Selection of Engineering Materials

IM 515E

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Definition of Material Properties

Young's Modulus (E) and Specific Stiffness (E/ρ)

Overview:

- Young's modulus measures the resistance of a material to elastic (recoverable) deformation under load.
- A *stiff* material has a high Young's modulus and changes its shape only slightly under elastic loads (e.g. diamond).
- A *flexible* material has a low Young's modulus and changes its shape considerably (e.g. rubbers).
- A *stiff* material requires high loads to *elastically* deform it - not to be confused with a *strong* material, which requires high loads to *permanently* deform (or break) it.

Definition of Material Properties

- The stiffness of a component means how much it deflects under a given load. This depends on the Young's modulus of the material, but also on how it is loaded (tension, or bending) and the shape and size of the component.
- Specific stiffness is Young's modulus divided by density (but should more properly be called "specific modulus").

Definition of Material Properties

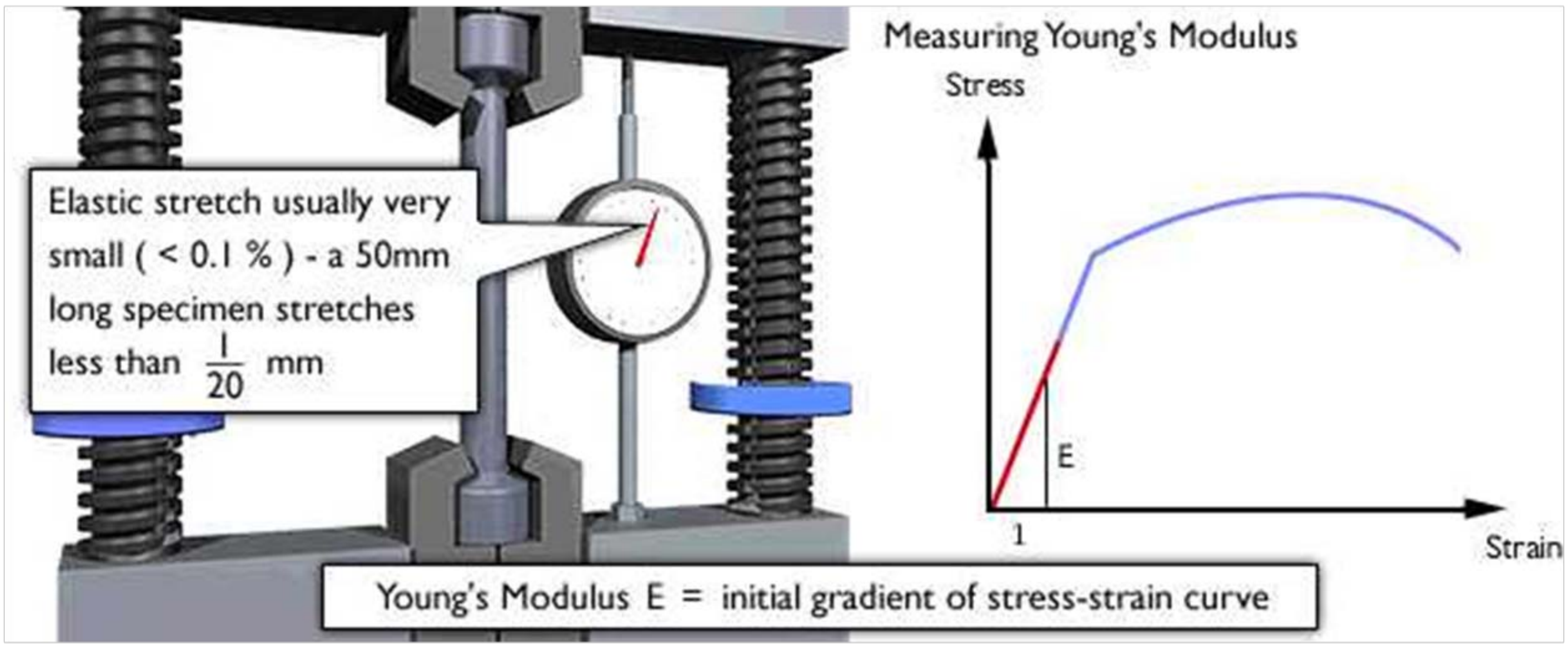
Design Issues:

- Stiffness is important in designing products which can only be allowed to deflect by a certain amount (e.g. bridges, bicycles, furniture).
- Stiffness is important in springs, which store elastics energy (e.g. vaulting poles, bungee ropes).
- In transport applications (e.g. aircraft, racing bicycles) stiffness is required at minimum weight. In these cases materials with a large specific stiffness are best.

Definition of Material Properties

<u>Measurement</u>:

- Tensile testing is used to find many important material properties. The compression test is similar but uses a stocky specimen to prevent bending.

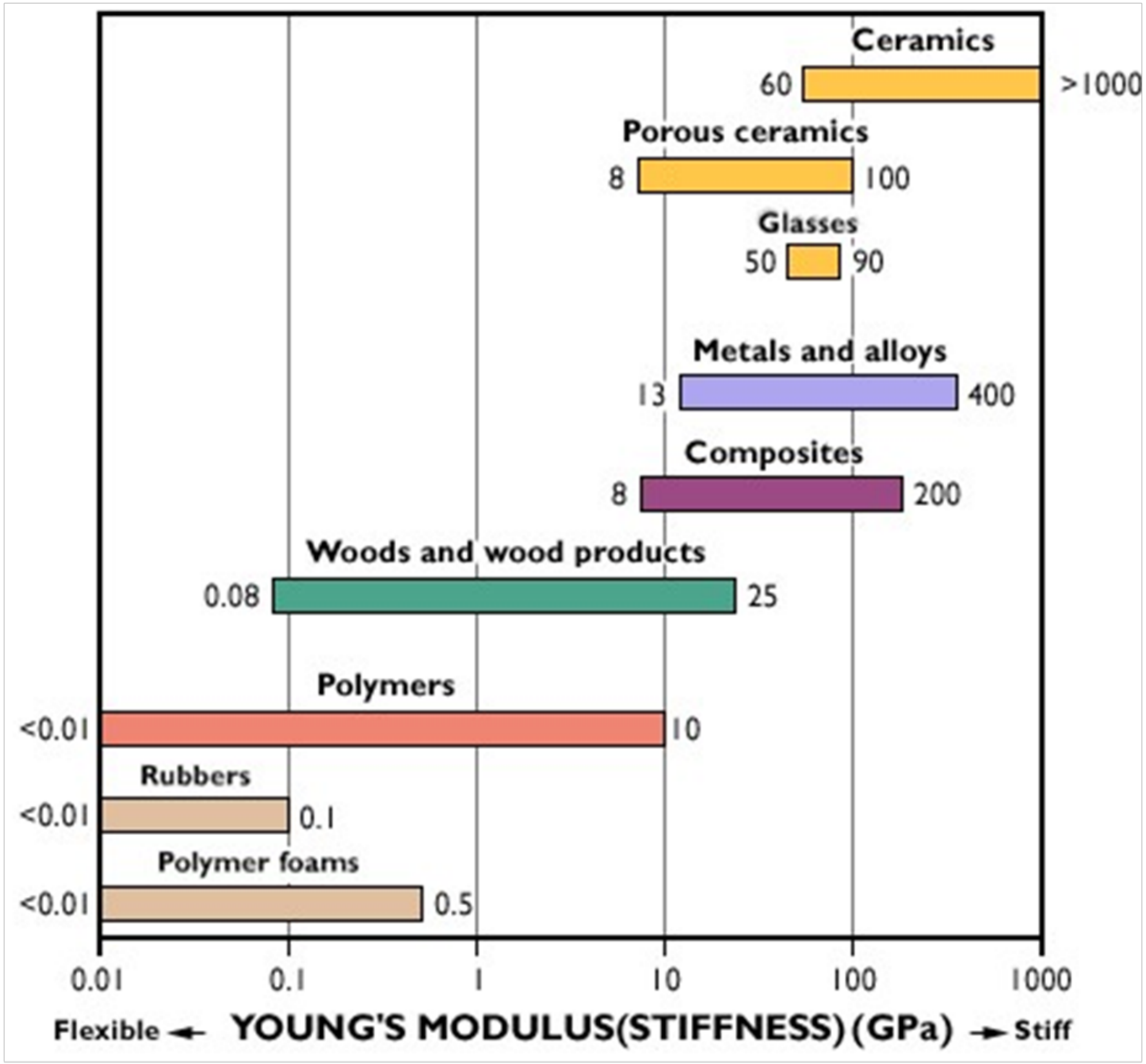


Definition of Material Properties

Units & Values:

- Young's modulus is equal to elastic stress/strain. Strain has no units to the units are the same as stress: N/m^2, or Pascals (1 Pa = $1N/m^2$; 1 GPa = 1000 N/mm^2)
- Specific stiffness (more properly called specific modulus) is Young's modulus/density - it is mostly used for comparing materials so the units are not important.

Young’s modulus for Different Materials



Definition of Material Properties

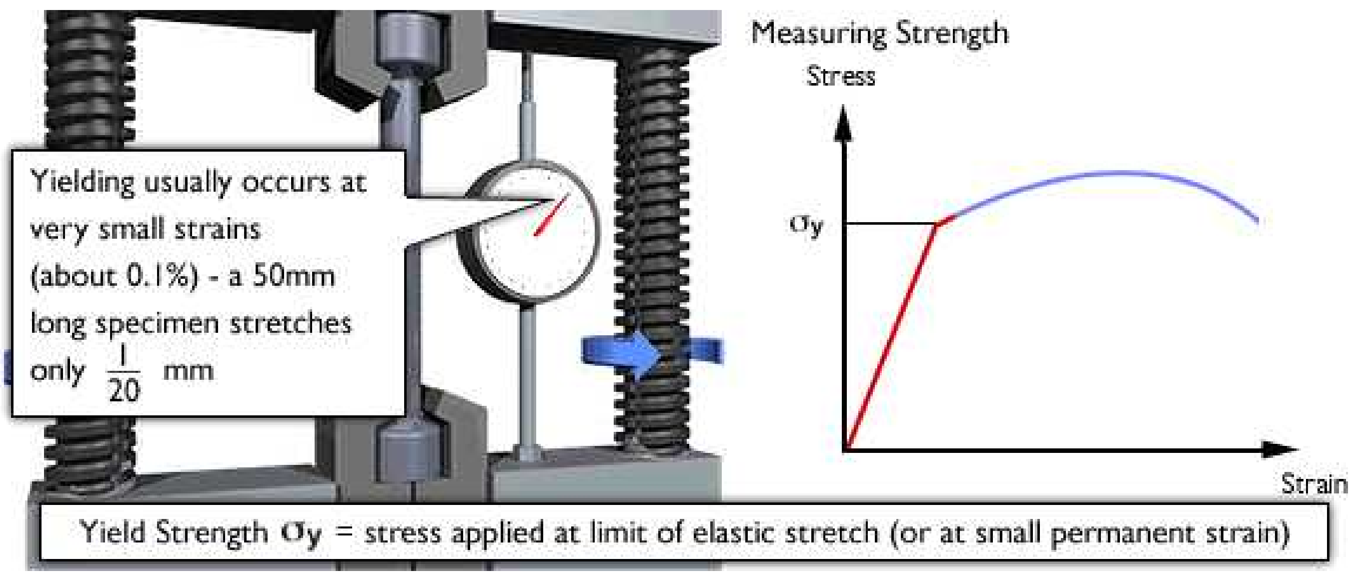
Strength and Specific Strength

Overview:

- The strength of a material is its resistance to failure by permanent deformation (usually by yielding).
- A *strong* material requires high loads to *permanently* deform (or break) it - not to be confused with a *stiff* material, which requires high loads to *elastically* deform it.
- For metals, polymers, woods and composites, "strength" on the selection charts refers to loading in tension (as failure is by yielding).

Definition of Material Properties

- For brittle materials (e.g. ceramics), failure in tension is by fracture, and the "tensile strength" is very variable.
- The "strength" on the selection charts is then "compressive strength" (which requires a much higher load).
- Specific strength is strength divided by density (σ_y/ρ).



Definition of Material Properties

Design issues:

- Many engineering components are designed to avoid failure by yield or fracture (cranes, bikes, most parts of cars, pressure vessels).
- In structural applications, brittle materials are nearly always used in compression (e.g. brick, stone and concrete for bridges and buildings).
- In transport applications (e.g., aeroplanes, racing bikes) high strength is needed at reduced weight. In these cases materials with a large "specific strength" are best.

Definition of Material Properties

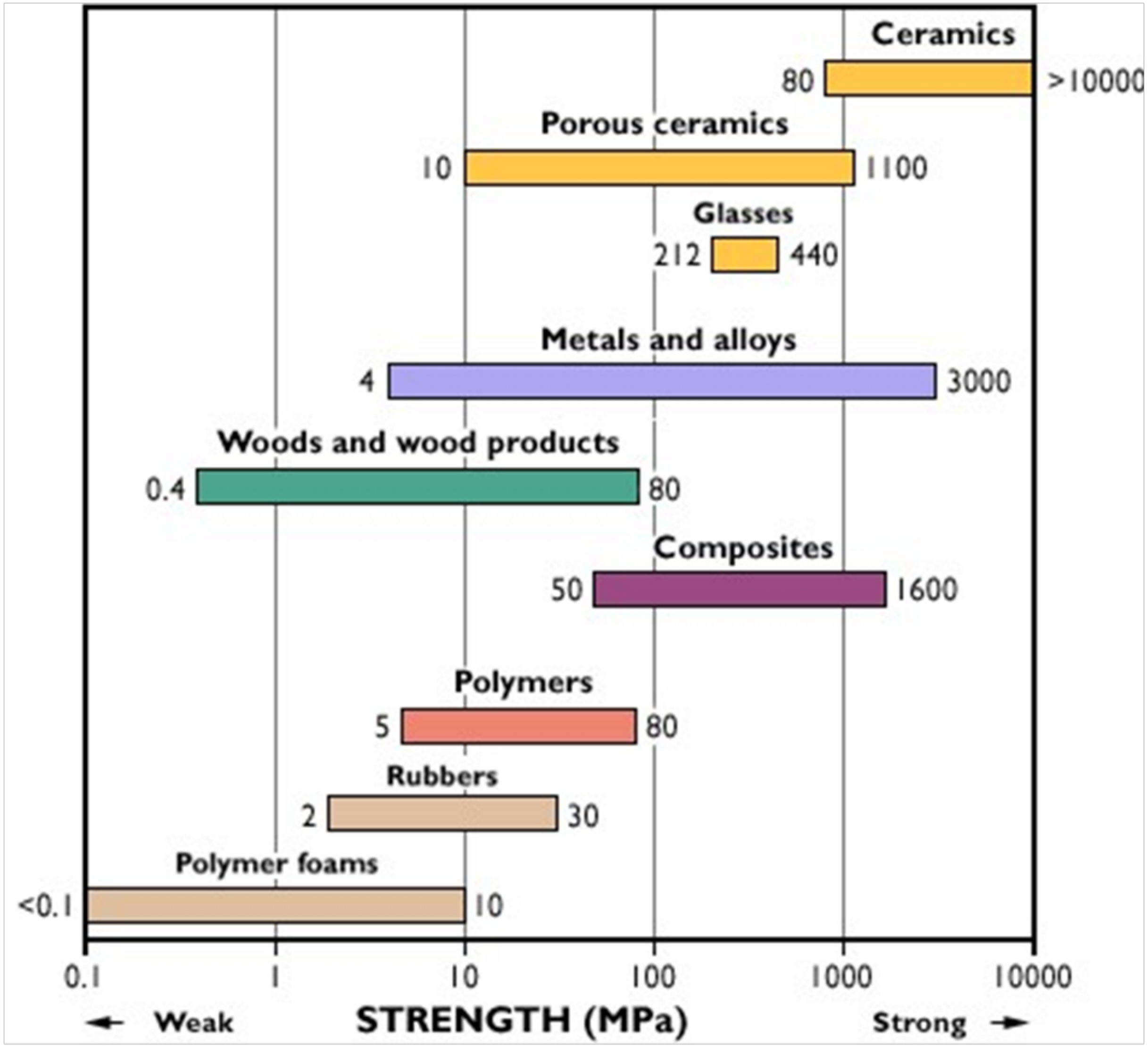
Measurement:

- Two measures of strength are defined - yield strength and ultimate tensile strength. *Strength* on the selection charts usually means yield strength.

Units & Values:

- Strength is measured by applied stress, which is equal to force/area. The units of stress are N/m^2 or Pascals (1 Pa = 1 N/m^2 ; 1 MPa = 1 N/mm^2).
- Specific strength is strength/density - it is mostly just used for comparing materials, so the units are not important.

Strength for Different Materials



Definition of Material Properties

Toughness

<u>Overview:</u>

- Toughness is the resistance of a material to being broken in two, by a crack running across it - this is called "fracture" and absorbs energy.
- The amount of energy absorbed during fracture depends on the size of the component which is broken in two.
- The amount of energy absorbed *per unit area* of crack is constant for a given material, and this is called the toughness.

Definition of Material Properties

- A *tough* material requires a lot of energy to break it (e.g. mild steel), usually because the fracture process causes a lot of plastic deformation.
- A *brittle* material may be strong but once a crack has started the material fractures easily because little energy is absorbed (e.g. glass).

Definition of Material Properties

Design issues:

- High toughness is particularly important for components which may suffer impact (cars, toys, bikes), or for components where a fracture would be catastrophic (pressure vessels, aircraft).
- Toughness varies with temperature; some materials change from being tough to brittle as temperature decreases (e.g. some steels, rubber).
- A famous example of this problem in steels was the battleships which broke in two in cold seas during the second World War!

Definition of Material Properties

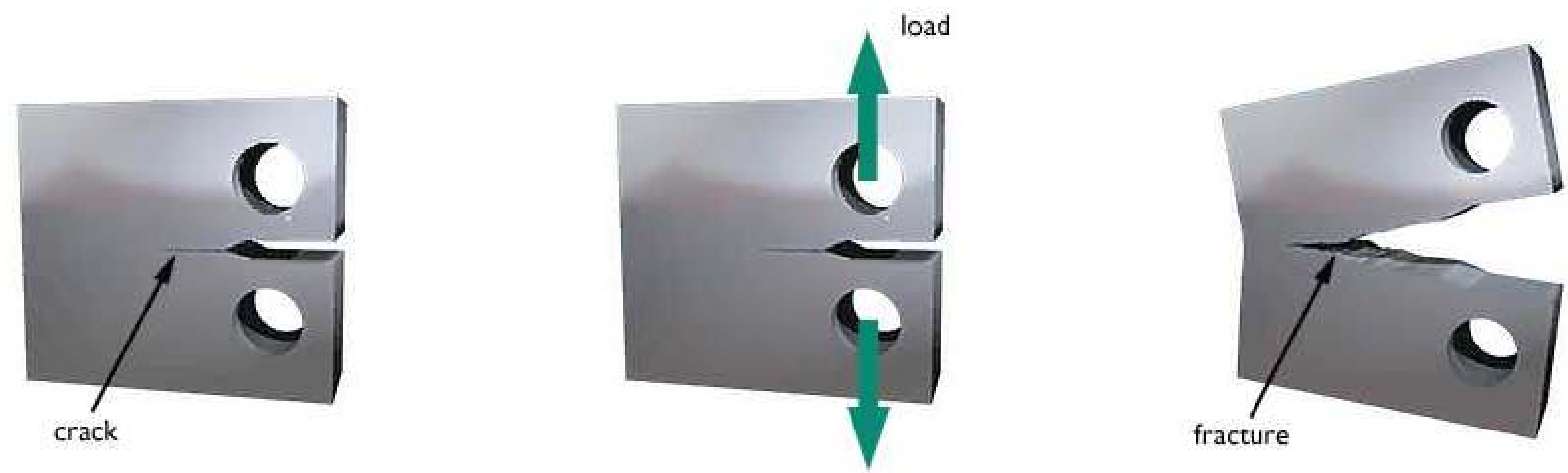
Measurement:

- Detailed toughness tests use specimens with starter cracks, and measure the energy per unit area as the crack grows. This can be applied to all materials, so the selection charts show toughness data measured this way.
- Simple toughness tests use specimens of fixed size with a machined notch, and just measure energy needed to break the specimen. This cannot be applied to all materials, but is a useful way to rank toughness for materials used in products which suffer impact (particularly for metals).

Definition of Material Properties

Compact tension test:

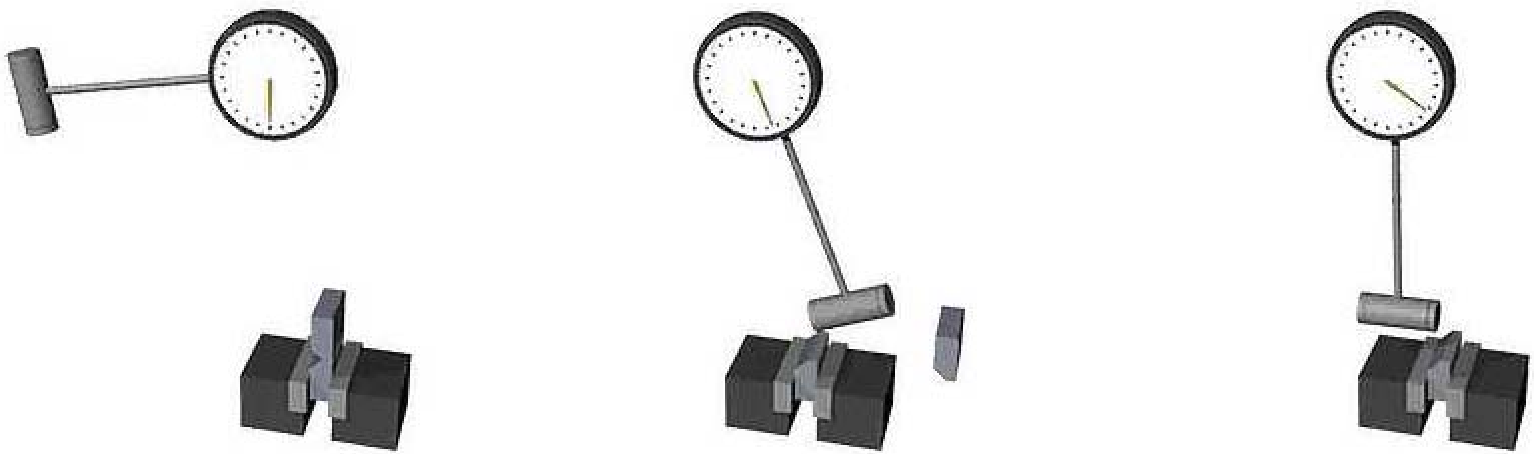
- The load is increased until the specimen fractures. The toughness (energy per unit area) is found by analysing the load-displacement curves for different specimens with different crack lengths.



Definition of Material Properties

Izod test:

- A specimen of standard size with a notch on one side is clamped in a vice. A heavy pendulum is lifted to a height h_0 above the vice and is released. It swings under gravity, strikes the specimen and continues to height h_1 shown by the final reading on the dial gauge.



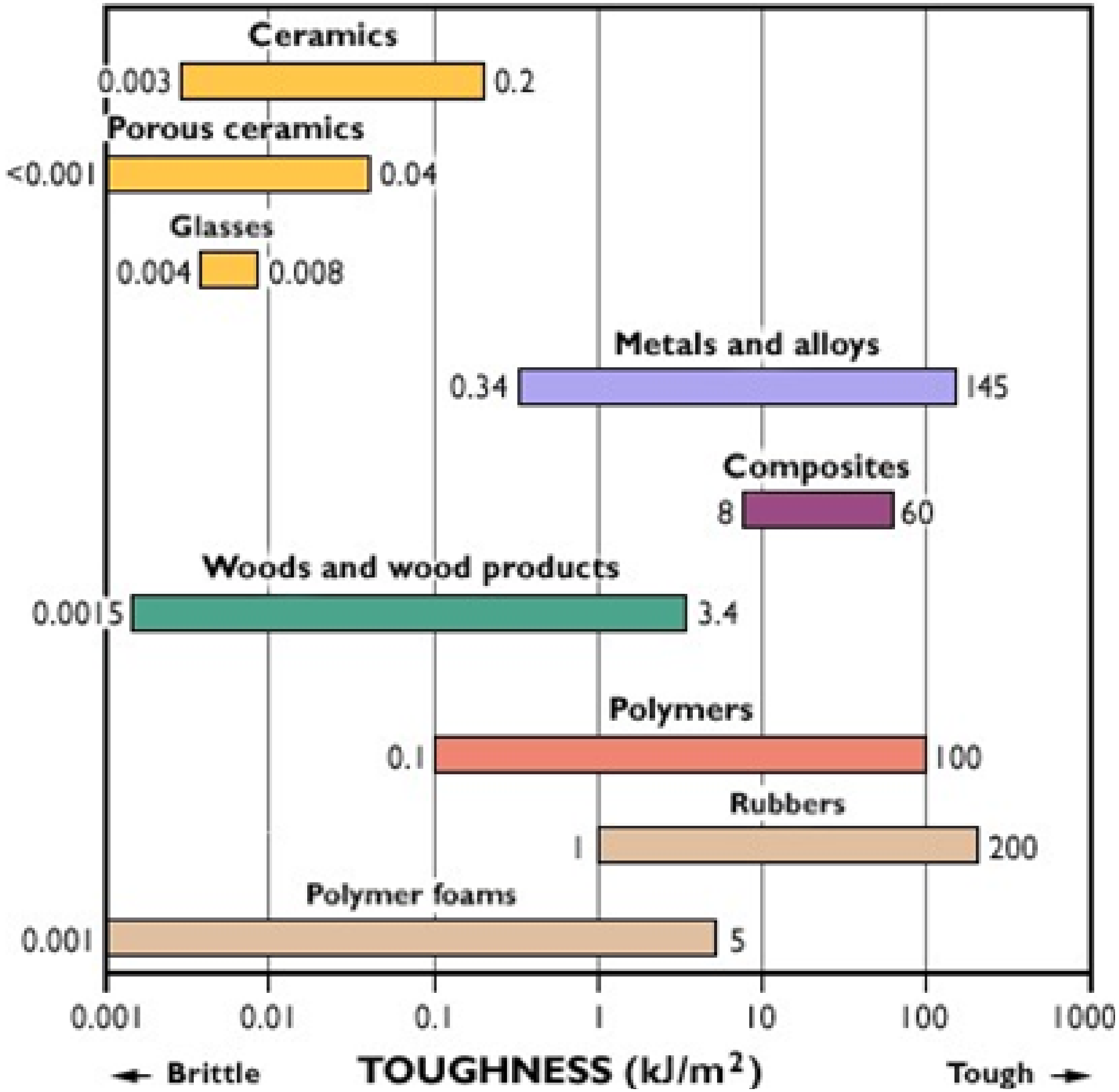
Impact energy = energy absorbed = mass of pendulum $\times$ g $\times$ (h_1 - h_0); where g is the acceleration due to gravity

Definition of Material Properties

Units & Values:

- Toughness is usually measured in energy per unit area or Joules/m^2 (J/m^2).
- Impact energy from Izod or Charpy tests is simple energy in Joules (J).

Toughness for Different Materials



Definition of Material Properties

Elongation

Overview:

- Elongation to failure is a measure of the ductility of a material, in other words it is the amount of strain it can experience before failure in tensile testing.
- A ductile material (most metals and polymers) will record a high elongation. Brittle materials like ceramics tend to show very low elongation because they do not plastically deform.
- Rubber extends by a large amount before failure, but this extension is mostly elastic and is recovered.

Definition of Material Properties

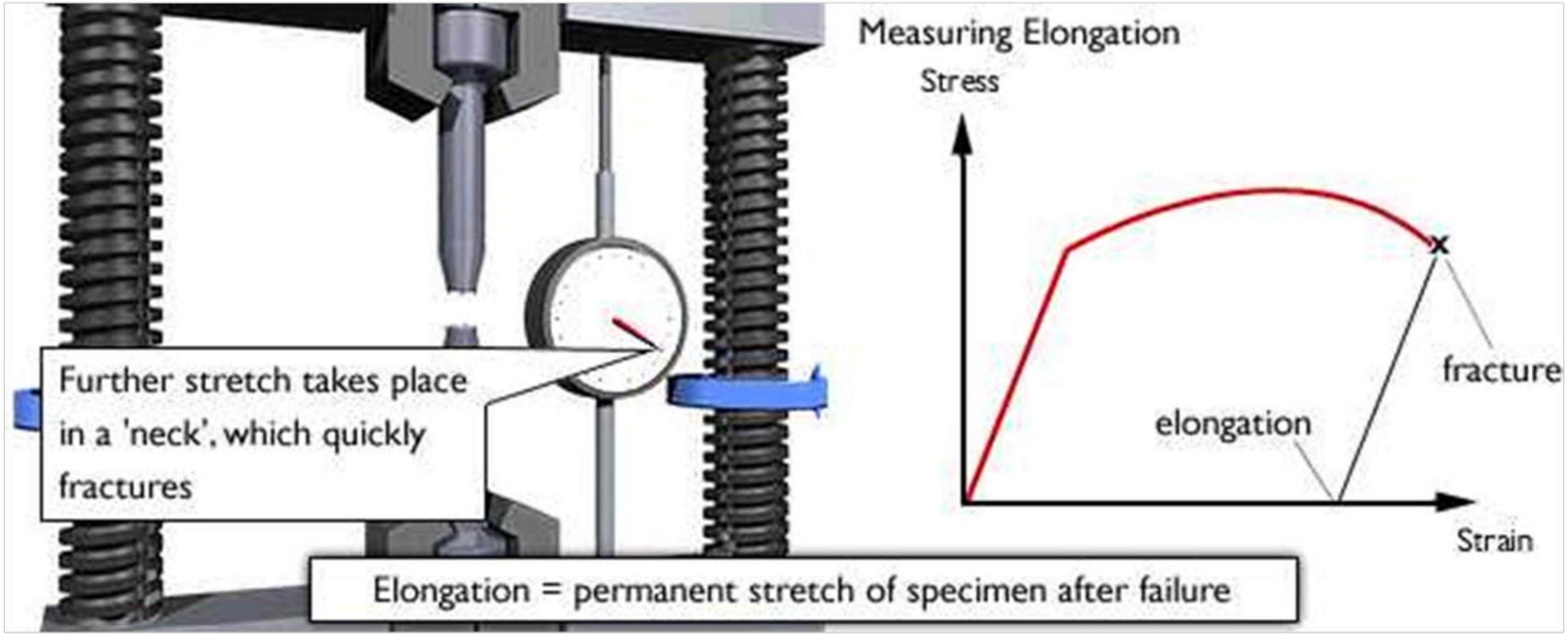
Design issues:

- Elongation is important in components which absorb energy be deforming plastically (e.g. crash barriers, car bumpers).
- High elongation to failure is important for "plastic hinges" (e.g. video cassette boxes).
- Elongation is important in manufacturing - it measures how much bending and shaping a material can withstand without breaking.

Definition of Material Properties

Measurement:

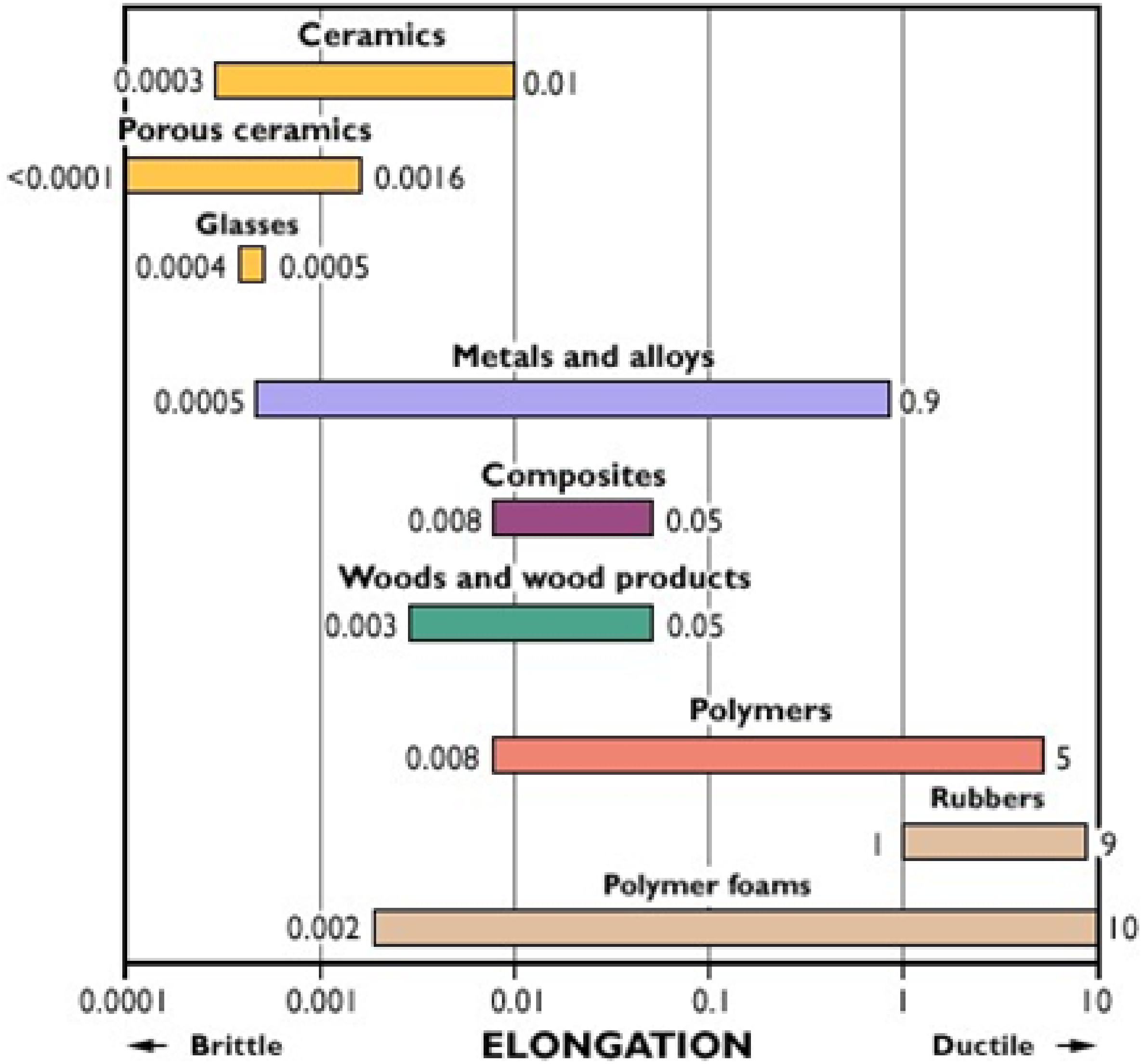
- The elongation is also obtained from the tensile test.



Units & Values:

- Because elongation is equal to the failure strain it has no units, but is often given in % strain.

Elongation (Ductility) for Different Materials



Definition of Material Properties

Density

Overview:

- Density is a measure of how heavy an object is for a given size, i.e. the mass of material per unit volume.
- Changes in temperature do not significantly affect the density of a material - although materials do expand when they are heated, the change in size is very small.
- Gold is well known for its high density - this is why people in films are often shown having difficulty carrying even one small ingot. Lead is another familiar dense metal, used for weights and lead shot.

Definition of Material Properties

- Many materials have a uniform internal structure (e.g. in metals the atoms are regularly packed together in a "crystalline" structure). The density of these materials is therefore well defined - there will be little variation in different samples of the same material.
- Some materials have a variable internal structure, for example wood is made of hollow cells which can vary in size and thickness between trees. Because of this, the density between different samples of the same material will show more variation.

Definition of Material Properties

Design issues:

- The weight of a product is a very common factor in design. In transport applications, lightweight design is very important – e.g., to reduce the environmental impact of cars, or to increase the payload of aircraft. Weight is also critical in many sports products - racing cycles, tennis racquets, golf clubs, rucksacks.
- In most lightweight design, the aim is to make a stiff or a strong component at a low weight. Density is often therefore considered alongside Young's modulus or strength.
- Specific stiffness of specific strength are then useful quantities.

Definition of Material Properties

- Specific stiffness is Young's modulus divided by density; light, stiff products require high values for specific stiffness (more properly called specific modulus).
- Specific strength is strength divided by density; light, strong products require high values of specific strength.
- In some design problems high density is desirable - e.g. weights for scales, bullets and shells, hammers, coins.

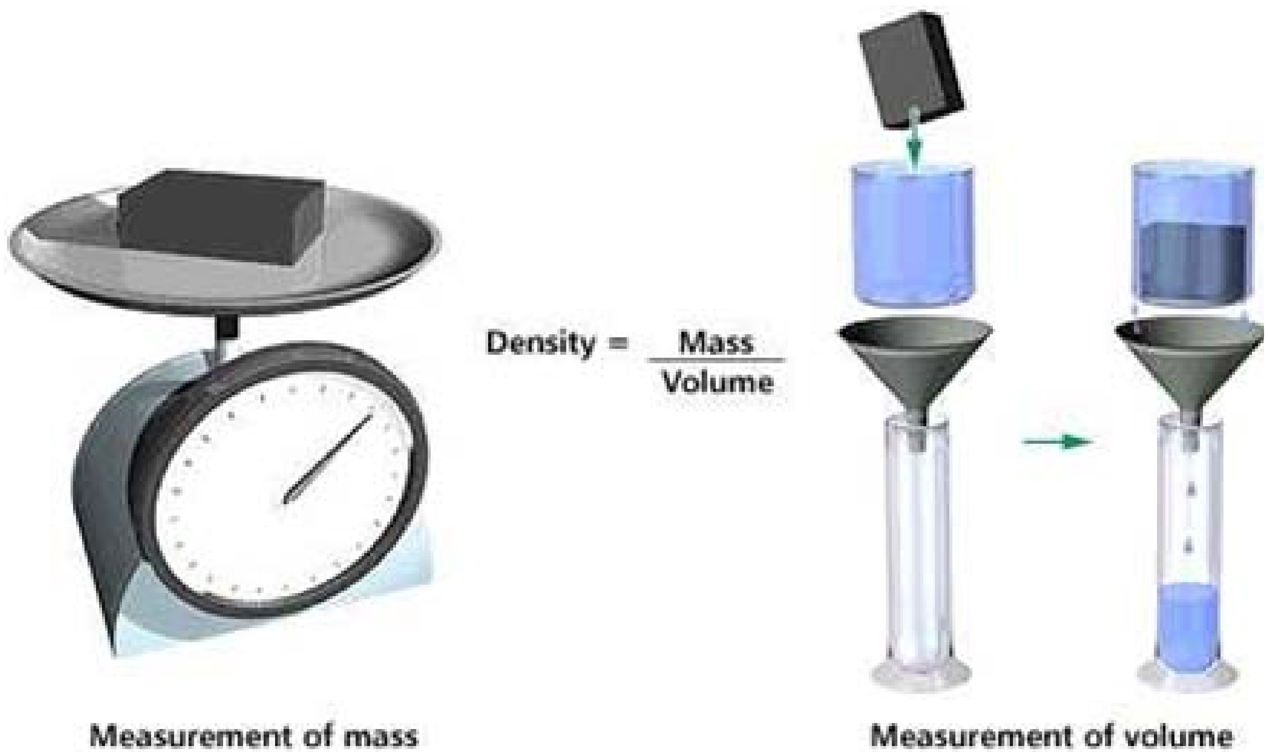
Measurement:

- The mass of material is easily and accurately measured on a sensitive balance, but the volume is more difficult to measure.
- An approximate value can be obtained for simple regular shapes from the dimensions.
- More accurate measurements can be made by measuring the amount of water displaced from a full container when the object is completely immersed (Archimedes method).

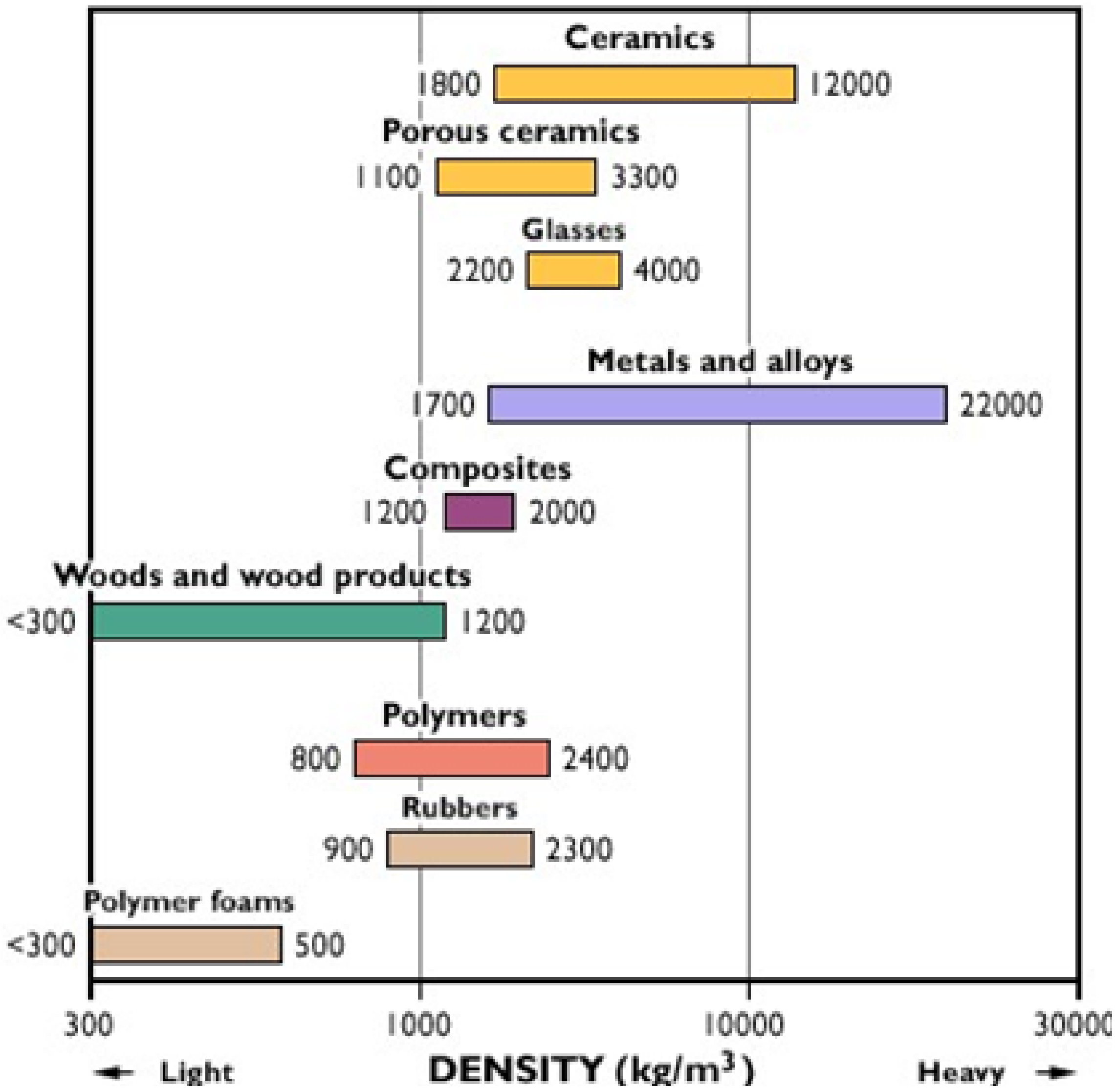
Definition of Material Properties

Units & Values:

- Density is measured in kg/m^3. Note sometimes the density relative to water is stated, i.e. relative density = density/density of water (=1000kg/m^3)



Density of Different Materials



Definition of Material Properties

Maximum Service Temperature

<u>Overview:</u>

- The strength of a material tends to fall quickly when a certain temperature is reached. This temperature limits the maximum operating temperature for which the material is useful.
- For metals the maximum operating temperature is usually around <u>two thirds</u> of the melting temperature.
- For prolonged loading the maximum stress will be lower because <u>creep</u> (permanent stretching over time) will occur.

Definition of Material Properties

- The data for a material on the selection chart shows the range in which the maximum service temperature fall (since a given "material" on the chart will include many different variants with the same name).
- Note that the range of maximum service temperature does not mean the range of temperature in which the material must be used! It may be assumed that any operating temperature below the maximum service temperature down to zero degrees Celsius is safe in design.
- Problems can occur when materials are used well below 0^oC - for example special steels must be used to contain liquefied gases, since ordinary carbon steels may become brittle at these very low temperatures.

Definition of Material Properties

Design issues:

- The maximum service temperature is important for applications where components become hot. Jet engines, brake discs and extrusion dies are all examples of products which operate at temperatures of 400^{o}C or more - metals and ceramics are then required.
- Temperatures of only 100^{o}C are enough to cause problems for lower melting point materials such as polymers - for example, plastic cups and kettles.
- If the load is applied for many hundreds of hours then the design loads must be lowered because the material is liable to *creep*.

Definition of Material Properties

- Creep is the slow permanent stretch of a material at temperatures approaching the melting point, which leads to failure by tearing or fracture.
- For the nickel alloys used in jet engines, creep only occurs at temperatures above 600^{o}C, but polythene shopping bags creep and fail at room temperature if the weight of the shopping is too large.

Definition of Material Properties

Measurement:

- The maximum service temperature is found by measuring the strength at different temperatures.
- A series of tests are carried out with the specimens in a furnace.
- Well below the maximum service temperature the strength only varies a little.
- The temperature at which the strength starts to fall sharply is defined as the maximum service temperature.

Definition of Material Properties

Units & Values:

- The maximum service temperature is measured in Kelvin (or degrees Celsius).
- Remember that the range of maximum service temperature does not mean the range of temperature in which the material must be used!
- It may be assumed that any operating temperature **below** the maximum service temperature down to zero degrees Celsius is safe in design.

Max. Service Temp. for Different Materials