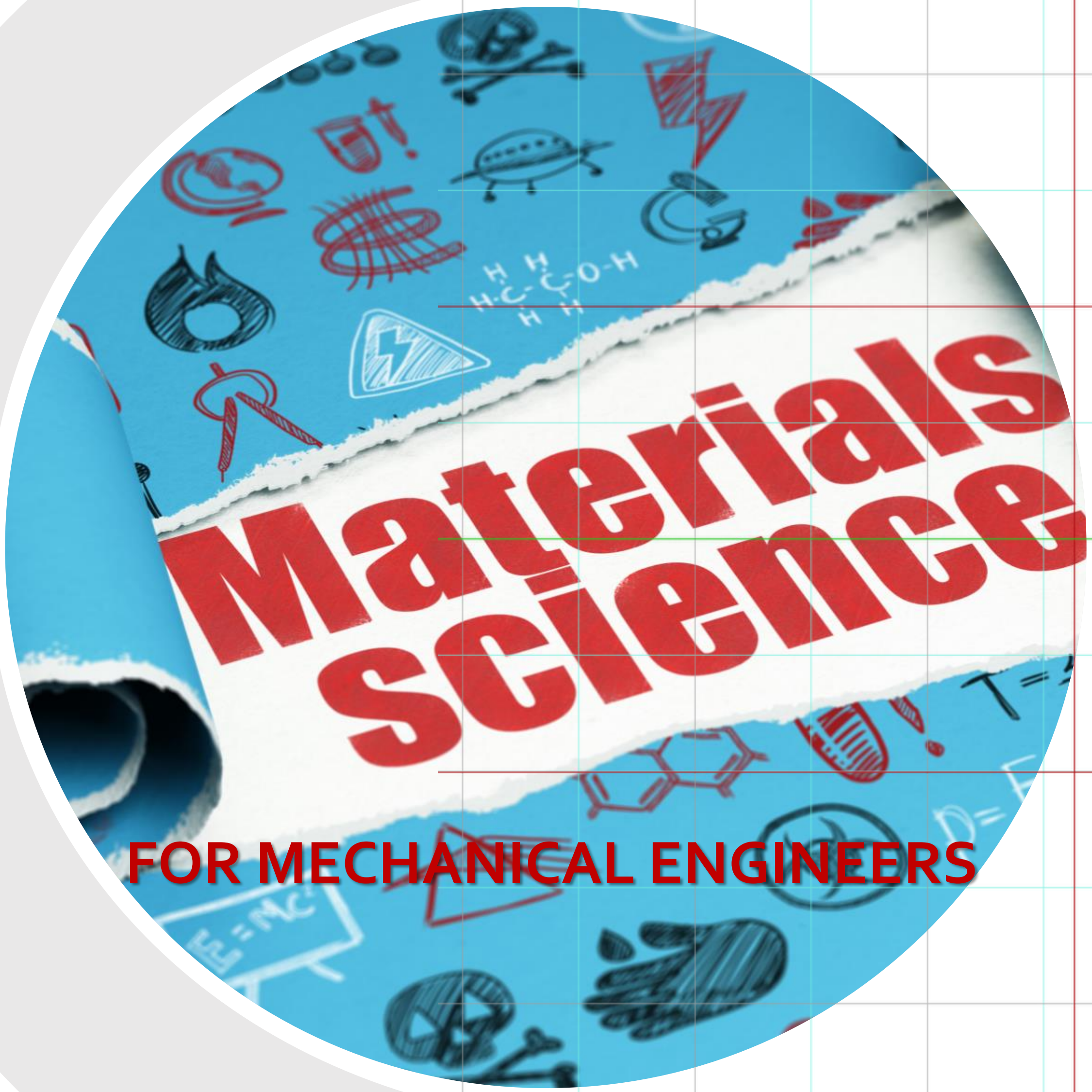


FOR MECHANICAL ENGINEERS

Mechanical Properties of Metals

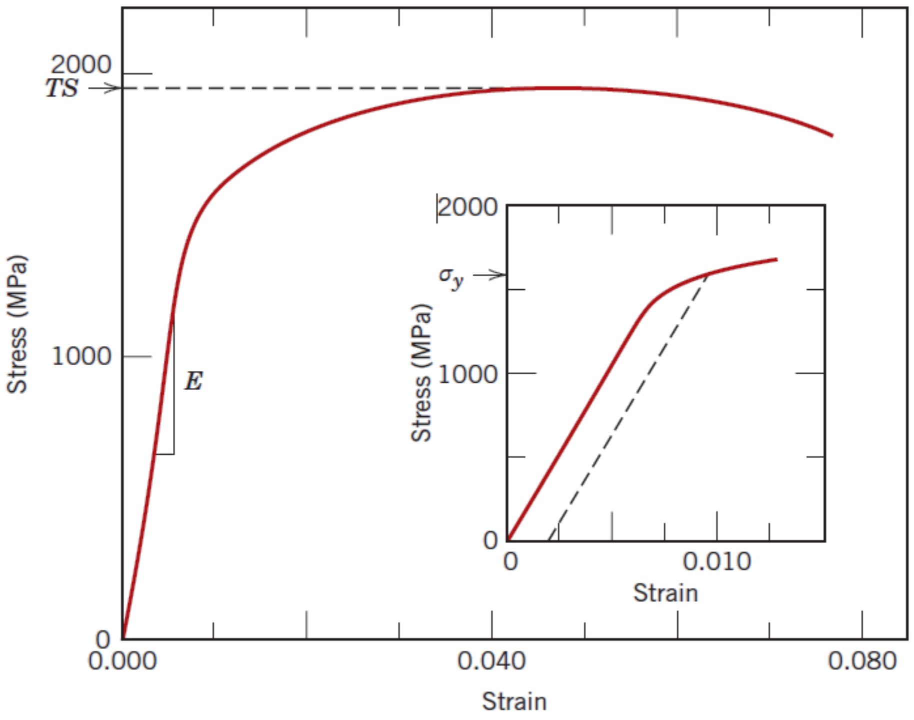
SPRING 2022-2023

INTRODUCTION

Learning Objectives

1. Define engineering stress and engineering strain.
2. State Hooke's law and note the conditions under which it is valid.
3. Define Poisson's ratio.
4. Given an engineering stress–strain diagram, determine (a) the modulus of elasticity, (b) the yield strength (0.002 strain offset), and (c) the tensile strength and (d) estimate the percentage elongation.
5. For the tensile deformation of a ductile cylindrical specimen, describe changes in specimen profile to the point of fracture.
6. Compute ductility in terms of both percentage elongation and percentage reduction of area for a material that is loaded in tension to fracture.
7. Give brief definitions of and the units for modulus of resilience and toughness (static).
8. For a specimen being loaded in tension, given the applied load, the instantaneous cross-sectional dimensions, and original and instantaneous lengths, be able to compute true stress and true strain values.
9. Name the two most common hardness-testing techniques; note two differences between them.
10. (a) Name and briefly describe the two different micro indentation hardness testing techniques, and (b) cite situations for which these techniques are generally used.
11. Compute the working stress for a ductile material.

INTRODUCTION



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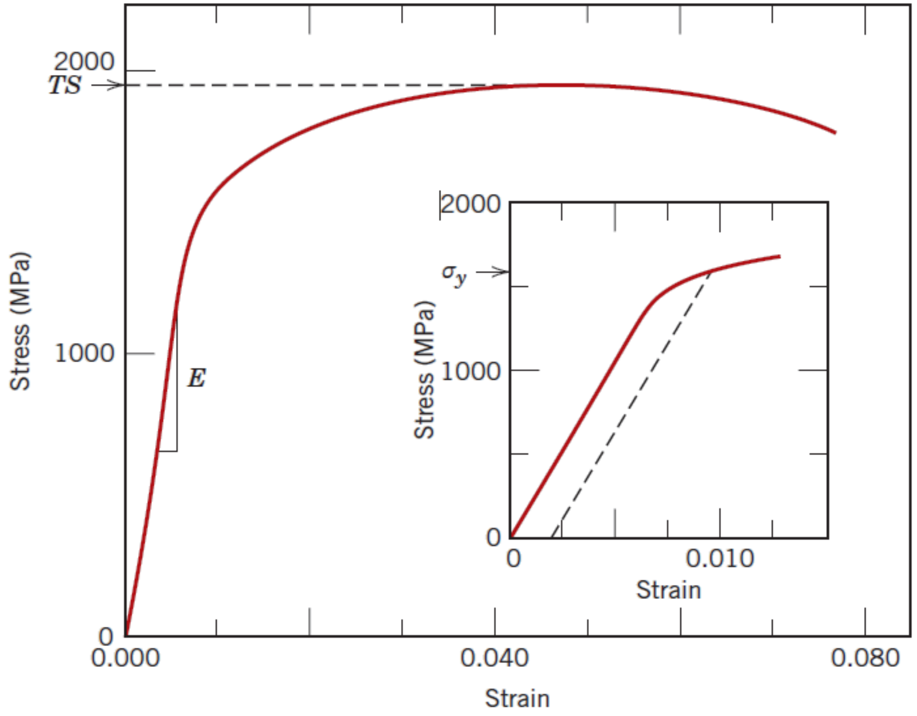
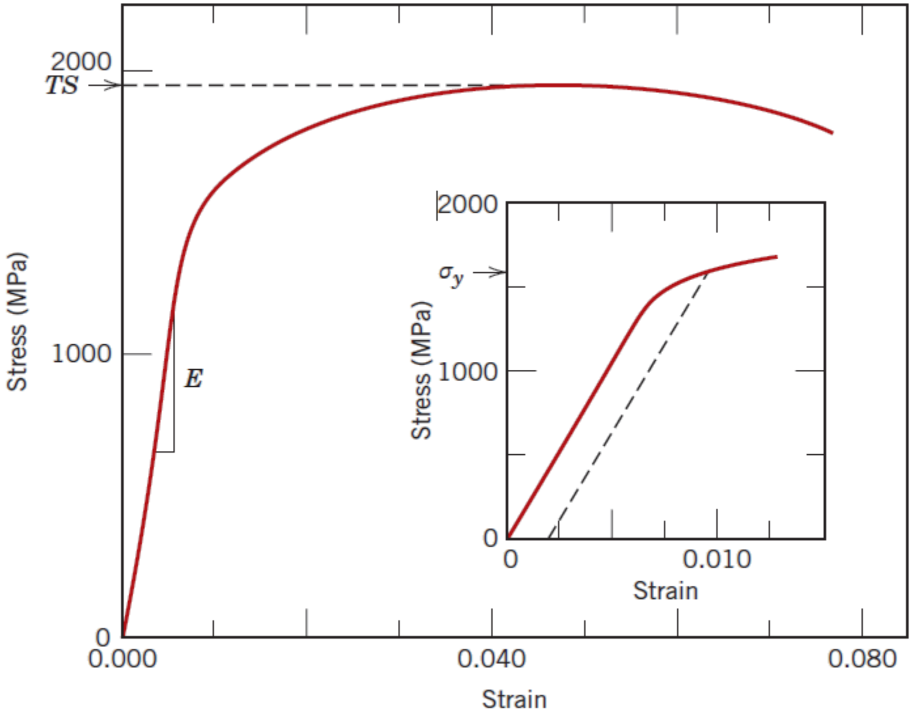
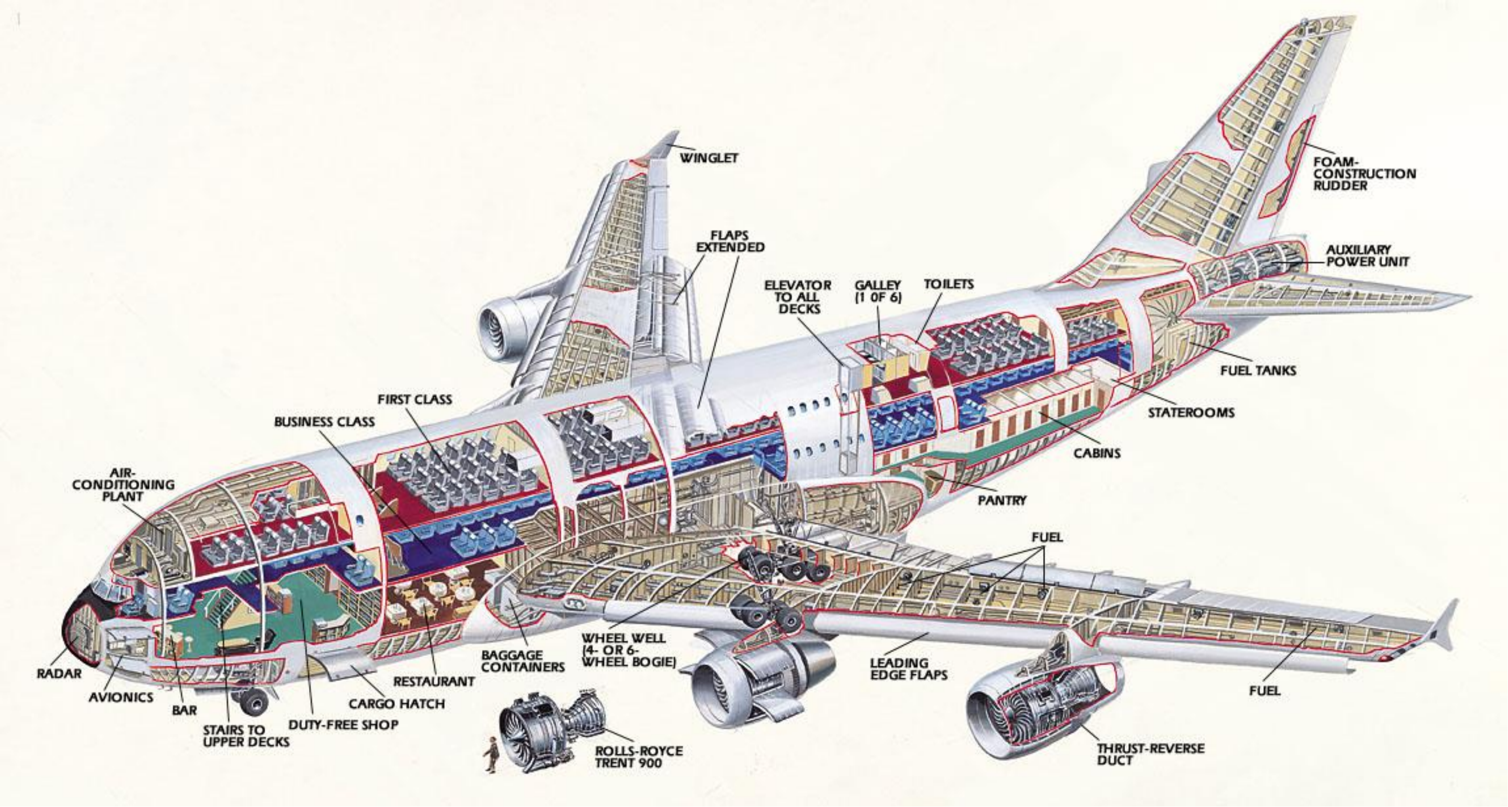


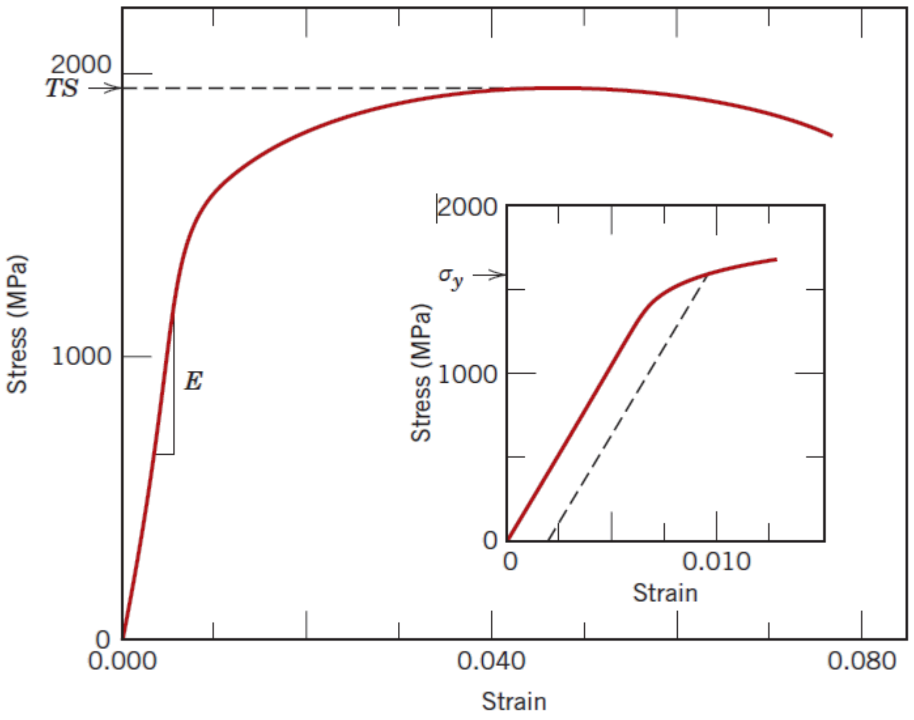
INTRODUCTION



Suspended 580 m
above the sea

INTRODUCTION





INTRODUCTION

- Many materials are subjected to forces or loads when in service; examples include the aluminium alloy from which an airplane wing is constructed and the steel in an automobile axle. In such situations it is necessary to know the characteristics of the material and to design the member from which it is made such that any resulting deformation will not be excessive and fracture will not occur.

- The mechanical behaviour of a material reflects its response or deformation in relation to an applied load or force. Key mechanical design properties are stiffness, strength, hardness, ductility, and toughness.

- The mechanical properties of materials are ascertained by performing carefully designed laboratory experiments that replicate as nearly as possible the service conditions.

- Factors to be considered include the nature of the applied load and its duration, as well as the environmental conditions. It is possible for the load to be tensile, compressive, or shear, and its magnitude may be constant with time, or it may fluctuate continuously.

- Application time may be only a fraction of a second, or it may extend over a period of many years. Service temperature may be an important factor.

- Mechanical properties are of concern to a variety of parties (e.g., producers and consumers of materials, research organizations, government agencies) that have differing interests.

INTRODUCTION

- It is imperative that there be some consistency in the manner in which tests are conducted and in the interpretation of their results.

- This consistency is accomplished by using standardized testing techniques. Establishment and publication of these standards are often coordinated by professional societies.

- In the United States the most active organization is the American Society for Testing and Materials (ASTM). Its *Annual Book of ASTM Standards* (http://www.astm.org) comprises numerous volumes that are issued and updated yearly; a large number of these standards relate to mechanical testing techniques.

- The role of structural engineers is to determine stresses and stress distributions within members that are subjected to well-defined loads. This may be accomplished by experimental testing techniques and/or by theoretical and mathematical stress analyses. These topics are treated in traditional texts on stress analysis and strength of materials.

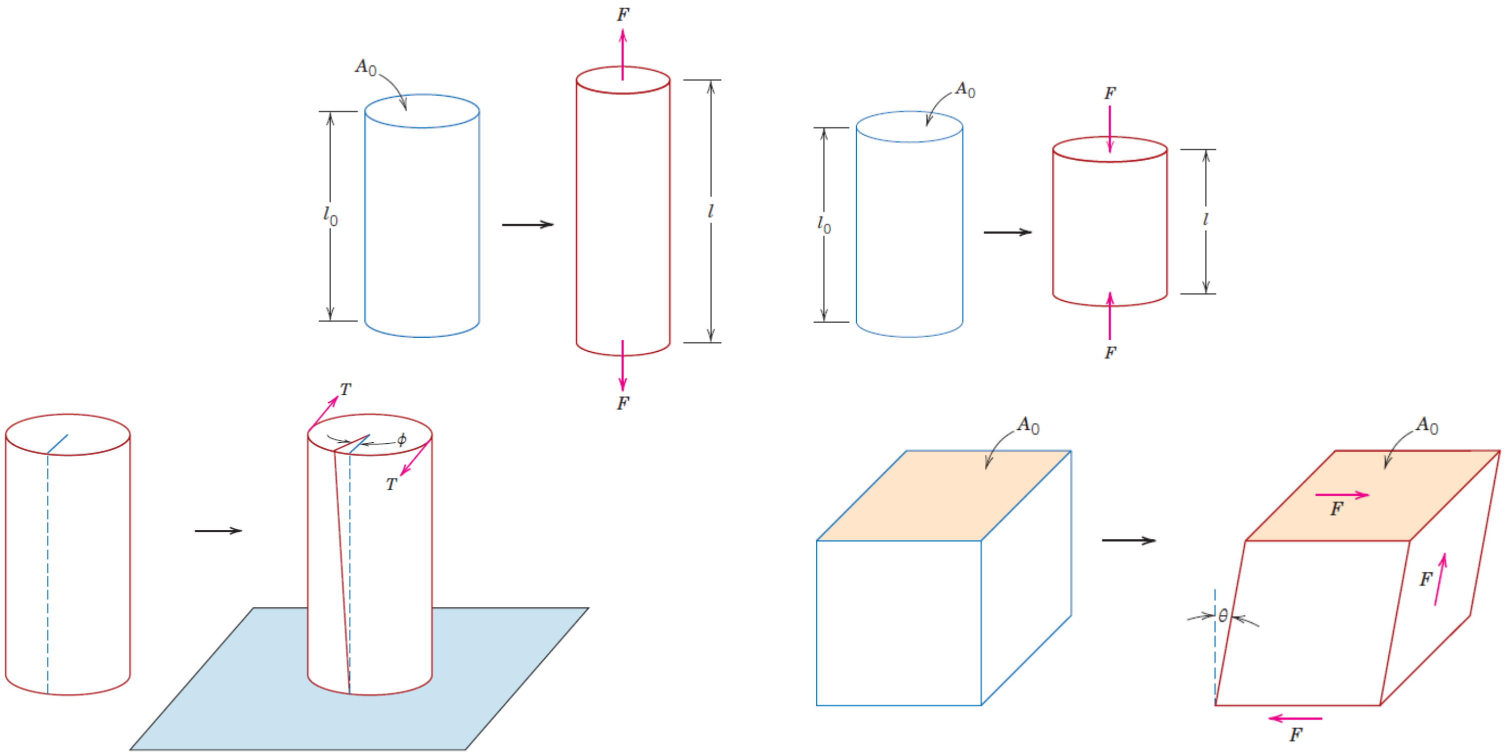
- Materials and metallurgical engineers, however, are concerned with producing and fabricating materials to meet service requirements as predicted by these stress analyses.

- This necessarily involves an understanding of the relationships between the microstructure (i.e., internal features) of materials and their mechanical properties. Materials are frequently chosen for structural applications because they have desirable combinations of mechanical characteristics.

CONCEPTS OF STRESS AND STRAIN

If a load is static or changes relatively slowly with time and is applied uniformly over a cross section or surface of a member, the mechanical behaviour may be ascertained by a simple stress–strain test; these are most commonly conducted for metals at room temperature.

There are three principal ways in which a load may be applied: namely, tension, compression, and shear. In engineering practice many loads are torsional rather than pure shear.



CONCEPTS OF STRESS AND STRAIN

Tension Tests

One of the most common mechanical stress–strain tests is performed in *tension*.

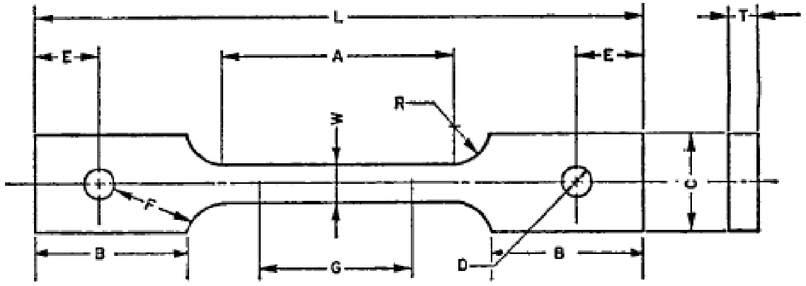
Designation: E8/E8M – 09

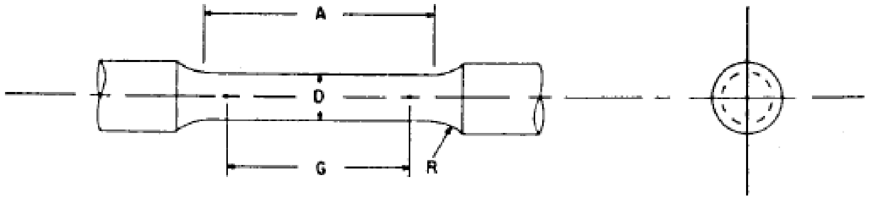
American Association State
Highway and Transportation Officials Standard
AASHTO No.: T68
An American National Standard

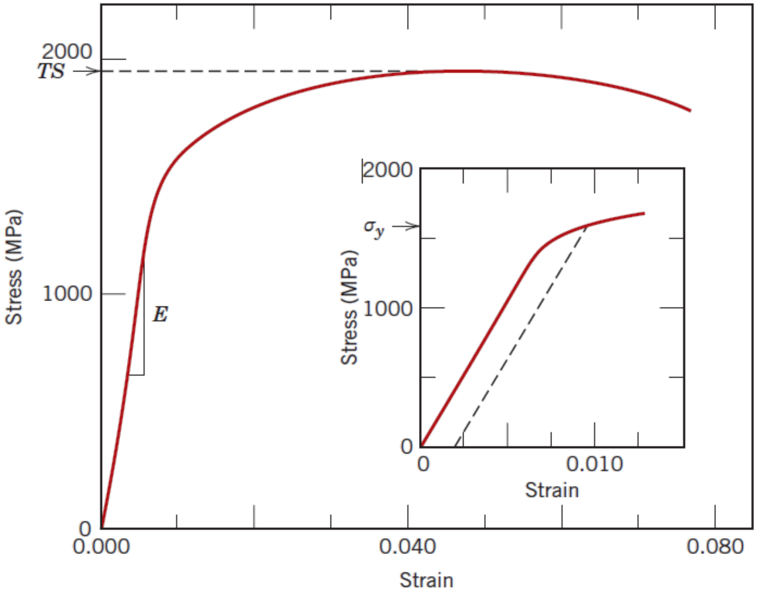
Standard Test Methods for Tension Testing of Metallic Materials[1]

This standard is issued under the fixed designation E8/E8M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

This standard has been approved for use by agencies of the Department of Defense.







CONCEPTS OF STRESS AND STRAIN

Tension Tests

CONCEPTS OF STRESS AND STRAIN

The output of such a tensile test is recorded (usually on a computer) as load or force versus elongation. These load–deformation characteristics depend on the specimen size.

For example, it requires twice the load to produce the same elongation if the cross-sectional area of the specimen is doubled. To minimize these geometrical factors, load and elongation are normalized to the respective parameters of **engineering stress** and **engineering strain.** Engineering stress σ is defined by the relationship:

$$\sigma = \frac{F}{A_0}$$

in which F is the instantaneous load applied perpendicular to the specimen cross section, in units of newtons (N) or pounds force (lbf), and A_0 is the original cross-sectional area before any load is applied (m^2 or $in.^2$). The units of engineering stress (referred to subsequently as just *stress*) are megapascals, MPa (SI) (where 1 MPa = 10^6 N/m^2), and pounds force per square inch, psi (customary U.S.).

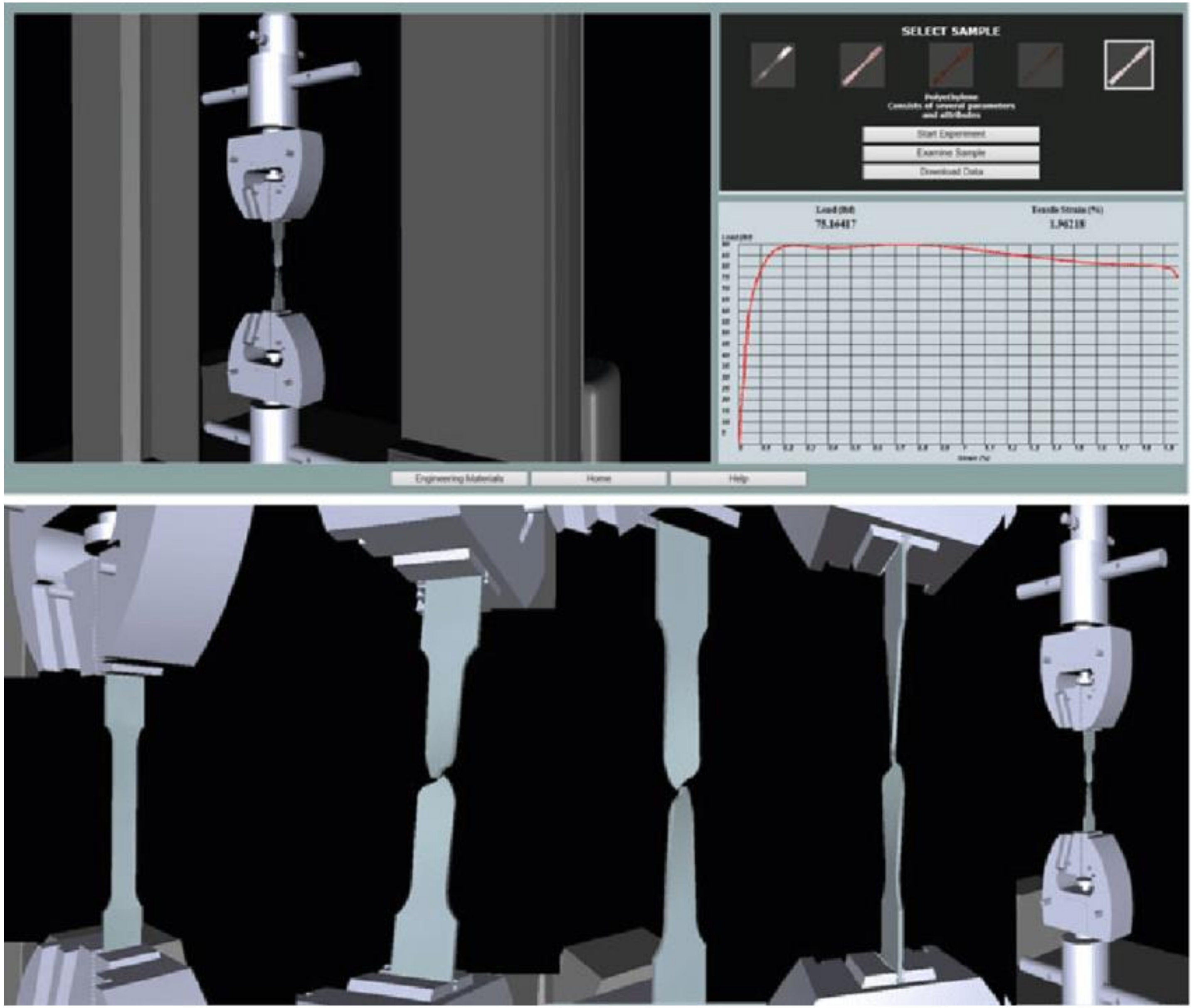
CONCEPTS OF STRESS AND STRAIN

Engineering strain ε is defined according to $$\varepsilon = \frac{l_i - l_0}{l_0} = \frac{\Delta l}{l_0}$$

in which l_0 is the original length before any load is applied and l_i is the instantaneous length. Sometimes the quantity $l_i - l_0$ is denoted as Δl and is the deformation elongation or change in length at some instant, as referenced to the original length.

Engineering strain (subsequently called just *strain*) is unitless, but meters per meter or inches per inch is often used; the value of strain is obviously independent of the unit system. Sometimes strain is also expressed as a percentage, in which the strain value is multiplied by 100.

CONCEPTS OF STRESS AND STRAIN



CONCEPTS OF STRESS AND STRAIN

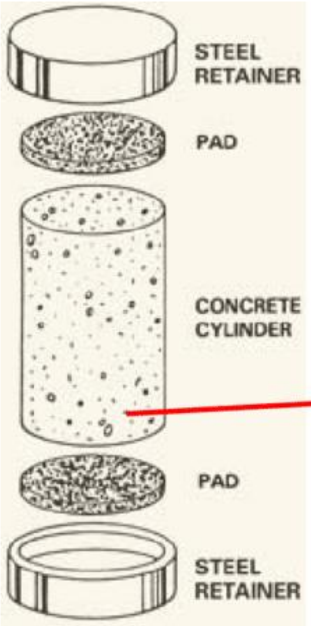
Compression Tests

Compression stress–strain tests may be conducted if in-service forces are of this type. A compression test is conducted in a manner similar to the tensile test, except that the force is compressive and the specimen contracts along the direction of the stress.

By convention, a compressive force is taken to be negative, which yields a negative stress. Furthermore, because l_0 is greater than l_i, compressive strains computed are necessarily also negative.

Tensile tests are more common because they are easier to perform; also, for most materials used in structural applications, very little additional information is obtained from compressive tests.

Compressive tests are used when a material's behaviour under large and permanent (i.e., plastic) strains is desired, as in manufacturing applications, or when the material is brittle in tension.



CONCEPTS OF STRESS AND STRAIN

Shear and Torsional Tests

For tests performed using a pure shear force, the shear stress τ is computed according to:

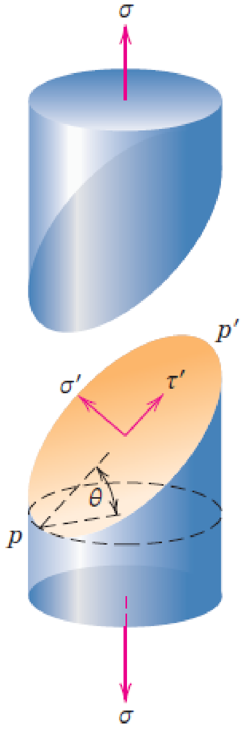
$$\tau = \frac{F}{A_0}$$

where F is the load or force imposed parallel to the upper and lower faces, each of which has an area of A_0. The shear strain γ is defined as the tangent of the strain angle θ, as indicated in the figure.

The units for shear stress and strain are the same as for their tensile counterparts.

Torsion is a variation of pure shear in which a structural member is twisted; torsional forces produce a rotational motion about the longitudinal axis of one end of the member relative to the other end.

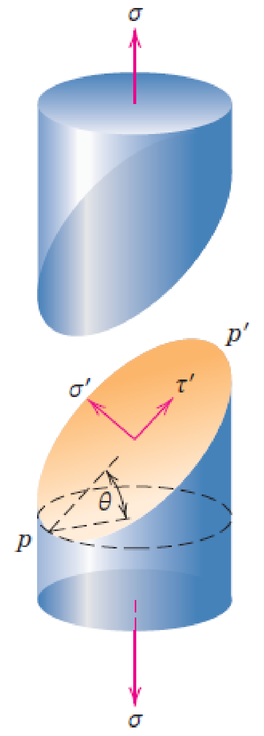
Examples of torsion are found for machine axles and drive shafts as well as for twist drills. Torsional tests are normally performed on cylindrical solid shafts or tubes. A shear stress τ is a function of the applied torque T, whereas shear strain γ is related to the angle of twist, ϕ.



CONCEPTS OF STRESS AND STRAIN

Geometric Considerations of the Stress State

Stresses that are computed from the tensile, compressive, shear, and torsional force states act either parallel or perpendicular to planar faces of the bodies.



Note that the stress state is a function of the orientations of the planes upon which the stresses are taken to act. For example, consider the cylindrical tensile specimen that is subjected to a tensile stress σ applied parallel to its axis.

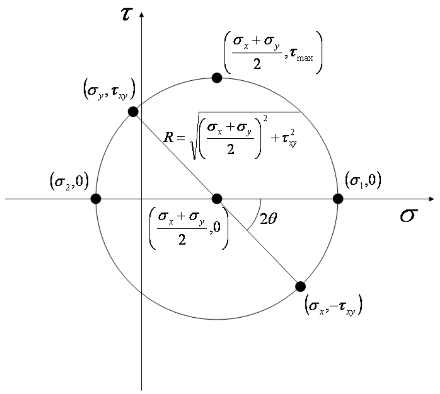
Furthermore, consider also the plane p-p' that is oriented at some arbitrary angle θ relative to the plane of the specimen end-face.

Upon this plane p-p', the applied stress is no longer a pure tensile one. Rather, a more complex stress state is present that consists of a tensile (or normal) stress σ' that acts normal to the p-p' plane and, in addition, a shear stress τ' that acts parallel to this plane; both of these stresses are represented in the figure.

Using mechanics-of-materials principles, it is possible to develop equations for σ' and τ' in terms of σ and θ, as follows: (Mohr's circle)

$$\sigma' = \sigma \cos^2\theta = \sigma\left(\frac{1 + \cos 2\theta}{2}\right)$$

$$\tau' = \sigma \sin\theta \cos\theta = \sigma\left(\frac{\sin 2\theta}{2}\right)$$



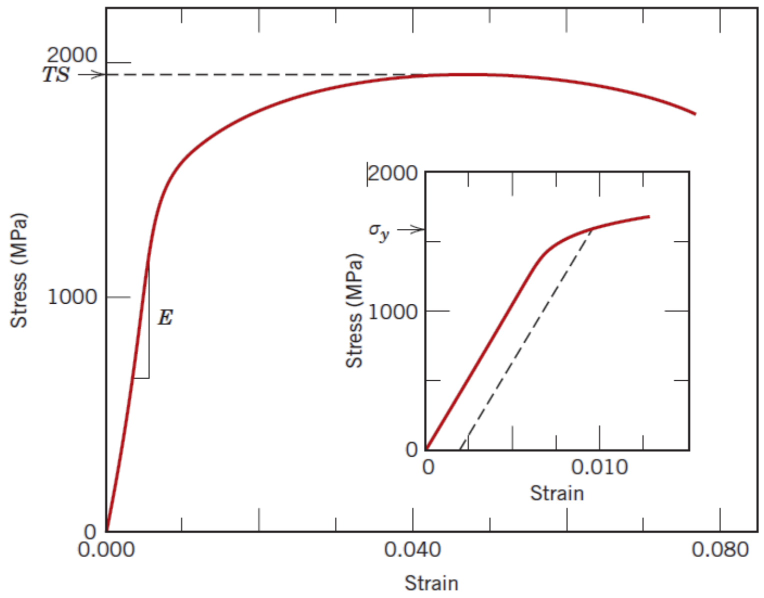
ELASTIC DEFORMATION

STRESS–STRAIN BEHAVIOR

The degree to which a structure deforms or strains depends on the magnitude of an imposed stress. For most metals that are stressed in tension and at relatively low levels, stress and strain are proportional to each other through the relationship: $\sigma = E\varepsilon$

This is known as *Hooke's law*, and the constant of proportionality E (GPa or psi) is the **modulus of elasticity,** or *Young's modulus*.

For most typical metals, the magnitude of this modulus ranges between 45 GPa (6.5×10^6 psi), for magnesium, and 407 GPa (59×10^6 psi), for tungsten.



Modulus of elasticity values for several metals at room temperature:

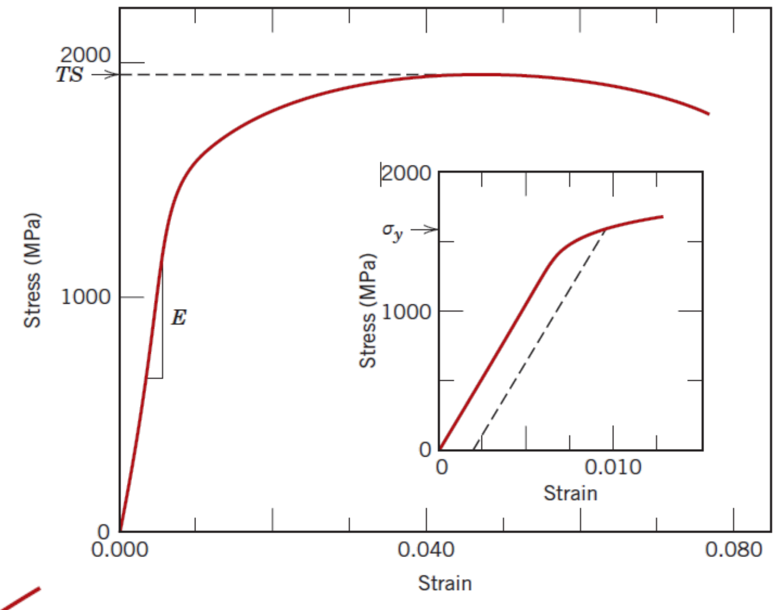
Metal Alloy	*Modulus of Elasticity* GPa	*Modulus of Elasticity* 10^6 psi	*Shear Modulus* GPa	*Shear Modulus* 10^6 psi	*Poisson's Ratio*
Aluminum	69	10	25	3.6	0.33
Brass	97	14	37	5.4	0.34
Copper	110	16	46	6.7	0.34
Magnesium	45	6.5	17	2.5	0.29
Nickel	207	30	76	11.0	0.31
Steel	207	30	83	12.0	0.30
Titanium	107	15.5	45	6.5	0.34
Tungsten	407	59	160	23.2	0.28

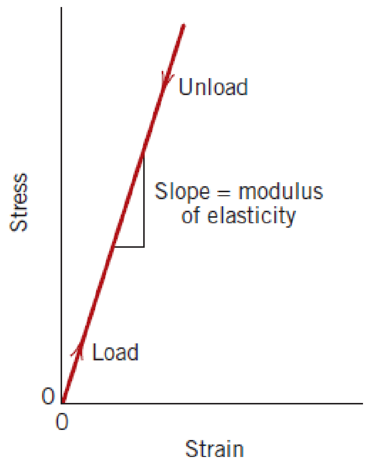
ELASTIC DEFORMATION

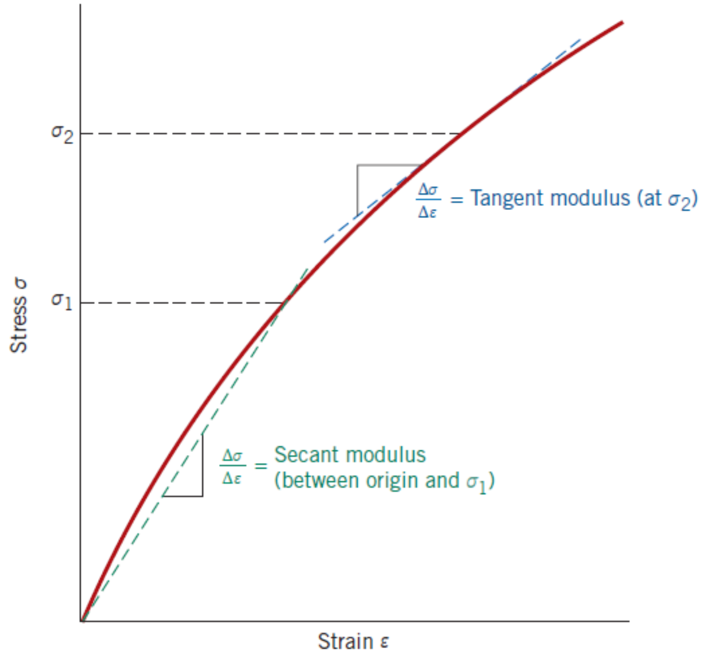
Deformation in which stress and strain are proportional is called **elastic deformation;** a plot of stress (ordinate) versus strain (abscissa) results in a linear relationship, as shown.

The slope of this linear segment corresponds to the modulus of elasticity *E*. This modulus may be thought of as stiffness, or a material's resistance to elastic deformation.

The greater the modulus, the stiffer the material, or the smaller the elastic strain that results from the application of a given stress. The modulus is an important design parameter for computing elastic deflections.







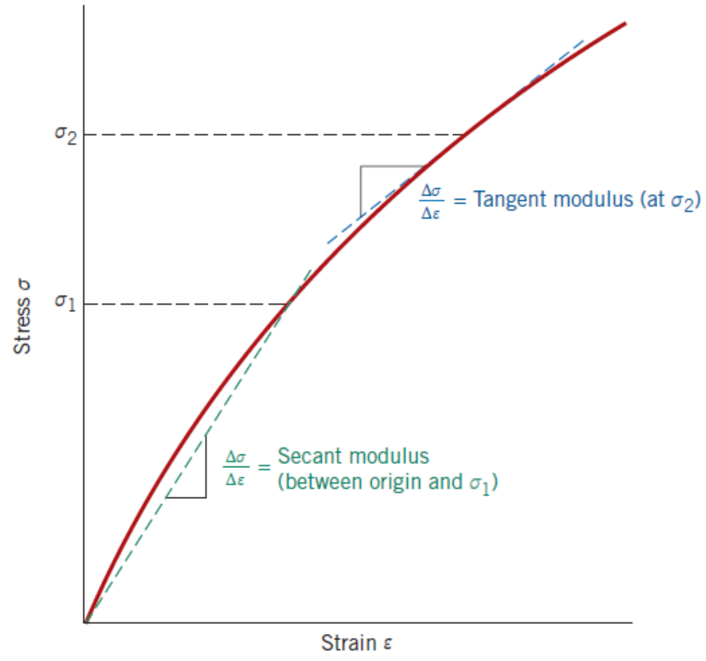
ELASTIC DEFORMATION

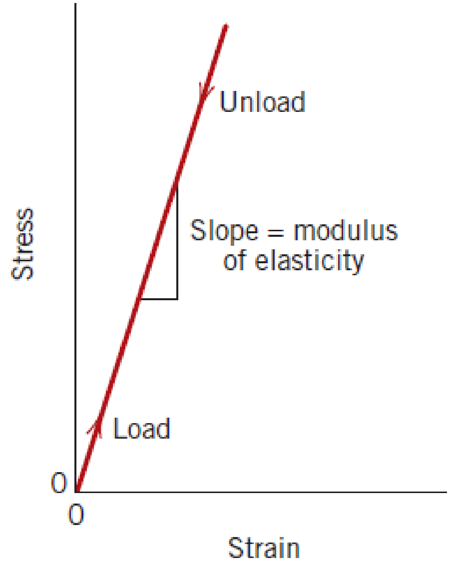
Elastic deformation is *non-permanent*, which means that when the applied load is released, the piece returns to its original shape. As shown in the stress–strain plot, application of the load corresponds to moving from the origin up and along the straight line.

Upon release of the load, the line is traversed in the opposite direction, back to the origin.

There are some materials (i.e., gray cast iron, concrete, and many polymers) for which this elastic portion of the stress–strain curve is not linear; hence, it is not possible to determine a modulus of elasticity as described previously.

For this nonlinear behaviour, either the *tangent* or *secant modulus* is normally used. The tangent modulus is taken as the slope of the stress–strain curve at some specified level of stress, whereas the secant modulus represents the slope of a secant drawn from the origin to some given point of the σ-ε curve.





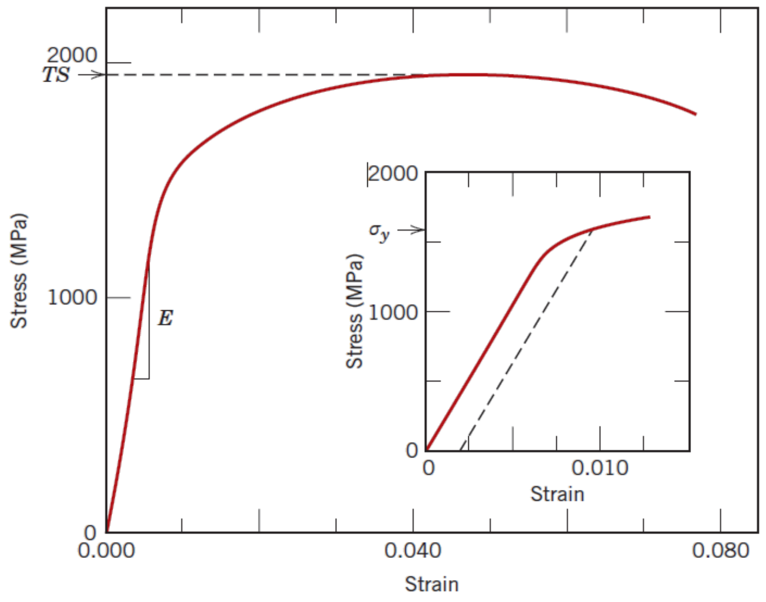
ELASTIC DEFORMATION

On an atomic scale, macroscopic elastic strain is manifested as small changes in the interatomic spacing and the stretching of interatomic bonds.

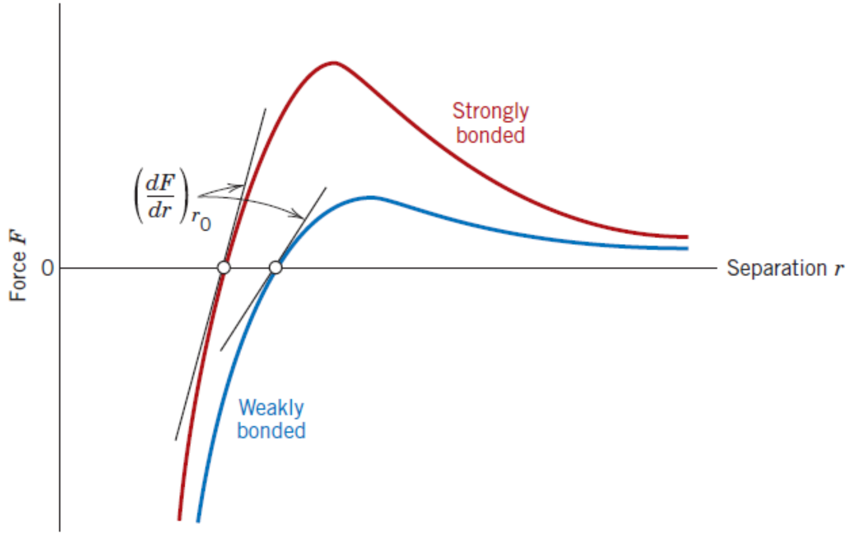
As a consequence, the magnitude of the modulus of elasticity is a measure of the resistance to separation of adjacent atoms, that is, the interatomic bonding forces.

Furthermore, this modulus is proportional to the slope of the interatomic force–separation curve at the equilibrium spacing:

$$E \propto \left(\frac{dF}{dr}\right)_{r_0}$$



The force–separation curves for materials having both strong and weak interatomic bonds is shown; the slope at r_0 is indicated for each.



Values of the modulus of elasticity for ceramic materials are about the same as for metals; for polymers they are lower. These differences are a direct consequence of the different types of atomic bonding in the three materials types.

ELASTIC DEFORMATION

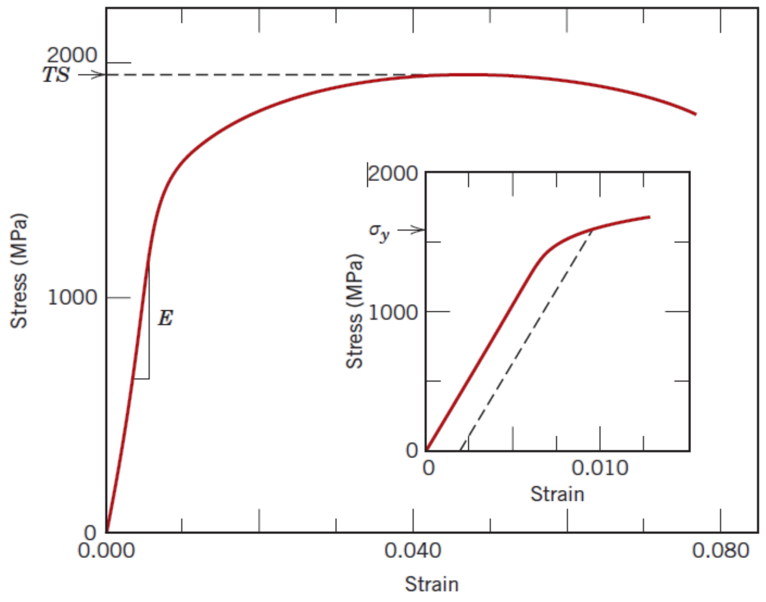
Furthermore, with increasing temperature, the modulus of elasticity decreases, as is shown for several metals.

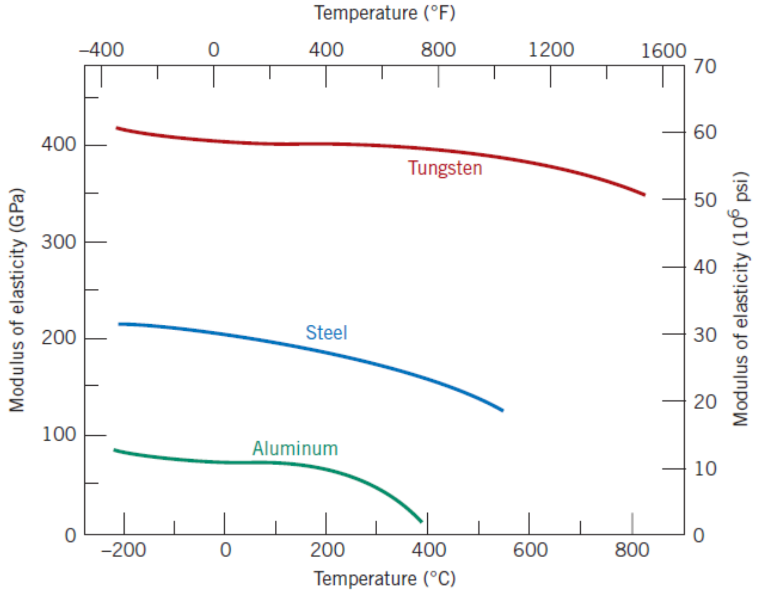
As would be expected, the imposition of compressive, shear, or torsional stresses also evokes elastic behaviour. The stress–strain characteristics at low stress levels are virtually the same for both tensile and compressive situations, to include the magnitude of the modulus of elasticity.

Shear stress and strain are proportional to each other through the expression

$\tau = G\gamma$

where G is the *shear modulus*, the slope of the linear elastic region of the shear stress–strain curve.

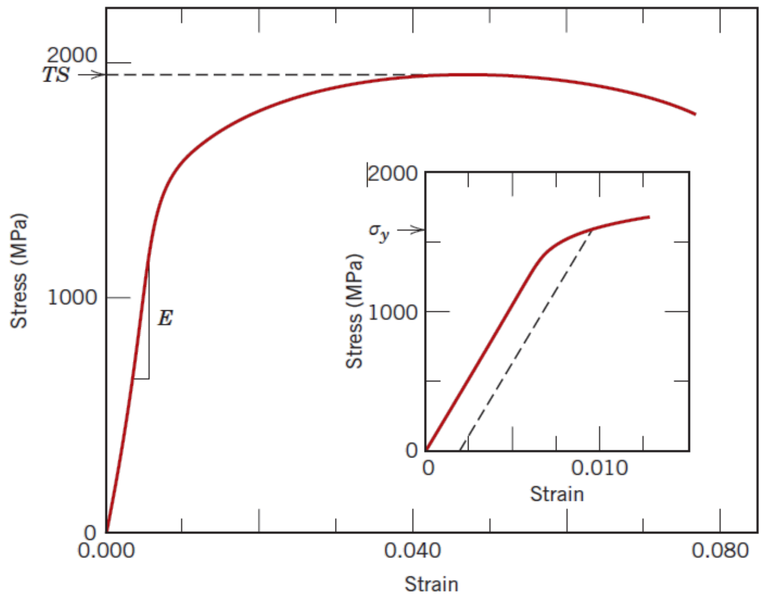




ELASTIC DEFORMATION

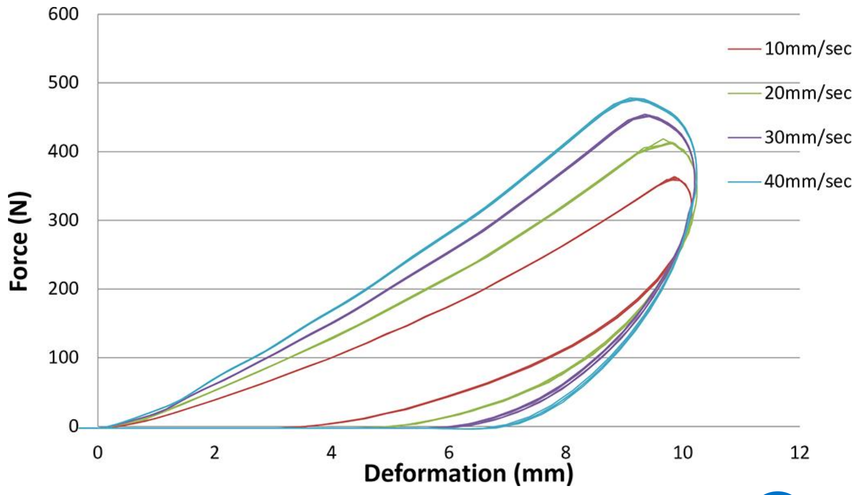
ANELASTICITY

To this point, it has been assumed that elastic deformation is time independent—that is, that an applied stress produces an instantaneous elastic strain that remains constant over the period of time the stress is maintained. It has also been assumed that upon release of the load, the strain is totally recovered—that is, that the strain immediately returns to zero.



In most engineering materials, however, there will also exist a time dependent elastic strain component—that is, elastic deformation will continue after the stress application, and upon load release, some finite time is required for complete recovery.

This time-dependent elastic behaviour is known as **anelasticity,** and it is due to time-dependent microscopic and atomistic processes that are attendant to the deformation.



For metals, the anelastic component is normally small and is often neglected.

However, for some polymeric materials, its magnitude is significant; in this case it is termed *viscoelastic behaviour.*

ELASTIC DEFORMATION

ELASTIC PROPERTIES OF MATERIALS

When a tensile stress is imposed on a metal specimen, an elastic elongation and accompanying strain ε_z result in the direction of the applied stress (arbitrarily taken to be the z direction).

As a result of this elongation, there will be constrictions in the lateral (x and y) directions perpendicular to the applied stress; from these contractions, the compressive strains ε_x and ε_y may be determined.

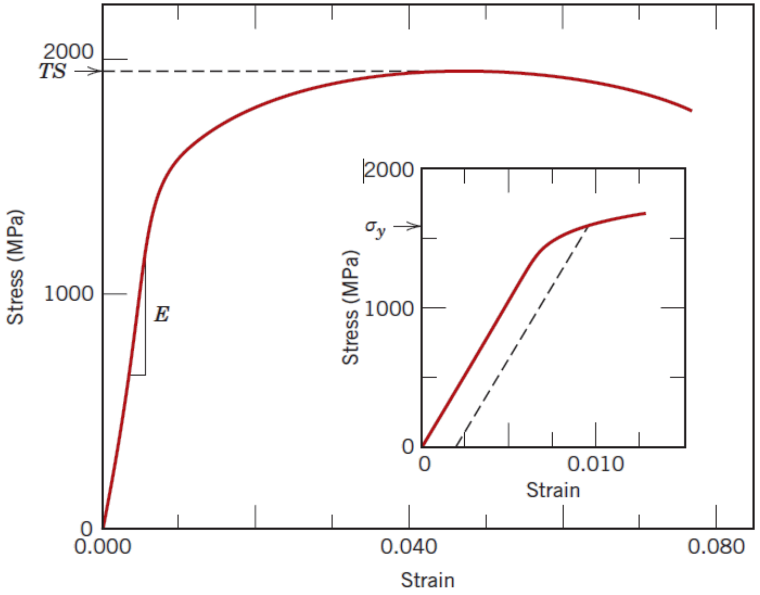
If the applied stress is uniaxial (only in the z direction) and the material is isotropic, then $\varepsilon_x = \varepsilon_y$.

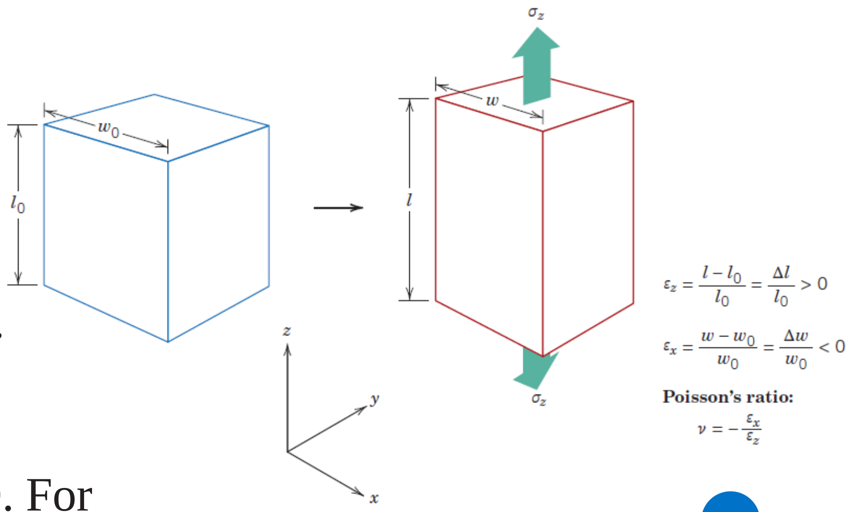
A parameter termed **Poisson's ratio** ν is defined as the ratio of the lateral And axial strains, or

$$\nu = -\frac{\varepsilon_x}{\varepsilon_z} = -\frac{\varepsilon_y}{\varepsilon_z}$$

For **virtually** all structural materials, ε_x and ε_y will be of opposite sign; therefore, the negative sign is included in the preceding expression to ensure that ν is positive.

Theoretically, Poisson's ratio for isotropic materials should be 1/4; furthermore, the maximum value for ν (or the value for which there is no net volume change) is 0.50. For many metals and other alloys, values of Poisson's ratio range between 0.25 and 0.35.





ELASTIC DEFORMATION

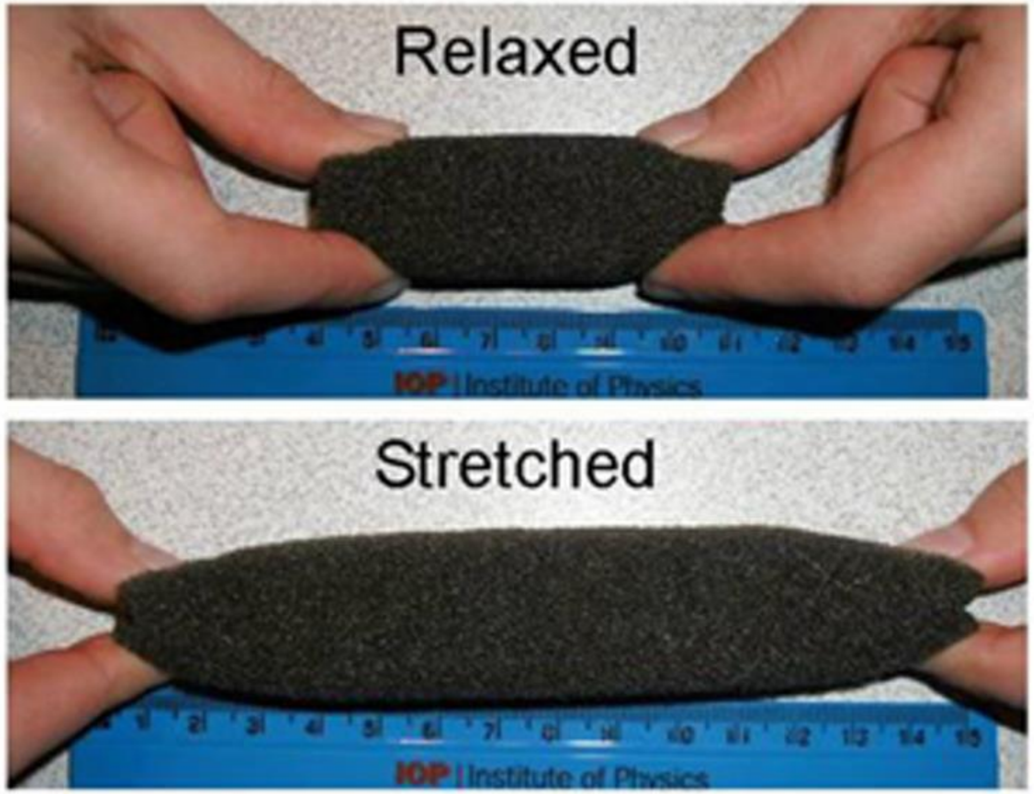
Auxetics
Auxetics are structures or materials that have a negative Poisson's ratio. When stretched, they become thicker perpendicular to the applied force.

This occurs due to their particular internal structure and the way this deforms when the sample is uniaxially loaded.

Auxetics can be single molecules, crystals, or a particular structure of macroscopic matter.

Such materials and structures are expected to have mechanical properties such as high energy absorption and fracture resistance.

Auxetics may be useful in applications such as body armour packing material, knee and elbow pads, robust shock absorbing material, and sponge mops.



ELASTIC DEFORMATION

For isotropic materials, shear and elastic moduli are related to each other and to Poisson's ratio according to: $E = 2G(1 + \nu)$.

In most metals, G is about $0.4E$; thus, if the value of one modulus is known, the other may be approximated.

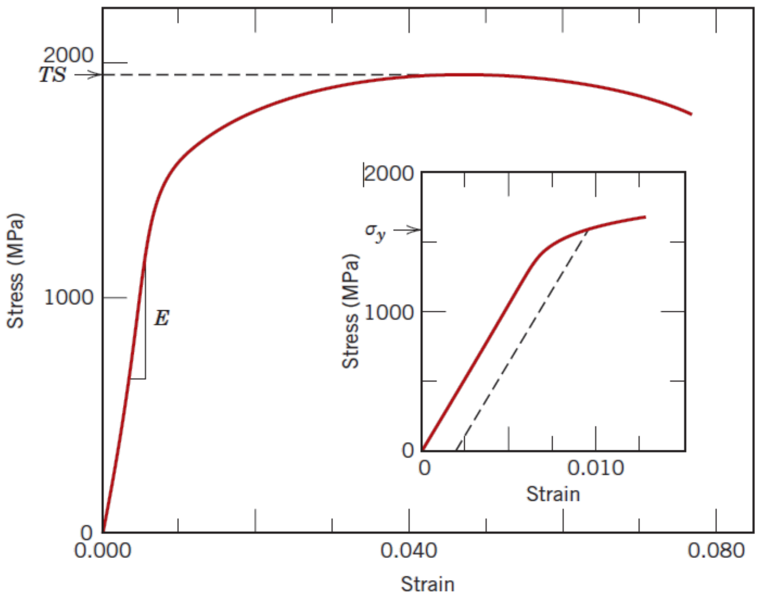
Many materials are elastically anisotropic; that is, the elastic behaviour (i.e., the magnitude of E) varies with crystallographic direction.

For these materials, the elastic properties are completely characterized only by the specification of several elastic constants, their number depending on characteristics of the crystal structure.

Even for isotropic materials, for complete characterization of the elastic properties, at least two constants must be given.

Because the grain orientation is random in most polycrystalline materials, these may be considered to be isotropic; inorganic ceramic glasses are also isotropic.

The remaining discussion of mechanical behaviour assumes isotropy and polycrystallinity because this is the character of most engineering materials.



PLASTIC DEFORMATION

For most metallic materials, elastic deformation persists only to strains of about 0.005.

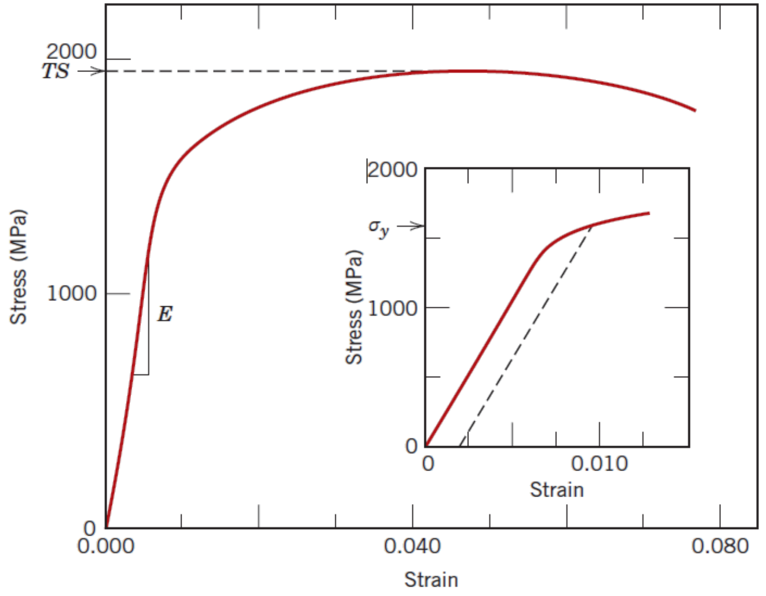
As the material is deformed beyond this point, the stress is no longer proportional to strain. and permanent, nonrecoverable, or **plastic deformation** occurs.

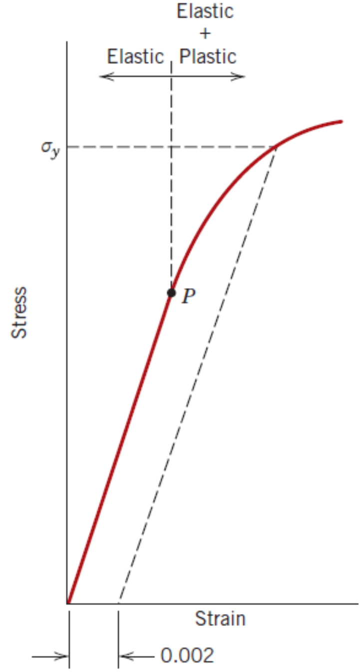
The transition from elastic to plastic is a gradual one for most metals; some curvature results at the onset of plastic deformation, which increases more rapidly with rising stress.

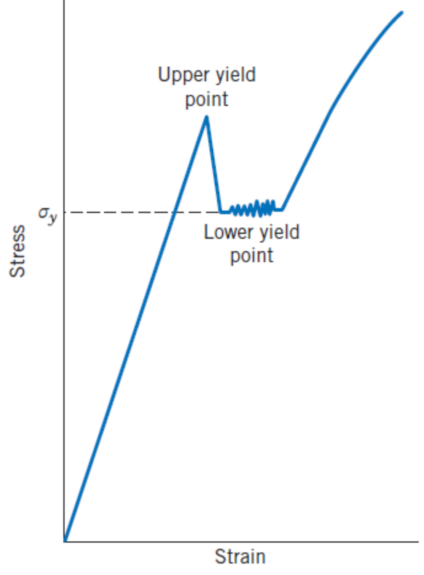
From an atomic perspective, plastic deformation corresponds to the breaking of bonds with original atom neighbours and then the re-forming of bonds with new neighbours as large numbers of atoms or molecules move relative to one another; upon removal of the stress, they do not return to their original positions.

The mechanism of this deformation is different for crystalline and amorphous materials. For crystalline solids, deformation is accomplished by means of a process called *slip*, which involves the motion of dislocations.

Plastic deformation in noncrystalline solids (as well as liquids) occurs by a viscous flow mechanism.







PLASTIC DEFORMATION

Yielding and Yield Strength

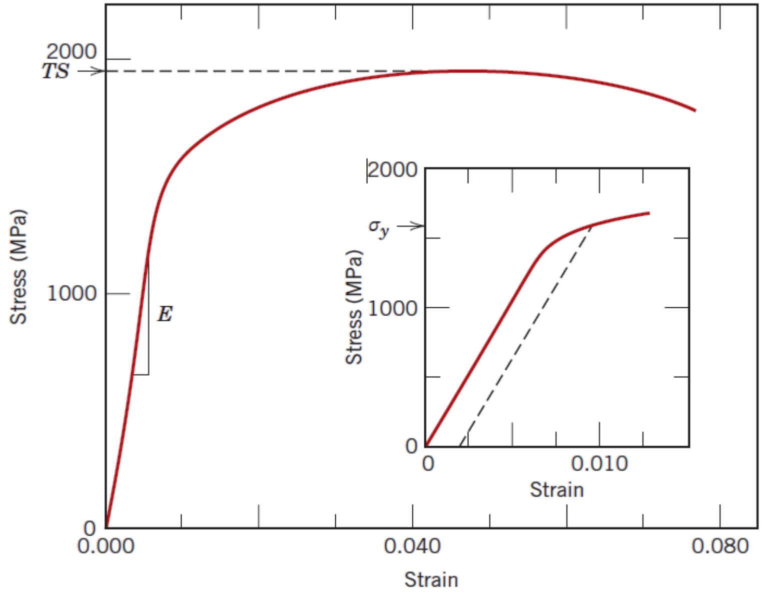
Most structures are designed to ensure that only elastic deformation will result when a stress is applied.

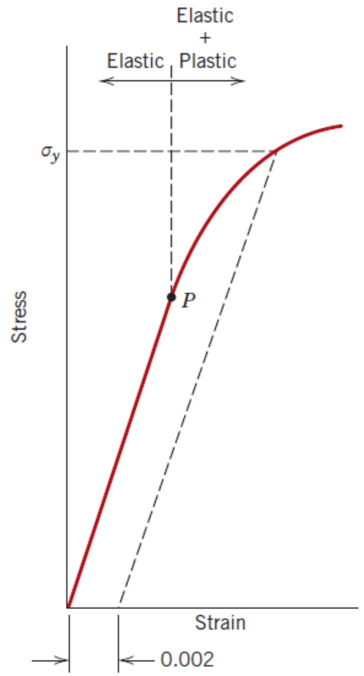
A structure or component that has plastically deformed—or experienced a permanent change in shape—may not be capable of functioning as intended.

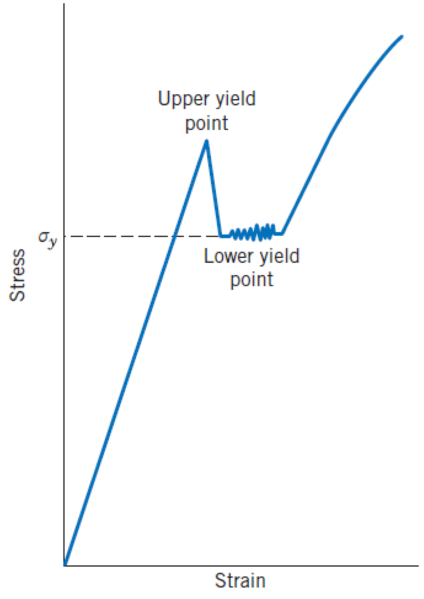
It is therefore desirable to know the stress level at which plastic deformation begins, or where the phenomenon of **yielding** occurs.

For metals that experience this gradual elastic–plastic transition, the point of yielding may be determined as the initial departure from linearity of the stress–strain curve; this is sometimes called the **proportional limit,** as indicated by point *P*, and represents the onset of plastic deformation on a microscopic level.

The position of this point *P* is difficult to measure precisely. As a consequence, a convention has been established by which a straight line is constructed parallel to the elastic portion of the stress–strain curve at some specified strain offset, usually 0.002.







PLASTIC DEFORMATION

The stress corresponding to the intersection of this line and the stress–strain curve as it bends over in the plastic region is defined as the **yield strength** σ_y. The units of yield strength are MPa or psi.

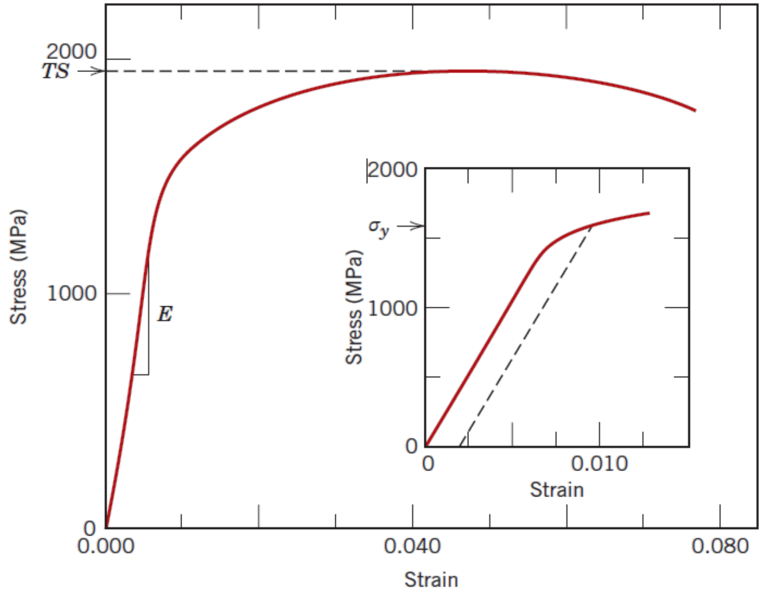
For materials having a nonlinear elastic region, use of the strain offset method is not possible, and the usual practice is to define the yield strength as the stress required to produce some amount of strain (e.g., $\varepsilon = 0.005$).

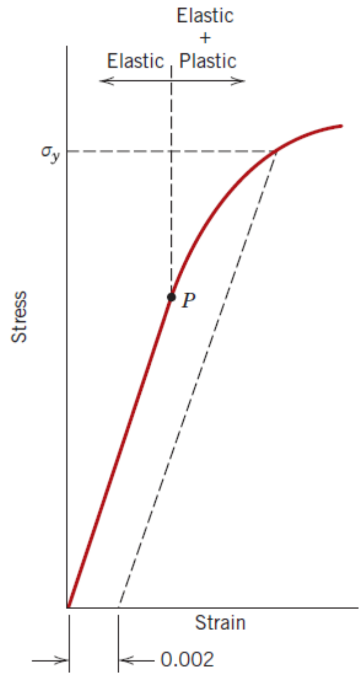
Some steels and other materials exhibit the tensile stress–strain behaviour shown in the lower left figure. The elastic–plastic transition is very well defined and occurs abruptly in what is termed a *yield point phenomenon*.

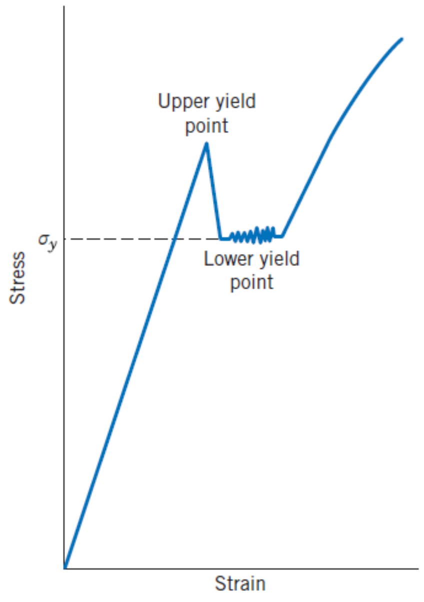
At the upper yield point, plastic deformation is initiated with an apparent decrease in engineering stress. Continued deformation fluctuates slightly about some constant stress value, termed the *lower yield point*; stress subsequently rises with increasing strain.

For metals that display this effect, the yield strength is taken as the average stress that is associated with the lower yield point because it is well defined and relatively insensitive to the testing procedure.

Thus, it is not necessary to employ the strain offset method for these materials.







PLASTIC DEFORMATION

The magnitude of the yield strength for a metal is a measure of its resistance to plastic deformation.

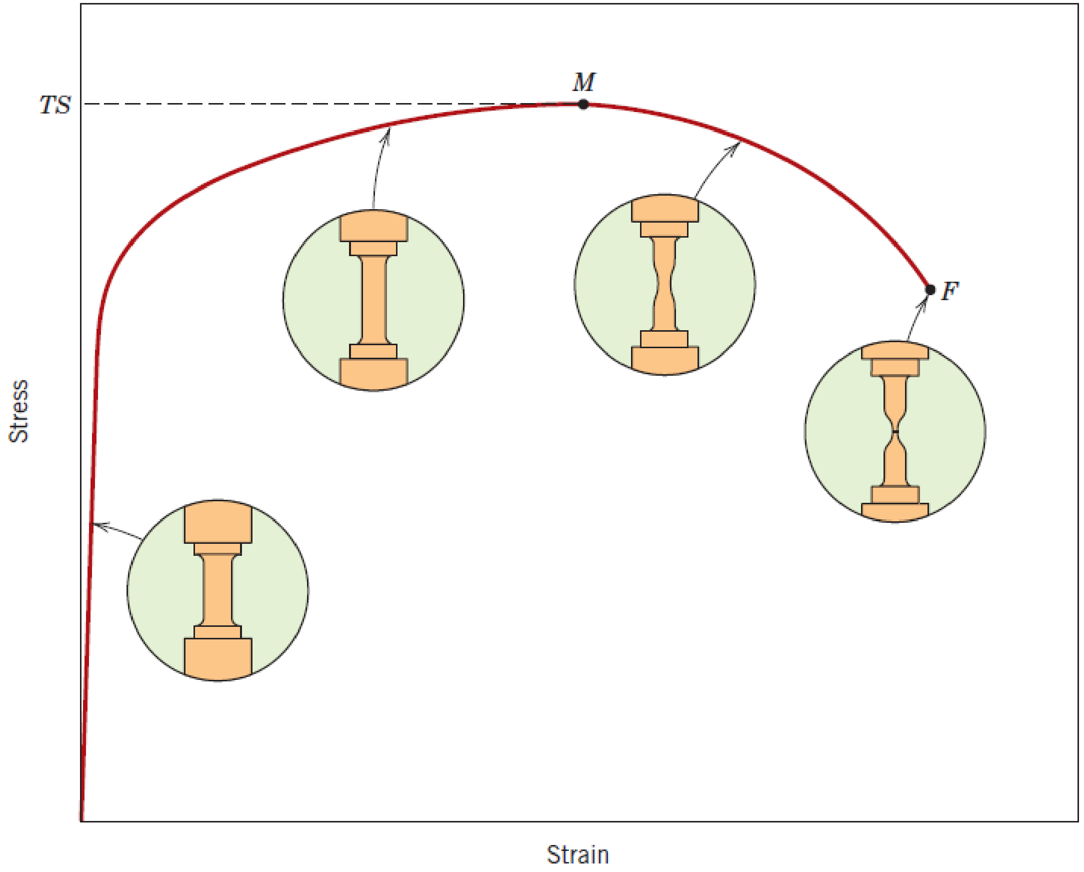
Yield strengths may range from 35 MPa (5000 psi) for a low-strength aluminium to greater than 1400 MPa (200,000 psi) for high-strength steels.

Tensile Strength

After yielding, the stress necessary to continue plastic deformation in metals increases to a maximum, point *M* in the figure, and then decreases to the eventual fracture, point *F*. The **tensile strength** *TS* (MPa or psi) is the stress at the maximum on the engineering stress–strain curve.

This corresponds to the maximum stress that can be sustained by a structure in tension; if this stress is applied and maintained, fracture will result.

All deformation to this point is uniform throughout the narrow region of the tensile specimen. However, at this maximum stress, a small constriction or neck begins to form at some point, and all subsequent deformation is confined at this neck, as indicated by the schematic specimen insets.



PLASTIC DEFORMATION

Ductility

Ductility is another important mechanical property. It is a measure of the degree of plastic deformation that has been sustained at fracture.

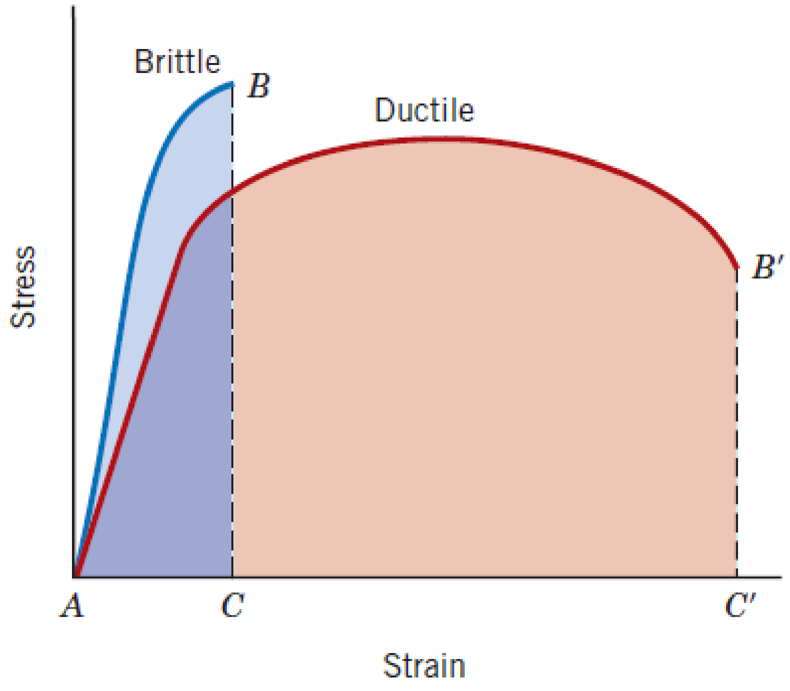
A metal that experiences very little or no plastic deformation upon fracture is termed *brittle*.

The tensile stress– strain behaviours for both ductile and brittle metals are schematically.

Ductility may be expressed quantitatively as either *percent elongation* or *percent reduction in area*.

$$\%EL = \left(\frac{l_f - l_0}{l_0}\right) \times 100$$

$$\%RA = \left(\frac{A_0 - A_f}{A_0}\right) \times 100$$



PLASTIC DEFORMATION

Knowledge of the ductility of materials is important for at least two reasons.

First, it indicates to a designer the degree to which a structure will deform plastically before fracture.
Second, it specifies the degree of allowable deformation during fabrication operations.

We sometimes refer to relatively ductile materials as being “forgiving,” in the sense that they may experience local deformation without fracture, should there be an error in the magnitude of the design stress calculation.

Brittle materials are *approximately* considered to be those having a fracture strain of less than about 5%.

Thus, several important mechanical properties of metals may be determined from tensile stress–strain tests.

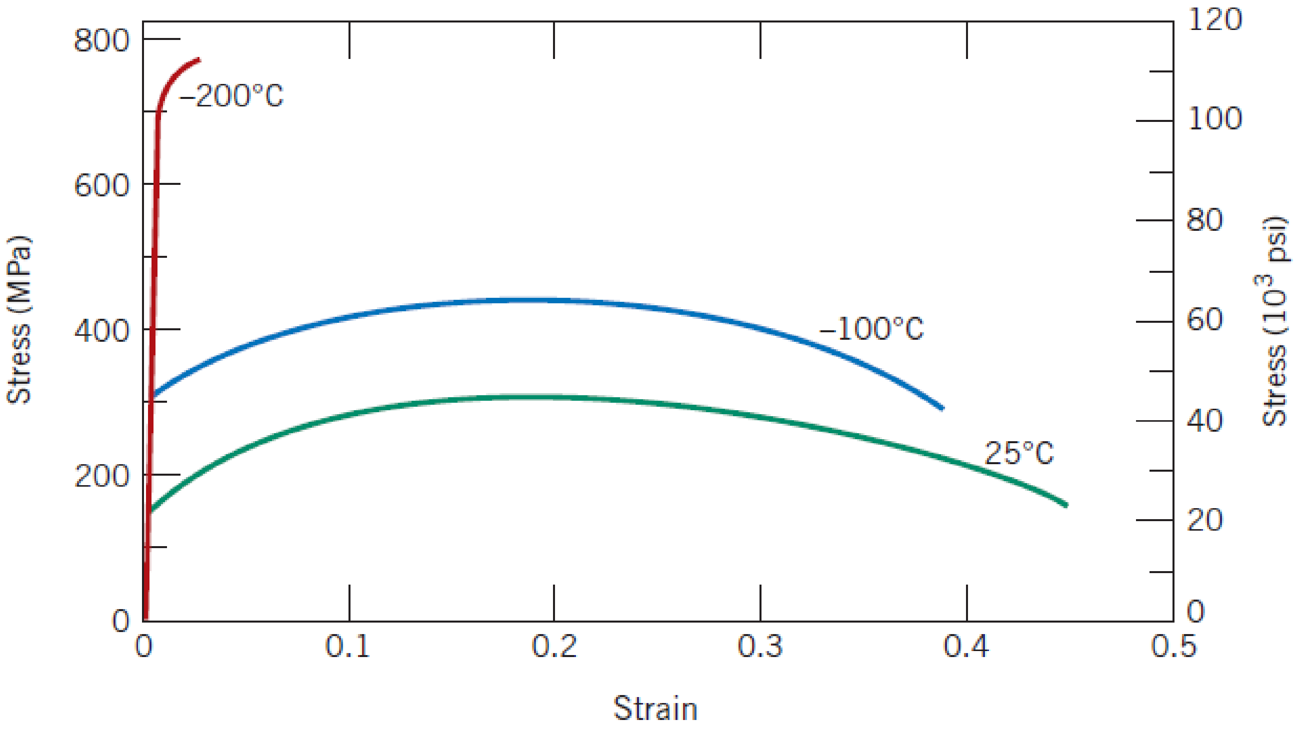
Metal Alloy	*Yield Strength, MPa (ksi)*	*Tensile Strength, MPa (ksi)*	*Ductility, %EL [in 50 mm (2 in.)]*
Aluminum	35 (5)	90 (13)	40
Copper	69 (10)	200 (29)	45
Brass (70Cu–30Zn)	75 (11)	300 (44)	68
Iron	130 (19)	262 (38)	45
Nickel	138 (20)	480 (70)	40
Steel (1020)	180 (26)	380 (55)	25
Titanium	450 (65)	520 (75)	25
Molybdenum	565 (82)	655 (95)	35

PLASTIC DEFORMATION

These properties are sensitive to any prior deformation, the presence of impurities, and/or any heat treatment to which the metal has been subjected.

The modulus of elasticity is one mechanical parameter that is insensitive to these treatments.

As with modulus of elasticity, the magnitudes of both yield and tensile strengths decline with increasing temperature; just the reverse holds for ductility—it usually increases with temperature.



PLASTIC DEFORMATION

Resilience

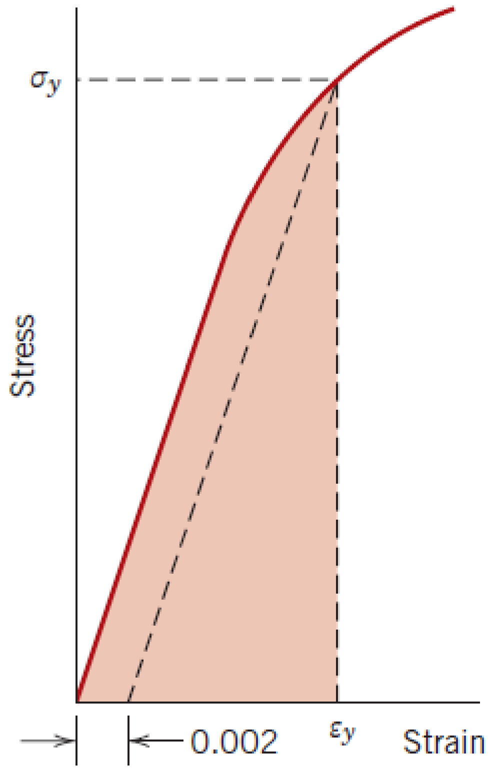
Resilience is the capacity of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered.

The associated property is the *modulus of resilience*, *Ur*, which is the strain energy per unit volume required to stress a material from an unloaded state up to the point of yielding.

Computationally, the modulus of resilience for a specimen subjected to a uniaxial tension test is just the area under the engineering stress–strain curve taken to yielding, or

$$U_r = \int_0^{\varepsilon_y} \sigma \, d\varepsilon$$

Assuming a linear elastic region, we have $U_r = \frac{1}{2}\sigma_y \varepsilon_y$ in which ε_y is the strain at yielding.



The units of resilience are the product of the units from each of the two axes of the stress–strain plot. For SI units, this is joules per cubic meter (J/m^3, equivalent to Pa), whereas with customary U.S. units, it is inch-pounds force per cubic inch (in.-lbf/in.^{3}, equivalent to psi). Both joules and inch-pounds force are units of energy, and thus this area under the stress–strain curve represents energy absorption per unit volume (in cubic meters or cubic inches) of material.

$$U_r = \frac{1}{2}\sigma_y \varepsilon_y = \frac{1}{2}\sigma_y\left(\frac{\sigma_y}{E}\right) = \frac{\sigma_y^2}{2E}$$

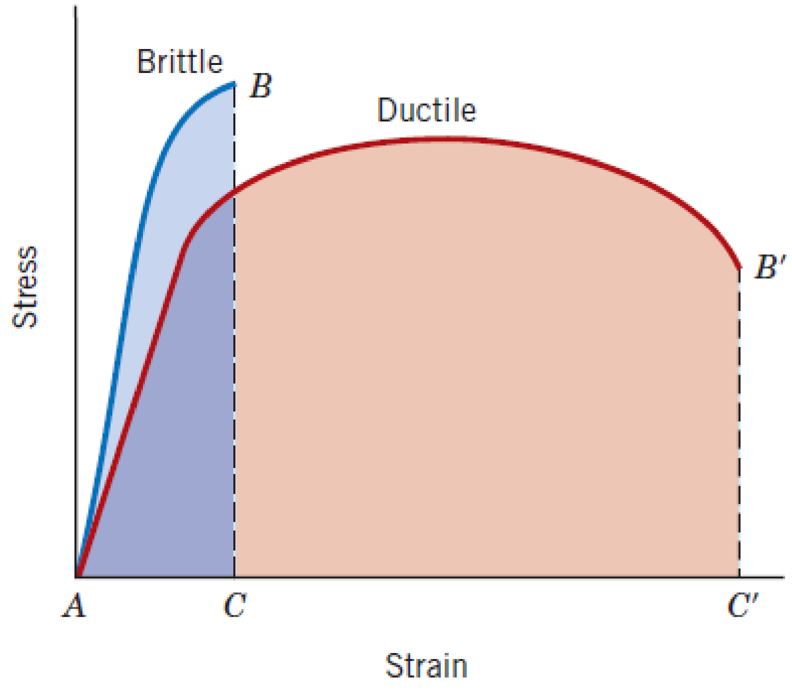
PLASTIC DEFORMATION

Toughness

Toughness is a mechanical term that may be used in several contexts. For one, toughness (or more specifically, *fracture toughness*) is a property that is indicative of a material's resistance to fracture when a crack (or other stress-concentrating defect) is present.

Because it is nearly impossible (as well as costly) to manufacture materials with zero defects (or to prevent damage during service), fracture toughness is a major consideration for all structural materials.

Another way of defining toughness is as the ability of a material to absorb energy and plastically deform before fracturing.



For dynamic (high strain rate) loading conditions and when a notch (or point of stress concentration) is present, *notch toughness* is assessed by using an impact test.

For the static (low strain rate) situation, a measure of toughness in metals (derived from plastic deformation) may be ascertained from the results of a tensile stress–strain test. It is the area under the σ–ε curve up to the point of fracture. The units are the same as for resilience (i.e., energy per unit volume of material). For a metal to be tough, it must display both strength and ductility. Hence, even though the brittle metal has higher yield and tensile strengths, it has a lower toughness than the ductile one, as can be seen by comparing the areas *ABC* and *AB′C′*.

TRUE STRESS AND STRAIN

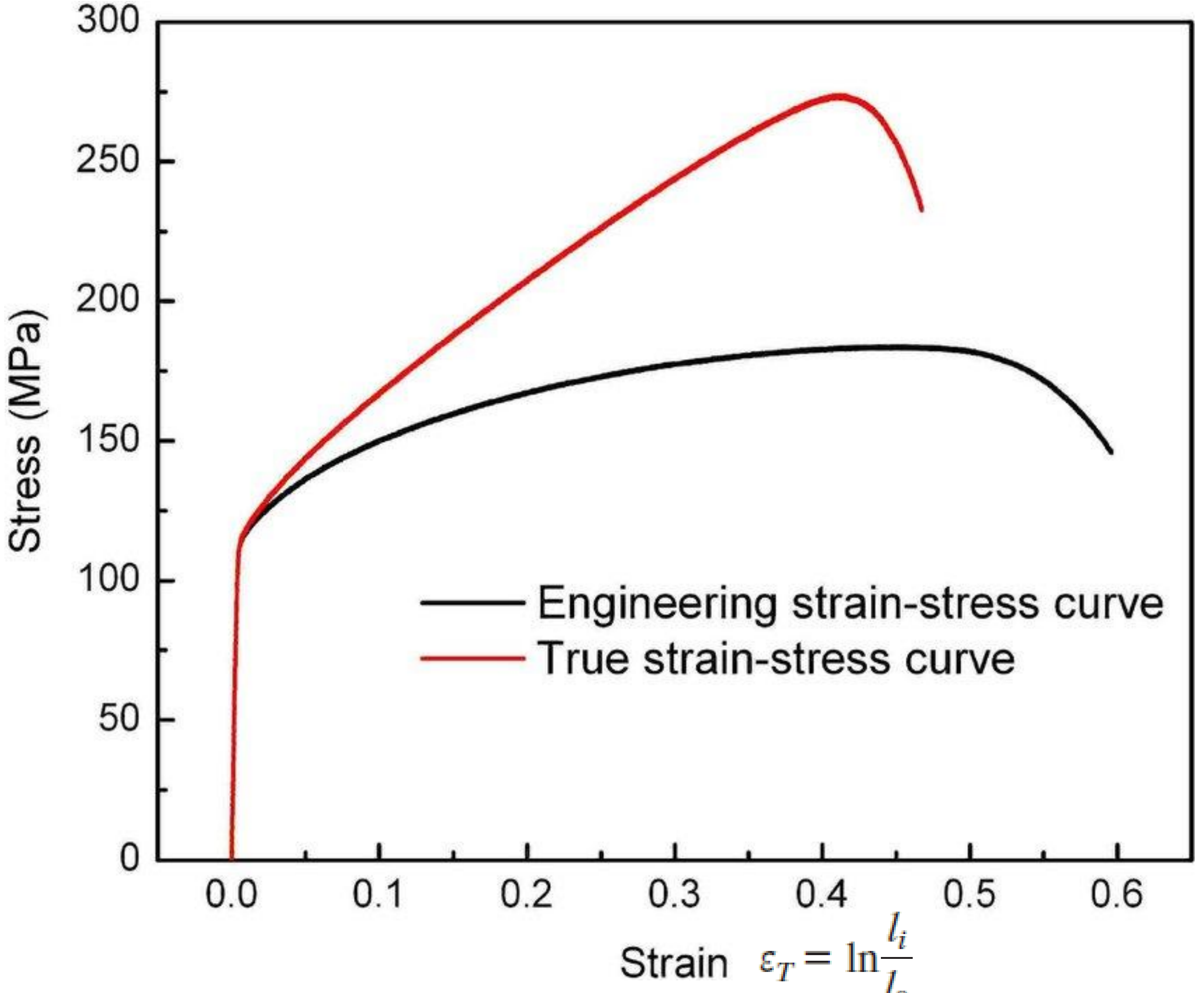
Stress σ	Strain ε
$\sigma = \dfrac{P}{A_{initial}}$	$\varepsilon = \dfrac{L - L_{initial}}{L_{initial}} = \dfrac{\Delta L}{L_{initial}}$

$$A_i l_i = A_0 l_0$$

$$\sigma_T = \sigma(1+\varepsilon)$$

$$\varepsilon_T = \ln(1+\varepsilon)$$

$$\sigma_T = \frac{F}{A_i}$$



$$\varepsilon_T = \ln\frac{l_i}{l_0}$$

TRUE STRESS AND STRAIN

For some metals and alloys the region of the true stress–strain curve from the onset of plastic deformation to the point at which necking begins may be approximated by Hollomon's equation : $\sigma_T = K\varepsilon_T^n$

In this expression, *K* and *n* are constants; these values vary from alloy to alloy and also depend on the condition of the material (whether it has been plastically deformed, heat-treated, etc.).

The parameter *n* is often termed the *strain-hardening exponent* and has a value less than unity.

MATERIAL	N	K (MPA)	K (PSI)
ALUMINUM 1100 ANNEALED	0.2	180	26 107
ALUMINUM 2024-T3	0.16	690	100 076
ALUMINUM 6061 ANNEALED	0.2	205	29 733
ALUMINUM 6061-T6	0.05	410	59 465
ALUMINUM 7075 ANNEALED	0.17	400	58 015
ALUMINUM 6111-T4	0.223	550	79 829
BRASS, NAVEL ANNEALED	0.49	895	129 809
BRASS 70-30 ANNEALED	0.49	900	130 534
BRASS 85-15 ANNEALED	0.34	580	84 122
COBALT-BASE ALLOY, HEAT-TREATED	0.5	2 070	300 228
COPPER ANNEALED	0.54	315	45 687
AZ-31B MAGNESIUM ALLOY ANNEALED	0.16	450	65 267
LOW-CARBON STEEL ANNEALED	0.26	530	76 870
4340 STEEL ALLOY (TEMPERED @ 315 °C)	0.15	640	92 824
304 STAINLESS STEEL ANNEALED	0.45	1 275	184 923

TRUE STRESS AND STRAIN

Other methods for generating stress-strain curves of metallic materials are sometimes published in the literature. However, not all stress-strain curves are available for all types of materials.

Therefore, it may be necessary to calculate an approximation of the stress strain curve using equations. In this case, a typical model is based on the Ramberg-Osgood equation, which describes the total strain (elastic and plastic) as a function of the stress.

This equation describes the linear portion of the curve and the plastic region: $\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{\sigma_{ty}}\right)^{1/n_h}$

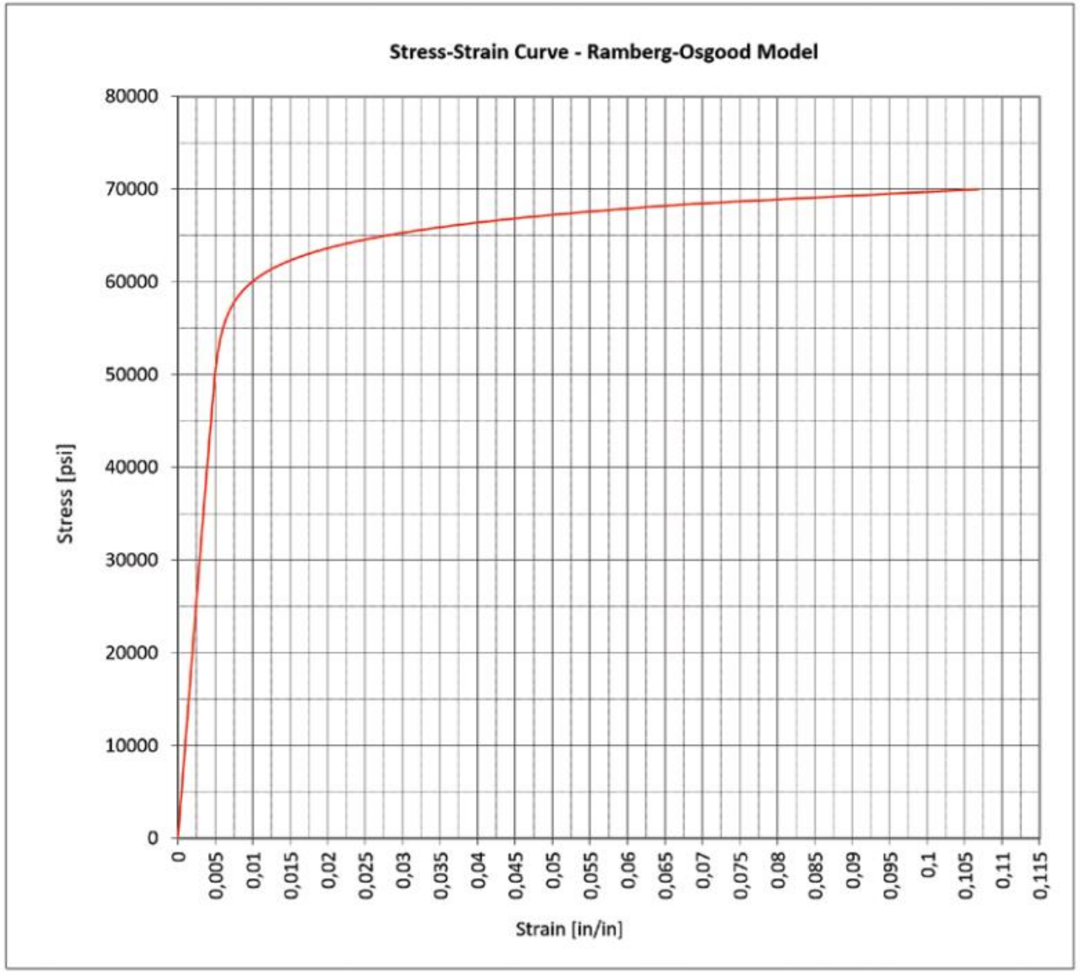
where:
ε is the value of strain.
σ is the value of stress.
E is the Young modulus of the material
σ_{ty} is the yield strength of the material
n_h is the strain hardening exponent of the material

The strain hardening exponent n_h is a measure of the nonlinearity of the plastic portion of the curve. It is calculated as per:

$$n_h = \frac{log\left(\frac{\sigma_{tu}}{\sigma_{ty}}\right)}{log\left(\frac{\varepsilon_f}{0.002}\right)}$$

TRUE STRESS AND STRAIN

The figure shows an example of stress-strain curve computation, using the Ramberg-Osgood equation and the material properties σ_{tu}, σ_{ty}, ε_f and E for aluminium 7475 T7351.

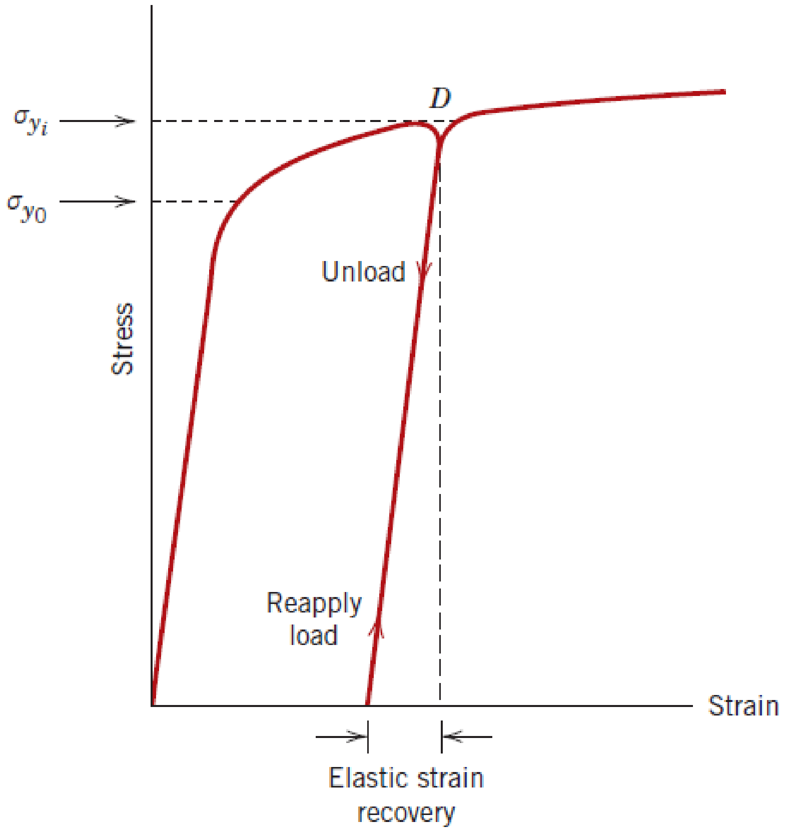


STRESS	STRAIN
0	0,0000
32000	0,0031
50000	0,0049
50700	0,0050
51400	0,0052
52100	0,0053
52800	0,0054
53500	0,0056
54200	0,0058
54900	0,0060
55600	0,0062
56300	0,0065
57000	0,0069
57700	0,0074
58000	0,0076
58700	0,0083
59400	0,0091
60100	0,0100
60800	0,0112
61500	0,0127
62200	0,0146
62900	0,0169
63600	0,0198
64300	0,0233
65000	0,0277
65700	0,0331
66400	0,0398
67100	0,0480
67800	0,0580
68500	0,0704
70000	0,1068

Material Properties		Calculated Parameters	
σ_{tu} =	70,000 psi	ε_u =	0.107
σ_{ty} =	58,000 psi	n_h =	0.0481
E =	10,300,000 psi	n =	20.8
ε_f = A% =	0.10		

ELASTIC RECOVERY AFTER PLASTIC DEFORMATION

Upon release of the load during the course of a stress–strain test, some fraction of the total deformation is recovered as elastic strain. This behaviour is demonstrated, a schematic engineering stress–strain plot.



During the unloading cycle, the curve traces a near straight-line path from the point of unloading (point *D*), and its slope is virtually identical to the modulus of elasticity, or parallel to the initial elastic portion of the curve.

The magnitude of this elastic strain, which is regained during unloading, corresponds to the strain recovery, as shown.

If the load is reapplied, the curve will traverse essentially the same linear portion in the direction opposite to unloading; yielding will again occur at the unloading stress level where the unloading began.

There will also be an elastic strain recovery associated with fracture.

Of course, metals may experience plastic deformation under the influence of applied compressive, shear, and torsional loads. The resulting stress–strain behaviour into the plastic region is similar to the tensile counterpart. However, for compression, there is no maximum because necking does not occur; furthermore, the mode of fracture is different from that for tension.

HARDNESS

Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number[a]
Brinell	10-mm sphere of steel or tungsten carbide	D, d	d	P	$HB = \dfrac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid	136°	d_1, d_1	P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid	t; $l/b = 7.11$; $b/t = 4.00$	b, l	P	$HK = 14.2P/l^2$
Rockwell and superficial Rockwell	Diamond cone: $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$ in. diameter steel spheres	120°		60 kg, 100 kg, 150 kg: Rockwell; 15 kg, 30 kg, 45 kg: Superficial Rockwell	

HARDNESS

Another mechanical property that may be important to consider is **hardness,** which is a measure of a material's resistance to localized plastic deformation (e.g., a small dent or a scratch). Early hardness tests were based on natural minerals with a scale constructed solely on the ability of one material to scratch another that was softer.

A qualitative and somewhat arbitrary hardness indexing scheme was devised, termed the *Mohs scale*, which ranged from 1 on the soft end for talc to 10 for diamond.

Quantitative hardness techniques have been developed over the years in which a small indenter is forced into the surface of

a material to be tested under controlled conditions of load and rate of application. The depth or size of the resulting indentation is measured and related to a hardness number; the softer the material, the larger and deeper the indentation, and the lower the hardness index number.

Measured hardness are only relative (rather than absolute), and care should be exercised when comparing values determined by different techniques.

Hardness tests are performed more frequently than any other mechanical test for several reasons:

1. They are simple and inexpensive—typically, no special specimen need be prepared, and the testing apparatus is relatively inexpensive.
2. The test is non-destructive—the specimen is neither fractured nor excessively deformed; a small indentation is the only deformation.
3. Other mechanical properties often may be estimated from hardness data, such as tensile strength.

HARDNESS

Watch online Tests

Rockwell Hardness Tests

The Rockwell tests constitute the most common method used to measure hardness because they are so simple to perform and require no special skills.

Several different scales may be used from possible combinations of various indenters and different loads, a process that permits the testing of virtually all metal alloys (as well as some polymers).

Indenters include spherical and hardened steel balls having diameters of (1.588, 3.175, 6.350, and 12.70 mm), as well as a conical diamond indenter, which is used for the hardest materials.

With this system, a hardness number is determined by the difference in depth of penetration resulting from the application of an initial minor load followed by a larger major load; utilization of a minor load enhances test accuracy.

On the basis of the magnitude of both major and minor loads, there are two types of tests: Rockwell and superficial Rockwell.

For the Rockwell test, the minor load is 10 kg, whereas major loads are 60, 100, and 150 kg.

Each scale is represented by a letter of the alphabet; several are listed with the corresponding indenter and load in.

Scale Symbol	*Indenter*	*Major Load (kg)*
A	Diamond	60
B	$\frac{1}{16}$-in. ball	100
C	Diamond	150
D	Diamond	100
E	$\frac{1}{8}$-in. ball	100
F	$\frac{1}{16}$-in. ball	60
G	$\frac{1}{16}$-in. ball	150
H	$\frac{1}{8}$-in. ball	60
K	$\frac{1}{8}$-in. ball	150

HARDNESS

For superficial tests, 3 kg is the minor load; 15, 30, and 45 kg are the possible major load values. These scales are identified by a 15, 30, or 45 (according to load) followed by N, T, W, X, or Y, depending on the indenter.

Superficial tests are frequently performed on thin specimens.

When specifying Rockwell and superficial hardness, both hardness number And scale symbol must be indicated.

The scale is designated by the symbol HR followed by the appropriate scale identification.14 For example, 80 HRB represents a Rockwell hardness of 80 on the B scale, and 60 HR30W indicates a superficial hardness of 60 on the 30W scale.

Scale Symbol	*Indenter*	*Major Load (kg)*
15N	Diamond	15
30N	Diamond	30
45N	Diamond	45
15T	$\frac{1}{16}$-in. ball	15
30T	$\frac{1}{16}$-in. ball	30
45T	$\frac{1}{16}$-in. ball	45
15W	$\frac{1}{8}$-in. ball	15
30W	$\frac{1}{8}$-in. ball	30
45W	$\frac{1}{8}$-in. ball	45

For each scale, hardness may range up to 130; however, as hardness values rise above 100 or drop below 20 on any scale, they become inaccurate; because the scales have some overlap, in such a situation it is best to utilize the next-harder or next-softer scale.

HARDNESS

Inaccuracies also result if the test specimen is too thin, if an indentation is made too near a specimen edge, or if two indentations are made too close to one another.

Specimen thickness should be at least 10 times the indentation depth, whereas allowance should be made for at least three indentation diameters between the centre of one indentation and the specimen edge, or to the centre of a second indentation.

Furthermore, testing of specimens stacked one on top of another is not recommended. Also, accuracy is dependent on the indentation being made into a smooth flat surface.

The modern apparatus for making Rockwell hardness measurements is automated and very simple to use; hardness is read directly, and each measurement requires only a few seconds. This apparatus also permits a variation in the time of load application. This variable must also be considered in interpreting hardness data.

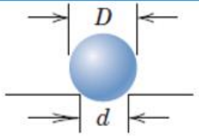
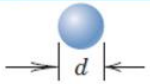
HARDNESS

Brinell Hardness Tests

In Brinell tests, as in Rockwell measurements, a hard, spherical indenter is forced into the surface of the metal to be tested. The diameter of the hardened steel (or tungsten carbide) indenter is 10.00 mm (0.394 in.).

Standard loads range between 500 and 3000 kg in 500-kg increments; during a test, the load is maintained constant for a specified time (between 10 and 30 s).

Harder materials require greater applied loads. The Brinell hardness number, HB, is a function of both the magnitude of the load and the diameter of the resulting indentation.

Test	*Indenter*	*Shape of Indentation*		*Load*	*Formula for Hardness Number*[a]
		Side View	*Top View*		
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$

This diameter is measured with a special low-power microscope using a scale that is etched on the eyepiece. The measured diameter is then converted to the appropriate HB number using a chart; only one scale is employed with this technique.

HARDNESS

Semiautomatic techniques for measuring Brinell hardness are available. These employ optical scanning systems consisting of a digital camera mounted on a flexible probe, which allows positioning of the camera over the indentation.

Data from the camera are transferred to a computer that analyses the indentation, determines its size, and then calculates the Brinell hardness number.

For this technique, surface finish requirements are normally more stringent than those for manual measurements.

Maximum specimen thickness and indentation position (relative to specimen edges) as well as minimum indentation spacing requirements are the same as for Rockwell tests. In addition, a well-defined indentation is required; this necessitates a smooth, flat surface in which the indentation is made.

HARDNESS

Knoop and Vickers Micro-indentation Hardness

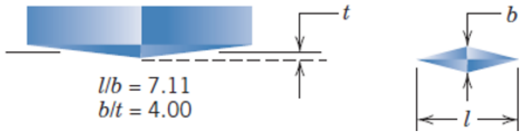
Two other hardness-testing techniques are the Knoop (pronounced *nup*) and Vickers tests (sometimes also called *diamond pyramid*).

For each test, a very small diamond indenter having pyramidal geometry is forced into the surface of the specimen. Applied loads are much smaller than for the Rockwell and Brinell tests, ranging between 1 and 1000 g.

The resulting impression is observed under a microscope and measured; this measurement is then converted into a hardness number.

Careful specimen surface preparation (grinding and polishing) may be necessary to ensure a well-defined indentation that may be measured accurately. The Knoop and Vickers hardness numbers are designated by HK and HV, respectively, and hardness scales for both techniques are approximately equivalent.

The Knoop and Vickers techniques are referred to as *micro-indentation-testing methods* on the basis of indenter size. Both are well suited for measuring the hardness of small, selected specimen regions; furthermore, the Knoop technique is used for testing brittle materials such as ceramics.

Vickers microhardness	Diamond pyramid		P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid		P	$HK = 14.2P/l^2$

HARDNESS

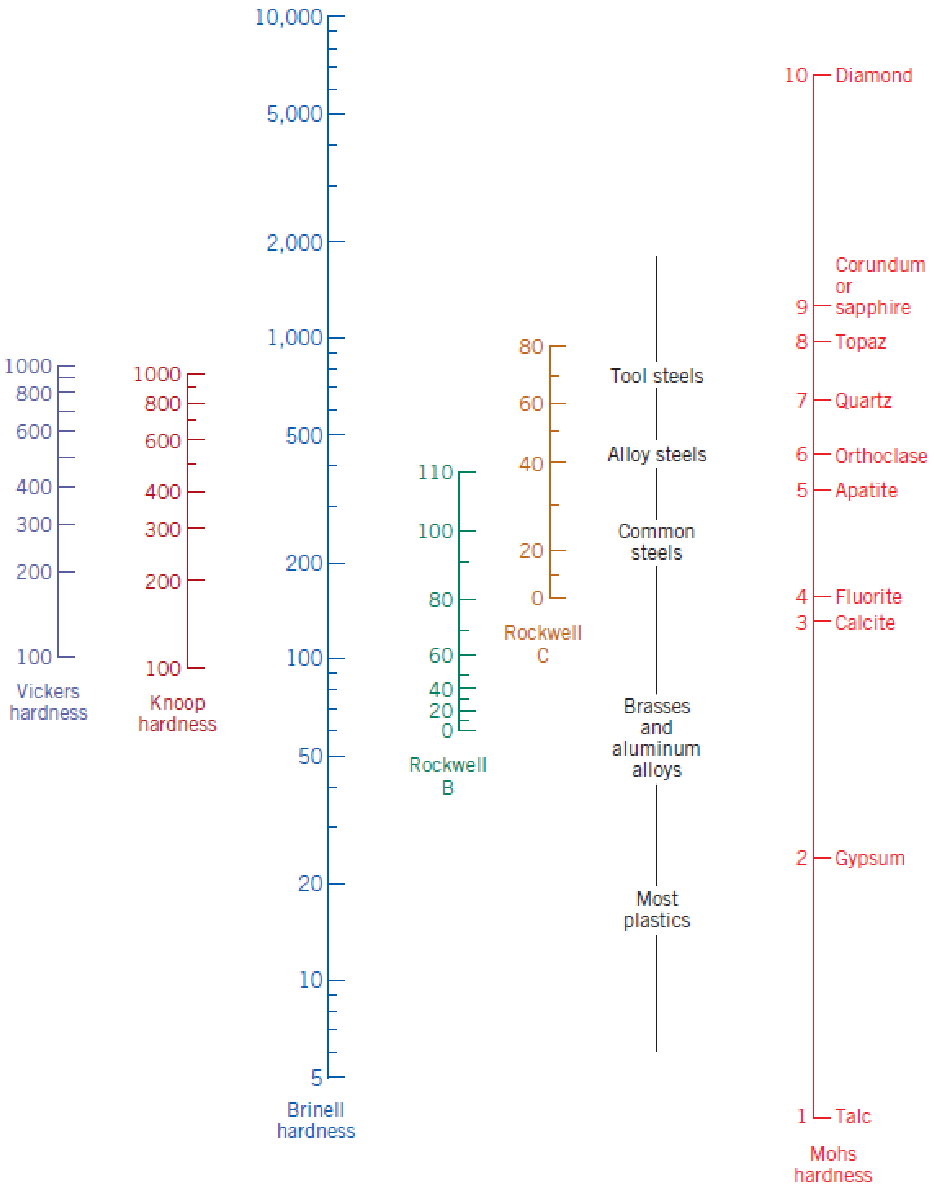
The modern micro-indentation hardness-testing equipment has been automated by coupling the indenter apparatus to an image analyser that incorporates a computer and software package. The software controls important system functions, including indent location, indent spacing, computation of hardness values, and plotting of data.

Other hardness-testing techniques are frequently employed but will not be discussed here; these include ultrasonic microhardness, dynamic (Scleroscope), durometer (for plastic and elastomeric materials), and scratch hardness tests.

Hardness Conversion

The facility to convert the hardness measured on one scale to that of another is most desirable. However, because hardness is not a well-defined material property, and because of the experimental dissimilarities among the various techniques, a comprehensive conversion scheme has not been devised.

Hardness conversion data have been determined experimentally and found to be dependent on material type and characteristics.



HARDNESS

Correlation between Hardness and Tensile Strength

Both tensile strength and hardness are indicators of a metal's resistance to plastic deformation.

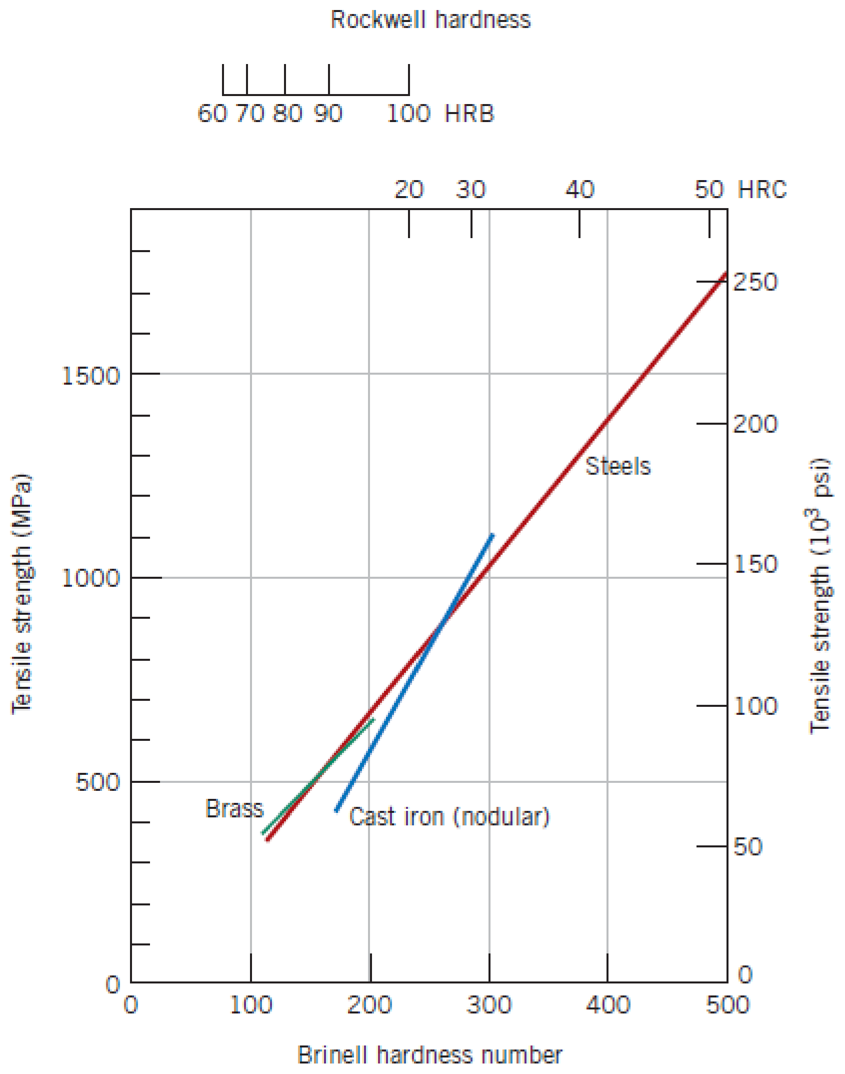
Consequently, they are roughly proportional, as shown, for tensile strength as a function of the HB for cast iron, steel, and brass.

The same proportionality relationship does not hold for all metals.

As a rule of thumb, for most steels, the HB and the tensile strength are related according to:

$$TS\,(\text{MPa}) = 3.45 \times \text{HB}$$

$$TS\,(\text{psi}) = 500 \times \text{HB}$$



DESIGN/SAFETY FACTORS

There will always be uncertainties in characterizing the magnitude of applied loads and their associated stress levels for in-service applications; typically, load calculations are only approximate.

Virtually all engineering materials exhibit a variability in their measured mechanical properties, have imperfections that were introduced during manufacture, and, in some instances, will have sustained damage during service.

Consequently, design approaches must be employed to protect against unanticipated failure. During the 20th century, the protocol was to reduce the applied stress by a *design safety factor*. Although this is still an acceptable procedure for some structural applications, it does not provide adequate safety for critical applications such as those found in aircraft and bridge structural components.

The current approach for these critical structural applications is to utilize materials that have adequate toughness and also offer redundancy in the structural design (i.e., excess or duplicate structures), provided there are regular inspections to detect the presence of flaws and, when necessary, safely remove or repair components.

For less critical static situations and when tough materials are used, a **design stress,** σ_d, is taken as the calculated stress level σ_c (on the basis of the estimated maximum load) multiplied by a *design factor, N′*; that is, $\sigma_d = N'\sigma_c$. where N' is greater than unity.

Thus, the material to be used for the particular application is chosen so as to have a yield strength at least as high as this value of σ_d.

DESIGN/SAFETY FACTORS

Research Topic

Alternatively, a **safe stress** or *working stress*, σ_w, is used instead of design stress.
This safe stress is based on the yield strength of the material and is defined as the yield strength divided by a *factor of safety*, *N*, or:

$$\sigma_w = \frac{\sigma_y}{N}$$

Utilization of design stress is usually preferred because it is based on the anticipated maximum applied stress instead of the yield strength of the material; normally, there is a greater uncertainty in estimating this stress level than in the specification of the yield strength.
However, in the discussion of this text, we are concerned with factors that influence the yield strengths of metal alloys and not in the determination of applied stresses; therefore, the succeeding discussion deals with working stresses and factors of safety.
The choice of an appropriate value of *N* is necessary. If *N* is too large, then component overdesign will result; that is, either too much material or an alloy having a higher-than-necessary strength will be used. Values normally range between 1.2 and 4.0.
Selection of *N* will depend on a number of factors, including economics, previous experience, the accuracy with which mechanical forces and material properties may be determined, and, most important, the consequences of failure in terms of loss of life and/ or property damage. Because large *N* values lead to increased material cost and weight, structural designers are moving toward using tougher materials with redundant (and inspectable) designs, where economically feasible.