Electronics Materials-Mechanical properties of metals

Stress

When a material is subjected to an external force, it will either totally comply with that force and be pushed away, like a liquid or powder, or it will set up internal forces to oppose those applied from outside. Solid materials generally act rather like a spring – when stretched or compressed, the internal forces come into play, as is easily seen when the spring is released.

A material subjected to external forces that tend to stretch it is said to be in tension, whereas forces which squeeze the material put it in compression.

An important aspect is not so much the size of the force, as how much force is applied per unit of cross-sectional area. The term ‘stress’, symbol σ (Greek letter sigma), is used for the force per unit area, and has the units of pascals (Pa) with 1Pa being one newton per square metre.

Because the reference area is so large, it is normally necessary to use high multiples such as the megapascal (MPa = 106 Pa) and gigapascal (GPa = 109 Pa). However, when we bear in mind that, in electronics, the area over which forces are applied is generally very much smaller, it is useful to keep in mind that one MPa is equivalent to a force of 1 newton applied on a square millimetre of area.

Strain

A material in tension or compression changes in length, and the change in length compared to the original length is referred to as the ‘strain’, symbol1 ε (Greek letter epsilon). Since strain is a ratio of two lengths it has no units and is frequently expressed as a percentage: a strain of 0.005 corresponds to a ½% change of the original length.

1 In some texts you may find η (Greek letter eta) used.

Hooke’s Law

As you know from a spring, if you gradually stretch it, the force needed increases, but the material springs back to its original shape when the force is released. Materials which react in the same way as a spring are said to be ‘elastic’. Typically if we measure the extension of different forces and plot the graph of this, we will find that the extension is proportional to the force applied. Materials that obey Hooke’s Law exhibit a linear relationship between the strain and the applied stress

(Figure 1).

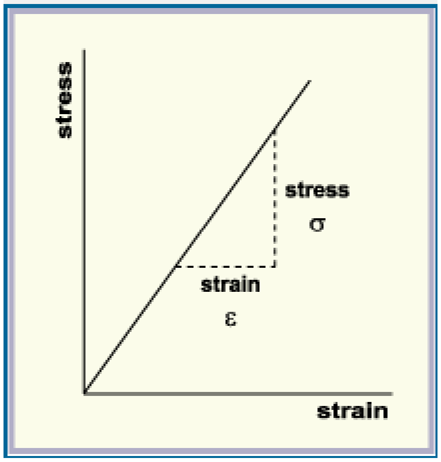


Figure 1: Stress-strain graph for an elastic solid

Many metals follow Hooke's Law until a certain level of stress has been applied, after which the material will distort more severely. The point at which straight line behaviour ceases is called the limit of proportionality: beyond this the material will not spring back to its original shape, and is said to exhibit some plastic behaviour (Figure 2). The stress at which the material starts to exhibit permanent deformation is called the elastic limit or yield point.

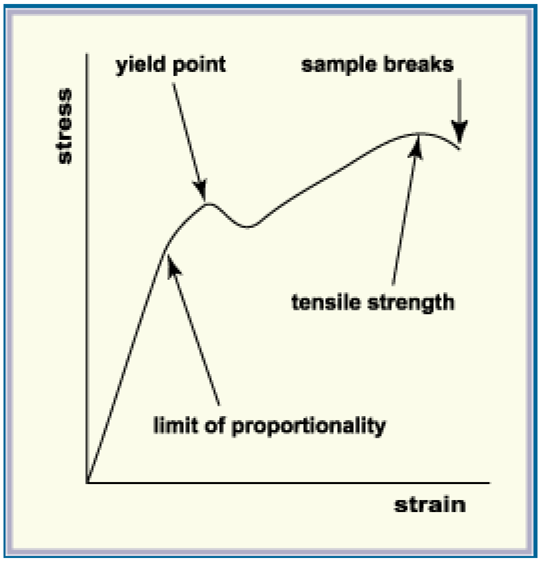


Figure 2: Stress-strain graph for a typical metal

As Figure 2 shows, if the stress is increased beyond the yield point the sample will eventually break. The term (ultimate) tensile strength is used for the maximum value of tensile stress that a material can withstand without breaking, and is calculated at the maximum tensile force divided by the original cross-sectional area.

Note that there may be substantial differences between the stress at the yield point and on breaking – for example, one source quotes the 'ultimate tensile strength' for AISI304 stainless steel as 505 MPa, and the 'yield tensile strength' as 215 MPa. For most engineering purposes, metals are regarded as having failed once they have yielded, and are normally loaded at well below the yield point.

With some materials, including mild steel, the stress/strain graph shows a noticeable dip beyond the elastic limit, where the strain (the effect of the load) increases without any need to increase the load. The material is said to have 'yielded', and the point at which this occurs is the yield point. Materials such as aluminium alloys on the other hand don't show a noticeable yield point, and it is usual to specify a 'proof' test. As shown in Figure 3, the 0.2% proof strength is obtained by drawing a line parallel to the straight line part of the graph, but starting at a strain of 0.2%.

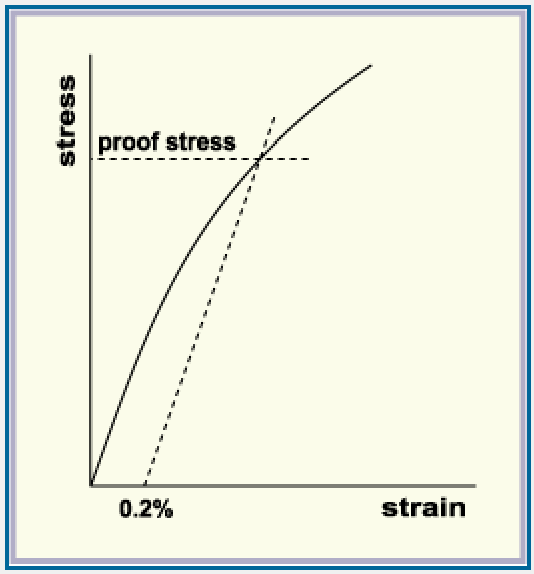
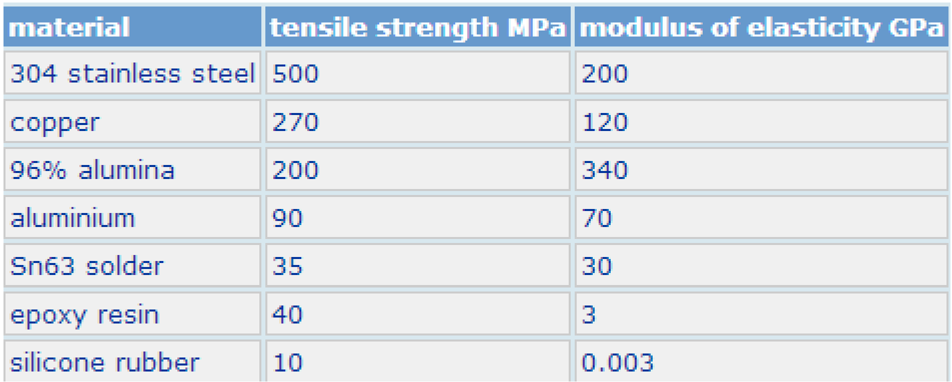


Figure 3: Stress-strain graph for an aluminium alloy

Young's modulus

As you will appreciate from the shapes of Figure 2 and Figure 3, the slope of the stress/strain graph varies with stress, so we generally take only the slope of the initial straight-line portion. The stress/strain ratio is referred to as the modulus of elasticity or Young's Modulus. The units are those of stress, since strain has no units. Engineering materials frequently have a modulus of the order of 109Pa, which is usually expressed as GPa. Some approximate figures for typical electronic materials are given in Table 1.

Table 1: Tensile strength and Young's modulus for selected materials



material	tensile strength MPa	modulus of elasticity GPa
304 stainless steel	500	200
copper	270	120
96% alumina	200	340
aluminium	90	70
Sn63 solder	35	30
epoxy resin	40	3
silicone rubber	10	0.003

Compression

The compressive strength is the maximum compressive stress that a material can withstand without being crushed. Both strengths have the same unit as stress, and are typically millions of Pa. For most engineering materials, Young's Modulus is the same in compression as in tension.

Hardness

Hardness is another measure of the ability of a material to be deformed. There are many different tests for this, but all measure the resistance of a material to indentation, applying a known force to a tool of defined radius which is very much harder than the material being tested. Empirical hardness numbers are calculated from measurements of the dimensions of the indentation.

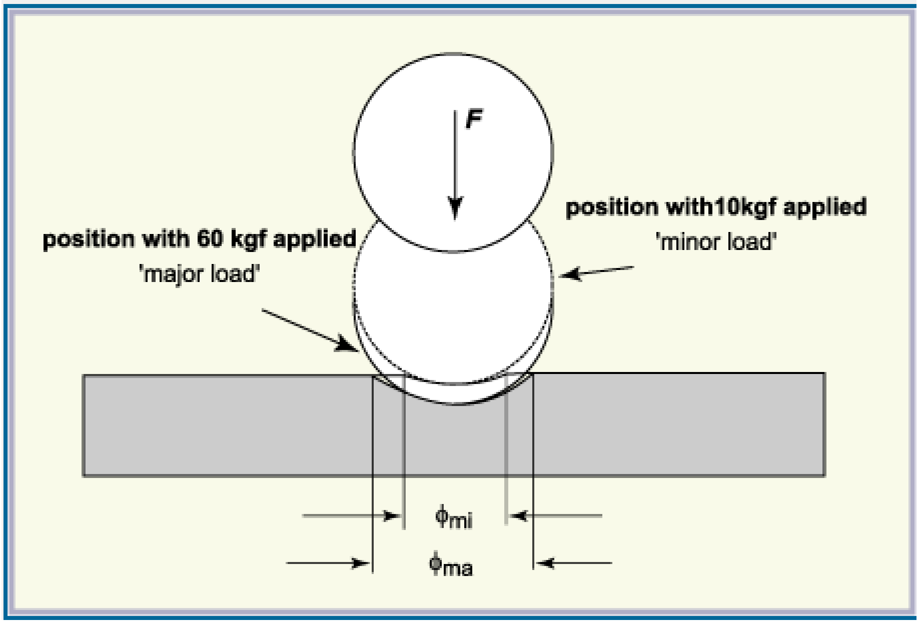


Figure 4: The Rockwell R hardness test

The principle of one of the simpler tests, the Rockwell R2 test, can be seen in Figure 9. A specimen at least ¼ inch (6.4 mm) thick is indented by a ½ inch (12.7 mm) diameter steel ball. A small load is applied, the apparatus is zeroed, and then a larger load is applied and removed. After a short time with the preload still applied, the remaining indentation is read from the scale.

2 As with many standard tests, the units used are American! We have kept kgf to help you gauge the magnitude of the force involved: 1 'kilogramforce' = 9.81N.

For metal measurements, there are alternative Rockwell tests, with different test heads and different loads. You will also find Brinell hardness numbers (BHN), derived from a test which uses a 10mm tungsten carbide ball. Brinell testing is sometimes preferred as it covers a wider hardness range than the Rockwell tests.

There is unfortunately little correlation between different hardness tests, but there is reasonable correlation between the hardness results and the tensile strength, at least for given families of alloys. Note that the correlation is to tensile strength rather than yield strength, because plastic deformation takes place during the hardness measurement.

Shear strength

Subjected to forces which cause it to twist, or one face to slide relative to an opposite face, a material is said to be in shear (Figure 5). Compared to tensile and compressive stress and strain, the shear forces act over an area which is in line with the forces.

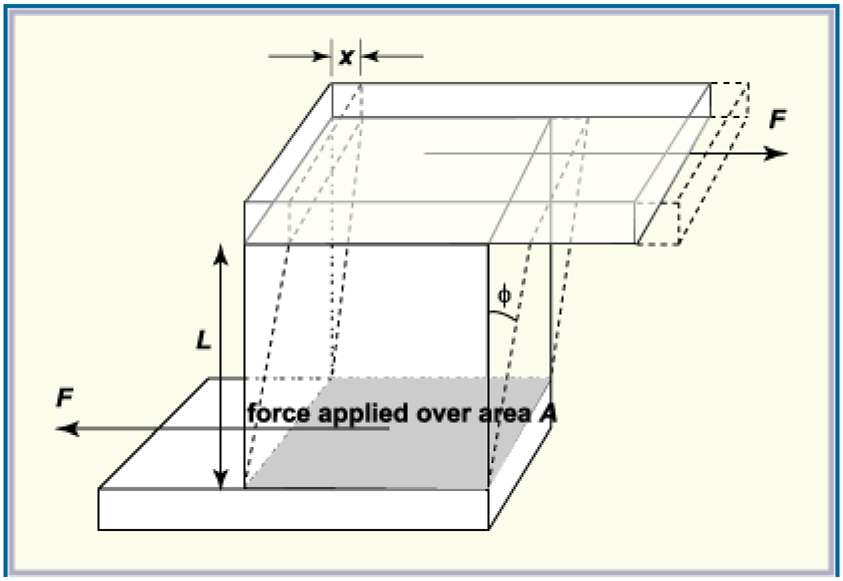


Figure 5: Shear stress applied to an object

The force per unit area is referred to as the shear stress, denoted by the symbol τ (Greek letter tau), where

$$\tau = \frac{F}{A}$$

Its unit is the pascal (Pa), where force is measured in newtons (N) and area in square metres.

When shear stress is applied, there will be an angular change in dimension, just as there is a change in length when materials are under tension or compression. Shear strain, denoted by the symbol γ (Greek letter gamma), is defined by

$$\gamma = \frac{x}{L} = \tan \phi \approx \phi$$

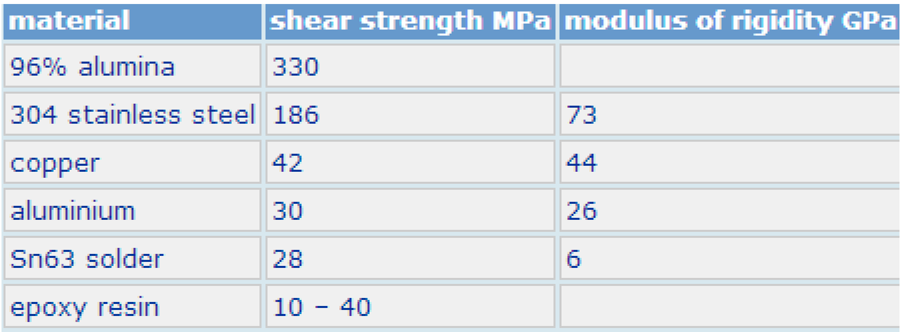
where the angular deformation, symbol φ (Greek letter phi) is expressed in radians. The last approximate equality results from the fact that the tangent of a small angle is almost the same as the angle expressed in radians. This is the reason why some texts give the radian as the unit of strain. Both shear strain and angular deformation are ratios, so have no units. However, it is not unusual for shear strain to be quoted in %, as with tensile strain.

Shear stresses are most evident where lap joints are fastened together and forces applied to pull them apart, but are also seen when rods are twisted, or laminated boards bent.

The shear strength of a material is the maximum stress that it can withstand in shear before failure occurs. For example, punching, cropping and guillotining all apply shear stresses of more than the maximum shear stress for that material.

As with Hooke's Law for tensile stress, most metals have a shear stress which is proportional to the shear strain. And in a similar way to Young's modulus, the gradient of the graph is referred to as the shear modulus or modulus of rigidity. Again the SI unit3 for shear modulus is the pascal (Pa).

3 You are very likely to find Young's modulus and shear modulus quoted in psi (pounds force per square inch) or kpsi (thousands of psi). To convert to MPa, multiply the figure in kpsi by 6.89. Watch the units! You should also expect there to be very wide variations in the figures quoted, as these depend critically on alloy composition and work hardening (for metals), on purity (for ceramics) and on formulation (for polymers).



material	shear strength MPa	modulus of rigidity GPa
96% alumina	330	
304 stainless steel	186	73
copper	42	44
aluminium	30	26
Sn63 solder	28	6
epoxy resin	10 – 40	

Table 2: Shear strength and shear modulus for selected materials

Stiffness

The stiffness of a material is an important aspect of PCB design, being the ability of the material to resist bending. When a board is bent, one surface stretches and the inside of the radius is compressed. The more a material bends, the more the outer surface stretches and the internal surface contracts. A stiff material is one that gives a relatively small change in length when subject to tension or compression, in other words, a small value of strain/stress.

However, on the basis that stiff = good, a natural feeling that this should be a larger figure means that we actually quote the ratio of stress/strain. So a stiff material has a high value of Young's modulus. From Table 1 you will be aware of the very wide range of properties in electronic materials. Note that the metals in this list are much stiffer than polymers, but well below the stiffness of a typical ceramic. However, this stiffness is accompanied by extreme brittleness. One of the features of a metal is that it is unlikely to shatter, as would a piece of glass or ceramic, but it will show permanent deformation when forces are applied – ask any car body shop!

Elongation

The stress-strain graph of a brittle material (Figure 6) shows that very little plastic deformation occurs before the point at which the stress is sufficient to induce failure. A brittle test piece after fracture will be almost the same length as it started. However, a 'ductile' material, such as copper will stretch a great deal before it finally breaks. Try stretching a piece of copper wire, and you will know that it stretches by 10-20% before the weakest point in the wire 'necks' and the wire breaks. The percentage elongation of a material is used as a measure of its ductility.

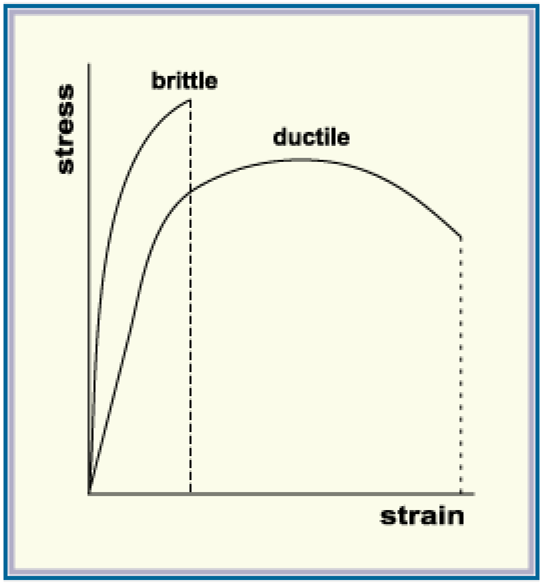


Figure 6: Brittle and ductile materials compared

An explanation of yield and deformation

The block slip model (Figure 7) is used to explain the elastic and plastic behaviour of metals. A metal is viewed as blocks of atoms which can move relative to each other. When stress is applied, these blocks become displaced until, when the yield stress is reached, large blocks of atoms slip past each other. The plane along which movement occurs is called the slip plane.

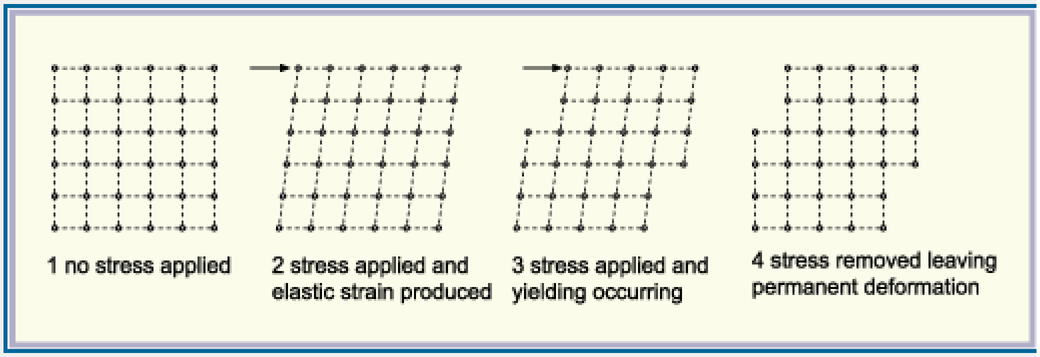


Figure 7: The block slip model, showing behaviour of metals under stress

Slip lines do not cross from one grain to another, but are confined by the grain boundaries (Figure 8). The bigger the grains, the more slippage and the greater the plastic deformation which occurs. Materials with a fine grain structure are therefore less ductile and more brittle – each slip process is confined and not allowed to spread.

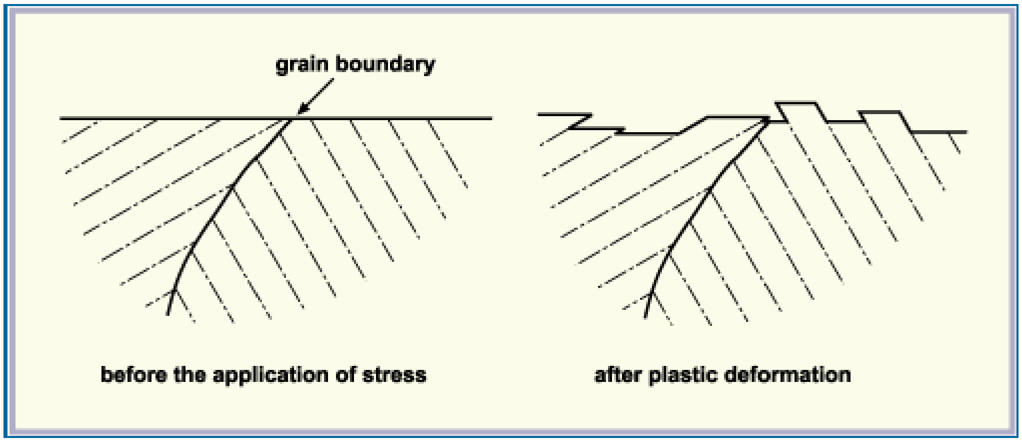


Figure 8: Grain boundaries modifying behaviour during deformation

The effect of temperature

Figure 9 shows how the strength and hardness of a metal varies with temperature: note that the temperature is measured on the Kelvin scale, whose origin is absolute zero (–273ºC). Provided that the curves are scaled correctly, and referenced to the melting temperature of the material (Tm), this is actually a generic relationship: the pattern follows a similar pattern for most metals, reducing to zero at the melting point, and reducing markedly as that temperature is approached.

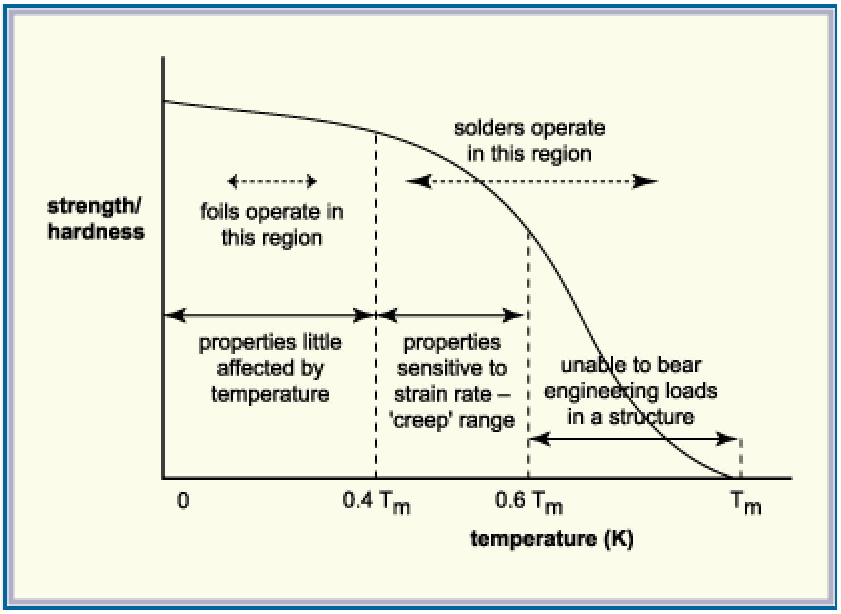


Figure 9: Strength/hardness of a metal related to its melting temperature

Metallurgists refer to the idea of a ‘homologous temperature’, where the actual temperature of a material is expressed as a fraction of its melting temperature expressed in Kelvin. Solder (m.pt 183°C = 456K) at 0.85Tm or 115ºC (= 388K), would thus be expected to have comparable properties to copper (m.pt 1085°C = 1358K) at 0.85Tm or 881ºC (= 1154K).

In electronics applications, where circuits typically operate over a –55ºC®+125ºC range, eutectic tin-lead (Sn63) solder is working at 0.48®0.87Tm. From this we can deduce that solder will have limited mechanical strength (as a bulk material) and be within the ‘creep range’. This is borne out by the comparatively low values for tensile strength, shear strength and modulus of elasticity which are given in Table 1 and Table 2.

Copper, on the other hand, has a much higher melting point, so foils are working at only 0.16®0.29Tm, and their properties are little affected by temperature.

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Source: http://www.ami.ac.uk/courses/topics/0123_mpm/index.html