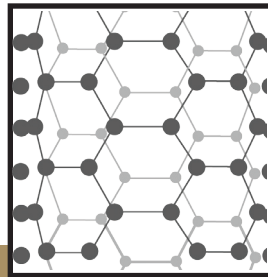


RAW MATERIALS TO FINAL PRODUCTION

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4

4.1 – PROPERTIES OF MATERIALS

ESSENTIAL IDEA

Materials are selected for manufacturing products based on their properties.

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Materials are often developed by materials engineers to have specific properties. The development of new materials allows designers to create new products which solve old problems in new ways. For example, the explosion of plastic materials following World War II enabled products to be made without using valuable metals.

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NATURE OF DESIGN

The rapid pace of scientific discovery and new technologies has had a major impact on material science, giving designers many more materials with which to choose from for their products. These new materials have given scope for 'smart' new products or enhanced classic designs. Choosing the right material is a complex and difficult task with physical, aesthetic, mechanical and appropriate properties to consider. Environmental, moral and ethical issues surrounding choice of materials for use in any product, service or system also need to be considered.

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AIM

Physical properties

The physical properties of a material are those properties that can be determined without damage or destruction and relate to the interaction of the material with energy and matter in its various forms. Some examples of physical properties are indicated below.

Mass

Mass (m) of a body is a measure of the amount of matter a body contains and is a constant. The SI unit for mass is the kilogram (kg).

Weight

Weight is a force and represents the mass of an object acted upon by gravity and is expressed by Newton's second law as:

$$\text{Force (weight)} = m \times a_g$$

Where a_g is acceleration due to gravity. On the Earth's surface a_g has a value of approximately 9.8m/s^2 while on the Moon its value would only be 1.6m/s^2 . Weight is therefore a variable quantity.

Because it is a force, the SI units for weight are Newtons (N) where

$$1 \text{ Newton} = 1\text{kg.m/s}^2$$

Confusion between mass and weight is seen every day in the use of bathroom scales. When we stand on a set of these scales we exert a force on them. The read-out of weight should therefore be expressed in Newtons, but a value of kilograms is indicated.

This is because a_g is a constant for any particular location, and these scales are typically used on the Earth's surface. The read-out is therefore adjusted to take this constant into consideration and give us a reading of our mass in kilograms which we colloquially refer to as our weight. To obtain our actual weight we would need to multiply the result by 9.8m/s^2 .

Electrical resistivity

Electrical conductivity (σ) and electrical resistivity (ρ) are measures of the ease with which free electrons move through a material and are inherent properties of a material. As might be expected, conductivity is inversely related to resistivity as indicated below:

$$\sigma = 1/\rho$$

This relationship is strictly true only when applied to metals. The values of resistivity and conductivity for a variety of common materials are presented in Figure 4.1.1.

Material	Electrical conductivity (σ)	Electrical resistivity (ρ)
Silver	6.29×10^7	1.59×10^{-8}
HC copper	5.98×10^7	1.67×10^{-8}
Gold	4.26×10^7	2.35×10^{-8}

Material	Electrical conductivity (σ)	Electrical resistivity (ρ)
Aluminium	3.77×10^7	2.65×10^{-8}
Tungsten	1.85×10^7	5.40×10^{-8}
Iron	1.02×10^7	9.76×10^{-8}
Platinum	9.43×10^5	10.6×10^{-8}
Titanium	2.38×10^7	42.0×10^{-8}
Graphite	10^5	10^{-5}
Magnetite	10^2	10^{-2}
Germanium	2.13	4.7×10^{-1}
Limestone	10^{-2}	10^2
Silicon	2×10^{-4}	5×10^3
Window glass	2×10^{-5}	5×10^4
Granite	10^{-6}	10^6
Marble	10^{-8}	10^8
Bakelite	10^{-9} to 10^{-11}	10^9 to 10^{11}
Borosilicate glass	10^{-9} to 10^{-15}	10^9 to 10^{15}
Mica	10^{-11} to 10^{-15}	10^{11} to 10^{15}
Polyethylene	10^{-15} to 10^{-17}	10^{15} to 10^{17}

Figure 4.1.1 Electrical resistivity and conductivity of selected materials

Resistivity in metals has been described in terms of resistance to the free flow of electrons. This resistance to motion was postulated to arise from the scattering of the electrons due to collisions with the positive ions of the metal lattice. According to this theory, resistivity arises from any phenomenon that disturbs the motion of electrons, such as:

- collisions with lattice imperfections (e.g. caused by cold working)
- collisions with solute atoms (e.g. impurities)

- collisions with thermally-induced lattice vibrations (e.g. temperature).

Temperature has the greatest effect on resistivity. As temperature increases, thermally-induced lattice vibrations increase, raising the chance of interaction with electrons. Therefore, as temperature increases, so does resistivity.

When the temperatures approach absolute zero, (0°K), thermally-induced lattice vibrations also approach zero and resistivity becomes a function of temperature-independent factors such as impurity content and microstructural effects such as lattice imperfections, precipitates and inclusions.

The SI unit for resistivity (ρ) is ohm-metres (Ω -m), while the SI unit for electrical conductivity (σ) is siemens per metre (S/m).

Thermal Conductivity

When a temperature gradient is present in a material, heat will flow from the region of higher temperature to the region of lower temperature. Thermal conductivity (K) is a measure of the efficiency with which thermal energy will travel through a material.

The higher the thermal conductivity the greater is the rate at which heat will flow. Thermal conductivity is therefore a physical property because temperature flow can be measured using thermocouples without damage to the material under test. The SI units for thermal conductivity are Weber/metre/°K ($Wm^{-1}K^{-1}$).

Metals typically have high thermal conductivity, while polymers and ceramics have a low thermal conductivity and are insulators rather than conductors of heat. The thermal conductivity of a number of materials at room temperature is provided in Figure 4.1.2.

Note, values are indicative only. For purposes of translation of values:

$$1 Wm^{-1}K^{-1} = 0.00239 \times Cal cm^{-1} s^{-1} K^{-1}$$

Material	Thermal conductivity ($Wm^{-1}k^{-1}$)	Thermal conductivity ($Cal cm^{-1} s^{-1} k^{-1}$)
Graphite	2 000	4.8
Silver	429	1.03
Copper	380	0.91
Gold	310	0.74
Aluminium	230	0.55
Brass	109	0.26
Grey cast iron	55	0.13
Mild steel	54	0.13
Ferritic stainless steel	25	0.6
Austenitic stainless steel	15	0.4
Alumina	20	0.05
Glass	1	0.002
Oak	0.16	0.0004
Plywood	0.13	0.0003
Polyurethane	0.02	0.00005
Nylon 6,6	0.25	0.0006
PTFE	0.25	0.0006
PVC	0.19	0.0005
Bakelite	0.23	0.0005

Figure 4.1.2 Thermal conductivity of selected materials at room temperature

Thermal expansion

When a material is heated, the thermal energy gained, results in an increase in atomic vibrations. This leads to an increase in atomic separation and an increase in the dimensions of the material overall. This increase in dimensions is typically quantified as the change in length per unit length per degree ($\text{m.m}^{-1} \text{K}^{-1}$) for the coefficient of linear thermal expansion (α). Figure 4.1.3 shows α values for a number of materials from 20° to 100°C .

Material	Mean coefficient of thermal expansion (10^{-1}K^{-1}) at 20°C
Graphite	7.9
Silver	19.5
Copper	18
Aluminium	24
Gold	14.2
Brass	18.7
Mild steel	11
Grey cast iron	10.8
Glass – Pyrex	4
Glass – plate	9
Bakelite	80
Polyurethane	57.6
Nylon 6,6	80
PVC	50.4

Figure 4.1.3 Thermal expansion of selected materials from 20° to 100°C

Hardness

Hardness refers to the resistance of a material to scratching or abrasion. It may also refer to resistance to indentation, penetration or cutting. The number of definitions for hardness, indicates that hardness may not be a fundamental property of a material, but rather a composite one including yield strength, work hardening, true tensile strength, modulus of elasticity, and others. Because of this, and the fact that the process of obtaining a hardness involves some surface damage, hardness is often listed as a mechanical property. The limited damage produced, however, and the utility of the measurement as an indicator of material condition sees hardness testing employed widely as a non-destructive quality control test.

As indicated above, hardness is routinely used as an indication of material condition. For example, increased hardness is often interpreted as a general indication of greater resistance to deformation and wear. As might be expected, a variety of tests have been developed to measure hardness. These tests fall into three broad groups, consisting of:

- scratch hardness (e.g. Mohs, Bierbaum, Pencil)
- static indentation hardness (eg Brinell, Rockwell, Vickers, Knoop, Janka, Durometer)
- dynamic hardness (Scleroscope, Leeb).

A selection of commonly used hardness tests are described below. The requirements for surface preparation vary but all necessitate some preparation of the surface to ensure it is clean and free of debris.

Scratch Hardness

As the name implies scratch hardness tests involve the scratching of the test surface with a stylus/indenter.

The German mineralogist Friedrich Mohs developed one of the earliest measures of material hardness in 1812. The Mohs hardness as it has come to be known is defined by how well a substance will resist scratching by another substance of known or defined hardness and a ranking from 1 to 10 assigned.

The scale contains ten minerals that Mohs proposed as exemplars of each position on the scale, starting with the mineral talc at position 1, which can be scratched by a fingernail, to diamond at 10, see Figure 4.1.4.

Mohs hardness	Mineral
1	Talc
2	Gypsum
3	Calcite
4	Fluorite
5	Apatite
6	Orthoclase
7	Quartz
8	Topaz
9	Corundum
10	Diamond

Figure 4.1.4 Mohs hardness scale

The Mohs scale therefore is not linear; that is, each increment in the scale does not indicate a proportional increase in hardness. For instance, the progression from calcite to fluorite (from 3 to 4 on the Mohs scale) reflects an increase in hardness of approximately 25%, while the progression from corundum to diamond, on the other hand, (9 to 10 on the Mohs scale), reflects a hardness increase of more than 300%.

For this reason, the Mohs test, while greatly facilitating the identification of minerals in the field, is not suitable for accurately gauging the hardness of most materials, particularly industrial materials such as steel or ceramics.

The Bierbaum test uses a standardised diamond indenter that is dragged across the test surface and the width of the scratch produced measured. This test is suited to a variety of materials, particularly plastics.

The pencil test uses a set of twenty pencils ranging from grades 9B to 9H. A pencil is placed in a holder at an angle of 45° to the test surface and the holder moved across the surface under a fixed force of 7.5 N. The test is repeated until a pencil grade that just scratches/indents the surface is found and that grade recorded as the hardness. This test has found use in the testing of polymer coatings.

Static Indentation Hardness

Static hardness tests typically involve the penetration of an indenter into the test surface using low loading rates.

The Barcol hardness test uses a cone shaped steel indenter that is pushed into the test surface until a spring is completely depressed, resulting in the application of a fixed load. The depth to which the indenter has penetrated the surface is then read off a dial gauge calibrated from 0 to 100 and recorded as the Barcol number. This test is often used to determine the degree to which plastic resin has cured.

Brinell tests use a hardened steel or tungsten carbide ball typically of 10mm diameter to produce an indentation in the surface of the material using a standard load. The diameter of the impression is measured with a small portable microscope and the Brinell hardness read from a conversion table.

Rockwell tests use either a small steel ball or a diamond indenter ground to form a cone of 120°, to form an impression. Several Rockwell hardness scales are available (A, B, C, etc) using various combinations of indenter and applied load, depending on the material to be tested. The depth of the impression is related to a Rockwell hardness that is read off a dial gauge or LCD.

Vickers tests use variable loads and a diamond pyramid indenter. Because the same indenter is used and only the applied load varied, a comparable hardness is obtained when testing a range of materials. Because of this, the Vickers test is the standard method for the reliable measurement of metal and ceramic hardness. The impression diagonals are measured and related to a Vickers hardness number by reference to a table selected based on the applied load used in the test.

Knoop tests explore microhardness by making rhombohedral indentations, (one long and one short diagonal), with a pyramidal diamond indenter. The aspect ratio of the impression diagonals allows impressions to be placed closer together without concerns of previous impressions affecting later hardness results.

The Brinell, Rockwell, Vickers and Knoop hardness testers use a standardized indenter and fixed load to determine hardness and are used extensively in the testing of metals. Their indentors are shown in Figure 4.1.5.

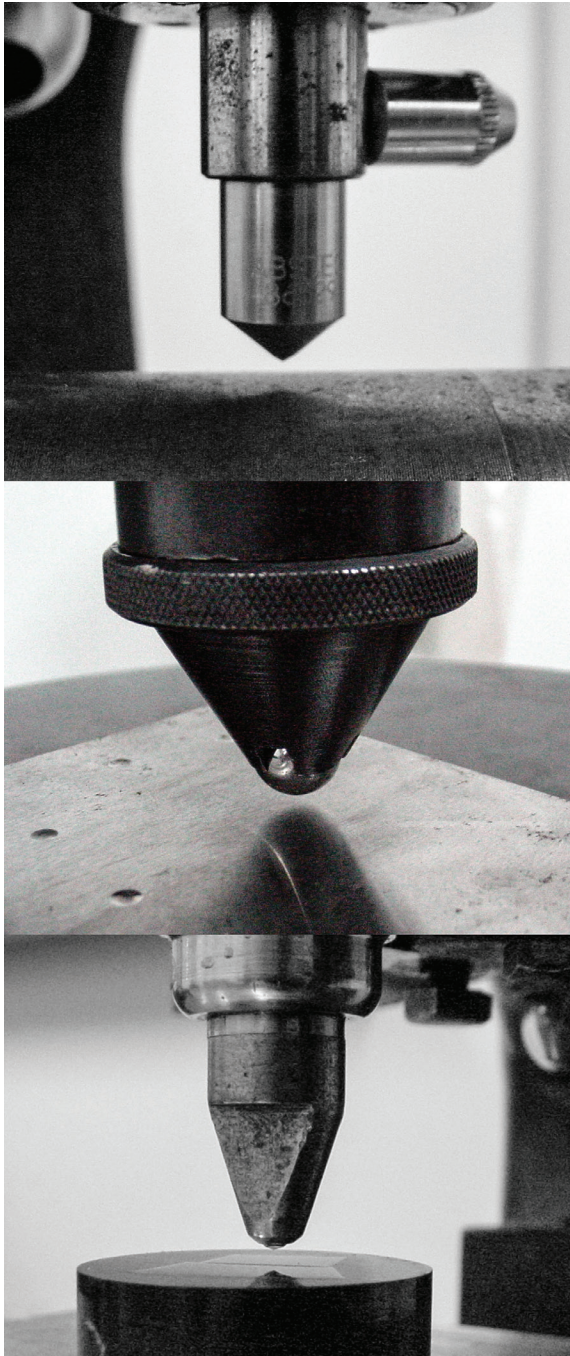


Figure 4.1.5 Commonly used indentors for hardness testing: Brinell (top), Rockwell (middle), Vickers (bottom)

The Janka hardness test is used for the testing of wood and is similar to the Brinell test in that a steel ball, this time of 11.28 mm is impressed into the surface to a depth of 5.64 mm (half the indenter diameter), leaving an impression of 100 mm². The force required to create this impression is measured in kN and is reported as the Janka hardness (JH).

The Durometer hardness test (Figure 4.1.6), is principally undertaken on polymers and involves the pressing of an indenter (consisting of a hardened steel rod) into the surface of the test piece and is similar to the Barcol test.

The indentation hardness is read from a dial gauge on the body of the instrument. If the indenter completely penetrates the sample, a reading of 0 is obtained, and if no penetration occurs, a reading of 100 results. This test is not a good predictor of other properties such as tensile strength, abrasion resistance or wear resistance and is generally used in concert with other tests for product specification.



Figure 4.1.6 Durometer Hardness tester

Dynamic Hardness

Dynamic hardness tests are rebound tests in which an indenter falls from a standard height and the change on rebound measured. These tests depend on elastic recovery of the test surface and use high rates of loading.

The Scleroscope or Shore Scleroscope tests measure the loss in kinetic energy from a falling diamond-tipped metal 'tup'. The tup is enclosed within a glass fronted graduated column and the bottom of the column placed against the surface to be tested. When the tup is released from the top of the column the tup falls, hits the test surface and rebounds. The height of rebound is recorded as the hardness (HSc). The test equipment is light and portable but must be held vertically and test access is restricted by the height of the column, see Figure 4.1.7



Figure 4.1.7 Scleroscope Hardness tester

The Leeb hardness test (Figure 4.1.8) uses a small pen-shaped device containing a spring-loaded impact body. During testing a small permanent magnet within the impact body passes through a coil in the impact device inducing a voltage proportional to the velocity. The hardness calculated is a ratio of the velocities before and after rebound. Values can be displayed as Leeb hardness (HL) or more usually displayed as a Vickers, Rockwell or Brinell equivalent.

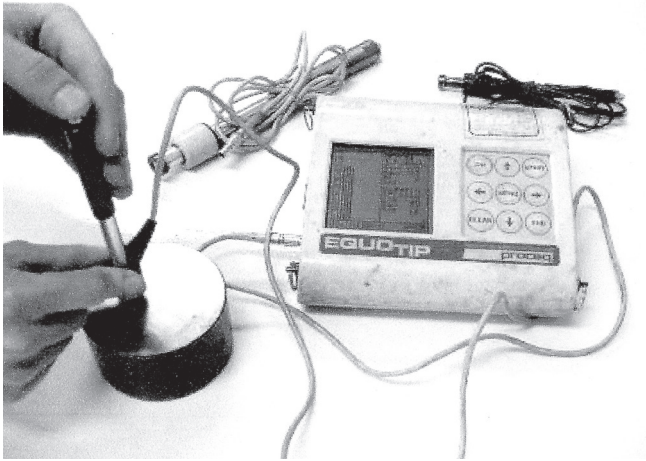


Figure 4.1.8 Equotip™ Hardness tester used to determine Leeb hardness

Many conversion tables are available that allow hardness measurements, undertaken with one method, to be compared with hardnesses obtained with a different method and to be equated approximately with tensile strength. These tables are developed from test data for a particular material such as steel or aluminium and cannot be extrapolated to include other materials not tested.

Mechanical properties

Mechanical properties are those properties that relate to the way in which the material responds to the application of a force.

Tensile and Compressive strength

Tensile strength is a measure of a material’s resistance to plastic deformation from a tensile or stretching type load. When the tensile strength of a material is quoted it is the maximum tensile strength known as the ultimate tensile strength (ultimate tensile stress). This is one of the most often quoted mechanical properties for a material.

The ultimate tensile strength (UTS) represents the maximum applied tensile load that a material can sustain, divided by the material’s original cross-sectional area. The tensile strength is therefore typically measured in kN/mm² or Mega Pascals (MPa), where 1Pa = 1N/m².

On the engineering stress-strain curve the tensile strength is represented by that position where the maximum stress is achieved as illustrated in Figure 4.1.9.

Determine the Ultimate Tensile Stress (UTS) of a 15 mm diameter rod if the maximum load it can withstand is 70 kN.

$$\begin{aligned} \text{Load} &= 70 \times 10^3 \text{N} \\ \text{Diameter} &= 15 \times 10^{-3} \text{m} \\ \text{Area} &= \pi (15 \times 10^{-3})^2 / 4 \\ &= 1.767 \times 10^{-4} \text{m}^2 \\ \text{UTS} &= \text{Load} / \text{area} \\ &= 70 \times 10^3 / 1.767 \times 10^{-4} \\ &= 396 \text{ MN/m}^2 \\ &= 396 \text{ MPa} \end{aligned}$$

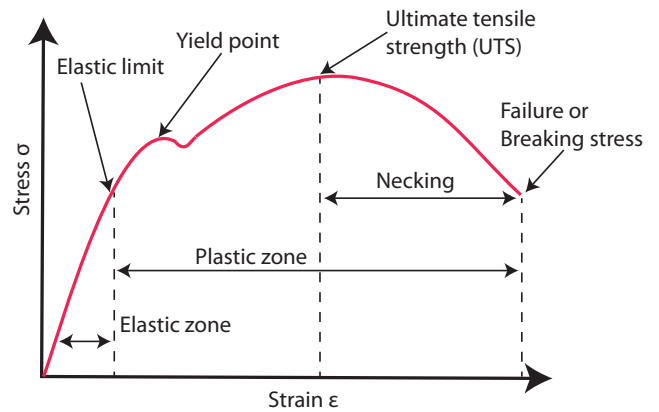


Figure 4.1.9 Engineering stress-strain diagram

Stiffness

Stiffness is the resistance of an elastic body to deflection by an applied force. There are several measures of material stiffness depending on the stress state imposed. These include the modulus of elasticity (also known as Young’s modulus), the shear modulus (also known as the Modulus of Rigidity), and the Bulk Modulus.

The most commonly quoted measure is the modulus of elasticity or Young’s modulus which is a measure of stiffness when a body is subjected to axial tensile or compressive stresses and is visible on the stress strain diagram as a straight line. The angle of the line (gradient) indicates the relative stiffness of the material, such that a stiff material will have a high Young’s modulus. Young’s

modulus is represented by the capital letter E and typically is expressed in Gigapascals (GPa).

The gradients typical of a number of materials are presented in Figure 4.1.10. In this Figure, it can be seen that a brittle material displays linear elastic behaviour and fails with little strain e.g. ceramics and glasses (1). A soft and tough material, on the other hand, exhibits a very small initial slope, but strain hardens and withstands larger strains before failure e.g. low carbon steel (2).

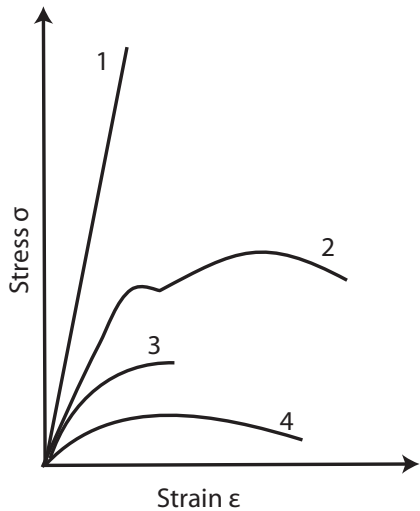


Figure 4.1.10 Typical Stress–strain curves for (1) ceramics and glasses, (2) low carbon steel, (3) Aluminium, (4) natural and synthetic rubbers.

The Young’s modulus for a selection of common materials is presented in Figure 4.1.11.

Material	Young’s modulus (GPa)
Rubber	0.01–0.1
Nylon	2–4
Oak (along the grain)	11
Glass	50–90
Aluminium	69
Copper	110–130
Carbon fibre reinforced plastic	150
Structural steel	190–210

Figure 4.1.11 Young’s modulus for a selection of common materials (Adapted from ASM Handbook).

Toughness

Toughness is the ability of a material to resist the propagation of cracks. A material’s stress-strain curve can be used to give an indication of the overall toughness of the material. The area under the stress-strain curve, within the plastic range, is a measure of a material’s toughness as illustrated in Figure 4.1.12. The greater the area under the graph, the tougher the material, and the greater the amount of energy required to cause it to fail.

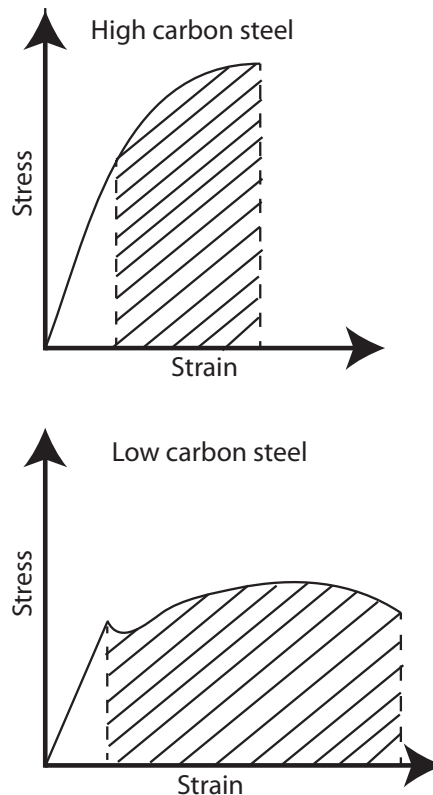


Figure 4.1.12 Comparison of stress-strain curves for low (above) and high (below) toughness materials

A commonly employed method of testing the toughness of a material is to measure its resistance to impact. A number of standard tests are available, such as the Izod impact test or the Charpy impact test for metals. In these tests, a test piece of standardised dimensions is obtained from the material to be evaluated and a notch machined into the surface to a ‘V’ or ‘U’ profile. The sample is subsequently fractured by impact with a pendulum and the swing height the pendulum attains following the sample fracture is used as a measure of the energy absorbed.

Metals that are tough will generally undergo a ductile fracture in which plastic deformation occurs during crack propagation. Ductile fractures typically exhibit dull fibrous surfaces with obvious plastic deformation. An illustration of the test piece used for the Charpy V-notch test is provided in Figure 4.1.13.



Figure 4.1.13 Illustration of a Charpy V-notch impact test piece.

The more plastic deformation required to advance the crack, the more energy required and hence a tougher material. Low toughness metals will generally fracture in a brittle manner in which the crack is able to propagate without the absorption of additional energy. Little work is done in brittle fracture and hence the material fails catastrophically. Brittle fractures are usually characterised by bright crystalline features with no evidence of plastic deformation.

The toughness of a material will vary depending on the temperature. If tested at elevated temperatures, a material will show ductile fracture behaviour and consequently may be considered to have good toughness. If tested at low temperature the same material may fracture in a brittle manner and may be considered to have poor toughness.

Typically, a plot of absorbed energy versus test temperature for metals will produce a graph with a sigmoidal profile, in which the absorbed energy levels off past a certain temperature into what is known as the upper shelf energy (ductile) or the lower shelf energy (brittle). The inflection point between these two regions is known as the transition temperature and marks the position where one form of fracture begins to dominate over the other. Because of this, the appearance of the fracture can also be used to measure toughness by assessing the fracture appearance in terms of % crystallinity or % fibrosity. A typical ductile-brittle transition curve obtained by Charpy V-notch testing of steel is presented in Figure 4.1.14. Representative fractures from each region are shown.

Historical note

The British metallurgist Constance Tipper pioneered research into brittle/ductile transitions. Investigating the failure of Liberty ships during WWII, she discovered that there was a critical temperature below which fractures in steel change from ductile to brittle mode. The 'Liberty Ships' in the North Atlantic were subjected to such low temperatures that they would have been susceptible to

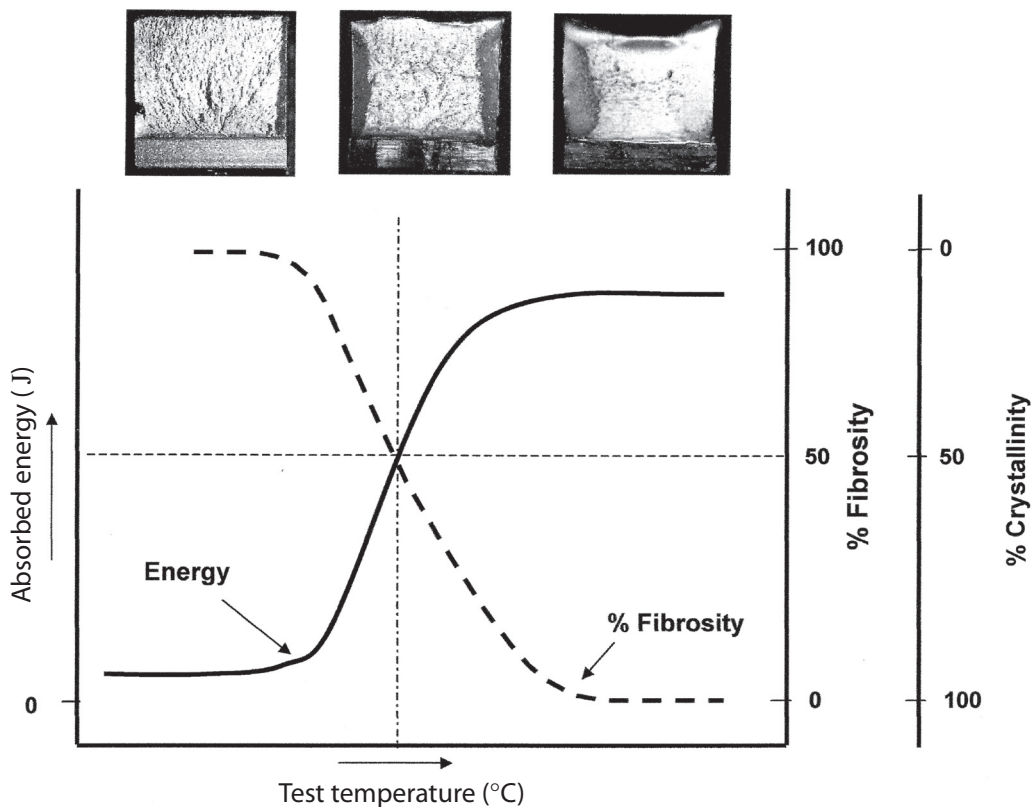


Figure 4.1.14 Ductile-brittle transition curves determined by impact testing of steel

brittle failure, see Figure 4.1.15. These ships were the first all-welded, mass produced, prefabricated cargo ships produced by the United States to assist in the war effort. The sudden and catastrophic failure of these vessels was a major problem for the Allies. Tipper demonstrated that the type of steel used, rather than the fact that the ships had been welded, was the cause of the fractures. The 'Tipper test' soon became the standard method for determining this form of brittleness in steel, although the test has now been largely superseded by the Charpy impact test.

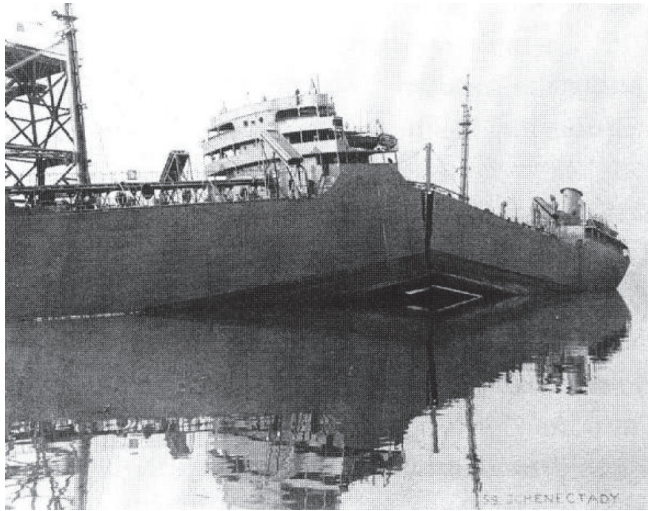


Figure 4.1.15 Fractured Liberty ship

Fracture toughness

The fracture toughness of a material relates to the size of crack that may be present before fracture will occur. Testing is performed using a notched specimen that is subjected to cyclic loading in tension or three point bending, in order to create a short fatigue crack as illustrated in Figure 4.1.16.

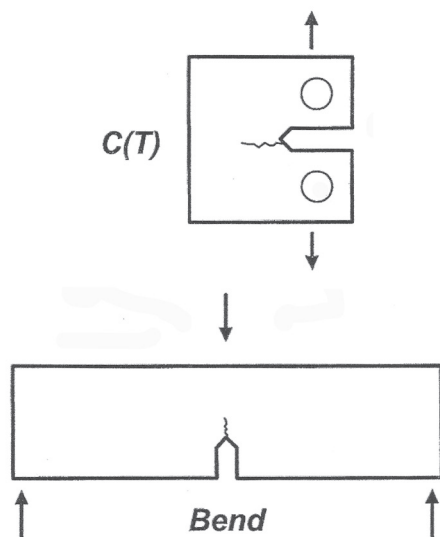


Figure 4.1.16 Fracture toughness test pieces

This pre-cracked sample is then fractured to determine a material constant known as the critical stress intensity or K_{1C}. This value is directly related to the energy for crack propagation within the material and to other material constants such as Young's modulus and Poisson's ratio. In this sense the K_{1C} value provides a more fundamental measure of material toughness compared to the Charpy test, which includes not only the energy of crack propagation to fracture but also the energy of crack initiation from the notch.

The limiting factor in the general use of fracture toughness tests lies in the difficulty and cost involved in producing a pre-cracked specimen compared with the ease of producing Charpy test pieces.

Ductility

Ductility is the ability of a material to undergo plastic deformation by extrusion or the application of tensile forces. Ductility should not be confused with the related concept of malleability, which is the ability of a material to be shaped plastically, generally by compressive forces. The amount of cold work that individual metals can withstand without failure therefore depends on their ductility. Conversely, a material that is unable to undergo plastic deformation without failing is described as being brittle.

Both elongation and reduction of area determined from measurement of the length and cross-section respectively of the tensile test piece after fracture are measures of ductility.

Elasticity

Elasticity of a material is a measure of its ability to stretch under load and then return to its original dimensions following the removal of that load. When a material is uniaxially loaded within its elastic region a linear relationship is obtained in which elongation is found to be proportional to load. This relationship is known as Hooke's Law, named after the 17th Century English Scientist Robert Hooke. This relationship is often restated as stress is proportional to strain and is the straight portion of the stress strain curve, see Figure 4.1.9.

Plasticity

The plasticity of a material is associated with elongation behaviour that exceeds the elastic region. Continued deformation past the elastic limit leads to more complex deformation where the relationship between stress and strain is no longer linear. On removal of load the material no longer returns to its original dimensions but instead retains some permanent deformation.

Plastic deformation of metals occurs as a result of atoms moving relative to each other along crystallographic planes of the metallic lattice by a process called 'slip'. This process will be discussed further in section 4.2a on Metals and metallic alloys.

Young's modulus

As indicated previously Young's modulus is a measure of a material's elasticity. It is an intrinsic property of the material as it is closely related to the bonding force between the constituent atoms. The atoms of a material with a high Young's modulus are therefore more difficult to separate resulting in greater stiffness and higher melting point. It indicates the elasticity of the material regardless of design.

Stress and Strain

Stress is a measure of the force being applied per unit area, ie Stress (σ) = F/A .

Stress can be divided into two classifications engineering stress, which uses the original cross sectional area (A_0) of the test piece as a constant, and true stress which uses the instantaneous (true) cross sectional area as it changes throughout the test.

Strain is a measure of the change in length occurring when under stress, divided by the unit length. Strain can also be divided into two classifications, engineering strain, which uses the original length of the test piece as a constant, that is:

$$\text{engineering strain } (\epsilon) = (l - l_0) / l_0$$

and true strain which uses the instantaneous (true) length as it changes throughout the test. This results in a slightly more complicated relationship where:

$$\text{true strain } (\epsilon_t) = l_n \times (l / l_0)$$

Engineering stress-strain relationships such as those shown in Figure 4.1.9 are most commonly used as they are easier to measure.

Aesthetic characteristics

Aesthetic characteristics might be defined as those features that have an appeal to human senses of beauty and pleasure. These features in turn are evaluated based on the social and cultural background of the individual and our five senses: taste, smell, hearing (sound), sight (appearance), and touch (texture). Our appreciation of products is therefore often a complex interplay of a number these features as Aradhna Krishna points out in

her book '*Customer Sense: How the five senses influence buying behaviour*'.

Because aesthetic appeal can be an important part of a decision to purchase goods, designers often manipulate the various characteristics of their designs, particularly when dealing with consumer products, to appeal to the aesthetic tastes of the proposed user group. Such considerations also help with product differentiation.

Taste: thousands of tiny receptors, known as taste buds, are distributed over the upper surface of the tongue, the soft palate, upper oesophagus and epiglottis, through these sensors we can distinguish 5 basic flavours, sweetness, sourness, bitterness, saltiness and umami. Our sense of taste is, however, an example of how the interplay of a variety of aesthetic properties such as colour, texture, appearance and smell can have a profound affect on our senses. The experience of having difficulty in identifying the taste of various common foods and drinks when pinching the nose and blindfolded, in order to eliminate input from smell and sight is a commonly performed science class experiment and party game.

Another example of the power of this interaction is indicated by an experiment described by Dr Krishna, in which subjects were asked to use a straw to drink a sample of water from a sturdy disposable cup and from a flimsy disposable cup and to rate the taste. The water from the flimsy cup was subsequently rated as significantly worse even though in both cases lips only touched the straw and the only contact with the cups was through touch.

Chefs such as Heston Blumenthal attempt to provide a multi-sensory experience that engages all the senses to enhance taste. Using cooking techniques associated with molecular gastronomy, Blumenthal uses scientific principles to modify the texture and appearance of food. In addition to the plating of the food, presentation is aimed at enhancing emotional connections for the diner, and may involve the playing of background sounds and the use of a spray or dry ice to deliver a scent, as accompaniments to a meal.

The food industry goes to great lengths to create packaging and processing techniques that will increase shelf life of foods while maintaining nutritive value and taste.

Hearing: our ability to hear relies on the detection of sound waves entering our ears and which stimulate the vibration of the ear drum and bones of the middle ear. These vibrations are subsequently transferred to the snail shaped Cochlea of the inner ear. Within the Cochlea is the Organ of Corti which contains small hair cells that transfer signals to the auditory cortex of the brain. We

interpret these signals in terms of their pitch, timbre, tone, clarity, volume, frequency and decay.

The sound produced by a material when struck depends in part on its modulus of elasticity and density.

Smell: we owe our sense of smell to the presence of approximately 10 million olfactory receptors consisting of 350 different receptor types situated in the olfactory mucosa at the top of the nasal cavity. Impulses are sent to the brain from these receptors, where the smell is identified, providing sufficient odour molecules were present. Our response to a scent appears to be largely learned or culturally determined having been associated with life experiences and emotions. Because of this, smells that may be considered pleasant in one culture may be considered unpleasant in another. Aradhna Krishna notes that the new car smell prized by many in the West, and created by the release of volatiles from the upholstery, is found to be objectionable by the Chinese who often attempt to remove it by drying tea leaves in the car. Similarly, the smell of pine, eucalyptus and sandalwood are commonly used as air fresheners because of their association with a clean fresh outdoor environment.

Appearance

Colour: photoreceptor cells in the retina allow us to see. There are two types of photoreceptors present in the retina, these are the rod cells and cone cells.

The rod cells contain a single pigment molecule known as rhodopsin. This pigment is very sensitive to light and is responsible for our vision in low light conditions. However, because only one pigment is present it cannot differentiate colours. By contrast the cone cells contain three different pigment molecules known as photopsins, each of which detects different frequencies of light. It is the cone cells of the retina that are responsible for our colour vision.

Because of the differences in the rod and cone cells, as the light level decreases the cone photoreceptors become less activated, until in very low light conditions only the rods are stimulated. This is why colours cannot be discerned in low light conditions.

Colour and our reactions to it have been studied widely by psychologists and marketers. Our reaction to colour is in large part culturally determined, but businesses spend considerable time on the colour pallet of products and packaging. In some instances certain colours are strongly associated with a product or manufacturer and in such cases the relationship is jealously guarded. This has led to a number of legal disputes around colour as intellectual property. Two examples are given below.

Because it was found that farmers liked to match the colour of their tractors and loader attachments, in 1982 John Deere attempted to trademark their colour green to stop a competitor (Farmhand) from using the same colour on their loaders. This application was disallowed because it was found that awarding exclusive use would disadvantage competitors for reasons unrelated to price or quality. A similar dispute erupted between Cadbury and Nestle regarding the colour purple. In this instance, Cadbury were denied registration of their colour after a ten year battle that went as far as the UK court of appeal.

Colour is of course only one aspect of a materials appearance. A wide variety of processing techniques are available to change the appearance of materials.

While metals are opaque, they can be polished to a high reflective surface or textured to a matte finish. By contrast many polymers and ceramics can be produced in a multitude of forms from opaque to transparent. Similarly, most materials have a natural colour that can be modified by the addition of alloying elements or pigments. Each metal for example has a distinctive natural colour of grey, silver, yellow, or orange, however a still greater colour variation is possible if metals are processed to form a tightly adherent surface oxide.

Colours have strong cultural ties and differences in meaning. The colour white, for example, in some cultures conveys images of purity and peace while in others it is associated with death and mourning. Similar cultural differences can be found with most colours either individually or in combination.

Further reading

Cousins, C. (2012). *Color and Cultural Considerations*
<http://www.webdesignerdepot.com/2012/06/color-and-cultural-design-considerations/>

Shape: features such as symmetry/asymmetry, textural balance, proportion, complexity/simplicity, curvature and size all contribute to aesthetic appearance.

Sharp angular features are often associated with masculine attributes while rounded shapes are associated with more feminine ones. While this is translated into designs aimed at specific groups, products with some curves are generally preferred by consumers.

Touch (or haptics): Our sense of touch and texture conveys not only feelings of rough, smooth, hard, soft, but perceptions of strength, delicacy, sensuality, etc., and is closely integrated with our other senses.

Sensations of touch arises from the presence of haptic sensors located over the outer surface of the body and in some internal locations such as the mouth. A number of sensors with different functions make up the haptic system. These include sensors for temperature (thermoreceptors), pain (nociceptors), and texture (mechanoreceptors).

There are four types of mechanoreceptors, each of which provides a different function as indicated in Figure 4.1.17. An important property of these receptors in determining texture is their rate of adaptation or the rate at which they react to external stimuli and return to normal:

		Adapting rate	
		Slow	Rapid
Vibration frequency	Low	Merkel	Meissner
	High	Ruffini	Pacinian

Figure 4.1.17 The four mechanoreceptors

Pacinian corpuscles – act rapidly or are said to exhibit fast adaptation, they fire at the onset/offset of stimulus, typically returning to normal in less than 0.1 seconds. These sensors are situated some distance below the surface and therefore have large receptor fields. Because of their rapid adaptation they transmit high-frequency vibrations and assist in discriminating fine surface textures. These receptors are also responsible for the extension of our perception field to the end of a hand held tool.

Meissner’s corpuscles – exhibit moderate adaptation, they typically return to normal in approximately 1 second. These receptors are situated close to the surface in the dermal ridges of the finger and therefore have small reception fields. They act to transmit low-frequency vibrations and are particularly sensitive to edges and corners.

Merkel’s discs - exhibit slow adaptation and are situated close to the surface being aligned with the dermal ridges of the finger. Because these sensors are slowly adapting, they continue to act as long as pressure is applied. They allow the detection of light pressure required for the maintenance of a grip and the discrimination of fine textural detail, being particularly sensitive to edges and corners.

Ruffini’s corpuscles – exhibit slow adaptation and are situated some distance below the surface and therefore have large receptor fields. They also assist in the maintenance of a grip.

The physical properties of materials such as thermal conductivity, ductility and hardness result in a wide range of features we discern through touch. Some materials such as metals and ceramics are typically hard and cold to the touch while materials such as wood, leather and rubber are often described as warm. Our sense of touch actually provides us with a wide range of descriptors we use for materials every day as shown in Figure 4.1.18.

Warm	Cold
Hard	Soft
Stiff	Flexible
Rough	Smooth
Heavy	Light

Figure 4.1.18 Range of sense descriptors

Properties of smart materials

Smart materials have one or more properties that can be dramatically altered, for example, transparency, viscosity, volume, conductivity. The property that can be altered influences the application of the smart material. Smart materials include piezoelectric materials, magneto-rheostatic materials, electro-rheostatic materials, shape memory alloys. Some everyday items are already incorporating smart materials (coffee pots, cars, eye-glasses, tennis racquets), and the number of applications for them is growing steadily.

Piezoelectricity

Piezoelectric material is a material that responds to the application of an applied stress by producing a small electrical discharge. Similarly, when an electric current is passed through a piezoelectric material a shape change occurs in response. By reversing the polarity of the electrical signal the shape again changes. An AC current can therefore produce a shape change about the rest state of the material as illustrated in Figure 4.1.19. Piezoelectric materials are widely used as sensors in different environments. Quartz (SiO_2) is a commonly used piezoelectric material, and has been extensively used in watches. A number of ceramics are also used such as barium titanate (BaTiO_3) and lead zirconate titanate ($\text{Pb}[\text{Zr}_x\text{Ti}_{1-x}]\text{O}_3$), known as PZT.

Piezoelectric materials are widely used for the thickness testing of pipes and vessels and the detection of internal flaws by ultrasonic testing as illustrated in Figure 4.1.20.

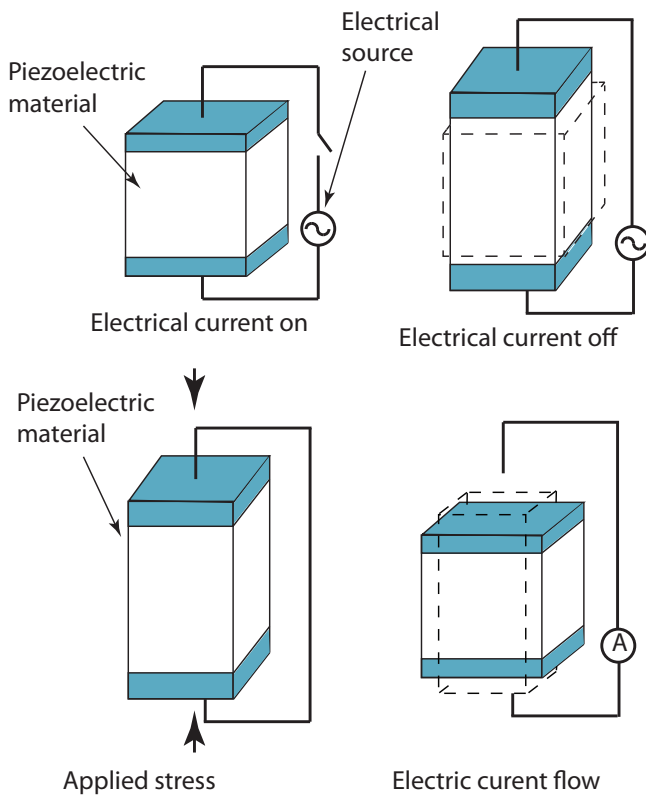


Figure 4.1.19 Piezoelectric material responding to an electric potential (top), and an applied stress (bottom)

In ultrasonic testing, an alternating voltage is supplied to a probe containing a piezoelectric crystal. The voltage stimulates the crystal to change dimensions (vibrate) producing sound waves of a defined frequency. When the probe is placed on the test surface, the sound waves travel into the material and are reflected back from the other side of the test piece and from any internal discontinuities.

When these returning sound waves reach the probe surface, the vibrations stress the piezoelectric crystal sufficiently to produce an electrical voltage in response. The initial sound pulse and the returning signal are recorded on an oscillograph screen allowing visual interpretation by a technician.

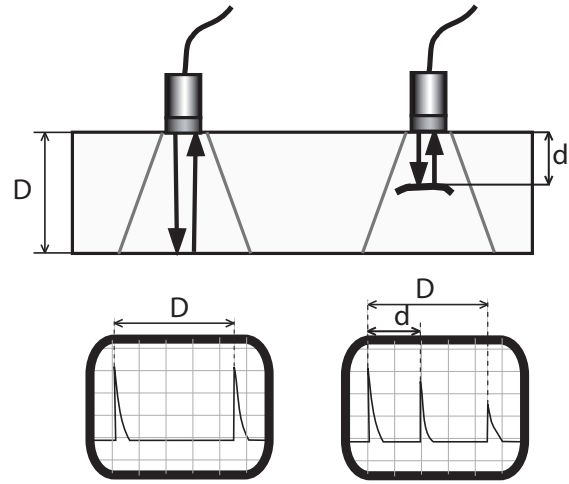


Figure 4.1.20 Ultrasonic testing

Shape memory

SMA's are metals that exhibit pseudo-elasticity and shape memory effect due to rearrangement of the atomic lattice. Discovered in the 1930s the shape memory alloys represent a group of materials that are capable of changing shape or size in a predetermined manner by undergoing a solid-state phase change at a defined temperature. Despite creating a great deal of interest, these alloys remained largely a laboratory curiosity until the 1960s when the NiTi alloy Nitinol (an acronym of the Nickel and Titanium Naval Ordnance Laboratory) was produced. Due to its excellent mechanical properties and biocompatibility Nitinol has since become one of the most widely used shape memory alloys. Nitinol is nonmagnetic and consists of almost equal amounts of Ni and Ti in a simple cubic lattice arrangement. If a shape memory alloy is in the stable lattice arrangement of the austenite phase, and is exposed to a mechanical stress, slip can occur leading to distortion of the lattice and the formation of martensite. Normally a reduction in temperature would be required to achieve this change, but under the influence of an applied stress, martensite formation can occur without the involvement of a temperature change and is referred to as deformation martensite. This change in structure is accompanied by an apparent non-linear deformation, typically associated with plastic deformation.

When the applied stress is removed, however, the atomic lattice returns to the austenite phase and the material returns to its original shape. Figure 4.1.21 illustrates this phenomenon in which an applied stress essentially

increases the temperature at which martensite will form and shows the reversible change back to austenite on the removal of the applied stress. Ms and Mf refer to the start and finish transformation stages of martensite formation, while As and Af refer to the start and finish transformation stages of austenite formation.

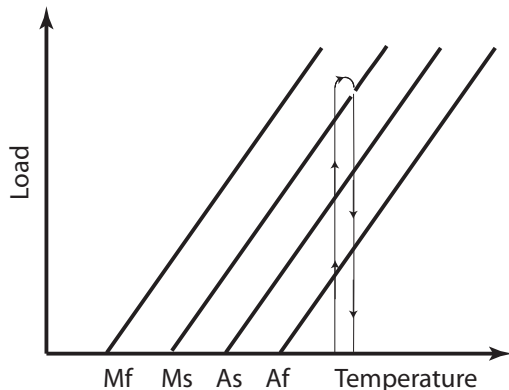


Figure 4.1.21 Load diagram of the pseudo-elastic effect

This ability to undergo plastic deformation and still return to its original shape is one of the defining characteristics of the shape memory alloys and is known as pseudo elasticity. Pseudo elasticity can be expressed symbolically as:

Austenitic structure + force (stimulus)

leads to

Martensitic structure - force (stimulus)

leads back to

Austenitic structure

Shape memory alloys (SMA) also exhibit pseudoelasticity by way of a reversible temperature induced martensite transformation. In this case, however, removal of the applied stress does not result in the material returning to the austenite phase and its original shape. This change requires moderate heating up to approximately 100°C. At elevated temperatures these alloys have an austenitic structure that is relatively strong. On cooling, these alloys undergo a phase transformation to martensite, which is relatively soft. The unique character of these alloys is seen when the alloy is formed to shape in the austenitic condition and then cooled to martensite. If another forming operation is then performed while it is in the martensitic condition, changing the shape of the material, it will maintain that shape until reheated to austenite, at which time the alloy reverts to its previous shape. Some alloys even have the ability to change back when the temperature has again been reduced, resulting in a two-way memory effect. These alloys can therefore cycle between shapes with changes in temperature.

Alloy	Transformation range °C	Transformation hysteresis °C
Ag-Cd	-190 to -50	~ 15
Cu-Al-Ni	-140 to -100	~ 35
Cu-Zn	-180 to -10	~ 10
Ni-Al	-180 to 100	~ 10
Ni-Ti	-50 to 110	~ 30
FeMnS	-200 to 150	~ 100

Figure 4.1.22 Transformation temperature ranges for a selection of SMA's (ASM Handbook)

A number of shape memory alloys have been developed, which operate at a variety of different temperatures, as indicated in Figure 4.1.22. Precise control of the material composition is required to ensure the reliable reproduction of the transformation temperatures.

The shape memory affect can be illustrated as shown in Figure 4.1.23 in which the phase changes have been represented at each stage along with the changes that would be seen with an arterial stent made from the shape memory alloy Nitinol. SMAs are considered to be passive response type devices, as they do not require separate sensors to operate, but rather react directly in response to the external stimulus, as opposed to the ER and MR fluids and piezoelectric materials that can be considered active response devices. In this capacity of passive response, the pseudoelastic properties of the shape memory alloys have been used in products such as electrical connectors, eyeglass frames and antennas for mobile phones.

Shape memory alloys have been used in products such as electrical connectors, safety taps to prevent hot water scalding children, vascular stents to repair blocked arteries, airflow controls, orthodontic arch wires and components of eyeglass frames. The excellent biocompatibility of Nitinol combined with its non-magnetic nature and excellent mechanical properties have resulted in its extensive use in biomedical applications such as coronary stents.

Some use of SMAs has been made in passive dampening systems to mitigate earthquake damage. The roof of the St Francis Basilica in Assisi has been joined to the wall with Nitinol anchors consisting of wire bundles that stretch in response to vibrations, dissipating the seismic loads.

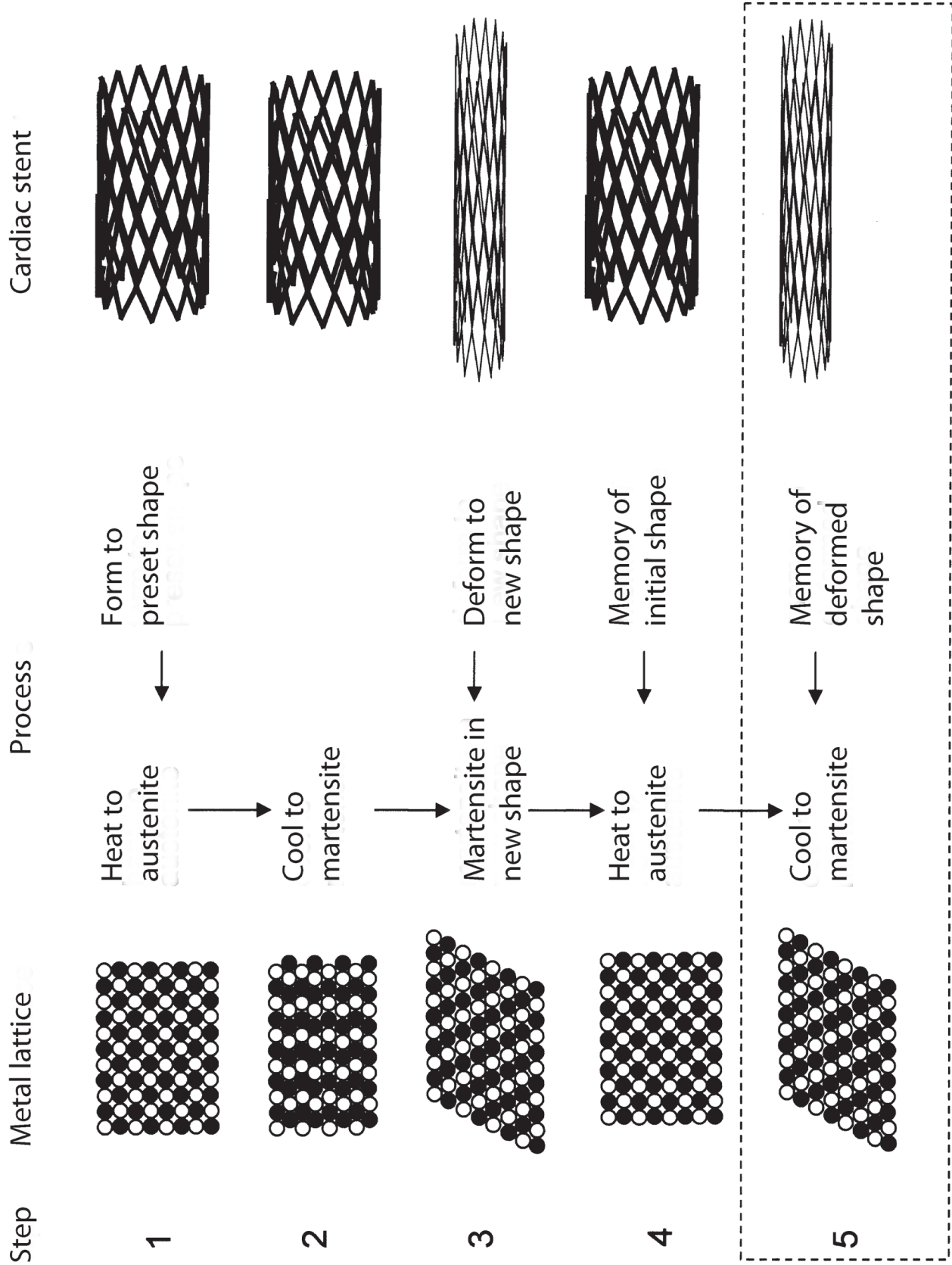


Figure 4.1.23 Illustration of the stages of transformation in an SMA. Stages 1 to 4 represent a one-way shape memory, while the addition of stage 5 represents a two-way shape memory

Photochromicity

Photochromic materials undergo a reversible photochemical reaction that results in darkening proportional to the level of exposure to Ultra Violet (UV) light. These materials are most commonly seen in photochromatic (also known as transition) lenses and may be made from glass or polymer such as polycarbonate. An example of this effect is shown in Figure 4.1.24 in which one lens was initially covered and the other exposed to sunlight for 30 seconds.

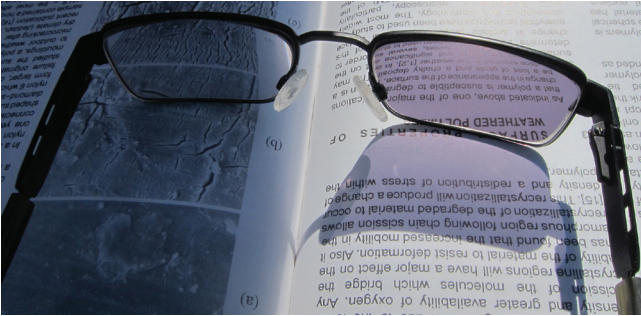
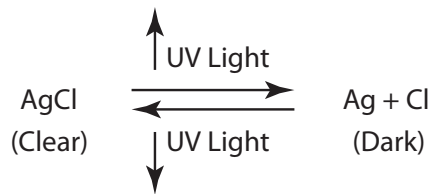


Figure 4.1.24 Photochromatic lenses

Glass lenses have molecules of silver chloride (AgCl) within the silica crystal structure of the glass. The presence or otherwise of UV light determines the direction in which a reversible oxidation-reduction reaction, representing a Le Chatelier type chemical reaction of the type indicated below, will proceed.



When the level of UV radiation exposure is low, light passes through largely unimpeded. When exposed to UV light, however, the reaction proceeds to the right forming colloidal silver that acts to absorb up to 80% of the incident light and leading to the observed darkening of the lens. On removal of the lens from exposure to the UV light, the reaction reverses direction and the silver recombines with the chloride ions to form AgCl and the glass clears.

The photochromatic lenses made from polycarbonate by contrast have a coating of an organic molecule, which changes shape on exposure to UV light leading to darkening of the lens and which reverses when exposure to UV light decreases.

Magneto-rheostatic and Electro-rheostatic

Electro-rheostatic (ER) and magneto-rheostatic (MR) materials are fluids that can undergo changes in their

viscosity, becoming semi-solid when exposed to an electric or magnetic field respectively. When the applied field is removed the materials return to their original fluid state.

These materials are most commonly colloidal suspensions within oil. Because of this, one of many considerations in their use is the length of time the particles remain in suspension. As a general rule, as the particle size decreases time in suspension increases.

The shear yield strength of an ER fluid is determined by the strength of the applied electric field, such that varying the field strength can control the viscosity. Similar to electro-rheostatic fluids, the shear yield strength of magneto-rheostatic (MR) fluids is determined by the strength of the applied magnetic field, such that varying the field strength can control the viscosity.

The ER and MR fluid must satisfy a number of criteria:

- low toxicity
- non-abrasive
- non-corrosive
- long storage life
- long working life
- high boiling point
- low freezing point
- particles must remain as a colloidal suspension and not settle out.

An example of an ER fluid is one containing lithium polymethacrylate particles in paraffin or silicon oil, while small ferromagnetic particle such as particles of carbonyl iron have been used in MR fluids.

The major advantage of MR fluids is that they can resist large forces, while ER fluids have the advantage that relatively small actuating elements can be developed.

The control over viscosity has allowed the ER and MR fluids to find uses in clutches, hydraulic valves and shock absorbers. The 2002 Cadillac Seville STS and second generation Audi TT automobiles have used MR fluids in the suspension system, while the National Museum of Emerging Science in Tokyo, Japan has installed MR fluid devices throughout the building to reduce shock loading from high winds and seismic activity.