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ENR116 Engineering Materials

Module 1 Introduction to Materials

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Introduction to materials

Mod. 1- Slide No. 4

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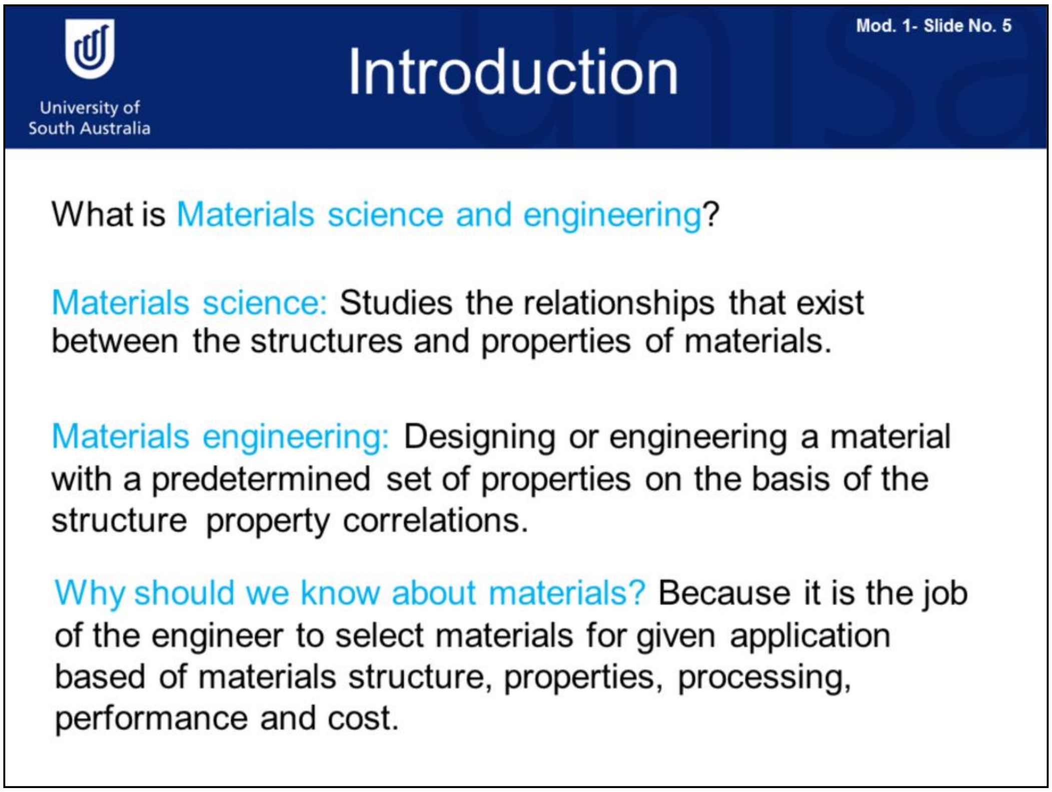
Intended Learning Outcomes

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

- Identify with examples the different classes of materials.
- Describe the distinctive chemical features of different materials.
- Identify 'Advanced Materials' and how these differ from the classical material classes.

The intended learning outcomes from this presentation are to be able to identify the different classes of materials, describe the distinctive chemical features of different materials and to recognise advanced materials and how these differ from the classical material classes.



What is materials science and engineering? In answering this question it is sometimes easier to separate them into materials science and materials engineering. Thus, materials science will be the science that studies the relationship between structure and properties of materials and materials engineering will be the design or engineering of new materials or materials with a pre-determined set of properties on the basis of the structure property correlations. Why do we need to know about materials? Well, as an engineer, whether you are a civil engineer, electrical engineer, mechanical engineer or whatever engineer, at some stage in your career you will have to select materials for a specific application. This selection will be based upon a material’s properties of structure, performance, processing, cost, etc.

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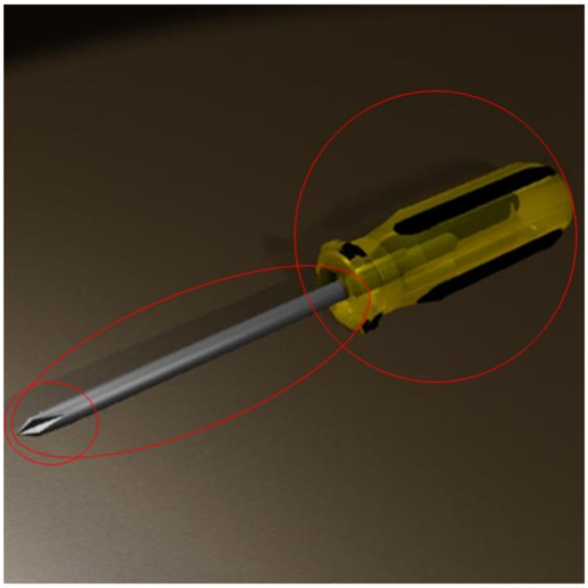
Mod. 1- Slide No. 6

Example - Screwdriver



So if we were to consider a simple device such as a screwdriver and we consider the question how much knowledge of materials do you need in order to build such a simple device? So let's take a look: Firstly, the blade is made out of metal because it needs to be strong in order to withstand a twisting motion. The head of the screwdriver has to be tough and hard, especially true for a Phillip's type screwdriver, in order to not wear away too quickly. Alternatively, some people abuse their screwdrivers for example using them to lever open tins of paint, so the shaft of the screwdriver needs to be resistant to bending, and some people use it as a chisel, so once again it has to have sufficient strength. Why is the handle made out of plastic or wood in some examples? Possibly, if it was made out of metal it would have been easier to produce but what about electrical conductivity? So if it was made out of metal, first it would be much heavier. We would also need to consider using it to fix your electrical socket and forgetting to turn off the mains power. The other thing is that the metal - if it was made out of metal – is also a good conductor of heat; so if you leave it in the sun it will become very hot and in cold climates it becomes very cold. So we can see that in order to design even a very simple device you need to have considerable knowledge of materials.

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What happens when we get it wrong?

Why did Titanic sink in 1912?

It was built with the wrong steel (containing excessive ratios of sulphur and phosphor) which undergo brittle fracture at low temperature.

Now, we may think that a screwdriver is a very cheap, almost disposable item. If it breaks we simply use or buy another but what about very complex and expensive items? Well, in some cases the breaking or failure could have very much more dramatic and catastrophic. You will probably all know about the Titanic, the biggest passenger liner of its time but do you know why it sank? Because the engineer selected the wrong material. The Titanic was built using inappropriate steel which contained an excessive amount of phosphor and sulphur such that at low temperature it became brittle.

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What happens when we get it wrong?

The Space Shuttle Challenger disaster:


Fuel leakage in the rocket booster caused by a O-ring.
The O-ring lost elasticity at low temperature.

Another well know catastrophe was the Space Shuttle Challenger, which exploded a few minutes after launch again, because of material problem.

In this instance it was a fuel leakage in the rocket booster which was caused by an o-ring seal which lost elasticity at low temperature – the day of the disaster was cold with estimates putting the lowest temperature of the o-rings at below freezing – outside the safe operating temperatures.

Mod. 1- Slide No. 9

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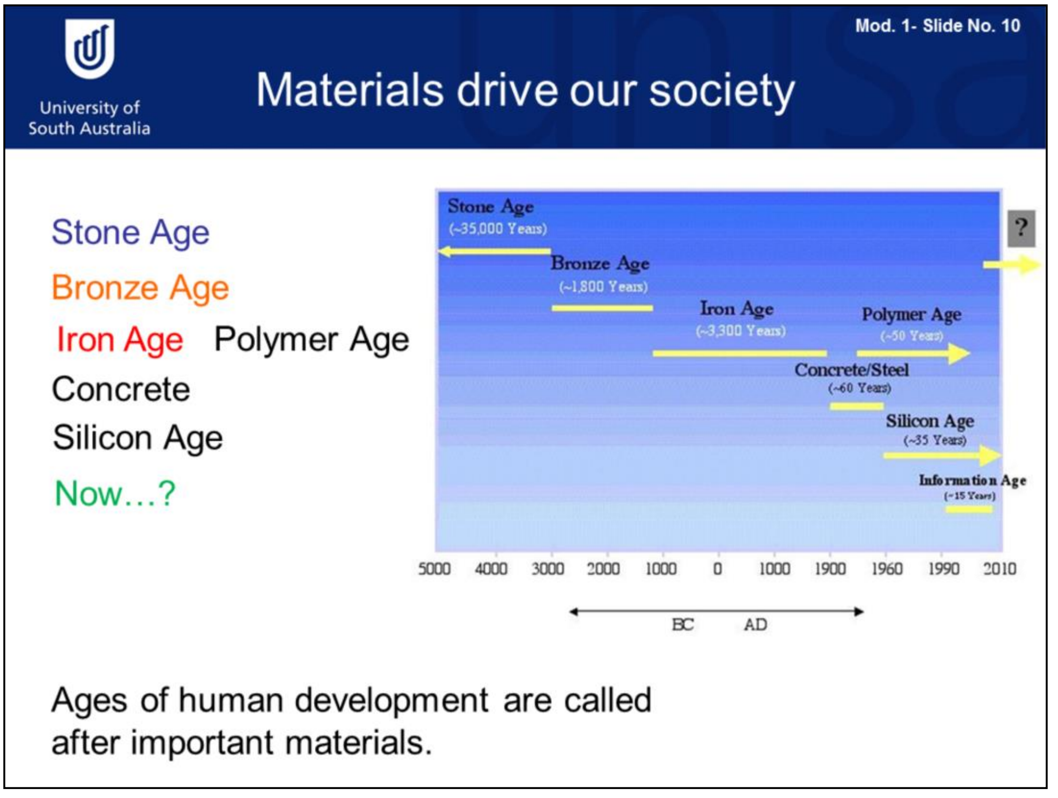
What happens when we get it wrong?

Eschede train disaster:

Caused by metal fatigue of the wheels.

A third example identifying the importance of material selection is the Eschede train disaster in Germany which resulted in one hundred and one deaths. Here the cause of the crash was attributed to a single fatigue crack in one wheel.



So you can see that it is important to understand materials, how they are used and what limits their use and this has been true throughout history. The important ages of human civilisation or human development are so known after the important materials of the age. In the beginning people knew only simple materials such as stone, bone, wood and skin and this age was called The Stone Age. Subsequently, people learned about metals and how to form and use them so the next stage was called The Bronze Age. More refined techniques and knowledge of how to process iron lead to the Iron Age and now we have the Concrete Age, the Polymer Age, the Silicon Age etcetera, so in 5 thousand years it will be interesting to imagine what the archaeologists will call the current Age.

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Mod. 1- Slide No. 11

Hunting 10000 BC and today

Prehistoric hunting tools

Hunting tools today

Let us consider some more examples. Here we have a selection of prehistoric hunting tools. Imagine how hard it was at that time to hunt an animal – a full-time occupation that was essential to survival. How does hunting today compare? Today it is simply a hobby but if one is interested somebody needs to have made this rifle. They need to have considered and selected the correct type of steel to make the barrel, the correct ceramics and how to process them to fabricate the optics for the telescopic sight and so on.

What about agriculture? These are agricultural tools - this is a harvester’s sickle from about 3000 BC. Imagine what hard work it was and how labour intensive it was to harvest the crops. Compare this with harvesting today. A much lower proportion of the population are involved with the process of harvesting today but to make this combine harvester we need to know about the different types of steel and metals, the ceramics for the glass cabin and the rubber and other plastics for the tyres, seats, wiring insulation, etc.

How have materials changed our lives in just the last 50 years? The aeroplane, 50 years ago and how it looks today. The modern plane is, of course, much faster and more powerful than the earlier model and this is because of the new alloys and composite materials we now have available as materials engineers. What about the electronics age and computers? Well this is an information storage device now in comparison to one from 50 years ago. The earlier model could store a few kilobytes and this can store a few gigabytes. The same can be said of the modern computer which would have occupied a large room in the sixties yet have less computing power than most people today carry under their arm. The electronics revolution is all due to the materials scientists and engineers who developed the fabrication and processing of silicon. With these few examples you should now have an appreciation of how important materials are to everyday life and why an understanding of their properties, processing and application has shaped the world we live in.

Mod. 1- Slide No. 14

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Things we need to know about materials

Structure:
The structure of a material is usually the arrangement of its internal components.

Atomic structure: the organisation of atoms or molecules relative to one another.

Microscopic structure: a larger structural realm, which contains large groups of atoms that are normally agglomerated together, which is subject to direct observation using some type of microscope.

Macroscopic structure: comprises structural elements that may be viewed with the naked eye.

So what do we need to know about materials? We need to know the material's structure; the arrangement of the material's internal elements. We can define these depending on the size of the internal elements and so we define atomic structure as the arrangement of the atoms and the molecules within the material. We can also define the microscopic structure which will be aggregates of a few or several hundred atoms or molecules which can be directly observed using an optical microscope. Finally, we define macroscopic structure which is comprised of features that can be seen with the naked eye.

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Mod. 1- Slide No. 15

Things we need to know about materials

Properties:

"A property is a material trait in terms of the kind and magnitude of response to a specific imposed stimulus."

Mechanical properties: for example, would relate deformation to an applied load or force; examples include elastic modulus and strength.

Electrical properties: such as electrical conductivity and dielectric constant, the stimulus is an electric field.

Thermal properties: measure for the behaviour of a material in response to temperature such as heat capacity and thermal conductivity.

So when we talk about a material property what are we actually talking about? The property of a material is simply the response of that material to an externally applied stimulus and it is the type of this stimulus that dictates the type of property. So for example here we have external forces in the form of loads being applied from which we can derive a number of the material's mechanical properties. Another type of stimulus would be electrical such that we can determine the material's electrical properties, for example conductivity. Thermal properties on the other hand would be concerned with a materials response to an external temperature.

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Mod. 1- Slide No. 16

Things we need to know about materials

Properties:

"A property is a material trait in terms of the kind and magnitude of response to a specific imposed stimulus."

Magnetic properties: the response of a material to the application of a magnetic field.

Optical properties: the stimulus is electromagnetic or light radiation. Index of refraction and reflectivity are representative optical properties.

Likewise magnetic properties being the response to an externally applied magnetic field and optical the interaction with light or electromagnetic radiation.

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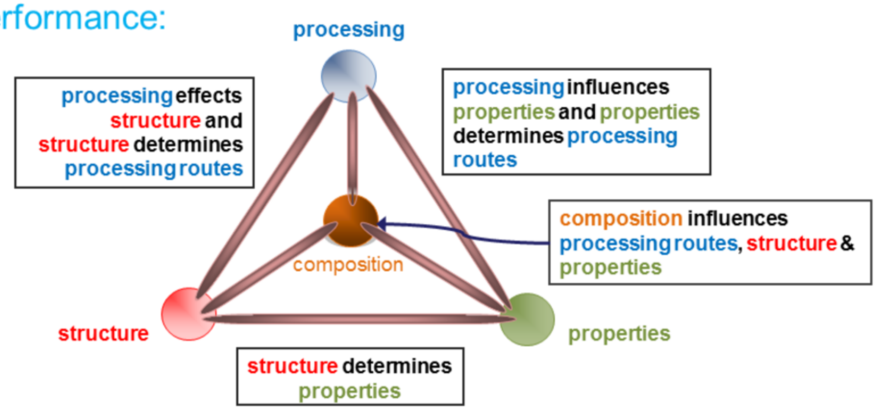
Mod. 1- Slide No. 17

Things we need to know about materials

Processing: The series of operations that transforms industrial materials from a raw-material state into finished parts or products.

Performance:



Processing is another important aspect of materials engineering and processing is defined as a series of operations to transform the raw materials into a finished product or component. As you can see here on this diagram the processing will influence both the structure and properties of the material and this slide serves to illustrate this point.

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Structure, Processing, & Properties are mutually related

Same material – aluminium oxide – different processing method – different structure

Adapted from Fig. 1.2, *Callister & Rethwisch 8e.* (Specimen preparation, P.A. Lessing; photo by S. Tanner.)

Single crystal

Polycrystalline made of very small single crystals

Polycrystalline with pores

Here we have an image of the same material, aluminium oxide which is a ceramic, but each sample has been processed in a different manner. On the left hand side is an example of a single crystal, in the centre a semi-crystal and on the right a poly-crystalline sample. All three samples are the same material however the processing has produced three distinctly different structures which, in this instance, have differing optical properties – transparent, semi-opaque and opaque.

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Classification of materials

Metals:

Composed of one or more metallic elements (such as iron, aluminium, copper, titanium, gold, and nickel), and often also non-metallic elements (for example, carbon, nitrogen, and oxygen) in relatively small amounts.

Atoms in metals and their alloys are arranged in a very orderly manner.

Properties:

Stiff and strong, but ductile

High thermal & electrical conductivity

Opaque, reflective

High density

Fig. 1.08 *Callister & Rethwisch 8e.*

Generally we classify materials into four distinct material types - metals, ceramics, polymers and composites. Hence, metals will be composed of one or more metallic elements such as iron, aluminium, copper, titanium, gold, etc. As part of their composition they may also have some non-metallic elements such as carbon, nitrogen, or oxygen, and these non-metallic elements will be in relatively small amounts. The atoms in the metals and their alloys, which are metallic materials composed of two or more elements, are arranged in a small number of very specific patterns and the final section of this week's lectures will examine these arrangements. Metals and their alloys have a range of particular properties; some can be stiff and strong whilst others can be flexible or ductile. Some will have high thermal and electrical conductivity but all are opaque, reflective, and, in comparison to the other material types, of high density.

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Mod. 1- Slide No. 20

Classification of materials

Polymers (plastics or rubber):

Many polymers are organic compounds that are chemically based on carbon, hydrogen, and other non-metallic elements (O, N, and Si). Inorganic polymers also exist such as silicon rubber.

Very large molecular structures often chain-like in nature.

Properties:

Soft, ductile, low strength, low density

Thermal & electrical insulators

Optically translucent or transparent

Fig. 1.10 *Callister & Rethwisch 8e.*

Polymers - many of these types of material are organic compounds that are chemically based on carbon, hydrogen or other non-metallic elements such as oxygen, nitrogen or silicon. There are also a class of inorganic polymers silicon rubber. Polymers are composed of very large molecules which have a chain-like nature. Polymers are generally soft, very flexible with low strengths and low densities. In general they are thermally and electrically insulating and can be optically translucent or transparent.

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Mod. 1- Slide No. 21

Classification of materials

Ceramics:

Compounds formed with metallic and non-metallic elements.

They are most frequently oxides, nitrides, and carbides.

Examples: aluminum oxide (or alumina, Al_2O_3), silicon dioxide (or silica, SiO_2), silicon carbide (SiC), silicon nitride (Si_3N_4), clay minerals (i.e., porcelain), cement, and glass.

Properties:

Brittle, glassy

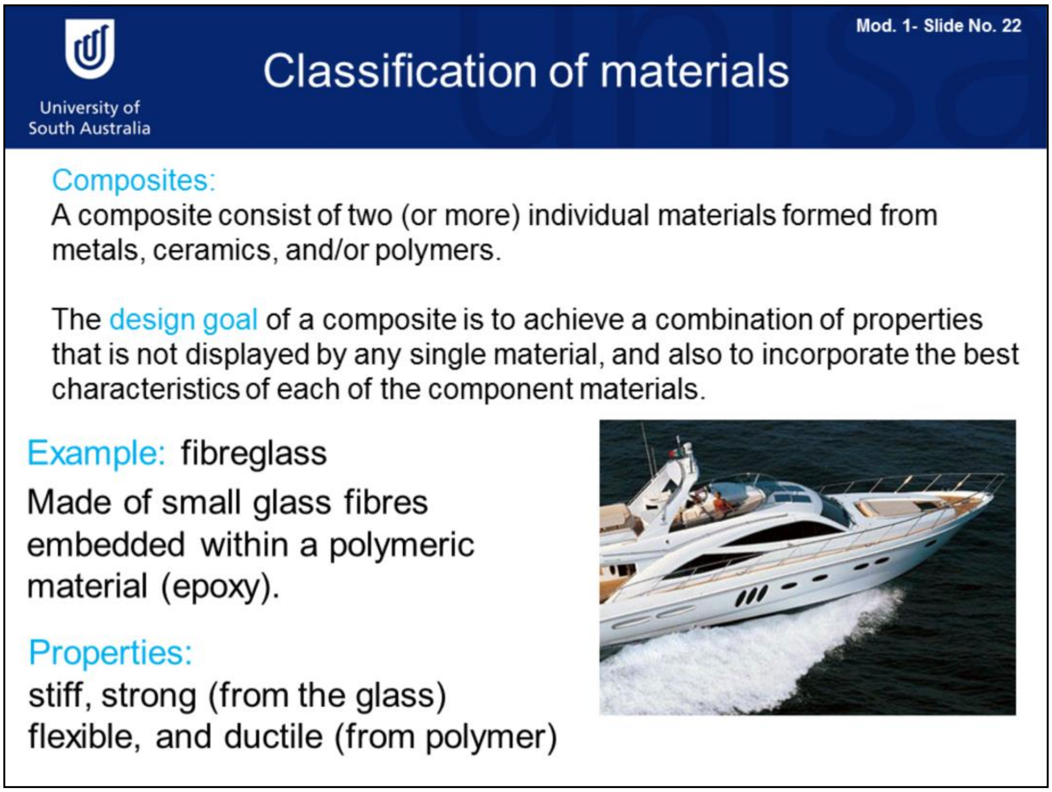
Strong

Non-conducting (insulators)

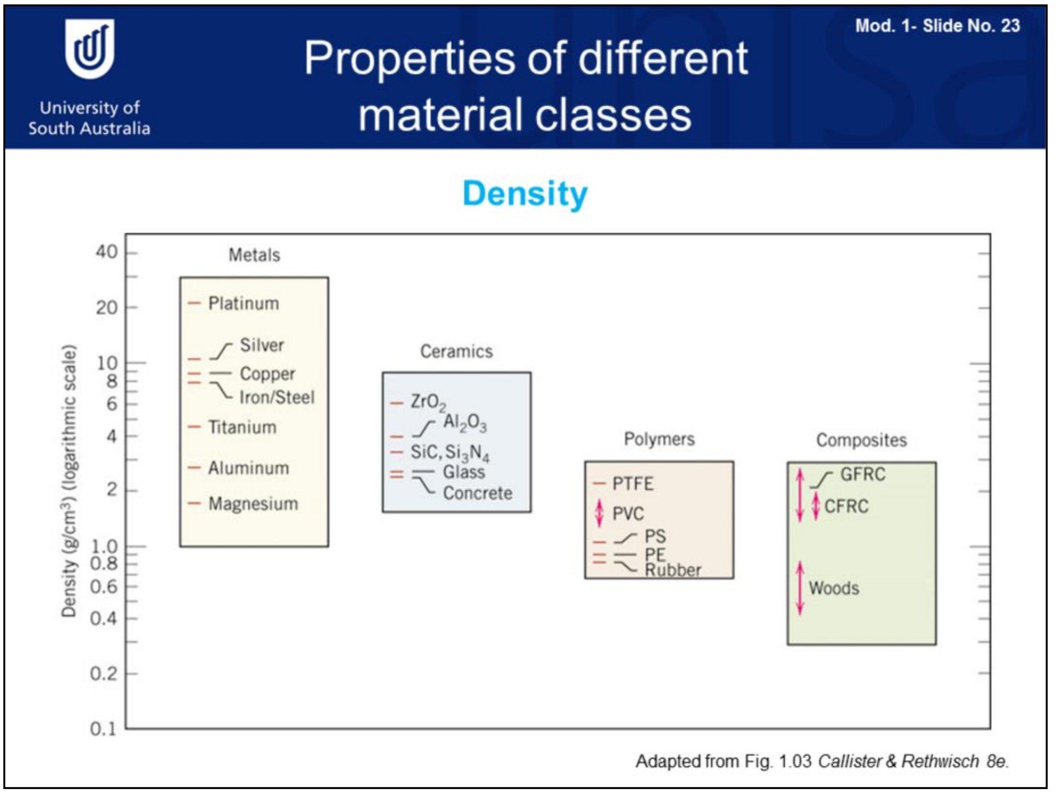
Optical characteristics – can be transparent, translucent, or opaque

Fig. 1.09 *Callister & Rethwisch 8e.*

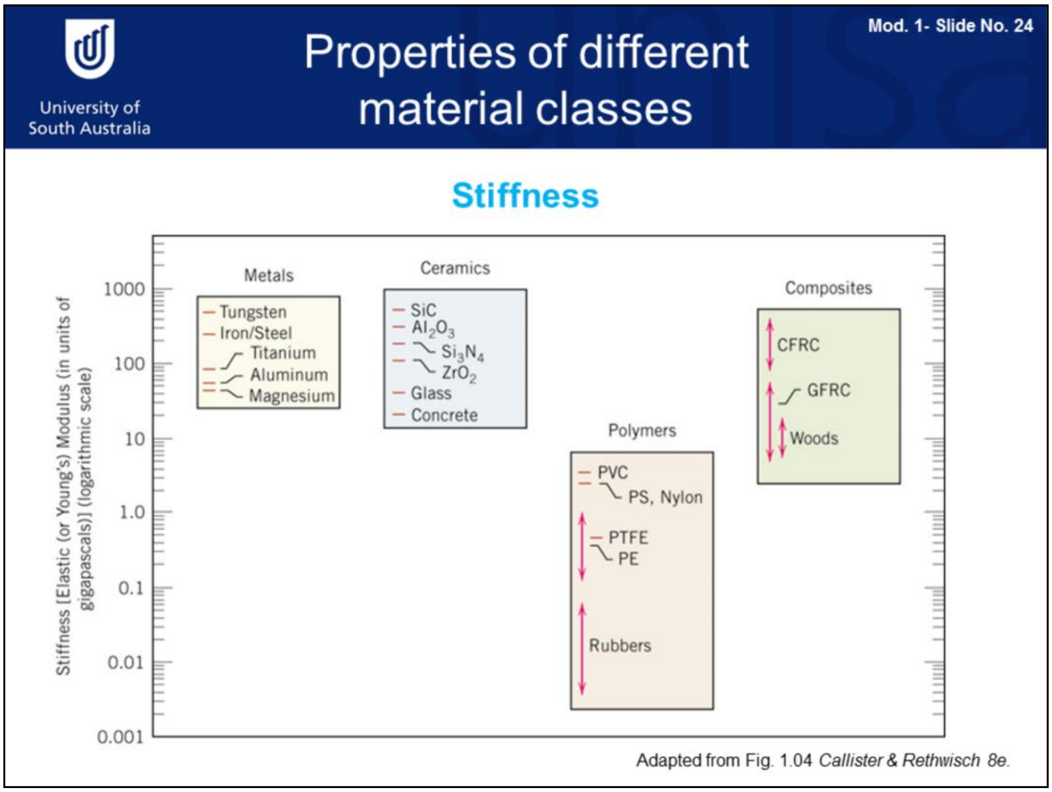
Ceramics – this class of material are compounds between metallic and non-metallic elements and are most frequently found as oxides, nitrides and carbides. Some of the more important examples would be aluminium oxide, silicon dioxide, silicon carbide, silicon nitride, clay minerals, cement, and the glasses. They are generally seen as brittle or glass-like but have a high strength and are typically non-conductive. So ceramics are used where insulation or optical transparency is a material requirement.



The final material type, Composites, is a special class of material that consist of two or more individual materials of metals, ceramics or polymers. The ultimate objective in the design of a composite material is to achieve a combination of properties that are not displayed by any single material whilst incorporating the best characteristics of each of the component materials. For example here we see a yacht made of fibreglass, a composite material of very small glass (ceramic) fibres embedded in an epoxy (polymer) matrix. The resultant composite is both stiff and strong from the glass fibres but also lightweight and flexible from the polymer matrix. There are also a number of natural composites, such as bone and wood which have similar combinations of properties.



Let’s now briefly consider some properties of the different classes of materials. Here we see material densities and we can see that the metals have the highest density, followed by the ceramics with the polymers and composites having the lowest densities.



However, compare this with the stiffness and then the strength of the different materials.

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Advanced materials

Materials that are utilized in high-technology:

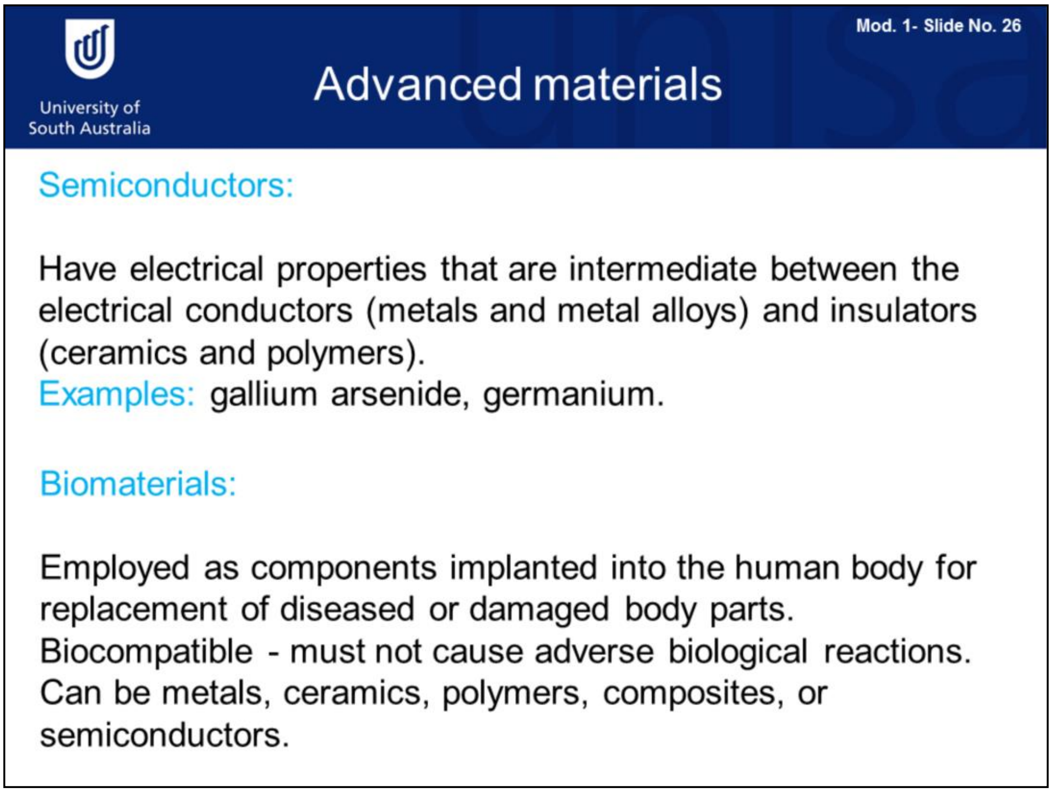
Typically traditional materials whose properties have been enhanced, newly developed, high-performance materials.

Include all material types (e.g., metals, ceramics, polymers).

Generally expensive.

Examples include: materials that are used for lasers, integrated circuits, magnetic information storage, fibre optics, etc.

To finish the section of this week's lecture I am going to briefly introduce another class of materials which are collectively described as Advanced Materials. This term 'advanced materials' is a little subjective in that what we consider to be advanced today may not be so advanced into the future. The typical characteristics of advanced materials are that they are usually recently developed, are high performing in some aspect or another when compared to the traditional materials and are generally very expensive.



Semi-conductors are one example of an advanced material and it's these materials, fabricated from elements and compounds such as silicon, gallium arsenide and germanium that have revolutionised the computer and electronic industries. Another class of advanced materials are Biomaterials which are employed externally in contact with or inside the human body in the form of medical devices or implants to replacement diseased or damaged tissue. A requirement of these materials is their need to be biocompatible but all classes of materials, metals, ceramics, polymers and composites are used.

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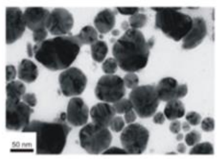
Advanced materials

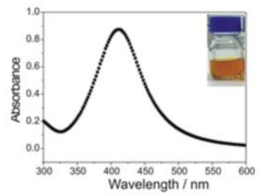
Nano-engineered materials:

Nanomaterials typically have sizes of below 100 nm (1 nm = 10^{-9}m).

At these dimensions materials can acquire novel properties (i.e. optical, mechanical, thermal).

Example: Bulk silver and silver nanoparticles.





Finally we have Nanomaterials, materials with sizes typically below 100 nm in diameter or by comparison ten to twenty times smaller than the diameter of a strand of hair. At this size the materials show some novel properties and here is an example of silver nanoparticles. Here we have bulk silver which is non-transparent however, with a suspension of silver nanoparticles, with a diameter of below 70 nm, is transparent solution with a yellowish colour and it has neutral optical properties because of this absorption of the silver nano-particles at about 400 nm.

In summary materials are mainly classified by their elemental composition and structure. Their performance is directed by this structure as is their processing or fabrication.

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Thank you

If you have any questions or desire further clarification please post a question or comment on the Engineering Materials Discussion Forum.