Seleção de Materiais
(Grandezas e Propriedades)

http://www-materials.eng.cam.ac.uk/mpsite/properties/default.html
PROPERTIES

• Young's Modulus and specific stiffness (módulo de elasticidade)
• Strength and specific strength (resistência)
• Toughness (tenacidade)
• Elongation (deformação residual)
• Density
• Max. Service Temperature
• Cost
• Energy Content
• Recycle Fraction (fração reciclável)
• Resistivity (resistividade elétrica)
PROPERTIES

• Young's Modulus and specific stiffness
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• Resistivity
Young's modulus

**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.

- 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").
Young's modulus

• **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.
Young's modulus

- **Measurement**
- Tensile testing is used to find many important material properties. The compression test is similar but uses a stocky specimen to prevent bending.
Young's modulus

- **Units & Values**
  - Young's modulus is equal to elastic stress/strain.
  - Strain has no units to the units are the same as stress: N/m², or Pascals (1 Pa = 1 N/m² ; 1 GPa = 1000 N/mm²)

- 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
PROPERTIES

• Young's Modulus and specific stiffness
• **Strength and specific strength**
• Toughness
• Elongation
• Density
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• Resistivity
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).
- For brittle materials (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.
Strength and Specific Strength

• **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 low weight. In these cases materials with a large "specific strength" are best.
**Strength and Specific Strength**

- **Measurement**
  - Tensile testing is used to find many important material properties. The compression test is similar but uses a stocky specimen to prevent bending. Two measures of strength are defined - yield strength and ultimate tensile strength.

- *Strength* on the selection charts means yield strength.
Strength and Specific Strength

• **Units & Values**
• Strength is measured by applied stress, which is equal to force/area. The units of stress are N/m² or Pascals (1 Pa = 1 N/m² ; 1 MPa = 1 N/mm²)
• Specific strength is strength/density - it is mostly just used for comparing materials, so the units are not important.
Strength and Specific Strength
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Toughness

• Overview
• 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.
• 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).
Toughness

• **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!
Toughness

- **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 machines 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).
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.
Toughness

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 * $g$ * $(h_1 - h_0)$
where $g$ is the acceleration due to gravity
Toughness

- **Units & Values**

- Toughness is usually measured in energy per unit area or Joules/m² (J/m²). Impact energy from Izod or Charpy tests is simple energy in Joules (J).
Toughness
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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.
Elongation

- **Design issues**
  - Elongation is important in components which absorb energy by 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.
Elongation

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

• **Units & Values**

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

The diagram illustrates elongation for various materials:
- **Ceramics**
- **Porous ceramics**
- **Glasses**
- **Metals and alloys**
- **Composites**
- **Woods and wood products**
- **Polymers**
- **Rubbers**
- **Polymer foams**

The x-axis represents elongation on a logarithmic scale, ranging from brittle (0.0001) to ductile (10).
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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.
- Many materials have a uniform internal structure (e.g. in metal the atoms are regularly packed together in a "crystal" 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 be more variable.
Density

- **Design issues**
  - The weight of a product is a very common factor in design. In transport applications, lightweight design is very important - for example, 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.
  - 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.
Density

- **Measurement**
- The mass of material is easily and with accuracy 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.
Density

• **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

- Ceramics: 1800 - 12000 kg/m³
- Porous ceramics: 1100 - 3300 kg/m³
- Glasses: 2200 - 4000 kg/m³
- Metals and alloys: 1700 - 22000 kg/m³
- Composites: 1200 - 2000 kg/m³
- Woods and wood products: <300 - 1200 kg/m³
- Polymers: 800 - 2400 kg/m³
- Rubbers: 900 - 2300 kg/m³
- Polymer foams: <300 - 500 kg/m³

DENSITY (kg/m³)

Light → 3000 → Heavy
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• Toughness
• Elongation
• Density
• Cost
• Energy Content
• Recycle Fraction
• Resistivity
Maximum Service Temperature

- **Overview**
  - 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 two thirds of the melting temperature.
  - For prolonged loading, the maximum stress will be lower because creep (permanent stretching over time) will occur.
  - The data for a material on the selection chart shows the range in which the maximum service temperature falls (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 Centigrade is safe in design.
  - Problems can occur when materials are used well below 0°C - for example, special steels must be used to contain liquified gases, since ordinary carbon steels may become brittle at these very low temperatures.
Maximum Service Temperature

- **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°C or more - metals and ceramics are then required. Temperatures of only 100°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*. 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°C, but polythene shopping bags creep and fail at room temperature if the weight of the shopping is too large.
Maximum Service Temperature

• 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.
Maximum Service Temperature

• Units & Values
• The maximum service temperature is measured in Kelvin (or degrees Centigrade).
• 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 Centigrade is safe in design.
Maximum Service Temperature

- Ceramics: >1000°C
- Porous ceramics: >1000°C
- Glasses: 500°C
- Metals and alloys: >1000°C
- Composites: 250°C
- Woods and wood products: 150°C
- Polymers: 250°C
- Rubbers: 250°C
- Polymer foams: 180°C
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• Cost
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• Recycle Fraction
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Cost

• **Overview**
  
  - Materials are usually sold by weight or by size. Material costs are therefore given as cost per unit weight or cost per unit volume.
  
  - Many materials are initially made in bulk (e.g. cast metal ingots). They are usually shaped into standard stock items (e.g. sheet or tube) before being bought by a manufacturer.
  
  - As a result, the cost of a material to a manufacturer is often higher than the cost of the raw material. Also, as a general rule, the more a material is "improved", e.g. by alloying, the more expensive it becomes.
  
  - Note that the cost of a product is not the same as its price. The cost is how much the manufacturer has to pay for it, while the price is what the product is sold for - the difference is the profit!
Cost

• **Design issues**
  - Cost is often one of the most important design considerations when choosing a material. In most designs the aim is to minimize the cost.
  - For products such as consumer goods, building materials and transport, material cost dominates design. This makes it difficult to introduce expensive, high performance materials like CFRP into products such as cars.
  - Cost only becomes less important when product performance is everything to the customer and they are prepared to pay for it! Examples are top-of-the-range sports products (racing bicycles, Formula 1 cars, gold clubs etc.), medical implants (such as hip prostheses and heart valves). In some cases cost is virtually irrelevant, for example in satellites.
Cost

• **Measurement**
  
• Material costs are not fixed properties, but are strongly affected by the marketplace and international trading, and by changes in the stability of the supply of the raw materials - which can be disrupted by wars and global politics.

• Some materials, e.g. steel, have had a very stable price for many years. Others, like aluminium, have varied by as much as a factor of 3 in the last decade. The cost of newer materials such as CRFP is steadily decreasing as their usage increases

• The most accurate information on material price can be obtained by phoning a supplier!

• Note that the price will depend on the form the material is supplied in (e.g. as raw material, or formed into sheet or tube), and that bulk discounts can be significant.
Cost

- **Units & Values**
- Cost can be measured as cost per unit weight, in US $/kg, or as cost per unit volume, in US $/m$^3$. Of course other currencies can be used instead of US $ besides the fact the international markets usually work in US $. 
Cost (100 – 100,000 £/m³)
Cost (0.01 – 100 £/Kg)
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Energy Content

• Overview

• Energy is used to mine, refine and process materials - this is called the "energy content" of the material. The energy used has environmental implications (global warming, CO₂ and other emissions).

• The energy content is just one of the environmental factors (disposal of wastes, final disposal of the product and transportation are others). It is relatively easy to measure and is therefore a simple indicator of "environmental friendliness" of a material.

• Naturally raw materials such as wood are energy efficient because there are no refining or synthesis costs. Metals tend to have the highest energy contents as most metals are extracted from ores, and need a lot of refining, which uses a lot of energy.
Energy Content

- **Design issues**
- All materials used for products have an environmental impact. This is of growing importance, so it is increasingly common to consider quantities such as energy content. Overall assessment of environmental impact over the whole lifetime of a product is very difficult to do with any certainty.
- Environmental issues are particularly important in design for one-use products (e.g. packaging, drink containers, nappies) or large volume products which may consume energy in use (e.g. cars, domestic appliances).
- Energy content is closely related to recycling - high energy content materials are particularly attractive to recycle, particularly if the energy used in recycling is much less than is needed to make new material (e.g. aluminium).
Energy Content

• Measurement

• The energy content of a material is defined as the total energy necessary to make it into a form in which it can be used to manufacture a product. This includes mining, refining or synthesizing, and forming it into usable sizes and shapes.
Energy Content

• **Units & Values**
  
  • The energy content is given as energy per unit weight, Joules/kg
  
  • Precise numerical ranges are not given here for material classes as they are not useful - see material selection charts for individual materials.
Energy Content
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• Toughness
• Elongation
• Density
• Max. Service Temperature
• Cost
• Energy Content
• Recycle Fraction
• Resistivity
Recycle Fraction

- **Overview**

The fraction recycled is a measure of the proportion of a material in use in products which can economically be recycled.

- Materials which can be remelted (like metals or thermoplastics) or shredded (like paper and wood) are most easily recycled. Some materials are difficult or impossible to recycle because they cannot be returned to their previous condition (like ceramics, thermosets and fibre composites).

- Many other factors influence whether a material is recycled. It must be possible to collect and separate the materials from products at the end of their lifetime. Recycling has costs associated with transport, separating and remelting or shredding, and these must be lower than the cost of using new raw material.

- Recycling is closely related to energy content, as energy is a significant factor in both the cost of recycling and the cost of new raw material. The highest fractions recycled tend to be for high energy content materials (e.g. gold) and for materials which use much less energy to recycle than to produce (e.g. aluminium).
Recycle Fraction

• Design issues
  • Materials can only be recycled if the different materials in a product can be easily separated and identified. For example, steel can be pulled out of mixed scrap using magnets, and products are increasingly labelled with the material used (e.g. polythene or PET on bottles).
  • Designers of complex systems such as cars, which contain many different materials, increasingly consider how a car could be made easier to dismantle at the end of its life to recover separate materials. Speed is critical is disassembly is to be economic.
  • In general, the more different materials used in a product, the harder it will be to recycle them.
  • Bottles, cans and newspaper can be cheaply recycled if individuals and organizations return them to central collection banks.
Recycle Fraction

• **Measurement**
• The fraction recycled is measured by governments, environmental agencies and material suppliers.
• Estimates for whether a material is likely to have a high or low fraction recycled can be made by considering the costs of recycling compared to the costs of using new raw material.
Recycle Fraction

• **Units & Values**
  
  Fraction recycled is simply a number between 0 and 1 (or a percentage) and has no units.

  Precise numerical ranges are not given here for material classes as they are not useful - see material selection charts for individual materials.
Recycle Fraction

The diagram illustrates the relationship between the recycle fraction and cost for various materials. Each area of the graph represents different materials and their recyclability, with labels indicating materials such as Metals and alloys, Glasses, Porous ceramics, Polymers, Wood and wood products, Foams, Ceramics, Rubbers, and Composites. The x-axis represents cost per kg (£/kg) ranging from cheap to expensive, while the y-axis shows the recycle fraction ranging from hardly recyclable to mostly recyclable.
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Resistivity

• **Overview**
• Resistivity is a measure of the resistance to electrical conduction for a given size of material. Its opposite is electrical conductivity (=1/resistivity).
• Metals are good electrical conductors (high conductivity and low resistivity), while non-metals are mostly poor conductors (low conductivity and high resistivity).
• The more familiar term electrical resistance measures how difficult it is for a piece of material to conduct electricity - this depends on the size of the piece: the resistance is higher for a longer or narrower section of material.
• To remove the effect of size from resistance, resistivity is used - this is a material property which does not depend on size.
• Resistivity is affected by temperature - for most materials the resistivity increases with temperature. An exception is semiconductors (e.g. silicon) in which the resistivity decreases with temperature.
• The ease with which a material conducts heat is measured by thermal conductivity. As a first estimate, good electrical conductors are also good thermal conductors.
Resistivity

• Design issues

• Resistivity is important in any product which conducts electricity. Components which must conduct easily (called "conductors") must have low resistivity, while those which must not conduct (called "insulators") must have high resistivity.

• Many products will contain both conductors and insulators, e.g. a 13A plug - the conductors take the electricity where it is wanted (the machine or appliance) and the insulators prevent it from getting where it isn't wanted (i.e. the user!)

• The resistivity of insulators and conductors differ by a huge factor - typically one million, million, million! Within a given class of materials (e.g. metals), the resistivity can still vary by a factor of 1000 or more. The differences look small compared to the difference between metals and insulators like polymers, but can be very significant in choosing the metal for a conductor - 1000 times more current for the same voltage.

• Electrical and thermal conductivity are closely related. Examples of products in which good thermal conduction is required are radiators and saucepans; thermal insulation is required for pan handles and cookers.
Resistivity

- Measurement
  - Observations of how the resistance varies with size of a sample suggest that resistivity obeys the relationship:
    - Electrical resistivity = resistance * cross-sectional area / length
  - The resistivity can therefore be calculated quite easily by measuring the resistance of a piece of wire of constant cross-section and known length.
  - In practice, resistivity is difficult to measure accurately because of the effect of temperature. More sophisticated techniques need to be used if accurate measurements are required, e.g. a Wheatstone bridge.
Resistivity

- **Units & Values**
- From the definition of resistivity it can be seen that it has units of ohm-metres. Giving exact values can be difficult because of the strong temperature dependence. Data are usually given for room temperature.
Resistivity
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• Toughness
• Elongation
• Density
• Max. Service Temperature
• Cost
• Energy Content
• Recycle Fraction
• Resistivity
Até aqui, tudo bem
Obrigado!