. It sank because it was made of iron, which has low toughness at low temperatures in icy water.

Face-centered materials, such as aluminium, are not as strong as body-centered cubic materials at room temperature. However, aluminium has very good toughness at low temperature. If the Titanic was made of aluminium instead of iron, it would not have sunk.

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2.12 Imperfections (Defects) in Crystals

- Imperfections often arise due to inability of solidifying material to continue replication of unit cell, e.g., grain boundaries in metals
- Imperfections can also be introduced purposely; e.g., addition of alloying ingredient in metal
- Types of defects:
 1. **Point defects**
 2. **Line defects**
 3. **Surface defects**

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During solidification processes, imperfection or defects in crystals of metals are produced when the temperature is reduced from melting temperature to room temperature. An example of defects is grain boundaries. As we have discussed, grain boundaries are the area between crystals and grains. There are three types of defects: point defects, line defects and surface defects. Surface defects are actually grain boundaries.

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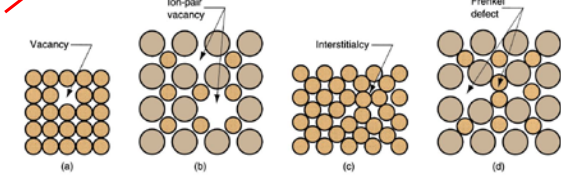
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1.121 Point Defects

Imperfections in crystal structure involving either a single atom or a few number of atoms



(a) Vacancy (b) Ion-pair vacancy (c) Interstitialcy (d) Frenkel defect


Figure Point defects: (a) vacancy, (b) ion-pair vacancy, (c) interstitialcy, (d) displaced ion (Frenkel Defect).

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Point defects are imperfections in the crystal structure of metals, in which only one or a few atoms are missing.

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2.122 Line Defects

Connected group of point defects that forms a line in the lattice structure

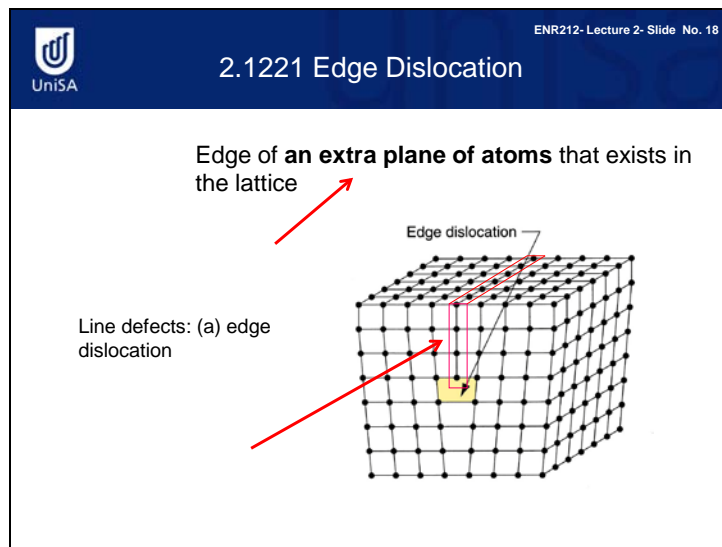
- Most important line defect is a *dislocation*, which can take two forms:
 - ✓ – Edge dislocation
 - ✓ – Screw dislocation

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Line defects are connected point defects that form a line in the lattice. Line defects are classified into edge dislocations and screw dislocations.

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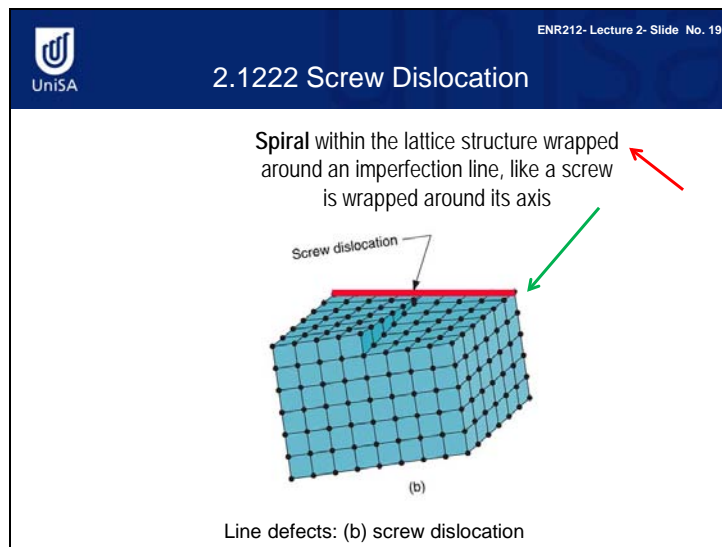
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An edge dislocation is the edge of an extra plane of atoms that exists in the lattice. In this image, the area included in the red rectangle represents an edge dislocation.

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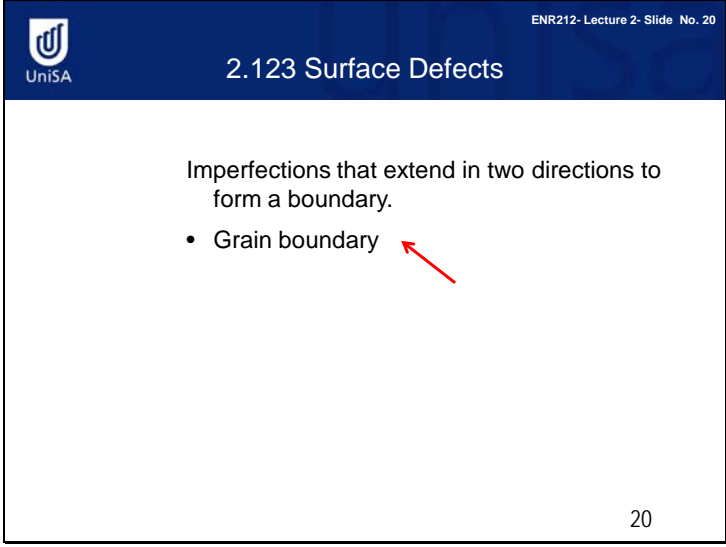
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A screw dislocation is a spiral in the lattice structure which is wrapped around an imperfection line, as you can see in this image. The red line represents an imperfection line.

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2.123 Surface Defects

Imperfections that extend in two directions to form a boundary.

- Grain boundary 

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Surface defects are actually grain boundaries. The grain boundaries are just areas between crystals, between the grains of metals.

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2.13 Elastic Strain

When a crystal experiences a gradually increasing stress, it first deforms *elastically*

- If force is removed lattice structure returns to its original shape

Deformation of a crystal structure: (a) original lattice: (b) elastic deformation, with no permanent change in positions of atoms.

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There are two types of deformation of materials: elastic deformation and plastic deformation. An example of elastic deformation is the elongation of a rubber band. Plastic deformation examples include the fracture of ductile thermal plastics.

This image shows the elastic deformation of a crystal lattice. Under shear loading and stress, the lattice structure changes slightly. Upon removal of the loading, the lattice is able to revert back to its original shape immediately and completely. This is called elastic deformation or elastic strain.

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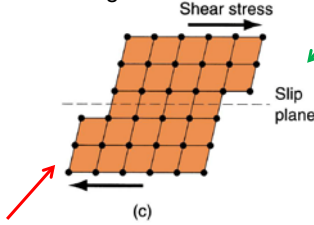
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2.14 Plastic Strain

If stress is higher than forces holding atoms in their lattice positions, a permanent shape change occurs



Slip involves the relative movement of atoms on opposite sides of a plane in a lattice

(c)

Deformation of a crystal structure: (c) plastic deformation (*slip*), in which atoms in the lattice are forced to move to new "homes".

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Plastic strain is similar to plastic deformation. The deformation produced is not recoverable. This image shows plastic strain in a lattice. Under increasing shear stress, plastic deformation occurs. This plastic deformation is permanent and not recoverable. This kind of deformation is called slip. What is slip? Slip involves the relative movement of atoms on opposite sides of a plane in a lattice.

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2.14 Effect of Dislocations on Strain

- In the series of diagrams, the movement of the defects allows deformation to occur under a lower stress than in a perfect lattice

(1) (2) (3)

Effect of dislocations in the lattice structure under stress

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As advised before, dislocations and defects are important in manufacturing. Defects and dislocations are desired, because more dislocations means lower yield strength, which means lower cutting force is needed in manufacturing. This saves energy and time.

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2.141 Slip on a Macroscopic Scale

- Slip occurs many times over throughout the metal when subjected to a deforming load, thus causing it to exhibit its macroscopic behavior in the stress-strain relationship
- Dislocations are a good-news-bad-news situation
 - Good news in manufacturing – the metal is easier to form
 - Bad news in design – the metal is not as strong as the designer would like

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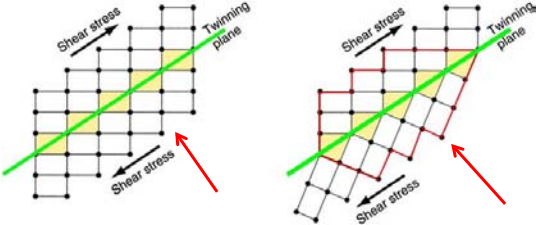
However, dislocation or defects are a double-edge sword. Dislocations are desired in manufacturing, because they reduce the manufacturing cost. However, dislocations are not good in material design, because dislocation reduces the strength of materials.

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2.142 Twinning

- A second mechanism of plastic deformation in which atoms on one side of a plane (the *twinning plane*) are shifted to form a mirror image of the other side



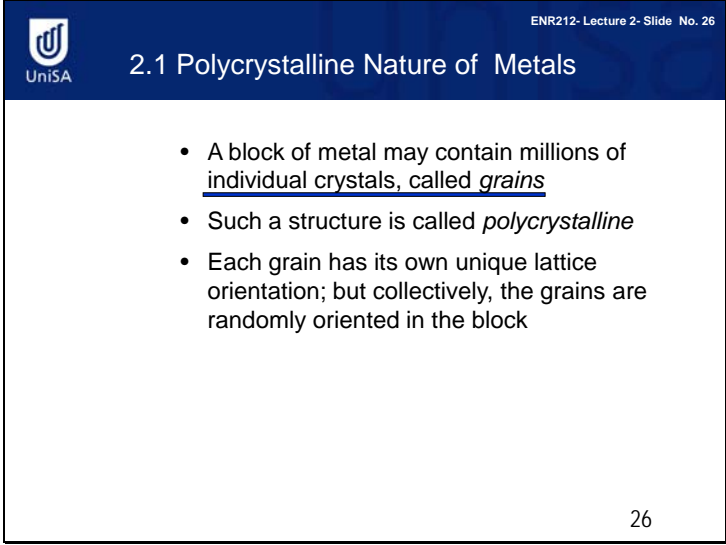
Twinning, involving the formation of an atomic mirror image on the opposite side of the twinning plane: (a) before, and (b) after twinning.

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Slip is the first mechanism of plastic deformation. The second mechanism is twinning. The left image shows a lattice before plastic deformation. The green line represents a twinning plane. You can see the lattice geometry above the plane is similar to the lattice below the plane. Now look at the second image. After the shear deformation, the geometry of the lattice above the plane is different to the lattice below the plane. This phenomenon is called twinning.

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2.1 Polycrystalline Nature of Metals

- A block of metal may contain millions of individual crystals, called *grains*
- Such a structure is called *polycrystalline*
- Each grain has its own unique lattice orientation; but collectively, the grains are randomly oriented in the block

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Metals are crystalline materials. Metals contain crystals. These crystals are also called grains. Here are two questions for you.

First, are all metals crystalline. Yes or no? The answer is no.

Second, are metals crystalline at room temperature. Yes or no? The answer is no, because mercury is liquid at room temperature.

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3. Amorphous Structures

- Many materials are noncrystalline
 - Water and air have noncrystalline structures
 - A metal loses its crystalline structure when melted
- Important engineering materials have noncrystalline forms in their solid state
 - Glass
 - Many plastics
 - Rubber

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Metals have crystalline structures. However, polymers are different. Some are crystalline, some are semi-crystalline and some are just amorphous. Amorphous materials should be transparent (such as glass).

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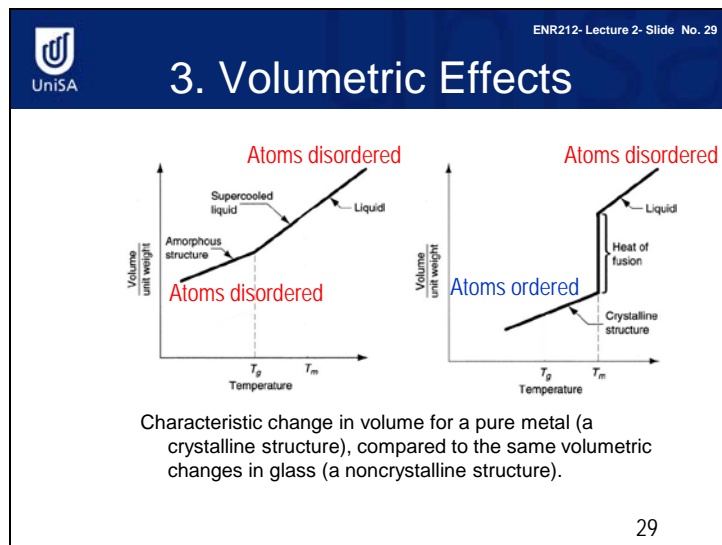
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3. Features of Amorphous Structures

- Differences between amorphous) from crystalline materials:
 - Absence of long-range order in molecular structure
 - ↓
 - Differences in melting and thermal expansion characteristics

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We have looked at crystalline structure. In crystalline structures, the atoms are arranged at regular and recurring positions. In amorphous structures, there is no long-range order in molecular structure. This means that there are huge differences in melting and thermal expansion characteristics.



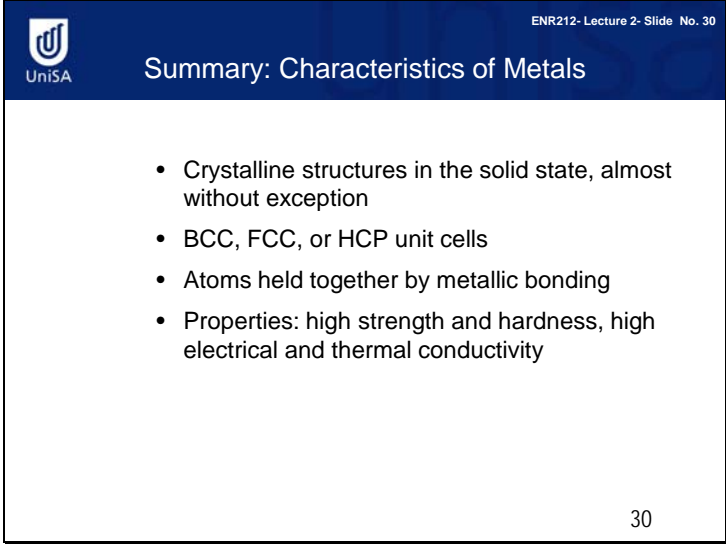
An amorphous material shows very different thermal behaviour to a crystalline material. For example, with temperature changes, the volume change for an amorphous material is different to the volume change for a crystalline material.

The right image shows you the volume change for a crystalline material. In the solid state of a crystalline material, all atoms are in a regular and recurring pattern; this means that all atoms are in an ordered state in the solid state. On the other hand, in the liquid state of a crystalline material, the regular and recurring pattern has disappeared; this means that all atoms are in a disordered state in the liquid. Therefore, when the material changes from liquid to solid, the atoms need energy and time to change from a disordered state to an ordered state. This is similar to what you do every day. You need time to make a messy room neat and tidy, you need time to change a disordered room into an ordered room. Atoms need time and energy to get themselves ordered at the melting temperature when the crystalline material changes from liquid to solid, and this leads to an obvious volume change at melting temperature.

The left image shows you the volume change with temperature for an amorphous material. Since the atoms of the amorphous material are in an disordered state in both the solid and liquid state, there is no obvious volume change at temperature.

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Summary: Characteristics of Metals

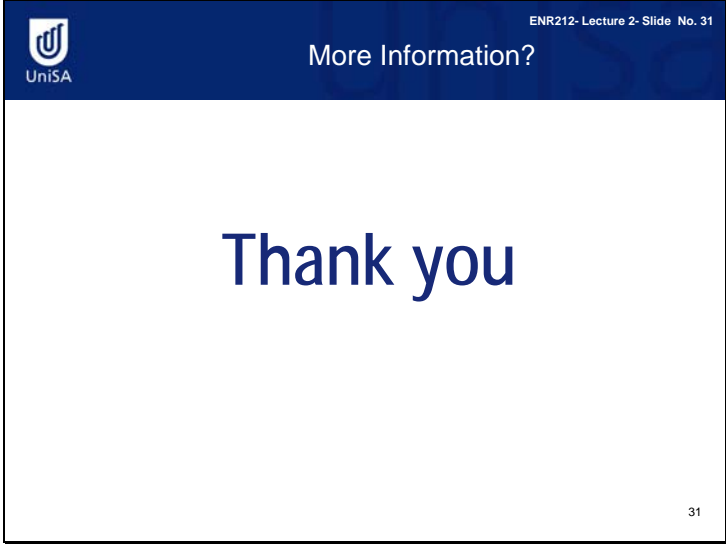
- Crystalline structures in the solid state, almost without exception
- BCC, FCC, or HCP unit cells
- Atoms held together by metallic bonding
- Properties: high strength and hardness, high electrical and thermal conductivity

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Metals are crystalline in their solid state. Metal atoms are held together by metallic bonding. There are a large number of free electrons, and this sets the high strength, high stiffness and high electrical and thermal conductivity of metal.

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More Information?

Thank you

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The slide features a dark blue header bar with the UniSA logo on the left and the text 'ENR212- Lecture 2- Slide No. 31' on the right. Below the header, the text 'More Information?' is centered. The main body of the slide is white with the text 'Thank you' centered in a large, dark blue font. A small number '31' is located in the bottom right corner of the slide frame.

Thanks for your attention.