Newnes

Engineering Materials Pocket Book

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Heinemann Newnes

Preface

The main aim of this book is to provide engineers and students with a concise, pocket-size, affordable guide to the full range of materials used in engineering: ferrous and non-ferrous metals, polymeric materials, ceramics and composites. It is seen as being particularly useful to students engaged on project work. Obviously no book this size, or even any single book, can be completely exhaustive and so the selection of materials has been restricted to those most commonly encountered in engineering and those details of properties most relevant to the general use of the materials. The book is not intended to replace the more detailed specifications given by the national and international standards groups.

To aid in interpreting the information given for the properties of materials, Chapter 1 gives a brief description of the main terms likely to be encountered, Chapter 2 gives an outline of the main testing methods and the Appendix lists conversion factors and tables for the various forms of units used to describe properties. The bulk of the book, Chapters 3 to 11, is devoted to the main engineering materials: ferrous, aluminium, copper, magnesium, nickel and titanium alloys, polymeric, ceramic and composite materials. In most cases, the chapters are broken down into five sections: a discussion of the materials, details of coding systems and compositions, heat treatment information, the properties of the materials, and typical uses to which they have been put. The codes and data given are for both American and British standards. To aid in selection, Chapter 12 gives comparisons of the properties of the different materials.

The book is essentially concerned with properties and there is only a very brief indication of the science of materials. For further information on materials science the reader is referred to textbooks, such as:

Anderson, J.C., Leaver, K.D., Rawlings, R.D. and Alexander, J.M. (1985). **Materials Science**. (3rd Ed. Van Nostrand.)

Bolton, W. (1989). **Engineering Materials Technology**. (Heinemann.)

Mills, N.N. (1986). **Plastics: Microstructure, Properties and Applications**. (Arnold.)

Smith, W.F. (1981) **Structure and Properties of Engineering Alloys**. (McGraw-Hill.)

The data used in this book have been obtained from a wide variety of sources. The main sources are:

The publications of the British Standards Institution
The publications of the American Society of Metals Materials
Manufacturers
Trade Associations

The interpretations and presentation of the data are however mine and should not be deemed to be those of any other organisation. For full details of standards, the reader is advised to consult the appropriate publications of the standards setting group.

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Acknowledgements

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Contents

1 Terminology

The following, in alphabetical order, are definitions of the common terms used in engineering in connection with the properties of materials.

Additives. Plastics and rubbers almost invariably contain, in addition to the polymer or polymers, other materials, i.e additives. These are added to modify the properties and cost of the material.

Ageing. This term is used to describe a change in properties that occurs with certain metals at ambient or moderately elevated temperatures after hot working, a heat treatment process or cold working. The change is generally due to precipitation occurring, there being no change in chemical composition.

Alloy. This is a metallic material composed of two or more elements of which at least one is a metal.

Amorphous. An amorphous material is a non-crystalline material, i.e. it has a structure which is not orderly.

Annealing. This involves heating to, and holding at, a temperature which is high enough to result in a softened state for a material after a suitable rate of cooling, generally slowly. In the case of ferrous alloys the required temperature is the upper critical temperature. The purpose of annealing can be to facilitate cold working, improve machinability, improve mechanical properties, etc.

Anodizing. This term is used to describe the process, generally with aluminium, whereby a coating is produced on the surface of the metal by converting it to an oxide.

Atactic structure. A polymer structure in which side groups, such as CH_3, are arranged randomly on either side of the molecular chain.

Austempering. This is a heat treatment used with ferrous alloys. The material is heated to austenizing temperature and then quenched to the M_s temperature at such a rate that ferrite or pearlite is not formed. It is held at the M_s temperature until the transformation to bainite is complete.

Austenite. This term describes the structure of a solid solution of one or more elements in a face-centred cubic iron crystalline structure. It usually refers to the solid solution of carbon in the face-centred iron.

Austenitizing. This is when a ferrous alloy is heated to a temperature at which the transformation of its structure to austenite occurs.

Bainite. This describes a form of ferrite–cementite structure consisting of ferrite plates between which, or inside which, short cementite rods form, and occurs when ferrous alloys are cooled from the austenitic state at an appropriate rate of cooling. It is a harder structure than would be obtained by annealing but softer than martensite. The process used is called austempering.

Bend, angle of. The results of a bend test on a material are specified in terms of the angle through which the material can be bent without breaking (Figure 1.1). The greater the angle the more ductile the material. See Bend test, Chapter 2.

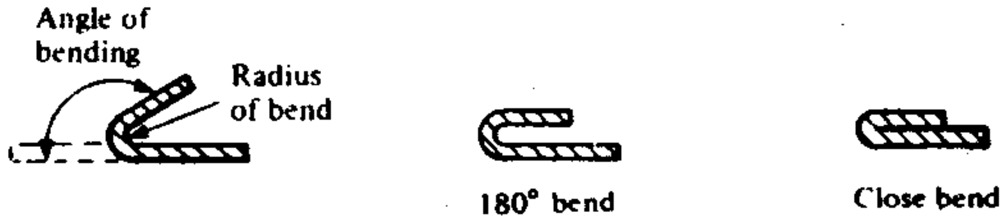

Figure 1.1 The angle of bend

Brinell number. The Brinell number is the number given to a material as a result of a Brinell test (see Hardness measurement, Chapter 2) and is a measure of the hardness of a material. The

larger the number the harder the material.
Brittle failure. With brittle failure a crack is initiated and propagates prior to any significant plastic deformation. The fracture surface of a metal with a brittle fracture is bright and granular due to the reflection of light from individual crystal surfaces. With polymeric materials the fracture surface may be smooth and glassy or somewhat splintered and irregular.
Brittle material. A brittle material shows little plastic deformation before fracture. The material used for a china teacup is brittle. Thus because there is little plastic deformation before breaking, a broken teacup can be stuck back together again to give a cup the same size and shape as the original.
Carburizing. This is a form of case hardening which results in a hard surface layer being produced with ferrous alloys. The treatment involves heating the alloy to the austenitic state in a carbon-rich atmosphere so that carbon diffuses into the surface layers, then quenching to convert the surface layers to martensite.
Case hardening. This term is used to describe processes in which by changing the composition of surface layers of ferrous alloys a hardened surface layer can be produced. See Carburizing and Nitriding.
Cementite. This is a compound formed between iron and carbon, often referred to as iron carbide. It is a hard and brittle material.
Charpy test value. The Charpy test, see Impact tests Chapter 2, is used to determine the response of a material to a high rate of loading and involves a test piece being struck a sudden blow. The results are expressed in terms of the amount of energy absorbed by the test piece when it breaks. The higher the test value the more ductile the material.
Cis structure. A polymer structure in which a curved carbon backbone is produced by bulky side groups, e.g. CH_3, which are grouped all on the same side of the backbone.
Compressive strength. The compressive strength is the maximum compressive stress a material can withstand before fracture.
Copolymer. This is a polymeric material produced by combining two or more monomers in a single polymer chain.
Corrosion resistance. This is the ability of a material to resist deterioration by chemical or electrochemical reaction with its immediate environment. There are many forms of corrosion and so there is no unique way of specifying the corrosion resistance of a material.
Creep. Creep is the continuing deformation of a material with the passage of time when it subject to a constant stress. For a particular material the creep behaviour depends on both the temperature and the initial stress, the behaviour also depending on the material concerned. See Creep tests, Chapter 2.
Creep modulus. The initial results of a creep test are generally represented as a series of graphs of strain against time for different levels of stress. From these graphs values, for a particular time, of strains at different stresses can be obtained. The resulting stress–strain values can be used to give a stress–strain graph for a particular time, such a graph being referred to as an isochronous stress–strain graph. The creep modulus is the stress divided by the strain, for a particular time. The modulus is not the same as the tensile modulus. See Creep tests, Chapter 2.
Creep strength. The creep strength is the stress required to produce a given strain in a given time.
Crystalline. This term is used to describe a structure in which there is a regular, orderly, arrangement of atoms or molecules.
Damping capacity. The damping capacity is an indicator of the

ability of a material to suppress vibrations.
Density. Density is mass per unit volume.
Dielectric constant. See permittivity.
Dielectric strength. The dielectric strength is a measure of the highest potential difference an insulating material can withstand without electric breakdown.

$$\text{Dielectric strength} = \frac{\text{breakdown voltage}}{\text{insulator thickness}}.$$

Ductile failure. With ductile failure there is a considerable amount of plastic deformation prior to failure. With metals the fracture shows a typical cone and cup formation and the fracture surfaces are rough and fibrous in appearance.
Ductile materials. Ductile materials show a considerable amount of plastic deformation before breaking.
Elastic limit. The elastic limit is the maximum force or stress at which, on its removal, the material returns to its original dimensions. For many materials the elastic limit and the limit of proportionality are the same, the limit of proportionality being the maximum force for which the extension is proportional to the force or the maximum stress for which the strain is proportional to the stress. See Tensile tests, Chapter 2.
Electrical conductivity. The electrical conductivity is a measure of the electrical conductance of a material, the bigger the conductance the greater the current for a particular potential difference. The electrical conductivity is defined by

$$\text{conductivity} = \frac{\text{length}}{\text{resistance} \times \text{cross-sectional area}},$$

$$\text{conductance} = \frac{1}{\text{resistance}}.$$

Conductance has the unit of ohm^{-1} or mho, conductivity has the unit $\Omega^{-1}\ \text{m}^{-1}$. The IACS specification of conductivity is based on 100%, corresponding to the conductivity of annealed copper at 20°C; all other materials are then expressed as a percentage of this value.
Electrical resistivity. The electrical resistivity is a measure of the electrical resistance of a material, being defined by

$$\text{resistivity} = \frac{\text{resistance} \times \text{cross-sectional area}}{\text{length}}.$$

Resistivity has the unit Ω m.
Endurance. The endurance is the number of stress cycles to cause failure. See Fatigue tests, Chapter 2.
Endurance limit. The endurance limit is the value of the stress for which a test specimen has a fatigue life of N. cycles. See Fatigue tests, Chapter 2.
Equilibrium diagram. This diagram is, for metals, constructed from a large number of experiments, in which cooling curves are determined for the whole range of alloys in a group, and provides a forecast of the states that will be present when an alloy of a specific composition is heated or cooled to a specific temperature.
Expansion, coefficient of linear. The coefficient of linear expansion is a measure of the amount by which a unit length of a material will expand when the temperature rises by one degree. It is defined by

$$\text{linear expansivity} = \frac{\text{change in length}}{\text{length} \times \text{temperature change}}.$$

It has the unit $°\text{C}^{-1}$ or K^{-1}.

Expansivity, linear. This is an alternative name for the coefficient of linear expansion.

Fatigue life. The fatigue life is the number of stress cycles to cause failure. See Fatigue tests, Chapter 2.

Fatigue limit. The fatigue limit is the value of the stress below which the material will endure an infinite number of cycles. See Fatigue tests, Chapter 2.

Fatigue strength. The fatigue strength at N cycles is the value of the stress under which a test specimen has a life of N cycles. See Fatigue tests, Chapter 2.

Ferrite. This is a solid solution of one or more elements in body-centred cubic iron. It is usually used for carbon in body-centred cubic iron. Ferrite is comparatively soft and ductile.

Fracture toughness. The plane strain fracture toughness or opening-mode fracture toughness, K_{Ic}, represents a practical lower limit of fracture toughness and is an indicator of whether a crack will grow or not.

Friction, coefficient of. The coefficient of friction is the maximum value of the frictional force divided by the normal force. In the situation where an object is to be started into motion, the maximum frictional force is the force needed to start the object sliding. Where an object is already in motion, the frictional force is that needed to keep it moving with a constant velocity. This is less than the frictional force needed to start sliding and so there are two coefficients of friction, a static coefficient and a dynamic coefficient, with the static coefficient larger than the dynamic coefficient.

Full hard. This term is used to describe the temper of alloys. It corresponds to the cold-worked condition beyond which the material can no longer be worked.

Glass transition temperature. The glass transition temperature is the temperature at which a polymer changes from a rigid to a flexible material. The tensile modulus shows an abrupt change from the high value typical of a glass-like material to the low value of a rubber-like material.

Half hard. This term is used to describe the temper of alloys. It corresponds to the cold-worked condition half-way between soft and full hard.

Hardenability. The term hardenability of a material is used as a measure of the depth of hardening introduced into a material by quenching (see Hardenability, Chapter 2).

Hardening. This describes a heat treatment by which hardness is increased.

Hardness. The hardness of a material may be specified in terms of some standard test involving indentation, e.g. the Brinell, Vickers and Rockwell tests, or scratching of the surface of the material, the Moh test. See Hardness measurement, Chapter 2.

Heat distortion/deflection temperature. This is the temperature at which a strip of polymeric material under a specified load shows a specified amount of deflection.

Heat-resisting alloy. This is an alloy developed for use at high temperatures.

Homopolymer. This describes a polymer that has molecules made up of just one monomer.

Hooke's law. When a material obeys Hooke's law its extension is directly proportional to the applied stretching forces. See Tensile tests in Chapter 2.

Impact properties. See Charpy test value and Izod test value, also Impact tests in Chapter 2.

Isochronous stress–strain graph. See the entry on Creep modulus.

Isotactic structure. A polymer structure in which side groups of molecules are arranged all on the same side of the molecular chain.

Izod test value. The Izod test, see Impact tests, Chapter 2, is used to determine the response of a material to a high rate of loading and involves a test piece being struck a sudden blow. The results are expressed in terms of the amount of energy absorbed by the test piece when it breaks. The higher the test value the more ductile the material.

Jominy test. This is a test used to obtain information on the hardenability of alloys. See Chapter 2 for more information.

Limit of proportionality. Up to the limit of proportionality, the extension is directly proportional to the applied stretching forces,i.e. the strain is proportional to the applied stress (see Figure 1.4).

Machinability. There is no accepted standard test for machinability and so it is based on empirical test data and is hence subjective. Machinability is a measure of the differences encountered in machining a material.

Maraging. This is a precipitation hardening treatment used with some ferrous alloys. See Precipitation hardening.

Martensite. This is a general term used to describe a form of structure. In the case of ferrous alloys it is a structure produced when the rate of cooling from the austenitic state is too rapid to allow carbon atoms to diffuse out of the face-centred cubic form of austenite and produce the body-centred form of ferrite. The result is a highly strained hard structure.

Melting point. This is the temperature at which a material changes from solid to liquid.

Mer. See Monomer.

Moh scale. This is a scale of hardness arrived at by considering the ease of scratching a material. It is a scale of 10, with the higher the number the harder the material. See Impact tests, Chapter 2.

Monomer. This is the unit, or mer, consisting of a relatively few atoms which are joined together in large numbers to form a polymer.

Nitriding. This is a treatment in which nitrogen diffuses into surface layers of a ferrous alloy and hard nitrides are produced, hence a hard surface layer.

Normalizing. This heat treatment process involves heating a ferrous alloy to a temperature which produces a fully austenitic structure, followed by air cooling. The result is a softer material, but not as soft as would be produced by annealing.

Orientation. A polymeric material is said to have an orientation, uniaxial or biaxial, if during the processing of the material the molecules become aligned in particular directions. The properties of the material in such directions is markedly different from those in other directions.

Pearlite. This is a lamellar structure of ferrite and cementite.

Percentage elongation. The percentage elongation is a measure of the ductility of a material, the higher the percentage the greater the ductility. See Tensile tests, Chapter 2.

$$\text{Percentage elongation} = \frac{\text{final} - \text{initial lengths}}{\text{initial length}} \times 100$$

Percentage reduction in area. The percentage reduction in area is a measure of the ductility of a material, the higher the percentage the greater the ductility. See Tensile tests, Chapter 2.

$$\text{Percent. reduction in area} = \frac{\text{final} - \text{initial areas}}{\text{initial area}} \times 100$$

Permeability. This term is used to describe the rate at which gases or vapours are transmitted through a material. The rate of transmis sion per unit surface area of the material is given by:

$$\text{rate of transmission/area} = P\,(p_1 - p_2)/L$$

where P is the permeability coefficient, p_1 and p_2 the pressures on each side of the material and L the material thickness. A variety of units are used for permeability values. In some the pressure is quoted in centimetres of mercury, in others in Pa or N m^{-2}. The time might be in days or seconds. The rate may be quoted in terms of volumes in cubic centimetres (cm^3) or mass in moles or kilograms (kg) or grams (g).

Permittivity. The relative permittivity ϵ_r, or dielectric constant, of a material can be defined as the ratio of the capacitance of a capacitor with the material between its plates compared with that of the same capacitor with a vacuum.

$$\epsilon = \epsilon_r\,\epsilon_0$$

where ϵ is the absolute permittivity and ϵ_0 the permittivity of free space, i.e. a vacuum.

Plane strain fracture toughness. See fracture toughness.

Poisson's ratio. Poisson's ratio is the ratio (transverse strain)/(longitudinal strain).

Precipitation hardening. This is a heat treatment process which results in a precipitate being produced in such a way that a harder material is produced.

Proof stress. The 0.2% proof stress is defined as that stress which results in a 0.2% offset,i.e. the stress given by a line drawn on the stress–strain graph parallel to the linear part of the graph and passing through the 0.2% strain value (Figure 1.2). The 0.1% proof stress is similarly defined. Proof stresses are quoted when a material has no well defined yield point. See Tensile tests, Chapter 2.

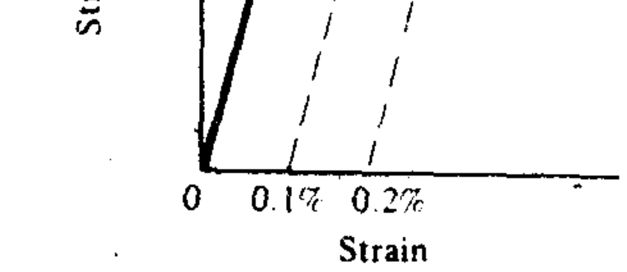

Figure 1.2 Determination of proof stress

Quenching. This is the method used to produce rapid cooling.

Recovery, fractional. The fractional recovery is defined as the strain recovered divided by the creep strain, when the load is removed.

Recrystallization. This is generally used to describe the process whereby a new, strain free grain structure is produced from that existing in a cold-worked metal by heating.

Refractive index. The refractive index of a material is the ratio (speed of light in a vacuum)/(speed of light in the material). For some materials the speed of light depends on the direction through the material the light is traversing and so the refractive index varies with direction.

Relative permeability. This is a measure of the magnetic properties

of a material, being defined as the ratio of the magnetic flux density in the material to the flux density in a similar situation when the material is replaced by a vacuum.
Relative permittivity. See permittivity.
Resilience. This term is used with elastomers to give a measure of the elasticity of a material. A high resilience material will suffer elastic collisions, when a high percentage of the kinetic energy before the collision is returned to the object after the collision. A less resilient material would loose more kinetic energy in the collision.
Rigidity, modulus of. The modulus of rigidity is the slope of the shear stress/shear strain graph below the limit of proportionality.
Rockwell test value. The Rockwell test is used to give a value for the hardness of a material. There are a number of Rockwell scales and thus the scale being used must be quoted with all test results (see Impact tests, Chapter 2).
Ruling section. The limiting ruling section is the maximum diameter of round bar, at the centre of which the specified properties may be obtained.
Rupture stress. The rupture stress is the stress to cause rupture in a given time at a given temperature and is widely used to describe the creep properties of materials. See Creep tests, Chapter 2.
Secant modulus. For many polymeric materials there is no linear part of the stress–strain graph and thus a tensile modulus cannot be quoted. In such cases the secant modulus is used. It is the stress at a value of 0.2% strain divided by that strain (Figure 1.3).

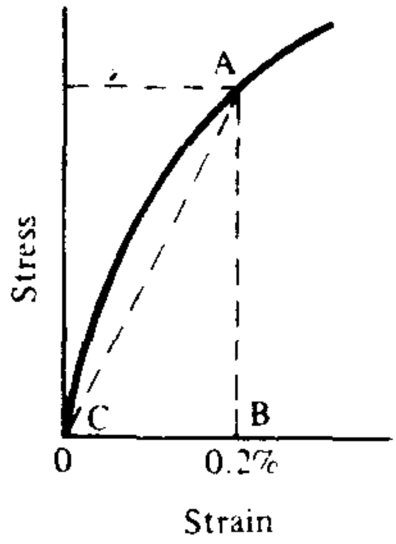

Figure 1.3 The secant modulus is AB/BC

Shear. When a material is loaded in such a way that one layer of the material is made to slide over an adjacent layer then the material is said to be in shear.
Shear strength. The shear strength is the shear stress required to produce fracture.
Shore durometer. This is a method for measuring the hardness of polymers and rubbers. A number of scales are used. See Chapter 2.
Sintering. This is the process by which powders are bonded by molecular or atomic attraction, as a result of heating to a temperature below the melting points of the constituent powders.
S/N graph. This is a graph of the stress amplitude S plotted against the number of cycles N for the results from a fatigue test. The stress amplitude is half the algebraic difference between the maximum and minimum stresses to which the material is subject. See Fatigue tests, Chapter 2.
Solution treatment. This heat treatment involves heating an alloy to a suitable temperature, holding at that temperature long enough for one or more constituent elements to enter into solid solution, and

then cooling rapidly enough for these to remain in solid solution.
Specific gravity. The specific gravity of a material is the ratio of its density compared with that of water.

$$\text{Specific gravity} = \frac{\text{density of material}}{\text{density of water}}.$$

Specific heat capacity. The amount by which the temperature rises for a material, when there is a heat input depends on its specific heat capacity. The higher the specific heat capacity the smaller the rise in temperature per unit mass for a given heat input.

$$\text{Specific heat capacity} = \frac{\text{heat input}}{\text{mass} \times \text{change in temperature}}.$$

Specific heat capacity has the unit $J\ kg^{-1}\ K^{-1}$.
Spheroidizing. This is a treatment used to produce spherical or globular forms of carbide in steel.
Strain. The engineering strain is defined as the ratio (change in length)/(original length) when a material is subject to tensile or compressive forces. Shear strain is the ratio (amount by which one layer slides over another)/(separation of the layers). Because it is a ratio, strain has no units, though it is often expressed as a percentage. Shear strain is usually quoted as an angle in radians.
Strain hardening. This is an increase in hardness and strength produced as a result of plastic deformation at temperatures below the recrystallization temperature, i.e. cold working.
Strength. See Compressive strength, Shear strength and Tensile strength.
Stress. In engineering tensile and compressive stress is usually defined as (force)/(initial cross-sectional area). The true stress is (force)/(cross-sectional area at that force). Shear stress is the (shear force)/(area resisting shear). Stress has the unit Pa (pascal) or $N\ m^{-2}$ with $1\ Pa = 1\ N\ m^{-2}$.
Stress relieving. This is a treatment to reduce residual stresses by heating the material to a suitable temperature, followed by slow cooling.
Stress–strain graph. The stress–strain graph is usually drawn using the engineering stress (see Stress) and engineering strain (see Strain). Figure 1.4 shows an example of the form one takes for a metal like mild steel. See Tensile tests, Chapter 2.

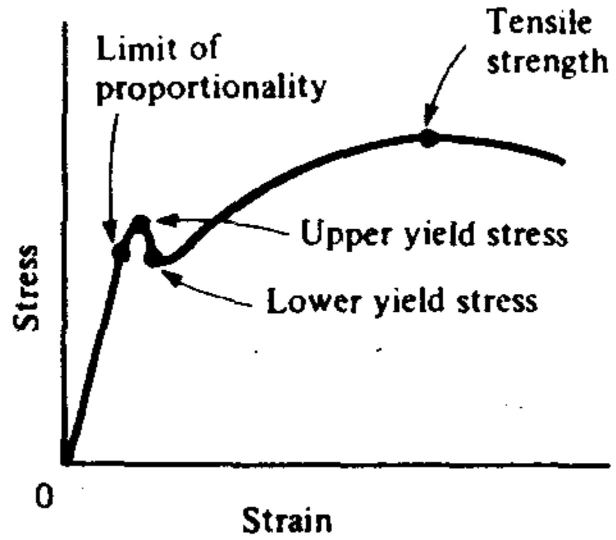

Figure 1.4 Stress–strain graph

Surface hardening. This is a general term used to describe a range of processes by which the surface of a ferrous alloy is made harder than its core.
Syndiatic structure. A polymer structure in which side molecular groups are arranged in a regular manner, alternating from one side