

Design and Materials

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Syllabus (1)

- Introduction to materials science and technology
- Structure of materials
- Mechanical properties
- Safety factors
- Fracture
- Creep
- Fatigue
- Impact properties

Syllabus (2)

- Polymer structures
- Composites
- Mechanical properties of polymers
- Introduction to phase diagrams
- Alloys
- Corrosion

Syllabus (3)

- Thermal properties
- Magnetic properties
- Optical properties
- Materials selection

Course texts

- Recommended texts:
 - Smallman, B.E. and Ngan, A.H.W. (2007), "Physical Metallurgy and Advanced Materials", Butterworth-Heinemann, seventh edition.
 - Callister, W. D. (2003). Materials Science and Engineering, An Introduction. John Wiley and Sons Ltd., sixth edition.

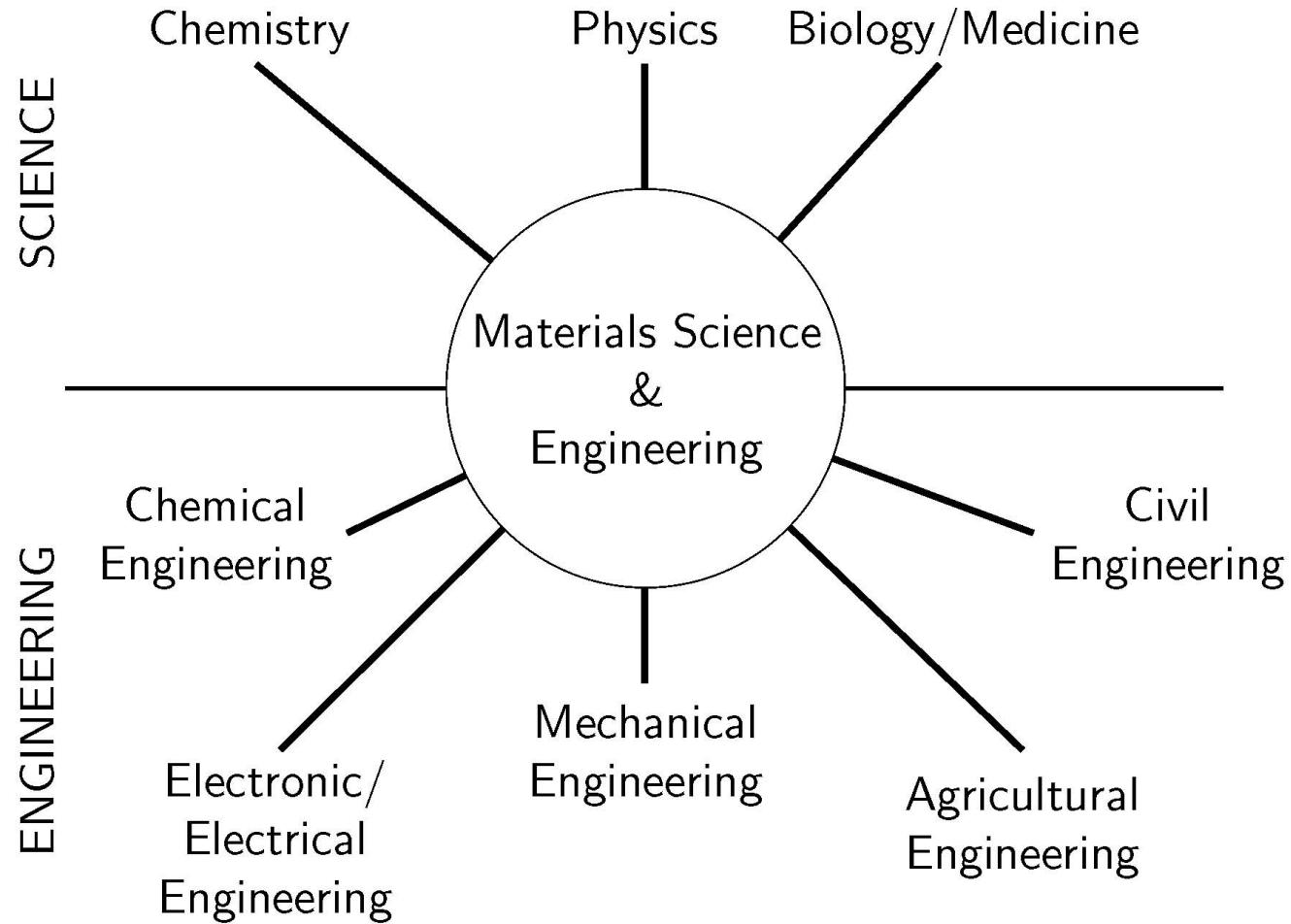
Recommended background reading

- Gordon, J. E. (1976). *The New Science of Strong Materials or Why You Don't Fall Through the Floor*. Penguin Books, London, UK, second edition.
- Street, A. and Alexander, W. (1998). *Metals in the Service of Man*. Penguin Books, London, UK, eleventh edition.

What is materials science and engineering?

- **Materials Science and Engineering** is the study of (man-made?) solid materials.
 - What are their properties?
 - What can they be used for?
 - How may they be improved?
 - What new materials can we think of?
- Historically, materials have always defined and limited the technology of the day:
 - Stone Age, Bronze Age, Iron Age
 - Today? . . . Silicon Age. . . perhaps this is too limiting.
- We have to draw on concepts from Chemistry, Physics and Biology to develop materials that are useful to engineers.

Materials science: the bridge between science and engineering



Components of MS&E

- In general, materials science is concerned with the relationship between **structure** and **properties**.
- Other components may also be included:
 - Processing
 - Performance
- There is a linear relationship between the components:

Processing → **Structure** → **Properties** → **Performance**

Structure

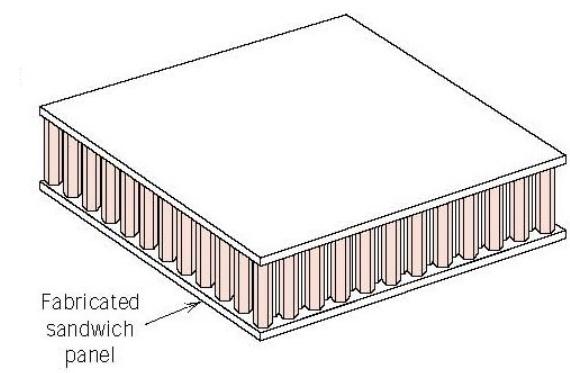
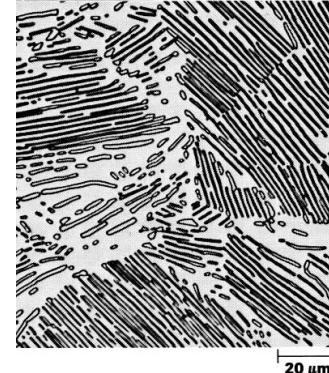
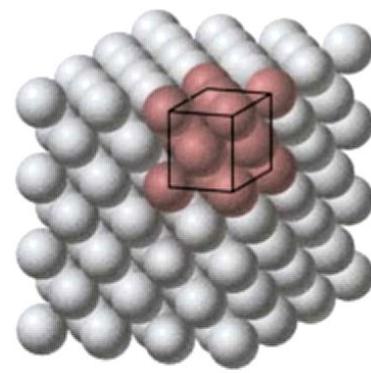
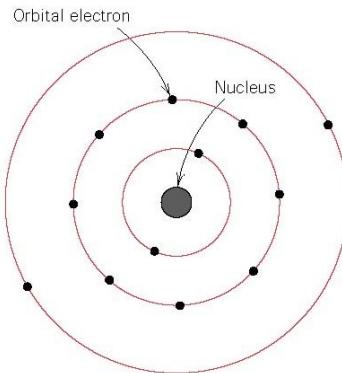
- Structure may be defined on four scales:

Subatomic structure: Involves the electrons within individual atoms and their relationship with the nucleus.

Atomic structure: Encompasses the organisation of atoms and/or molecules relative to one another.

Microscopic structure or microstructure: May be subject to direct observation with the aid of a microscope.

Macroscopic structure or macrostructure: Defines structural elements that may be observed with the naked eye.



Properties

- A **property** is a material trait that defines how it behaves in response to an applied stimulus.
- Virtually all important properties for solid materials may be grouped into six categories:

Mechanical E.g. Strength, elastic modulus, toughness.

Electrical E.g. Conductivity, resistance, dielectric strength.

Thermal E.g. Thermal conductivity, heat capacity.

Magnetic E.g. Magnetic susceptibility

Optical E.g. Reflectivity, refractive index.

Deteriorative E.g. Chemical reactivity.

Defining properties

- Properties may be defined **quantitatively**, e.g.:

The fracture toughness, K_{Ic} , of reaction bonded silicon nitride is 3.6 MPa $\sqrt{\text{m}}$.

or **qualitatively**, e.g.:

Ceramics are brittle.

- As engineers it is your job to be quantitative!

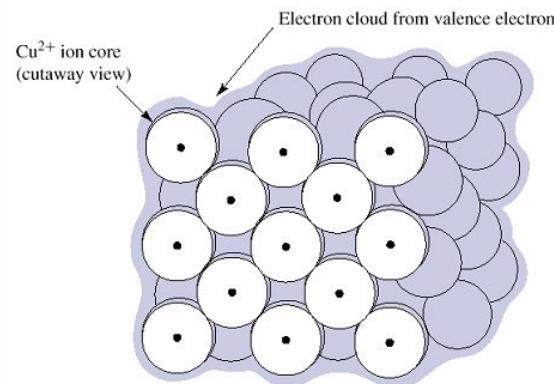
- You should be able to identify and understand exactly what properties are important for a given application.
 - Be able to correctly relate units to properties.

Classification of Materials

- There are four main kinds of materials:
 - **Metals**
 - **Ceramics**
 - **Polymers**
 - **Composites**
- In addition, other important classifications exist:
 - Semiconductors
 - Biomaterials
- Other terms are being invented all the time:
 - Smart materials
 - Nanomaterials. . .

Metals

- Normally combinations of metallic elements.
- Many properties attributable to large numbers of non-localised electrons.
 - Good conductors of electricity and heat.
 - Not transparent to visible light (opaque).
 - A polished surface will have a lustrous appearance.
- Mechanically, metals are quite strong yet deformable.
 - This is why they are so useful for structural use.

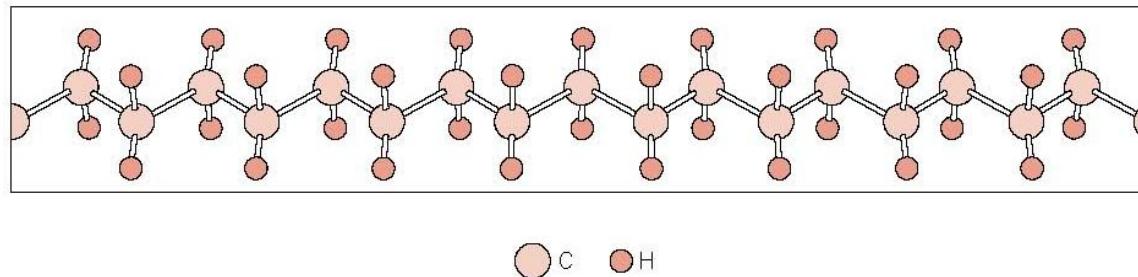


Ceramics

- Ceramics are inorganic non-metallic solids.
 - I.e. They are best defined by what they're not!
- Chemically they are compounds between metallic and non-metallic elements:
 - Oxides, e.g. aluminium oxide, Al_2O_3 .
 - Carbides, e.g. tungsten carbides, WC.
 - Nitrides, e.g. silicon nitride, Si_3N_4 .
- Includes clay minerals, cements and glasses.
- Typically electrically and thermally insulative.
- Resistant to harsh environments and high temperatures.
- Mechanically hard but brittle.

Polymers

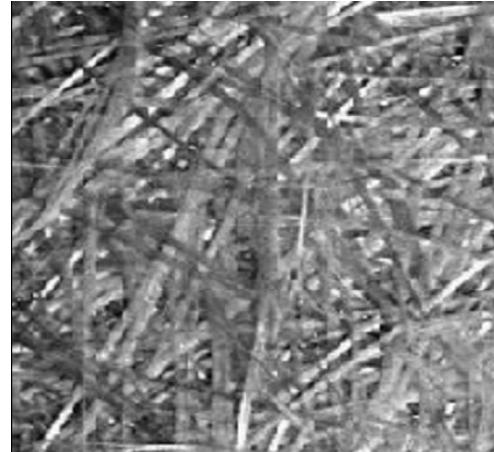
- Include familiar plastics and rubber materials.
- Organic materials:
 - Chemically based on carbon, hydrogen and other non-metallic elements.
- Molecules resemble long chains.
 - I.e. Polymers have high molecular weights
- Generally these materials are insulative to heat and electricity.
- They have relatively low densities and may be quite flexible.



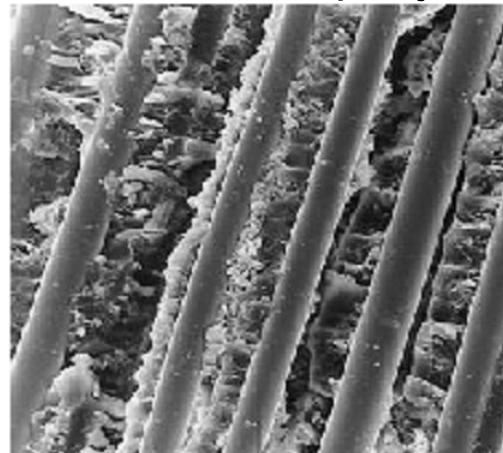
Composites

- Combinations of two or more other materials.
- Designed to display a combination of the best properties of each of the component materials
- An example is fibre-glass:
 - The material gains strength from the glass fibres and flexibility from the polymer.
- Many composites can be found in nature:
 - Wood may be considered to be a composite where the reinforcing component are the cellulose fibres and the matrix component is lignin.
 - Human bones and teeth are composites where the reinforcing phase is the mineral hydroxyapatite, $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ and the matrix is collagen.

Composites: Fractographs (1)

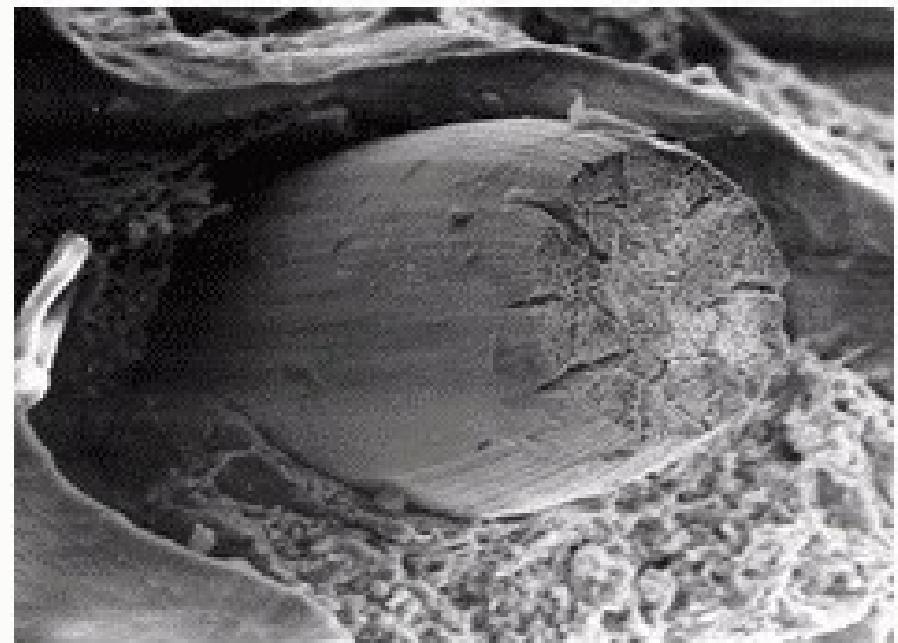
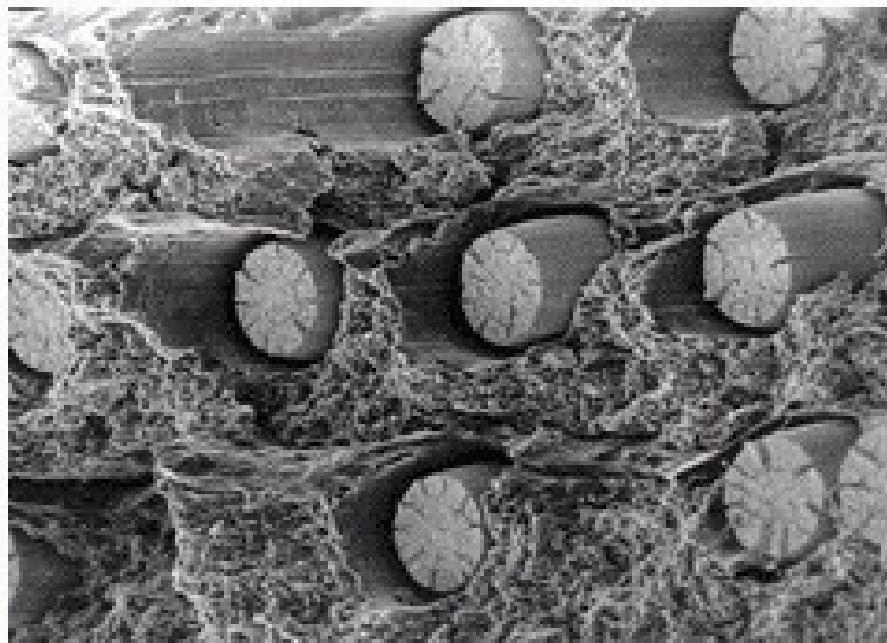


Glass fibres in an epoxy matrix.



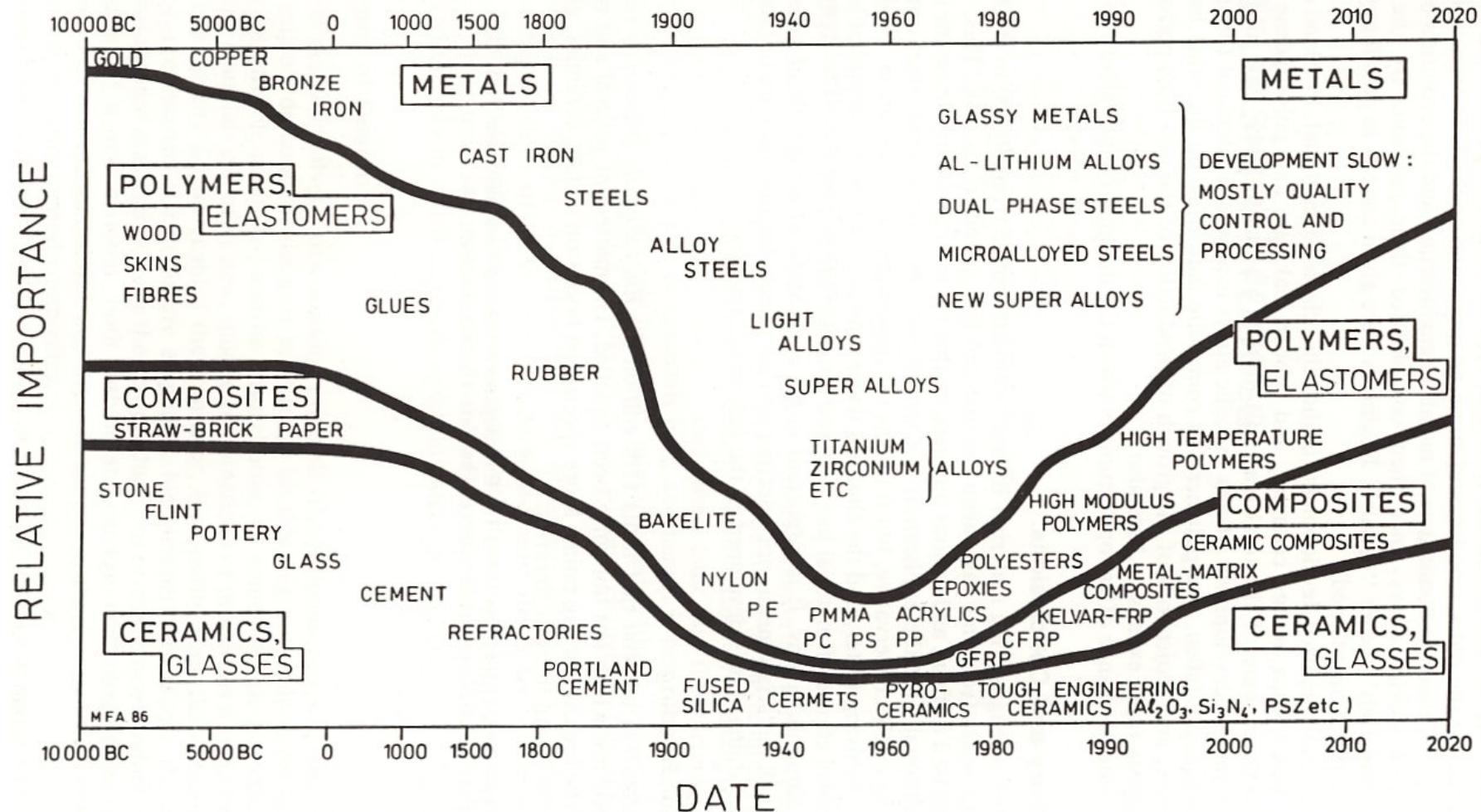
Continuous aligned carbon fibres in epoxy matrix.

Composites: Fractographs (2)



Cu matrix / W wire prepared by vacuum diffusion bonding

Historical use of materials



1

¹Ashby, M. F. (1992). Materials Selection in Mechanical Design. Butterworth-Heinemann, Oxford.

Key concept: Phases

- A concept that is used frequently in materials science is that of a **phase**:
 - A phase is a homogeneous portion of a system that has uniform physical and chemical characteristics.
- Every pure material is considered to be a phase as is every solid, liquid or gaseous solution.
- How many phases exist in the following?:

Cup of black tea Answer = 1

White sweet tea Answer = 1, assuming that too much sugar hasn't been added, both milk and sugar will be in solution

Bottle of sparkling mineral water Answer = 1 or 2, depending whether bottle has been opened and CO₂ has been allowed to come out of solution in which case the bubbles constitute a second phase. If closed, pressure holds CO₂ in solution.

Phases in materials

- Phases are important in materials because most materials are made up of different phases.
 - Steel is composed of several phases such as solid solutions and other compounds.
 - Polymers which may appear to consist of only one phase may in fact contain an amorphous phase which has no 3D ordering of structural components and a crystalline phase which is ordered.
 - Composites are defined by the fact that they contain more than one phase.
- Phases may sometimes transform, usually as a result of applied temperature or pressure. This is known as a **phase transformation**.
 - Carbon in graphite form may transform to diamond.
 - Ice melts at 0°C to form water.
 - Phase transformations may be used to engineer materials with specific desired properties.

Atomic structure

- Of paramount importance to materials science is the arrangement of atoms in a material.
- Why are some metals soft and ductile while others hard and brittle?
- Why are some ceramics transparent while others opaque?
- Why do some polymers stretch like rubber while others are stiff like epoxy?
- **Atomic arrangement** is the key.

Order in atomic arrangement

- Several levels or order may be defined:

No order: This applies only to gases and pure liquids. Atoms occupy completely random positions in 3D space. *Examples include Argon gas or liquid mercury.*

Short range order: Where the special arrangement of atoms is valid only between nearest neighbours. This applies in molecules and substances made from definable structural elements. *Examples include the relationship between hydrogen and oxygen in liquid water or between silicon and oxygen in glass.*

Medium range order: Considerations of medium range order only apply to advanced materials science ².

Long range order: This is where a special arrangement of atoms extends throughout the entire material. Substances with long range order are termed **crystals**.

²Jeanloz, R., and Williams, Q. Glasses come to order. Nature 350 (April 25th 1991), 659–660.

Structures of Metals and Ceramics

- In general, atomic structure in metals and ceramics can be either:
 - **Crystalline**
 - * All atoms are situated in a repeating or periodic array over large atomic distances; that is, long-range order exists, such that upon solidification, the atoms will position themselves in a repetitive three-dimensional pattern, in which each atom is bonded to its nearest-neighbor atoms.
 - * All metals, many ceramic materials, and certain polymers form crystalline structures under normal solidification conditions.
 - * Such substances may be said to exhibit both long range order and short range order.
 - **Amorphous**
 - * For materials that do not crystallise, long-range atomic order is absent; these are known as *noncrystalline* or *amorphous* materials.
 - * Such materials possess only short range order (see page 23).

Crystalline Materials: Examples



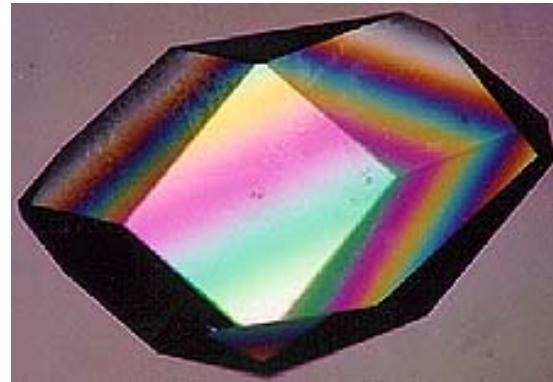
A snowflake exhibiting 6-fold symmetry.



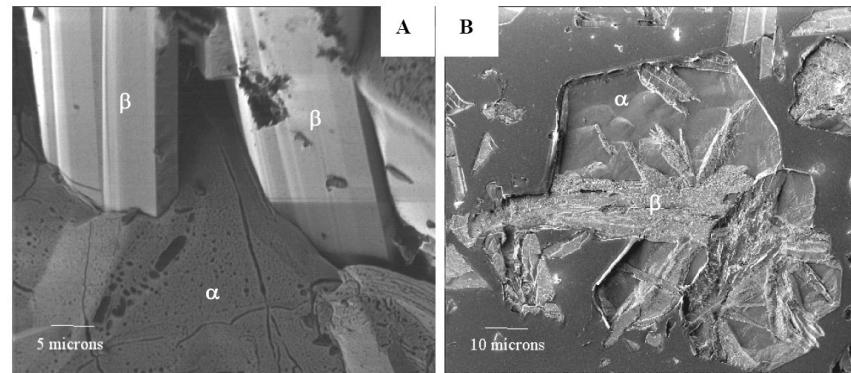
Crystalline spherulites in a glass-ceramic³.

³Stanton, K.T. and R.G. Hill, "Crystallisation in apatite-mullite glass-ceramics as a function of fluorine content", *J. Cryst. Growth*, In Press

Crystalline Materials: Examples 2



A crystal of lysozyme grown in space.

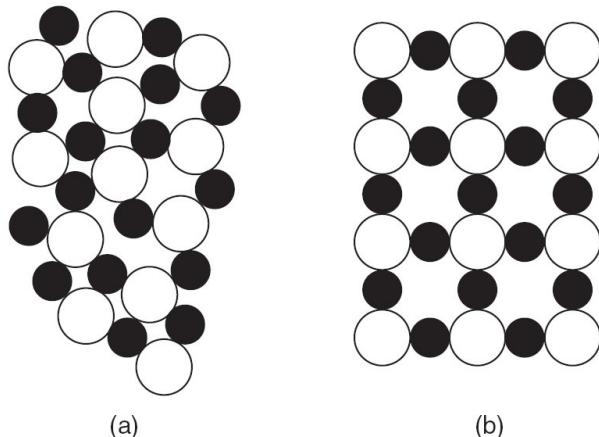


Polymorphism in L-glutamic acid⁴.

⁴Hodnett, B.K., C. Cashell, L. O'Mahony, M. Raty, D. Sutton, M. Mihov, K. Stanton, D. Corcoran and M. Loan, "Focused ion beam microscopy as a tool in crystal growth elucidation", *J. Cryst. Growth*, In Press

Amorphous Materials

- Amorphous materials are far less common than crystalline materials.
 - The reason for this is that amorphous materials have higher internal energies than the equivalent crystals.
- Most common examples include glasses and some polymeric materials.
- It is possible to make metallic glasses but involves cooling from the melt at rates of $1 \times 10^6 \text{ }^\circ\text{C min}^{-1}$. These materials have therefore not found widespread use.



Arrangement of a binary-alloy metallic glass (a) compared with the crystalline state (b).

Mechanical Properties

- Many materials, when in service, are subjected to **forces or loads**.
- 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 behavior** of a material reflects the relationship between its response or deformation to an applied load or force.
- Important mechanical properties are:
 - Strength
 - Hardness
 - Ductility
 - Stiffness

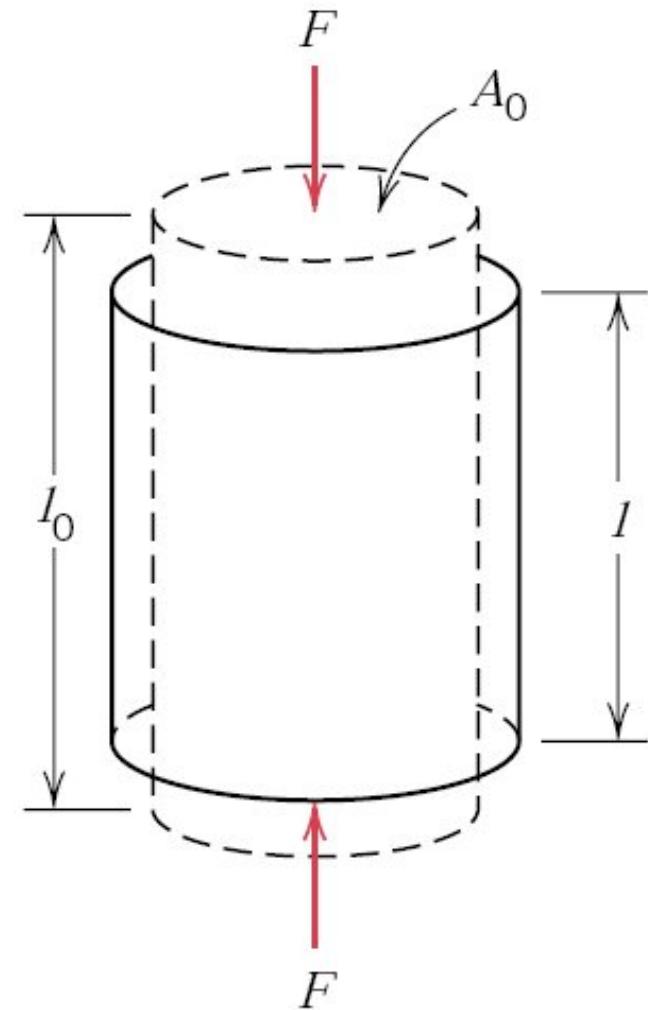
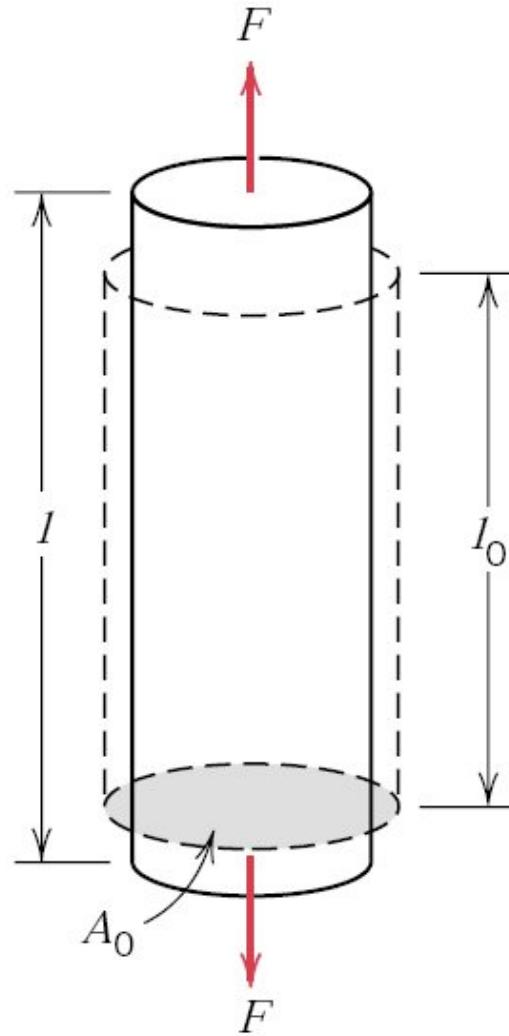
Mechanical Testing

- 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:**
 - * It is possible for the load to be tensile, compressive, or shear. Its magnitude may be constant with time, or it may fluctuate continuously.
 - **Its duration:**
 - * Application time may be only a fraction of a second, or it may extend over a period of many years.
 - **Environmental conditions:**
 - * Service temperature may be an important factor.

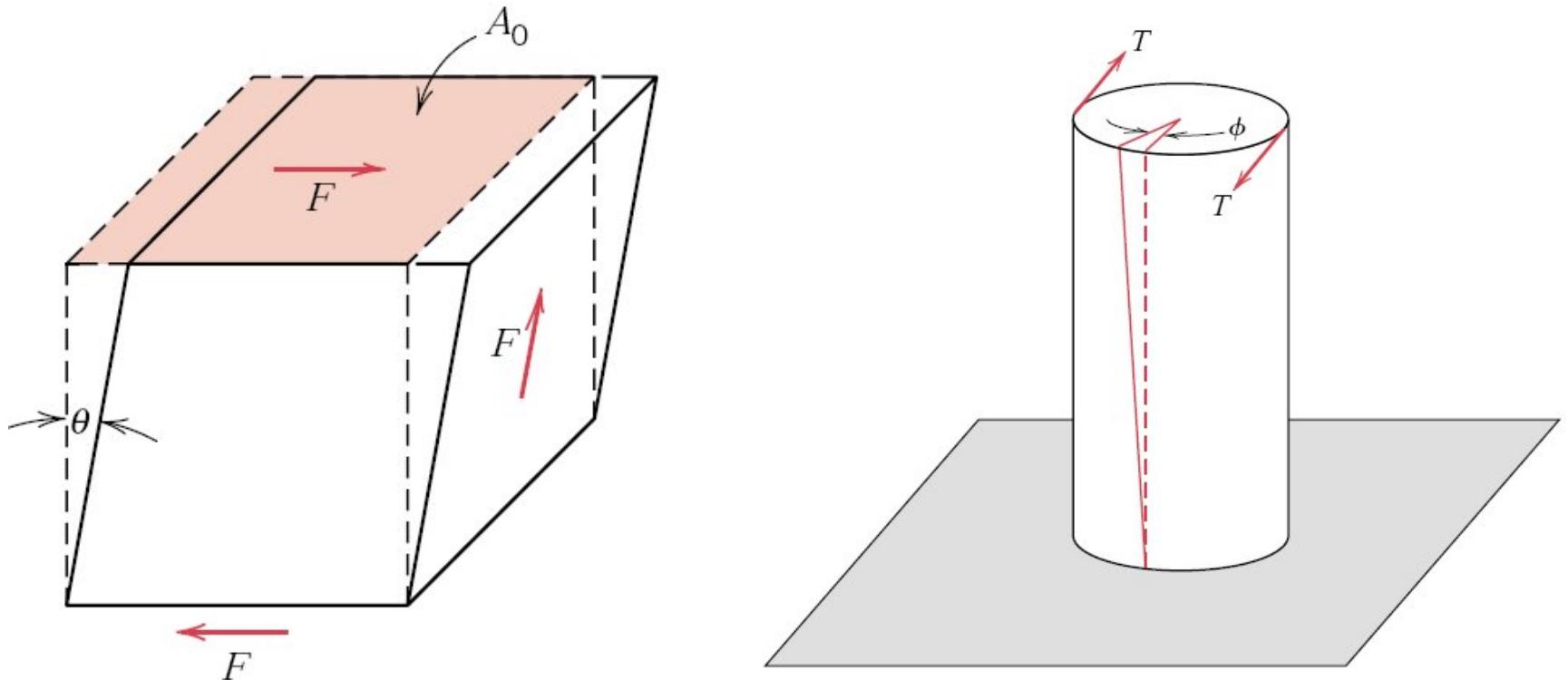
Stress and Strain

- 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 behavior 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:
 - **Tension**
 - **Compression**
 - **Shear**
 - * In engineering practice many loads are **torsional** rather than pure shear.

Tension and Compression



Shear and Torsion



Stress

To minimise complications due to the instantaneous change in sample geometry, load and elongation are normalised to the respective parameters of **Engineering Stress** and **Engineering Strain**.

- **Engineering Stress**
 - Stress, σ , is defined by the relationship

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

- where F is the load in newtons and A_0 is the original cross-sectional area.
- Units for σ are Nm^{-2} or Pascals, Pa.

Strain

- **Engineering Strain**

- Strain, ϵ , is given by

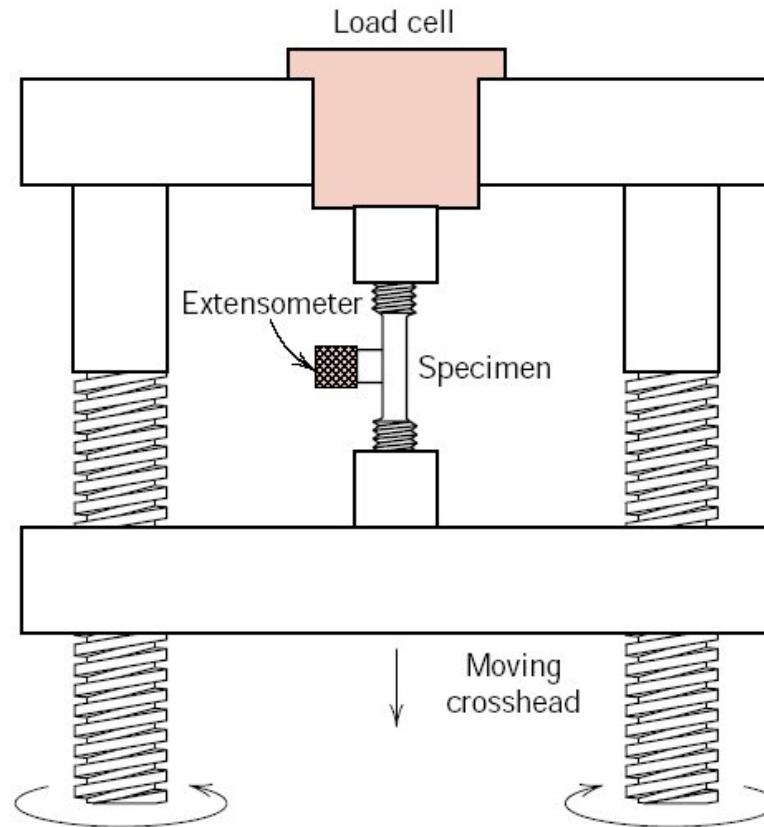
$$\epsilon = \frac{l - l_0}{l_0} = \frac{\Delta l}{l_0}$$

where l is the instantaneous length and l_0 is the original length.

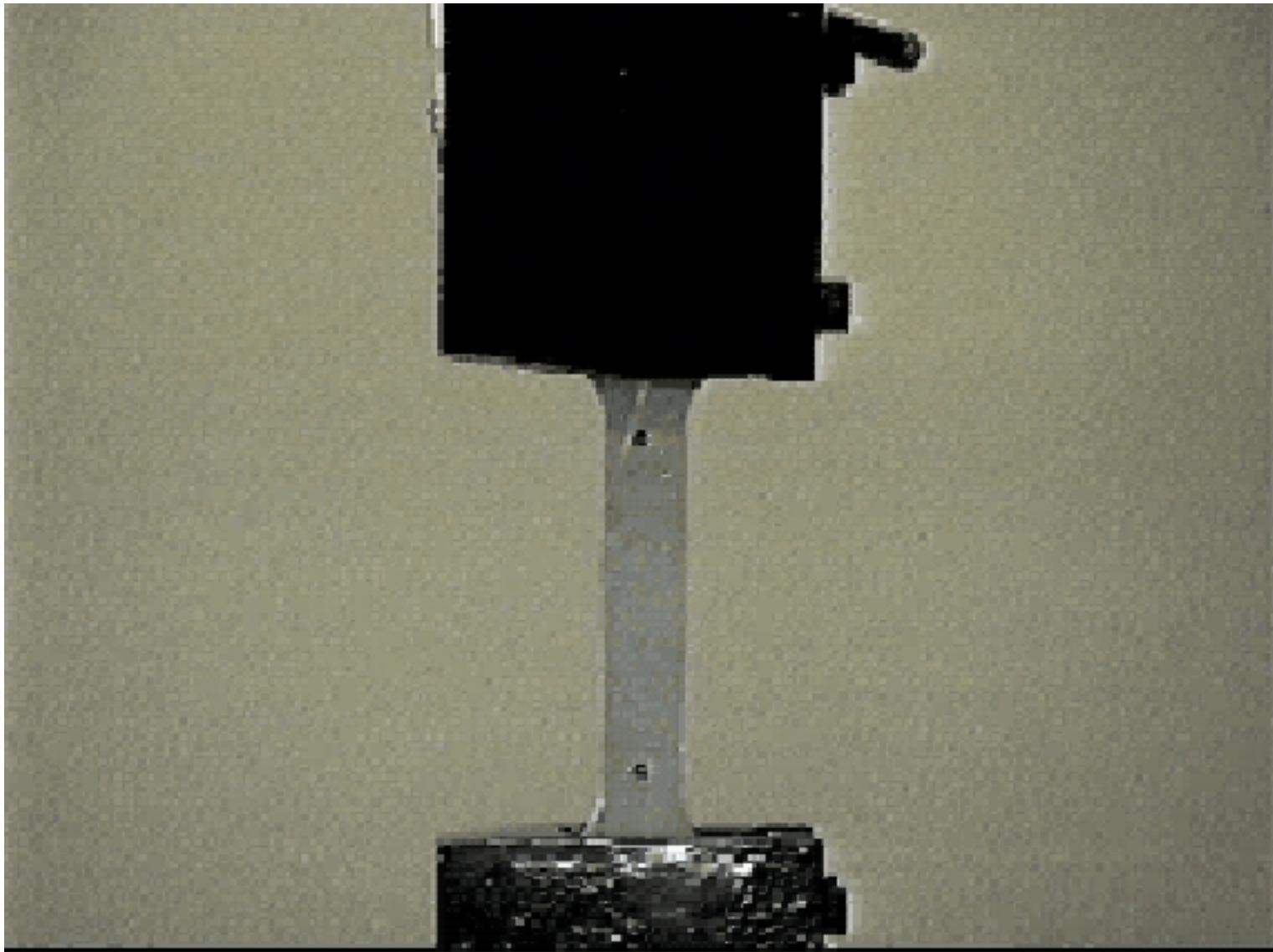
- Strain is unitless but is sometimes expressed as a percentage in which case the value is multiplied by 100.

The Tensile Test

- The stress and strain values for materials are most often determined by stressing a sample in tension and plotting the resultant strain.



The Tensile Test (Movie)



Stress-Strain Behaviour

- 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

$$E = \frac{\sigma}{\epsilon}$$

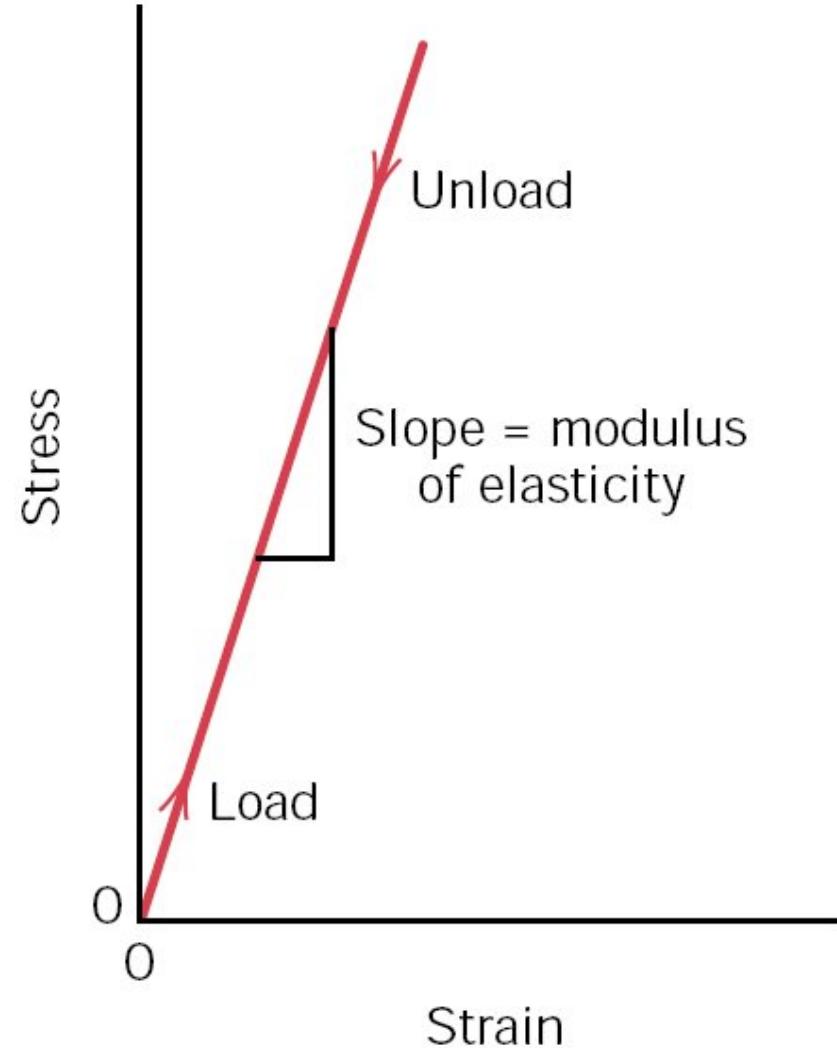
- This is known as **Hooke's law**, and the constant of proportionality E (GPa) is the **modulus of elasticity**, or *Youngs modulus*.
- For most typical metals the magnitude of this modulus ranges between 45 GPa, for magnesium, and 407 GPa, for tungsten.

Young's Moduli

- The moduli of elasticity are slightly higher for ceramic materials than for metals, and range between about 70 and 500 GPa.
- Polymers have modulus values that are smaller than both metals and ceramics, and which lie in the range 0.007 and 4 GPa.
- Deformation in which stress and strain are proportional is called **elastic deformation**.
- Young's modulus may be thought of as **stiffness**, or a materials 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 used for computing elastic deflections.

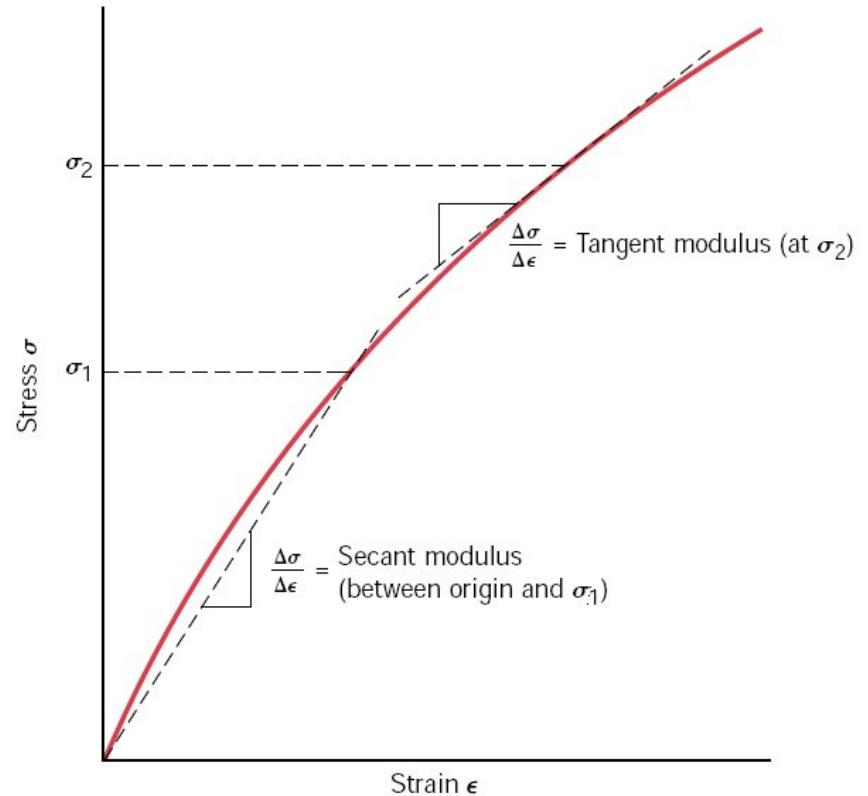
Determination of Young's Modulus

- A plot of stress σ versus strain ϵ results in a linear relationship.
- The slope of this linear segment corresponds to the modulus of elasticity E .
- Elastic deformation is nonpermanent, which means that when the applied load is released, the piece returns to its original shape.

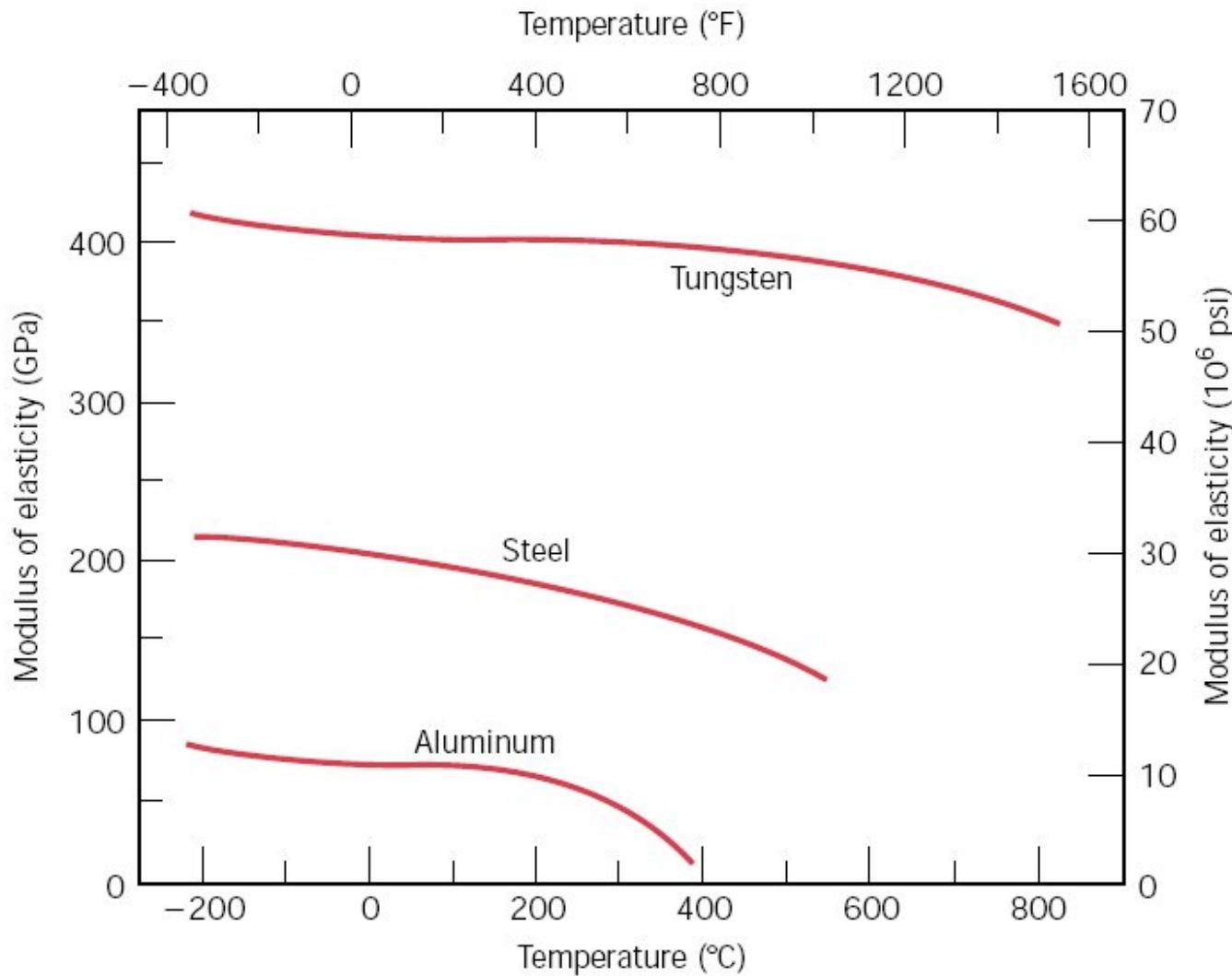


Tangent and Secant Moduli

- There are some materials (e.g., gray cast iron, concrete, and many polymers) for which the initial elastic portion of the stress-strain curve is not linear.
- For this nonlinear behavior, either *tangent* or *secant* modulus is normally used:
 - **Tangent modulus** is taken as the slope of the stress-strain curve at some specified level of stress.
 - **Secant modulus** represents the slope of a secant drawn from the origin to some given point of the σ - ϵ curve.

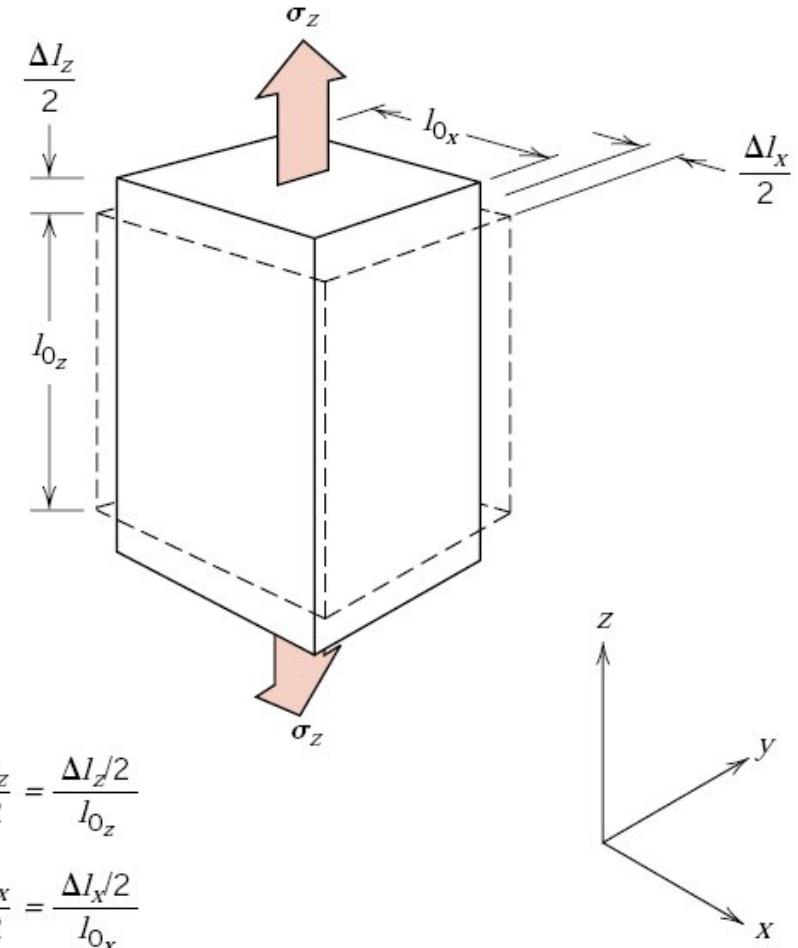


Effect of Temperature on Young's Modulus



Poisson's Ratio (1)

- When a tensile stress is imposed on virtually all materials, 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.



Poisson's Ratio (2)

- If the applied stress is uniaxial (only in the z direction), and the material is isotropic, then $\epsilon_x = \epsilon_y$.
- A parameter termed **Poissons ratio** is defined as the ratio of the lateral and axial strains, or

$$\nu = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\epsilon_y}{\epsilon_z}$$

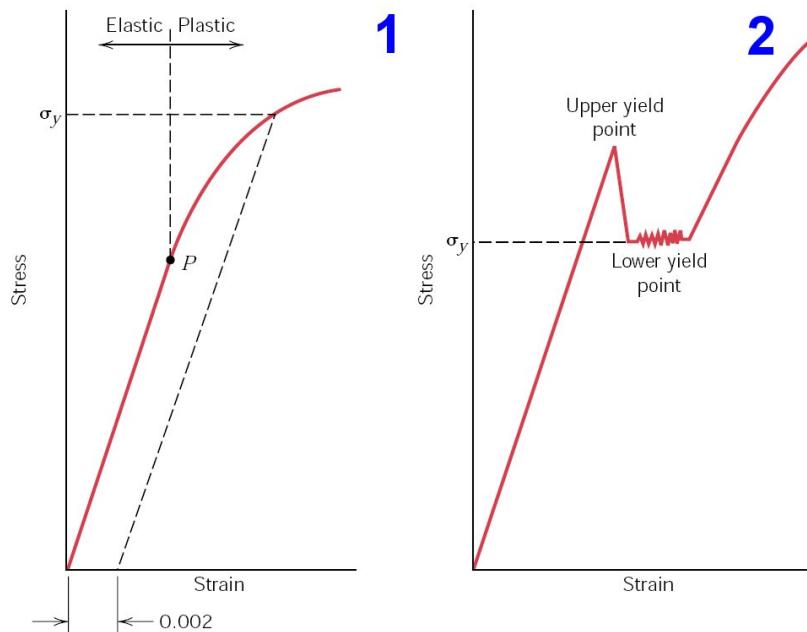
- The negative sign is included in the expression so that ν will always be positive, since ϵ_x and ϵ_z will always be of opposite sign.
- Theoretically, Poissons ratio for isotropic materials should be $\frac{1}{4}$; furthermore, the maximum value for ν (or that value for which there is no net volume change) is 0.50.
- For many metals and other alloys, values of Poissons ratio range between 0.25 and 0.35.

Plastic Deformation (1)

- 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
 - Hookes law ceases to be valid.
- 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.

Yielding Phenomena (1)

1. Typical stress-strain behavior for a metal showing elastic and plastic deformations, the **proportional limit** P , and the **yield strength** σ_y , as determined using the 0.002 strain offset method.
2. Representative stress-strain behavior found for some steels demonstrating the **yield point** phenomenon.



Yielding Phenomena (2)

- For those materials having a nonlinear elastic region, use of the strain offset method is not possible.
 - The usual practice is to define the yield strength as the stress required to produce some amount of strain (e.g., $\epsilon = 0.005$).
- Some steels and other materials exhibit the tensile stress-strain behavior as shown in Figure 2 on Page 45.
 - The elasticplastic 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 actual decrease in stress.
 - Continued deformation fluctuates slightly about some constant stress value, termed the lower yield point; stress subsequently rises with increasing strain.

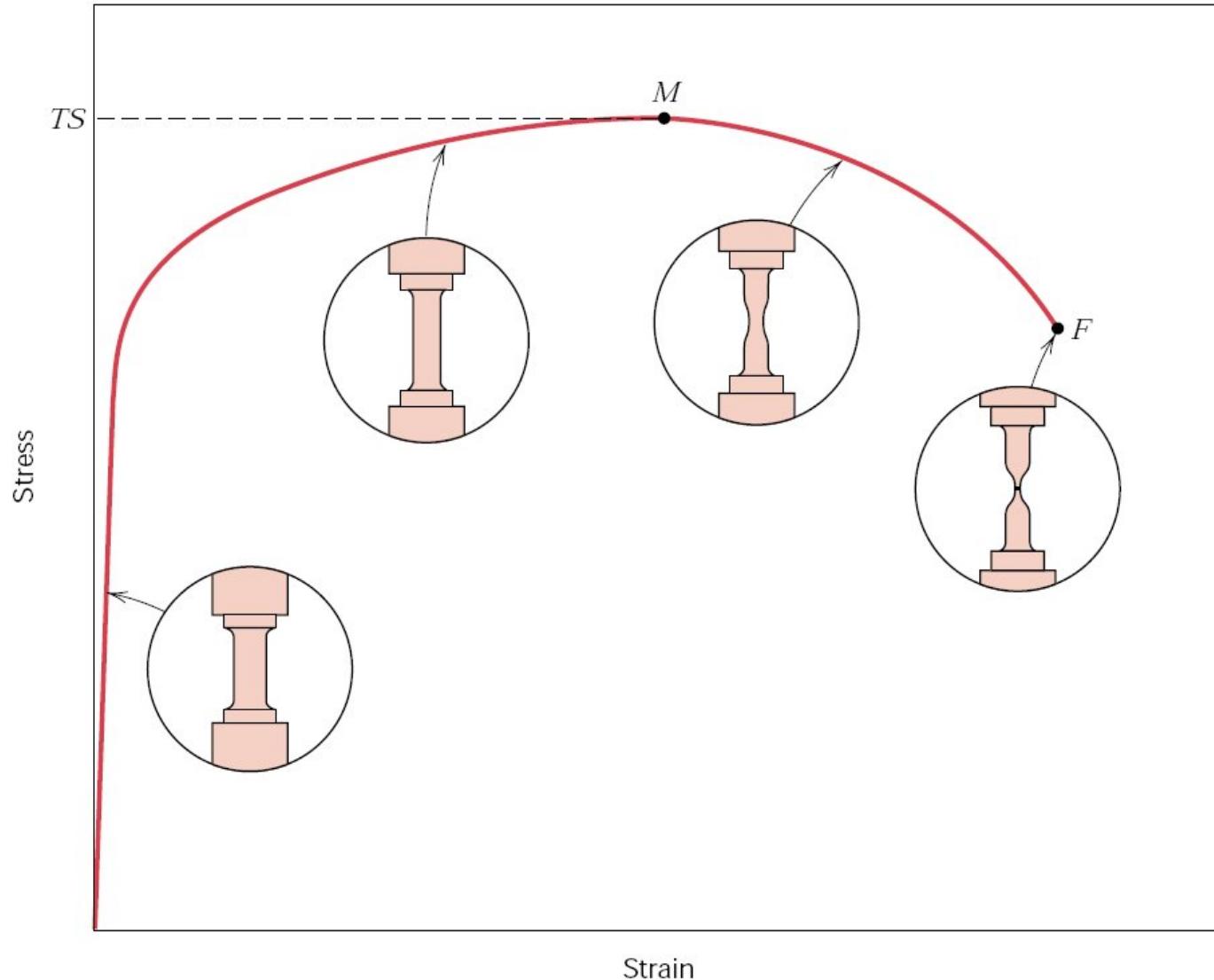
Yielding Phenomena (3)

- For metals that display this effect, the yield strength is taken as the average stress that is associated with the lower yield point, since 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.
- **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 aluminum to over 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 and then decreases to the eventual fracture.
- The **tensile strength TS** (MPa) is the stress at the maximum on the engineering stressstrain 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 up 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:
 - * This phenomenon is termed **necking**, and fracture ultimately occurs at the neck.

Necking and Fracture

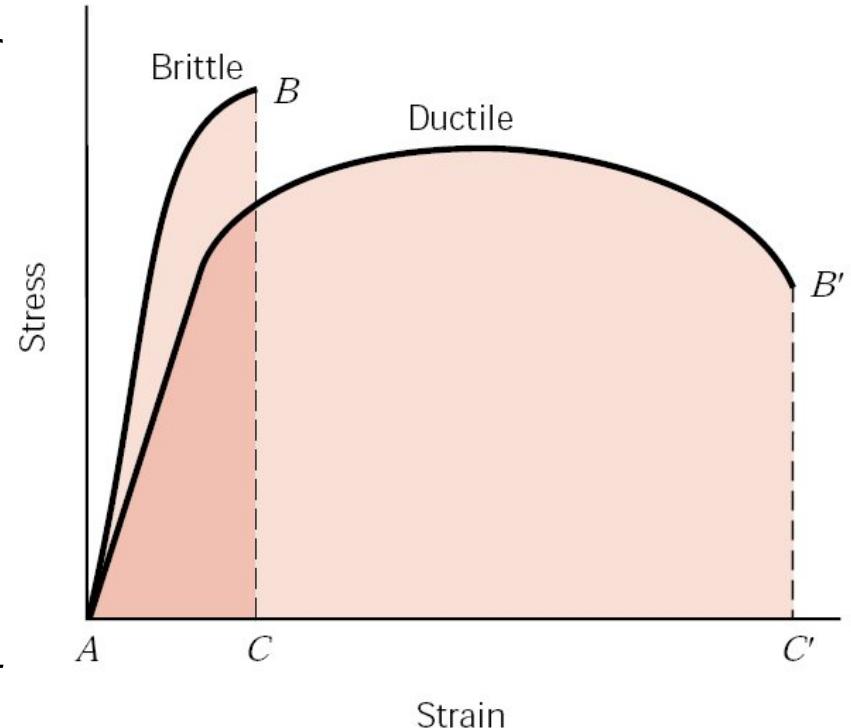


Tensile, Yield and Fracture Strengths

- Tensile strengths may vary anywhere from 50 MPa (7000 psi) for an aluminum to as high as 3000 MPa (450,000 psi) for the high-strength steels.
- Ordinarily, when the strength of a metal is cited for design purposes, the yield strength is used.
 - This is because by the time a stress corresponding to the tensile strength has been applied, often a structure has experienced so much plastic deformation that it is useless. Furthermore, fracture strengths are not normally specified for engineering design purposes.
- The **fracture strength** corresponds to the stress at fracture.

Ductility (1)

- Ductility is another important mechanical property.
 - It is a measure of the degree of plastic deformation that has been sustained at fracture.
- A material that experiences very little or no plastic deformation upon fracture is termed **brittle**.
- Ductility may be expressed quantitatively as either *percent elongation* or *percent reduction in area*.



Ductility (2)

- The percent elongation %EL is the percentage of plastic strain at fracture, or

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

where l_f is the fracture length and l_0 is the original gauge length.

- l_0 should be specified when percent elongation values are cited; it is commonly 50 mm.
- Percent reduction in area %RA is defined as

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

where A_0 is the original cross-sectional area and A_f is the cross-sectional area at the point of fracture.

Ductility (3)

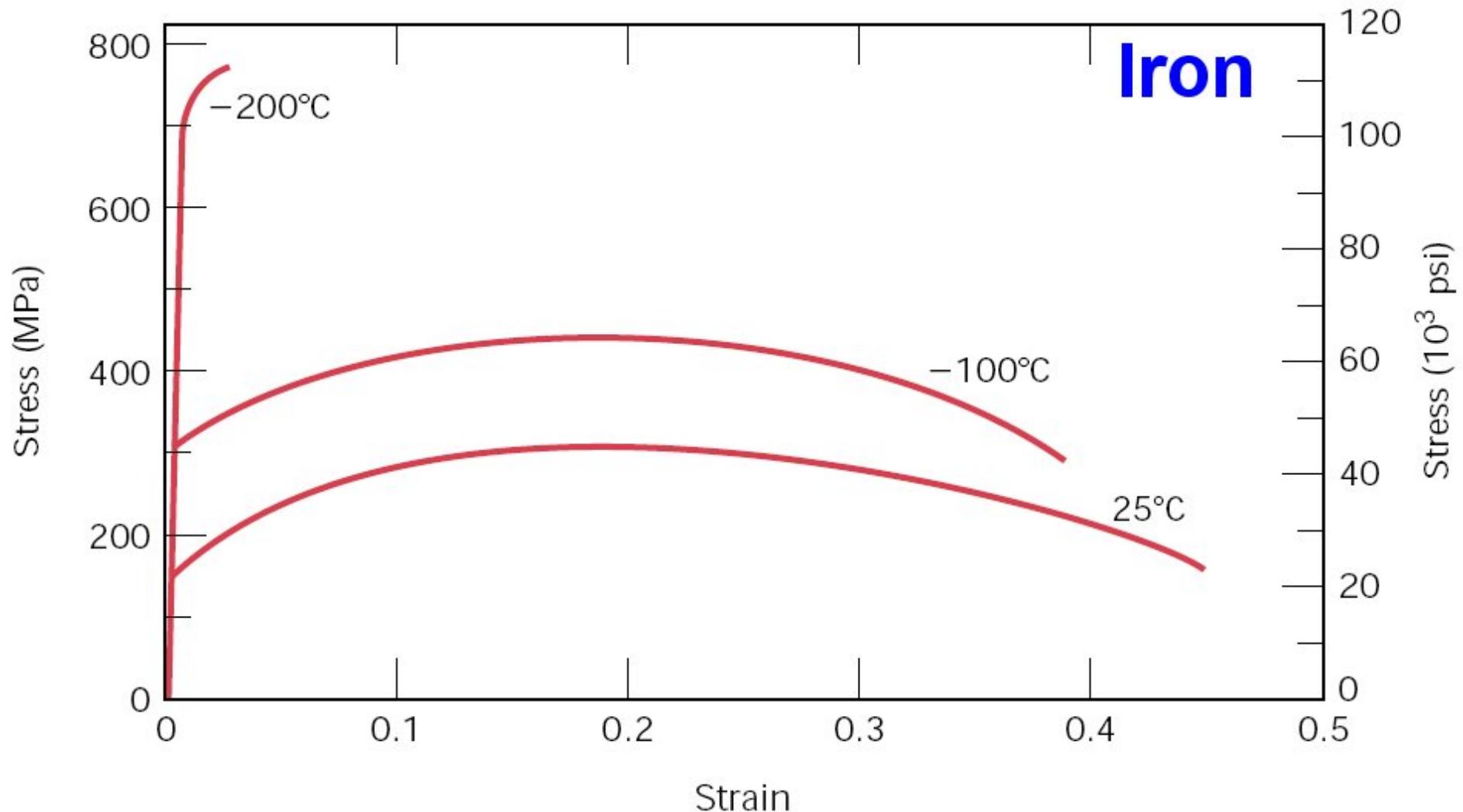
- Most metals possess at least a moderate degree of ductility at room temperature; however, some become brittle as the temperature is lowered.

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

Ductility (4)

- A knowledge of the ductility of materials is important for at least two reasons.
 1. It indicates to a designer the degree to which a structure will deform plastically before fracture.
 2. It specifies the degree of allowable deformation during fabrication operations.
- We sometimes refer to relatively ductile materials as being *forgiving*.
- **Brittle** materials are *approximately* considered to be those having a fracture strain of less than about 5%.

Stress–Strain Temperature Dependence



Toughness (1)

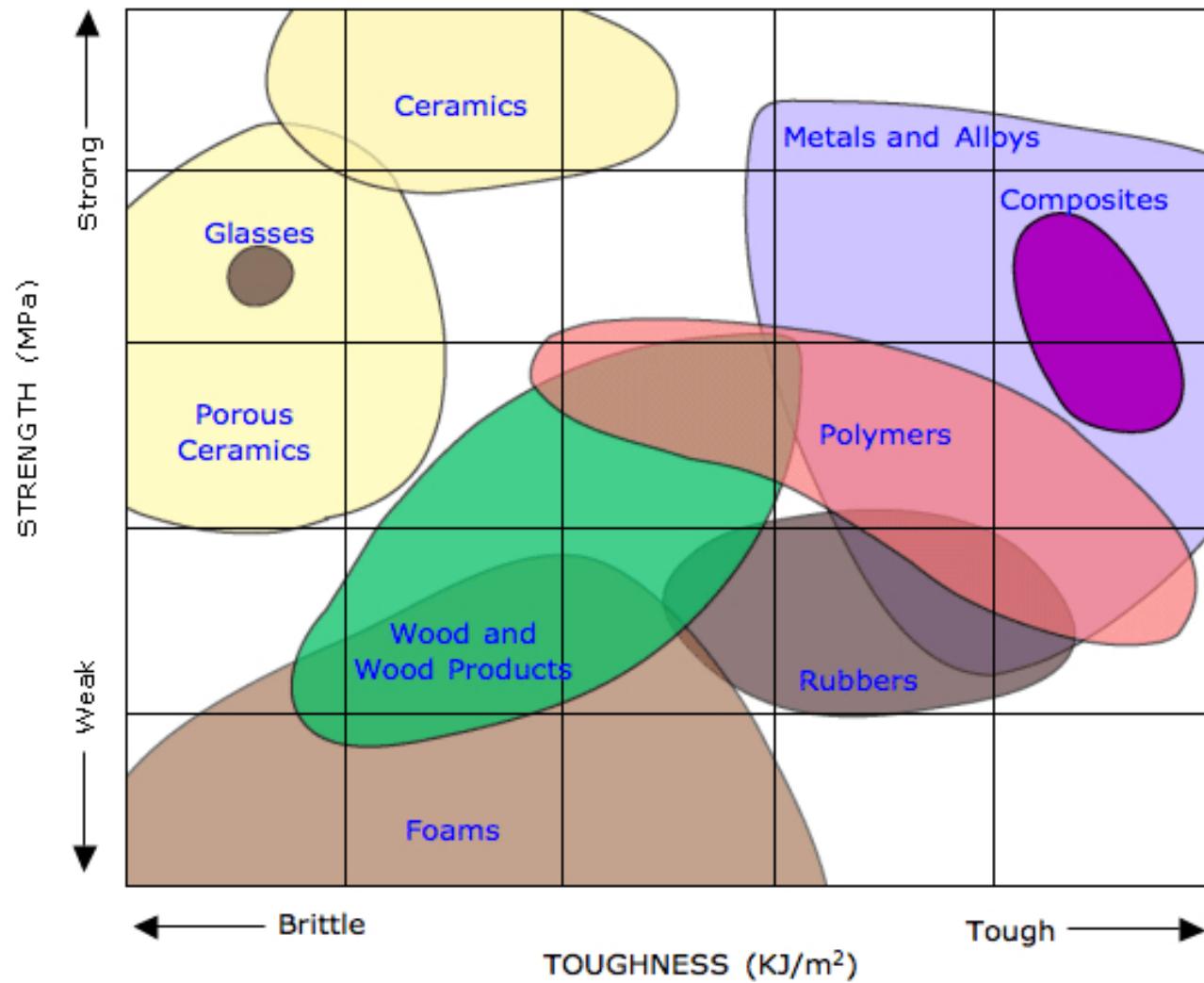
- **Toughness** is a mechanical term that is used in several contexts.
 - Loosely speaking, it is a measure of the ability of a material to absorb energy up to fracture.
- Specimen geometry as well as the manner of load application are important in toughness determinations.
- For dynamic (high strain rate) loading conditions and when a notch (or point of stress concentration) is present, *notch toughness* is assessed by using an impact test⁵.
- Furthermore, **fracture toughness** is a property indicative of a materials resistance to fracture when a crack is present.

⁵This will be discussed later in the present course

Toughness (2)

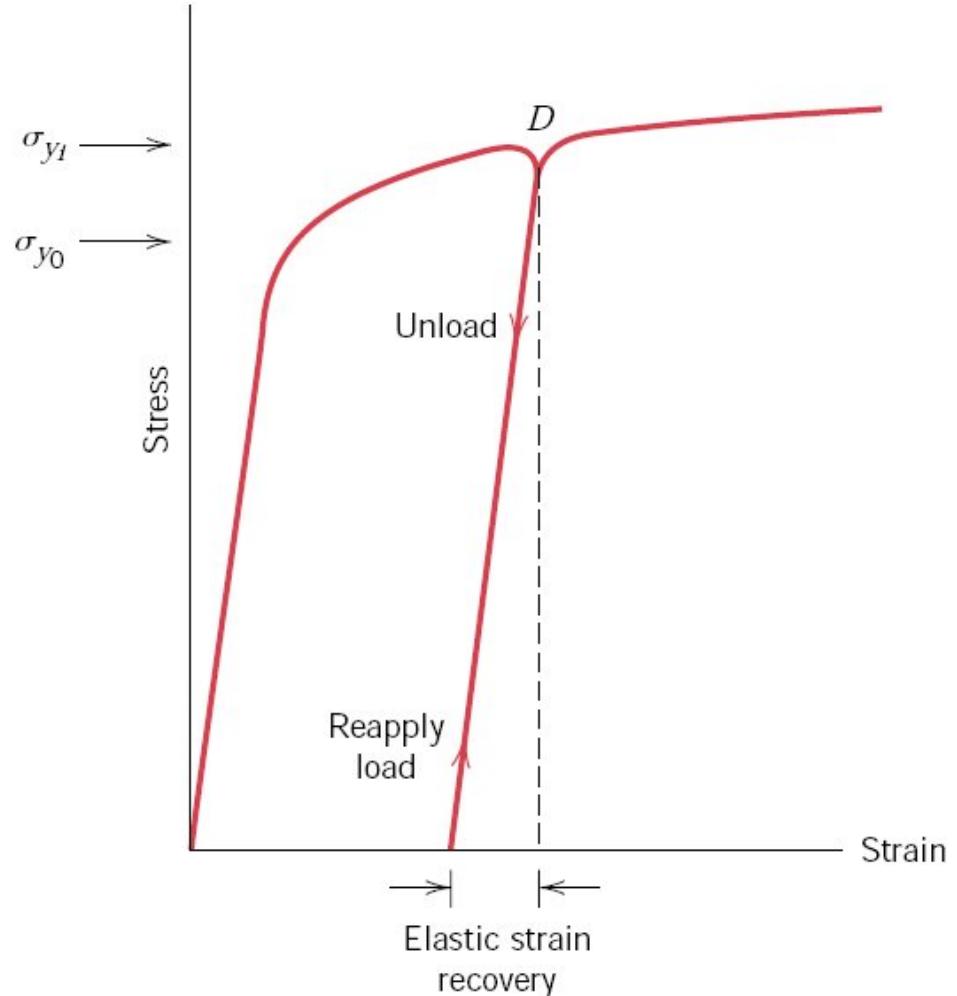
- For the static (low strain rate) situation, toughness may be ascertained from the results of a tensile stress–strain test.
 - It is the area under the σ – ϵ curve up to the point of fracture.
- For a material to be tough, it must display both strength and ductility; and often, ductile materials are tougher than brittle ones.
- This is demonstrated in the Figure given on Page 51, in which the stress–strain curves are plotted for both material types.
 - Hence, even though the brittle material has higher yield and tensile strengths, it has a lower toughness than the ductile one, by virtue of lack of ductility; this is deduced by comparing the areas ABC and $AB'C'$.

Toughness vs. Strength



Elastic Recovery (1)

- Upon release of the load during the course of a stress-strain test, some fraction of the total deformation is recovered as elastic strain.
- 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.



Elastic Recovery (2)

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

Compressive, Shear, And Torsional Deformation

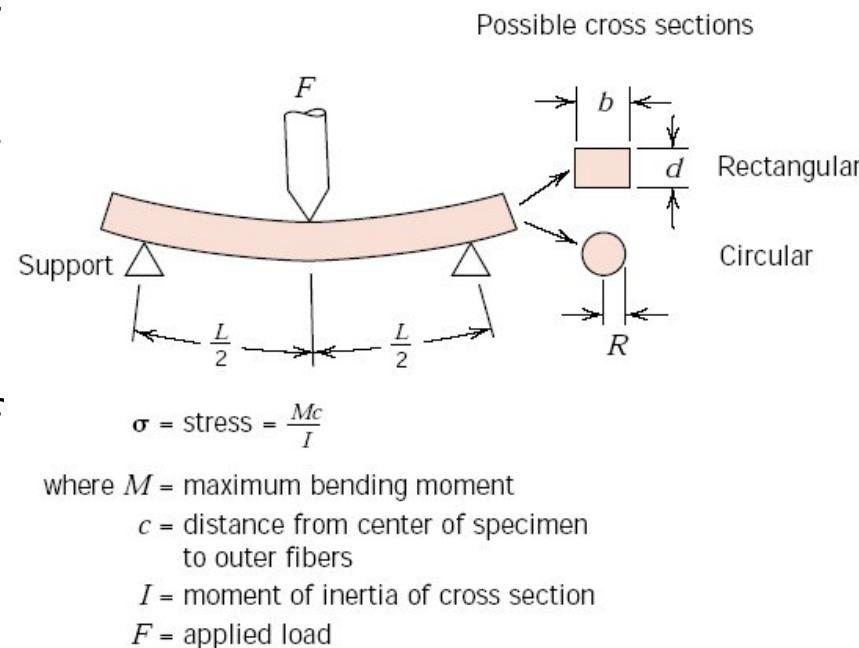
- Of course, metals may experience plastic deformation under the influence of applied compressive, shear, and torsional loads.
- The resulting stress-strain behavior into the plastic region will be similar to the tensile counterpart.
- However, for compression, there will be no maximum, since necking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

Mechanical Properties of Ceramics

- Ceramic materials are somewhat limited in applicability by their mechanical properties, which in many respects are inferior to those of metals.
- The principal drawback is a disposition to catastrophic fracture in a brittle manner with very little energy absorption.
- The stress-strain behavior of brittle ceramics is not usually ascertained by a normal tensile test, for three reasons:
 1. It is difficult to prepare and test specimens having the required geometry.
 2. It is difficult to grip brittle materials without fracturing them.
 3. Ceramics fail after only about 0.1% strain, which necessitates that tensile specimens be perfectly aligned in order to avoid the presence of bending stresses, which are not easily calculated.

Flexural Strength (1)

- For ceramics, a more suitable transverse bending test is most frequently employed.
- A rod specimen having either a circular or rectangular cross section is bent until fracture using a three- or four-point loading technique.
- At the point of loading, the top surface of the specimen is placed in a state of compression, whereas the bottom surface is in tension.
- Stress is computed from the specimen thickness, the bending moment, and the moment of inertia of the cross section



Flexural Strength (2)

- The maximum tensile stress exists at the bottom specimen surface directly below the point of load application.
- Since the tensile strengths of ceramics are about one-tenth of their compressive strengths, and since fracture occurs on the tensile specimen face, the flexure test is reasonable substitute for the tensile test.
- The stress at fracture using this flexure test is known as the **flexural strength**, *modulus of rupture*, *fracture strength*, or the *bend strength*.

Flexural Strength (3)

- For a rectangular cross section, the flexural strength σ_{fs} is equal to

$$\sigma_{fs} = \frac{3F_f L}{2bd^2}$$

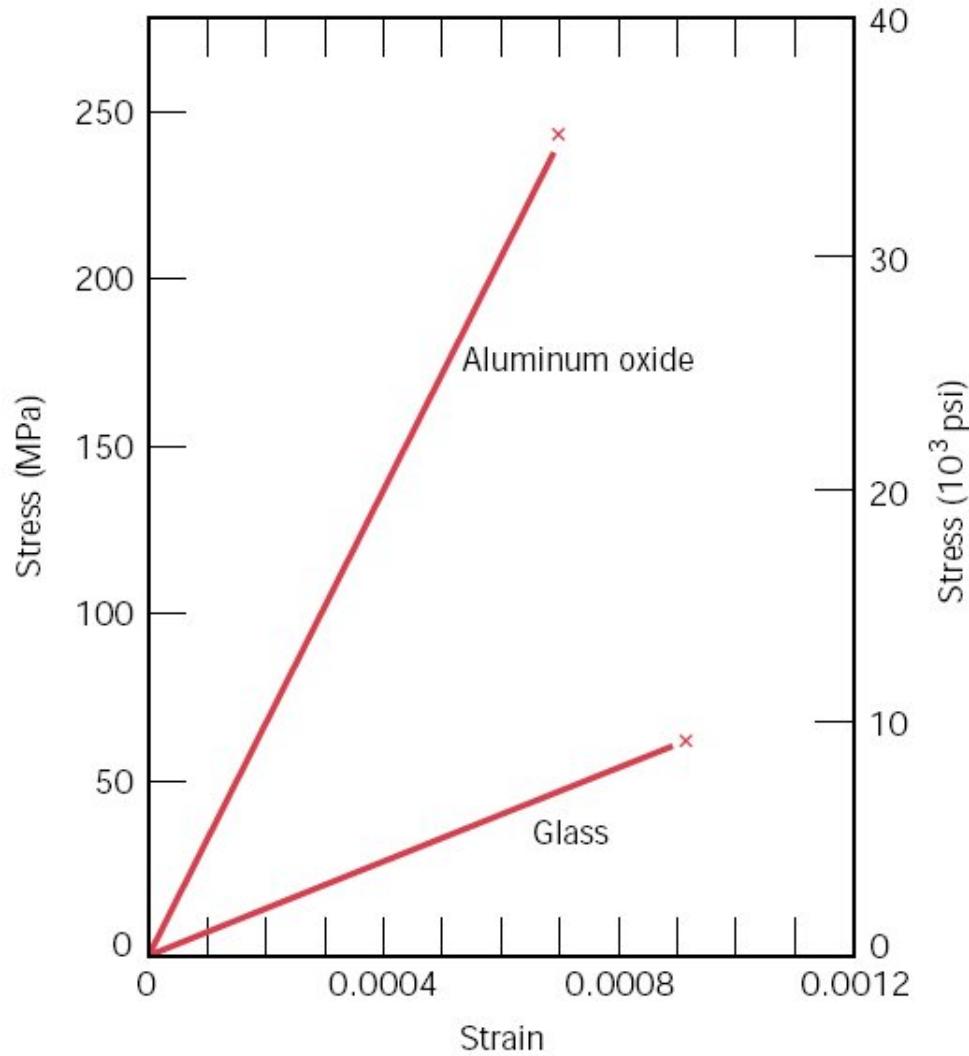
where F_f is the load at fracture, L is the distance between support points, and the other parameters are as indicated in the Figure on Page 63.

- When the cross section is circular, then

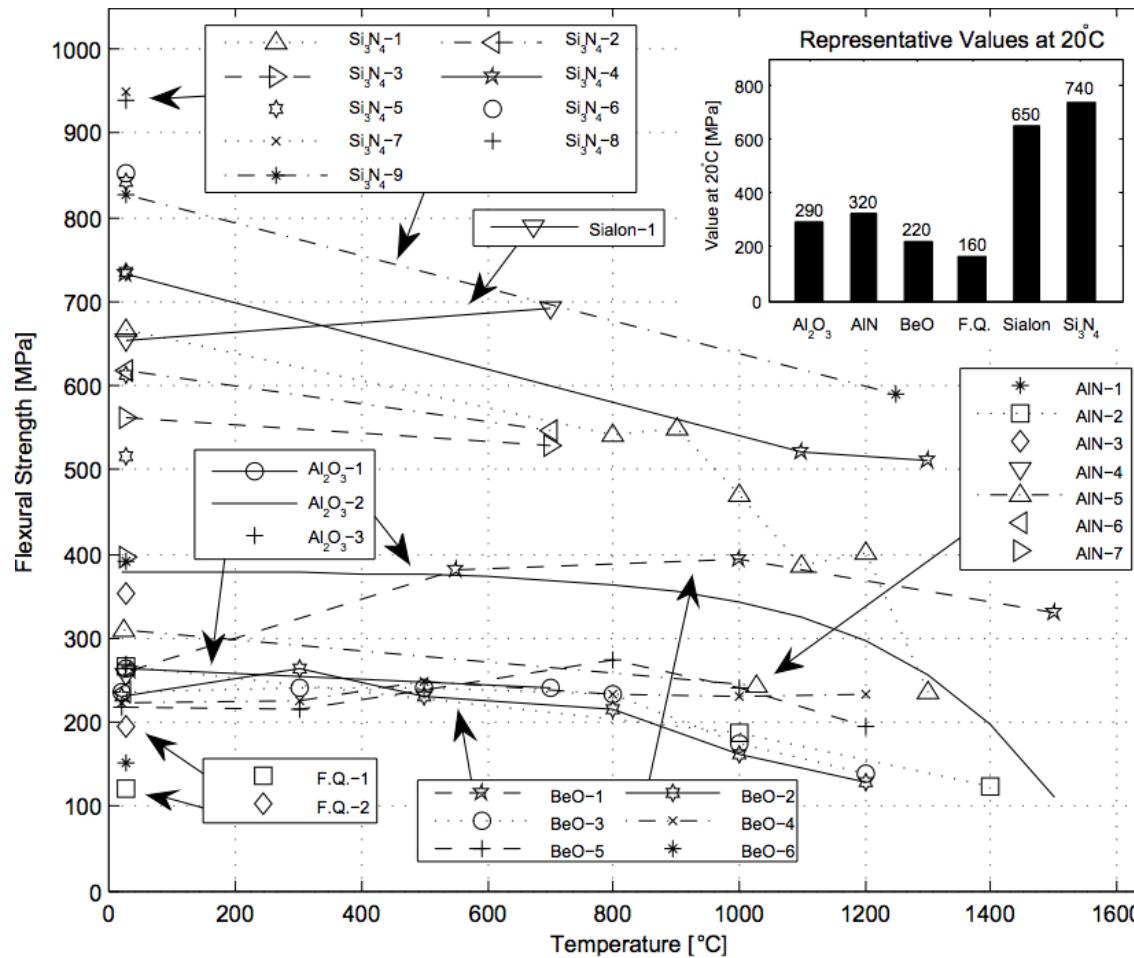
$$\sigma_{fs} = \frac{F_f L}{\pi R^3}$$

where R is the specimen radius.

Flexural Strength (4)



Flexural Strength (5)



Source: D.E. de Faoite, D.J. Browne, F. Chang-Diaz and K.T. Stanton, "A review of the processing, composition and temperature-dependent mechanical and thermal properties of dielectric technical ceramics", *Journal of Materials Science*, **47** 10 (2012) 4211–4235

Hardness

- Another mechanical property that may be important to consider is **hardness**.
- This is a measure of a materials 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 Tests

- 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, which in turn is related to a hardness number.
 - The softer the material, the larger and deeper the indentation, and the lower the hardness index number.
- Measured hardness values are only relative (rather than absolute), and care should be exercised when comparing values determined by different techniques.

Hardness Tests (1)

- Hardness tests are performed more frequently than any other mechanical test for several reasons:
 1. They are simple and inexpensive.
 - Ordinarily no special specimen need be prepared, and the testing apparatus is relatively inexpensive.
 2. The test is nondestructive.
 - 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.
- There are a few hardness tests including **Rockwell**, **Brinell**, **Knoop** and **Vickers** tests.

Hardness Tests (2)

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	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	{ Diamond cone 1/16, 1/8, 1/4, 1/2 in. diameter steel spheres			60 kg 100 kg 150 kg 15 kg 30 kg 45 kg	Rockwell Superficial Rockwell

^a For the hardness formulas given, P (the applied load) is in kg, while D , d , d_1 , and l are all in mm.

Rockwell Hardness Scales

<i>Scale Symbol</i>	<i>Indenter</i>	<i>Major Load (kg)</i>
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

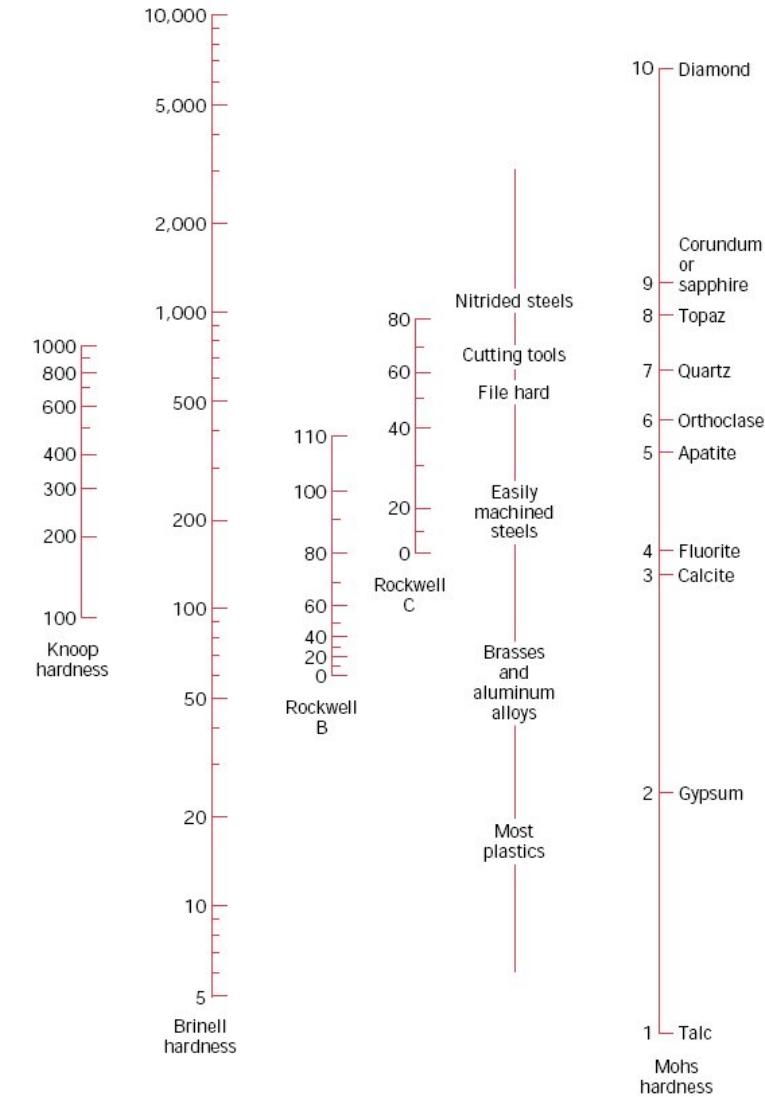
Hardness Testing

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



Comparison Between Hardness Scales

Comparison between scales is not always accurate and no reliable conversion criteria exist.

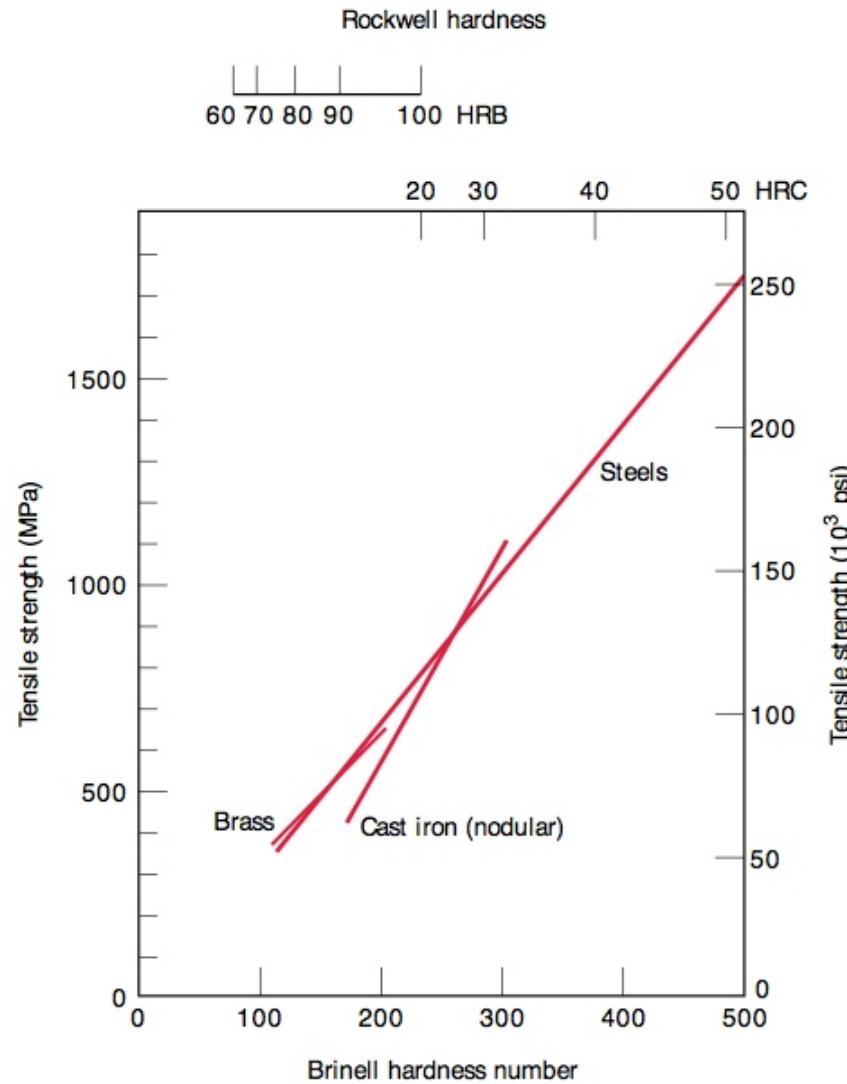


Correlation Between Hardness And Tensile Strength (1)

- Both tensile strength and hardness are indicators of a metals resistance to plastic deformation.
 - Consequently, they are roughly proportional 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

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

Correlation Between Hardness And Tensile Strength (2)



Knoop Values

<i>Material</i>	<i>Approximate Knoop Hardness</i>
Diamond (carbon)	7000
Boron carbide (B_4C)	2800
Silicon carbide (SiC)	2500
Tungsten carbide (WC)	2100
Aluminum oxide (Al_2O_3)	2100
Quartz (SiO_2)	800
Glass	550

Variability in Data

- It is important to note that measured material properties are not exact quantities.
 - There will always be some scatter or variability in the data that are collected from specimens of the same material
- It is important for the design engineer to realize that scatter and variability of materials properties are inevitable and must be dealt with appropriately.
 - For example, instead of asking the question,
“What is the fracture strength of this alloy?”
the engineer should become accustomed to asking the question,
“What is the probability of failure of this alloy under these given circumstances?”

Design/Safety Factors (1)

- Due to variability in data, design allowances must be made to protect against unanticipated failure.
- One way this may be accomplished is by establishing, for the particular application, a **design stress**, denoted as σ_d .
- For static situations and when ductile materials are used, 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' , such that

$$\sigma_d = N' \sigma_c$$

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 (2)

- 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 (Equation on Page 79) is usually preferred since 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.

Values for N

- The choice of an appropriate value of N is necessary.
 - If N is too large, then component overdesign will result:
 - * In other words, either too much material or a material 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
 - *The consequences of failure in terms of loss of life and/or property damage.*

Mechanical Failure



Fracture

- Fracture is the separation of a body into two or more pieces in response to an imposed stress that is static, (i.e., constant or slowly changing with time) and at temperatures that are low relative to the melting temperature of the material.
- For engineering materials, two fracture modes are possible:
 - **Ductile**
 - **Brittle**
- Classification is based on the ability of a material to experience plastic deformation.
- Ductile materials typically exhibit substantial plastic deformation with high energy absorption before fracture.
- There is normally little or no plastic deformation with low energy absorption accompanying a brittle fracture.

Mechanisms of Fracture (1)

- Any fracture process involves two steps—crack formation and propagation.
- The mode of fracture is highly dependent on the mechanism of crack propagation.
- **Ductile fracture:**
 - Characterized by extensive plastic deformation in the vicinity of an advancing crack.
 - The process proceeds relatively slowly as the crack length is extended.
 - Such a crack is often said to be *stable*.
 - * It resists any further extension unless there is an increase in the applied stress.
 - In addition, there will ordinarily be evidence of appreciable gross deformation at the fracture surfaces (e.g., twisting and tearing).

Mechanisms of Fracture (2)

- **Brittle fracture:**

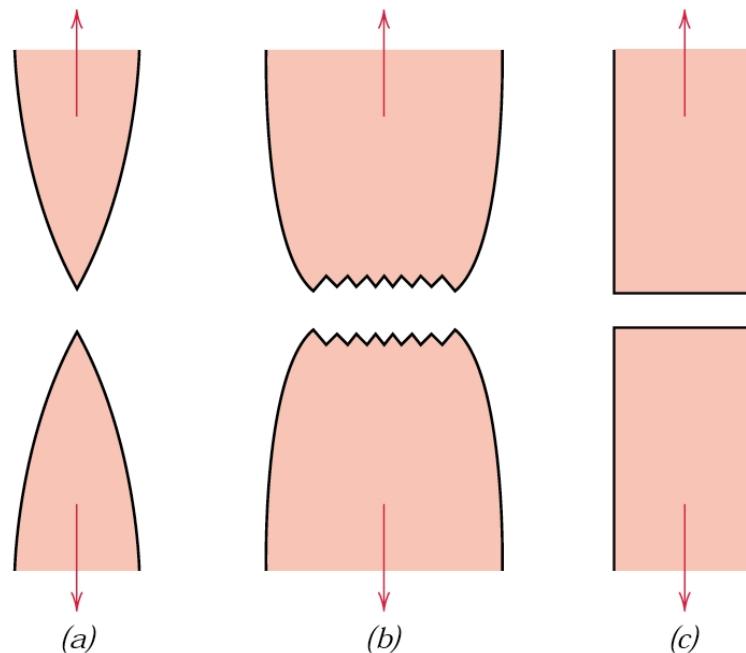
- Cracks may spread extremely rapidly, with very little accompanying plastic deformation.
 - * Such cracks may be said to be *unstable*.
- Crack propagation, once started, will continue spontaneously without an increase in magnitude of the applied stress.

- Ductile fracture is almost always preferred for two reasons:

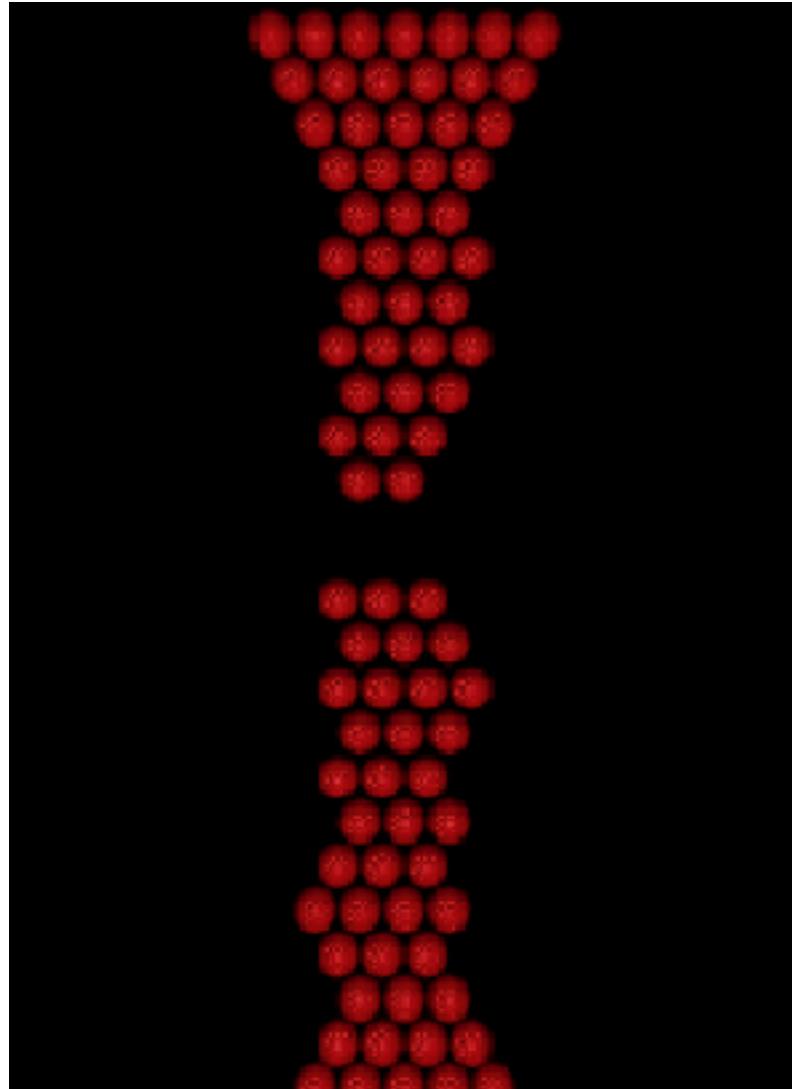
1. Brittle fracture occurs suddenly and catastrophically without any warning
 - This is a consequence of the spontaneous and rapid crack propagation.
 - For ductile fracture, the presence of plastic deformation gives warning that fracture is imminent, allowing preventive measures to be taken.
2. More strain energy is required to induce ductile fracture inasmuch as ductile materials are generally tougher.

Macroscopic Evidence of Failure Mechanism

- a Highly ductile fracture in which the specimen necks down to a point.
- b Moderately ductile fracture after some necking.
- c Brittle fracture without any plastic deformation.

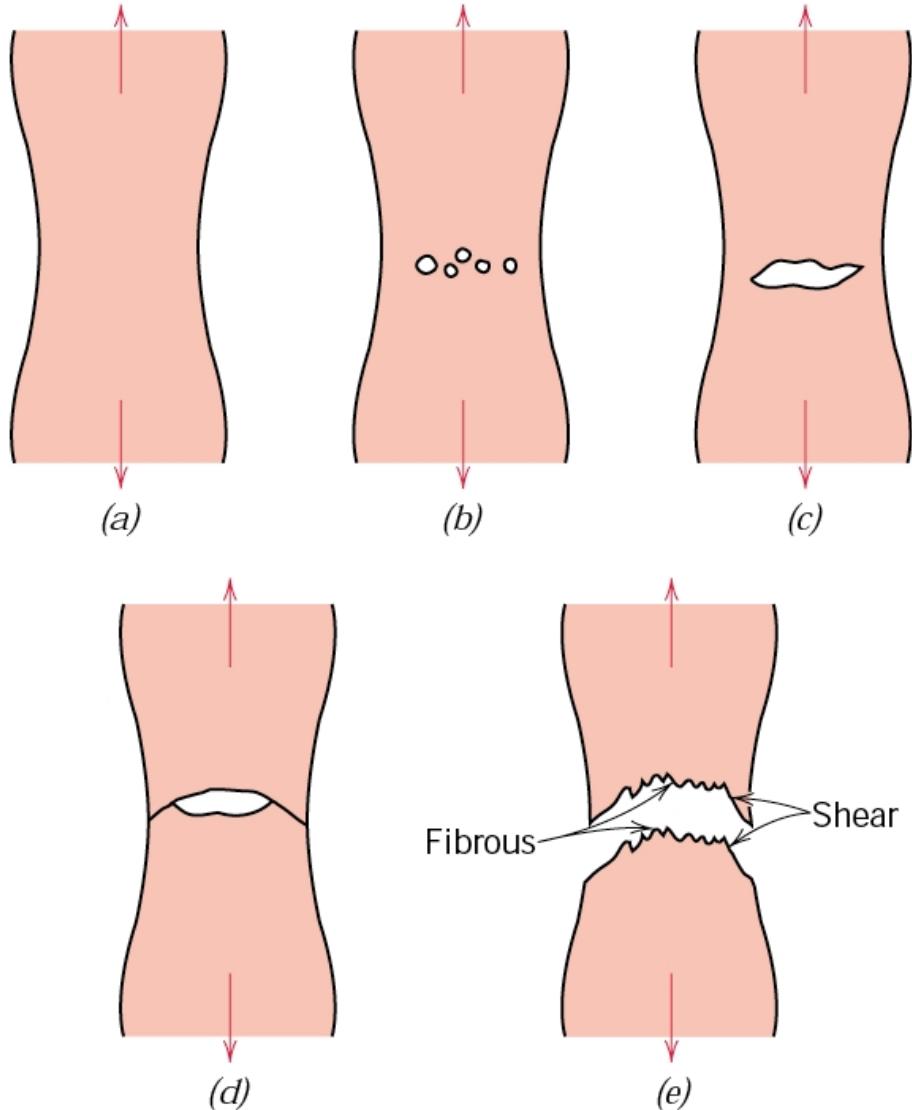


Mechanism of Necking



Cup and Cone Fracture

- Stages in cup and cone fracture for relatively ductile materials.
 - Initial necking.
 - Small cavity formation.
 - Coalescence of cavities to form a crack.
 - Crack propagation.
 - Final shear fracture at a 45° angle relative to the tensile direction.



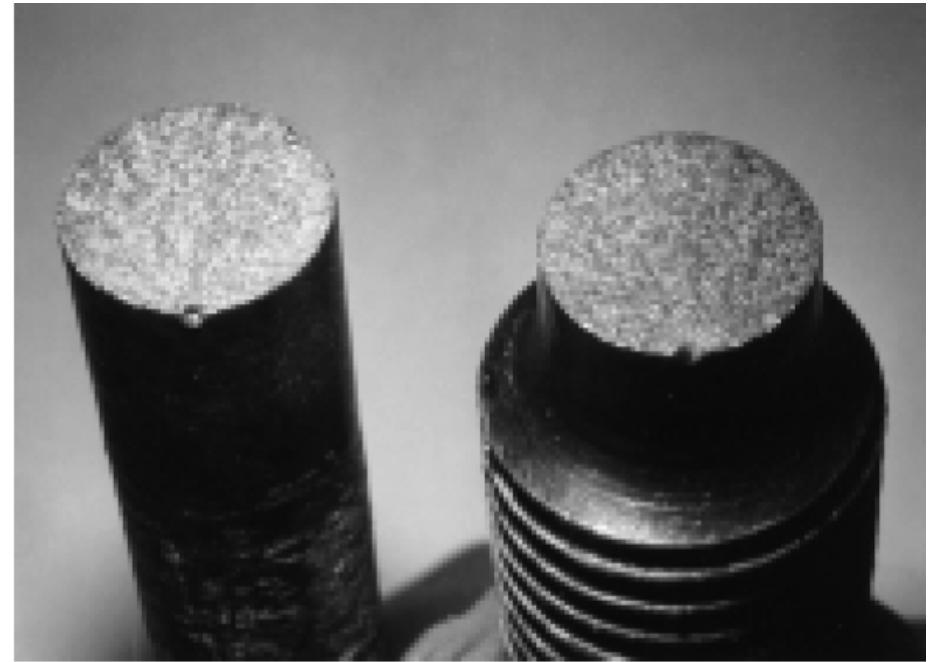
Macroscopic Failure

a Cup-and-cone fracture in aluminum.

b Brittle fracture in a mild steel.



(a)



(b)

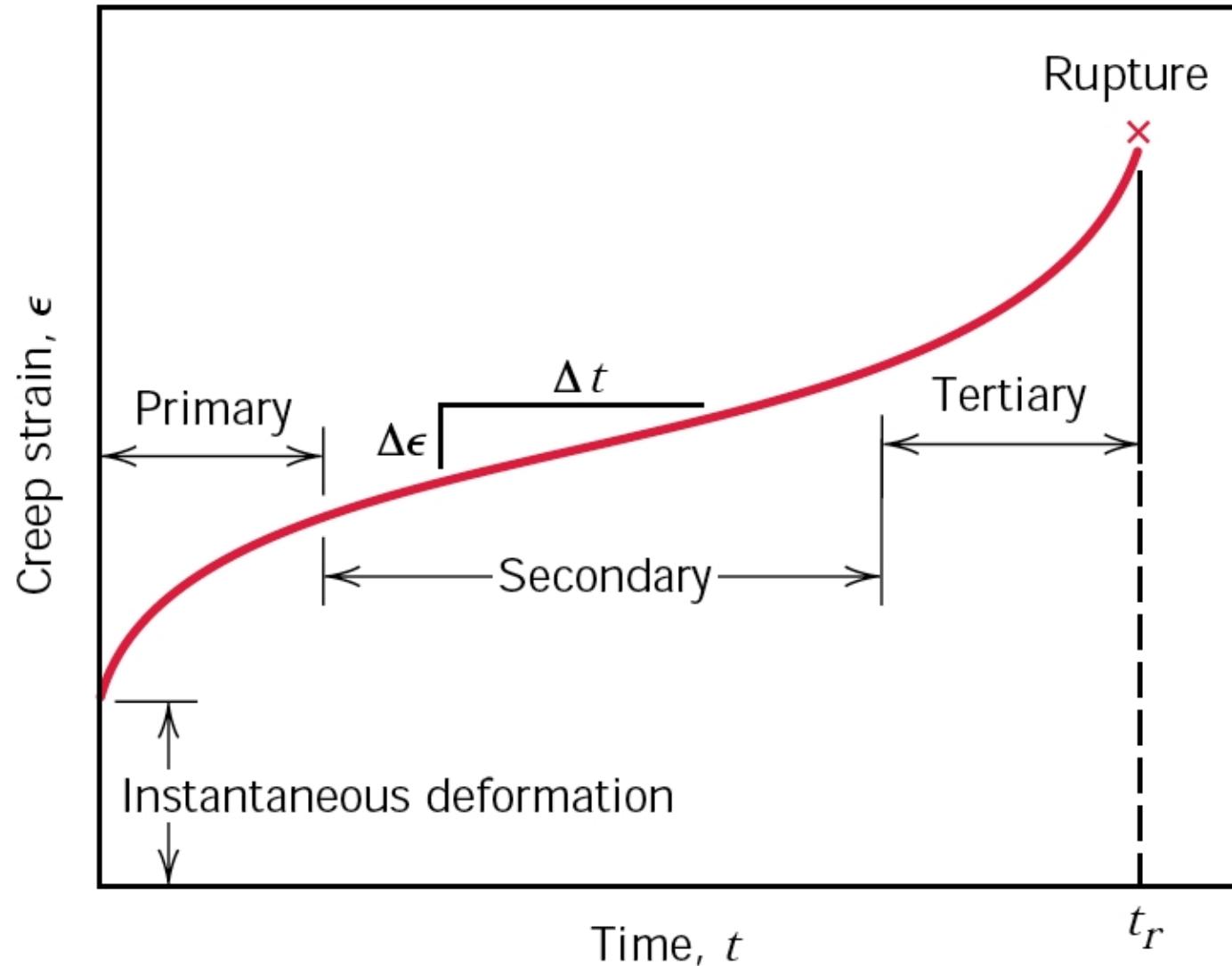
Creep

- Materials are often placed in service at elevated temperatures and exposed to static mechanical stresses.
 - E.g., turbine rotors in jet engines and steam generators that experience centrifugal stresses.
- Deformation under such circumstances is termed **creep**.
 - Defined as the time-dependent and permanent deformation of materials when subjected to a constant load or stress.
- Creep is normally an undesirable phenomenon and is often the limiting factor in the lifetime of a part.
- It is observed in all materials types; for metals it becomes important only for temperatures greater than about $0.4T_m$ (T_m = absolute melting temperature).

Creep Testing

- A typical creep test consists of subjecting a specimen to a constant load or stress while maintaining the temperature constant.
- Deformation or strain is measured and plotted as a function of elapsed time.
- Most tests are the constant load type, which yield information of an engineering nature.
- The resulting creep curve consists of three regions, each of which has its own distinctive strain–time feature.
 - **Primary**
 - **Secondary**
 - **Tertiary**

Creep Curve



Stages of Creep

Primary Sometimes termed *transient creep*. Typified by a continuously decreasing creep rate; that is, the slope of the curve diminishes with time. This suggests that the material is experiencing an increase in creep resistance or strain hardening.

Secondary Sometimes termed *steady-state creep*, the rate is constant; that is, the plot becomes linear. This is often the stage of creep that is of the longest duration. The constancy of creep rate is explained on the basis of a balance between the competing processes of strain hardening and recovery.

Tertiary There is an acceleration of the rate and ultimate failure. This failure is frequently termed rupture and results from microstructural and/or metallurgical changes; for example, grain boundary separation, and the formation of internal cracks, cavities, and voids.

Important Parameters

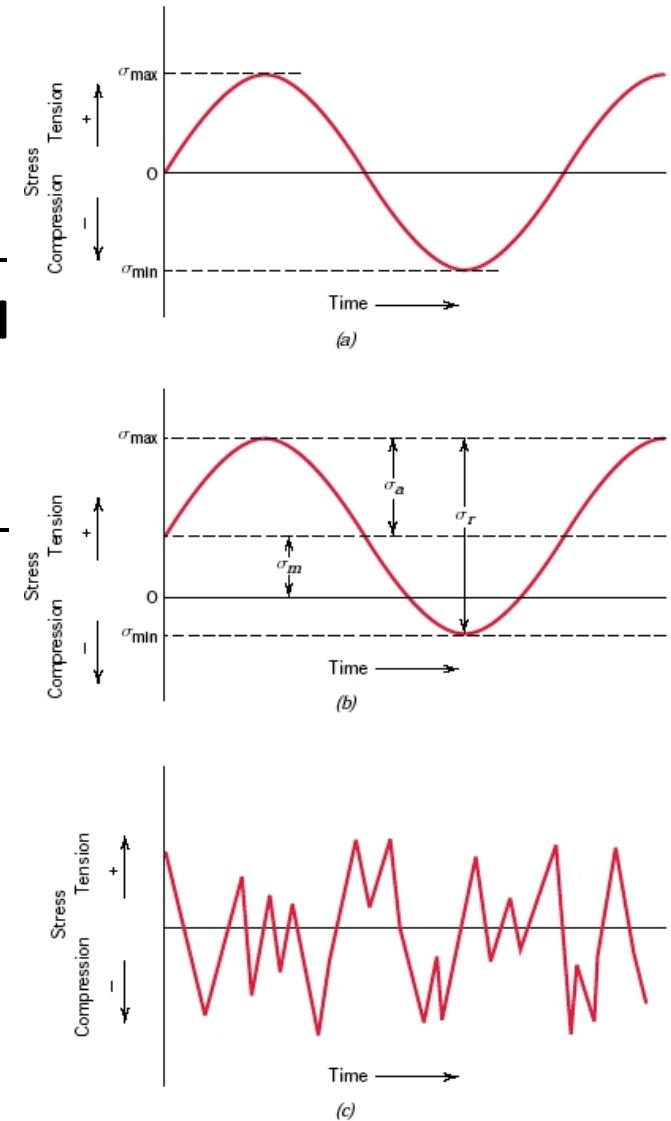
- The most important parameter from a creep test is the slope of the secondary portion of the creep curve.
 - Given as $\frac{\Delta\epsilon}{\Delta t}$ in Figure on Page 92.
 - This is often called the minimum or *steady-state creep rate* $\dot{\epsilon}_s$.
- It is the engineering design parameter that is considered for long-life applications, such as a nuclear power plant component that is scheduled to operate for several decades, and when failure or too much strain is not an option.
- Creep tests must be conducted to the point of failure; these are termed *creep rupture* tests.

Fatigue

- **Fatigue** is a form of failure that occurs in structures subjected to dynamic and fluctuating stresses (e.g., bridges, aircraft, and machine components).
- Under these circumstances it is possible for failure to occur at a stress level considerably lower than the tensile or yield strength for a static load.
- Fatigue is important inasmuch as it is the single largest cause of failure in metals, estimated to comprise approximately 90% of all metallic failures.
 - Polymers and ceramics (except for glasses) are also susceptible to this type of failure.
- It is catastrophic and insidious, occurring very suddenly and without warning.
- Fatigue failure is brittlelike in nature even in normally ductile metals, in that there is very little, if any, gross plastic deformation associated with failure.

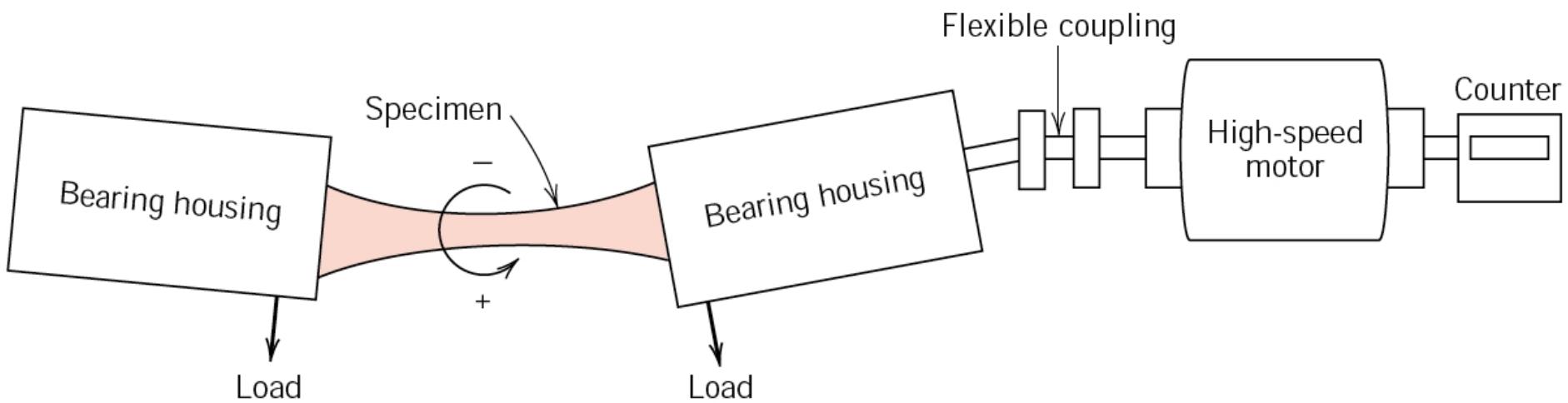
Cyclic Stresses

- The applied stress may be **axial** (tension-compression), **flexural** (bending), or **torsional** (twisting) in nature.
- In general, three different fluctuating stress-time modes are possible.
 - Reversed stress cycle
 - Repeated stress cycle
 - Random stress cycle



Fatigue Testing

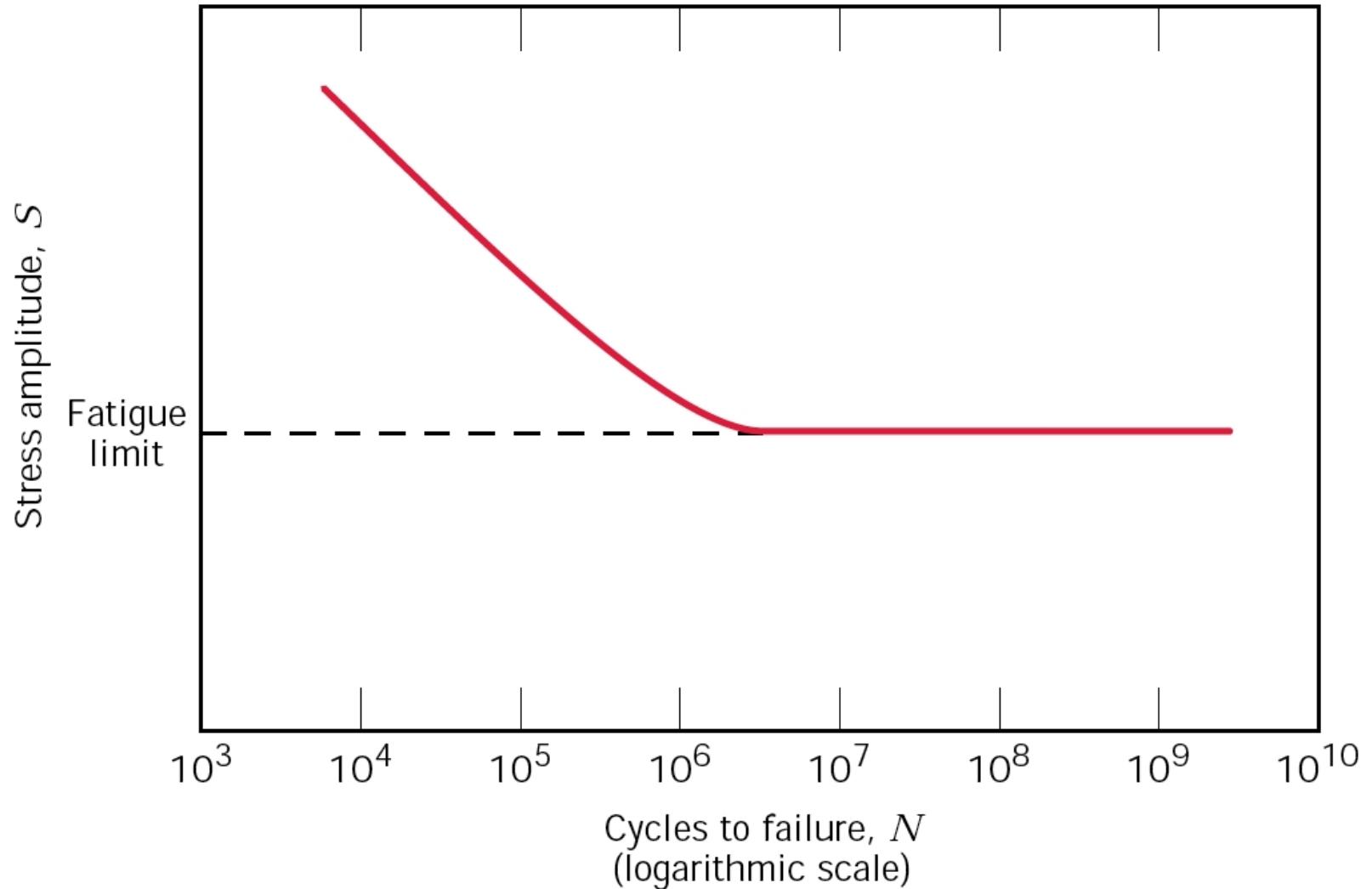
- The fatigue properties of materials can be determined from laboratory simulation tests.
- Using a rotating-bending test as shown, compression and tensile stresses are imposed on the specimen as it is simultaneously bent and rotated.
- Tests are also frequently conducted using an alternating uniaxial tension-compression stress cycle.



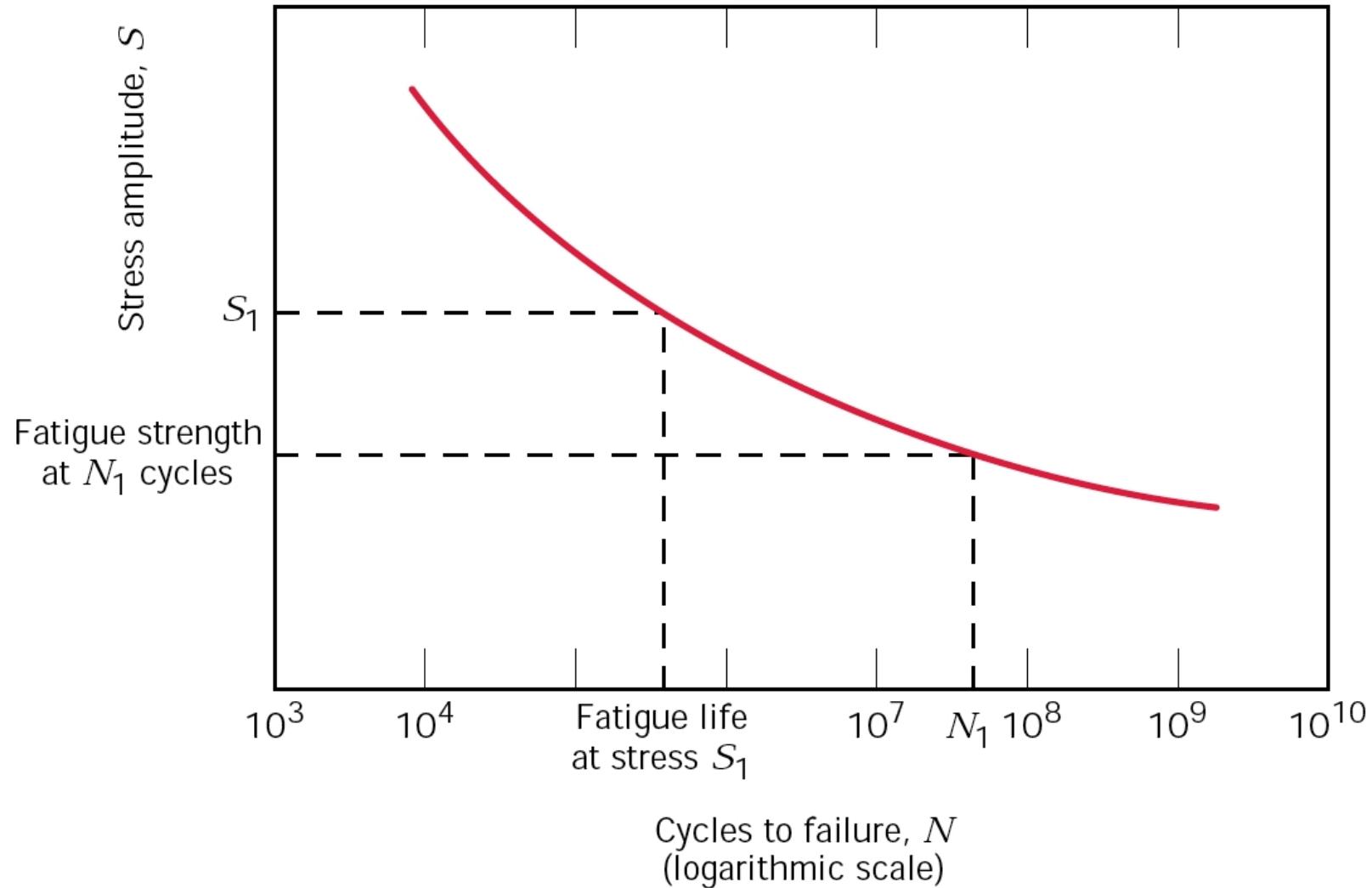
The $S-N$ Curve

- Data are plotted as stress S versus the logarithm of the number N of cycles to failure for each of the specimens.
- The values of S are normally taken as stress amplitudes σ_a although on occasion, σ_{\max} or σ_{\min} values may be used.
- Two distinct types of $S-N$ behavior are observed:
 - For some ferrous (iron base) and titanium alloys, the $S-N$ curve becomes horizontal at higher N values; or, there is a limiting stress level, called the **fatigue limit** (also sometimes the *endurance limit*), below which fatigue failure will not occur.
 - * For many steels, fatigue limits range between 35 and 60% of the tensile strength.
 - Most nonferrous alloys (e.g., aluminum, copper, magnesium) do not have a fatigue limit, in that the $S-N$ curve continues its downward trend at increasingly greater N values.

S-N Curve with Fatigue Limit



S-N Curve with No Fatigue Limit



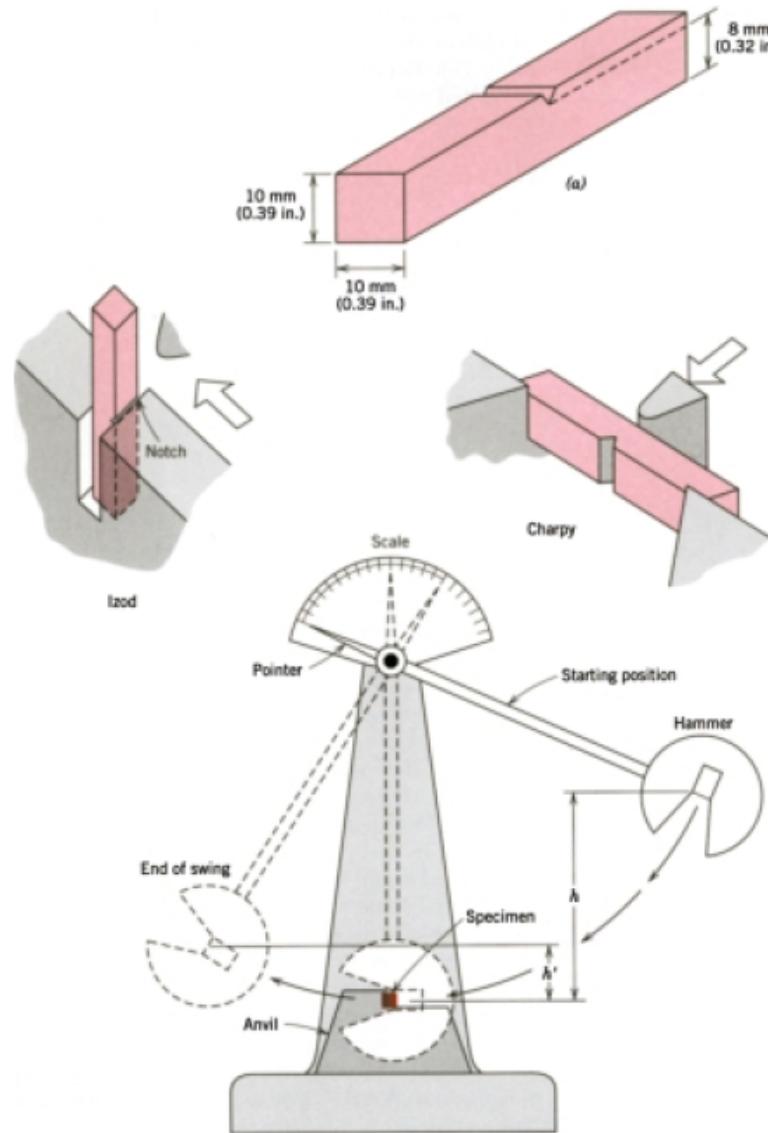
Impact Testing

- The results of laboratory tensile tests can not be extrapolated to predict fracture behaviour.
- Under some circumstances normally ductile metals fracture abruptly and with very little plastic deformation.
- **Impact tests** have been developed whereby test conditions were chosen to represent those most severe relative to the potential for fracture, namely:
 1. Deformation at a relatively low temperature.
 2. A high strain rate.
 3. A triaxial stress state
 - This may be introduced by the presence of a notch.

Impact tests

- There are two standardised tests which determine the **impact energy**, sometimes also termed *notch toughness*:
 - **Charpy test**
 - **Izod test**
- The Charpy V-notch (CVN) technique is most commonly used in the United States.
- For both Charpy and Izod, the specimen is in the shape of a bar of square cross section, into which a V-notch is machined.
- The only difference between the techniques lies in the way that the sample is held during the test.

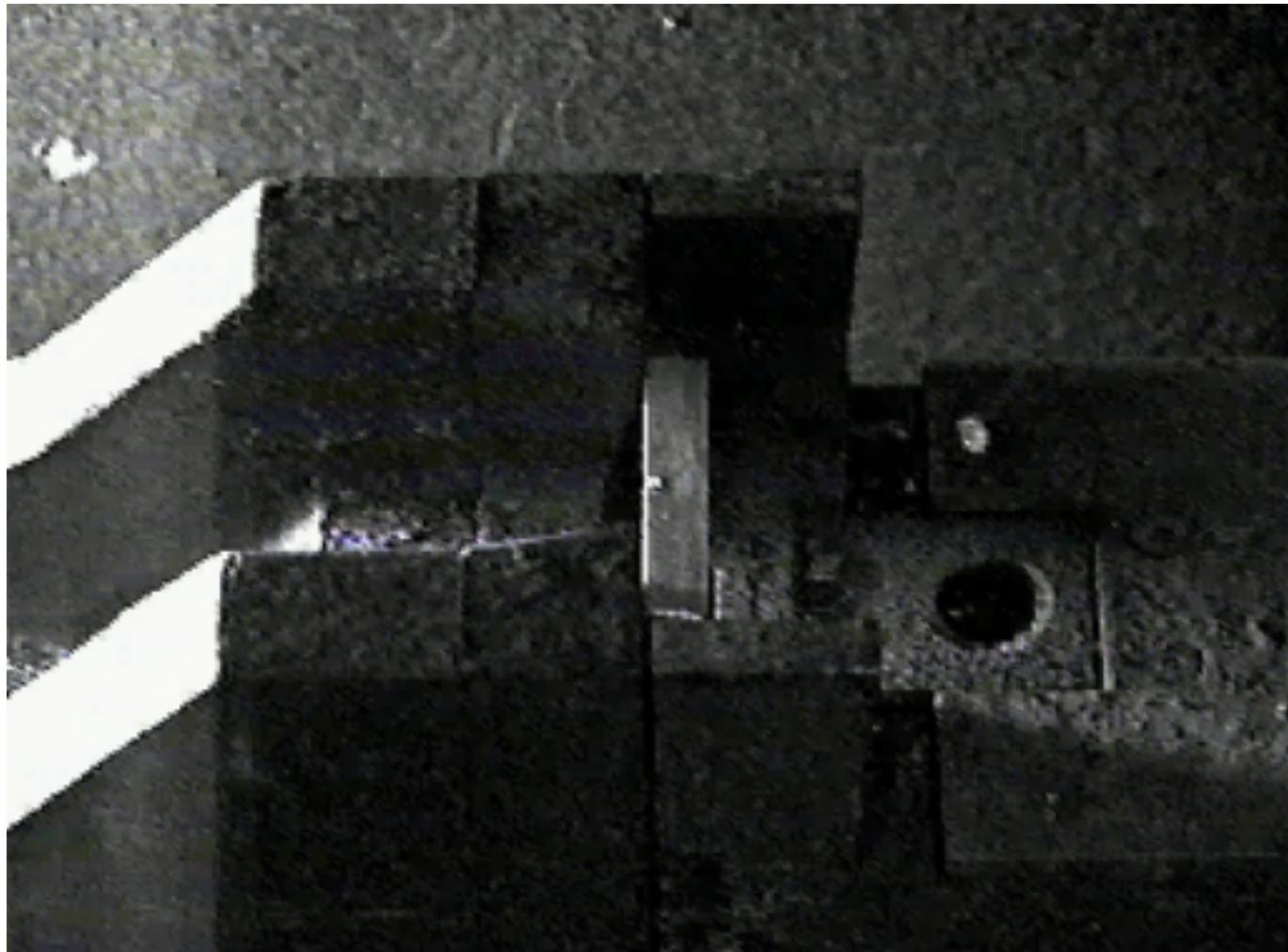
Charpy and Izod Tests



How the Test is Carried Out

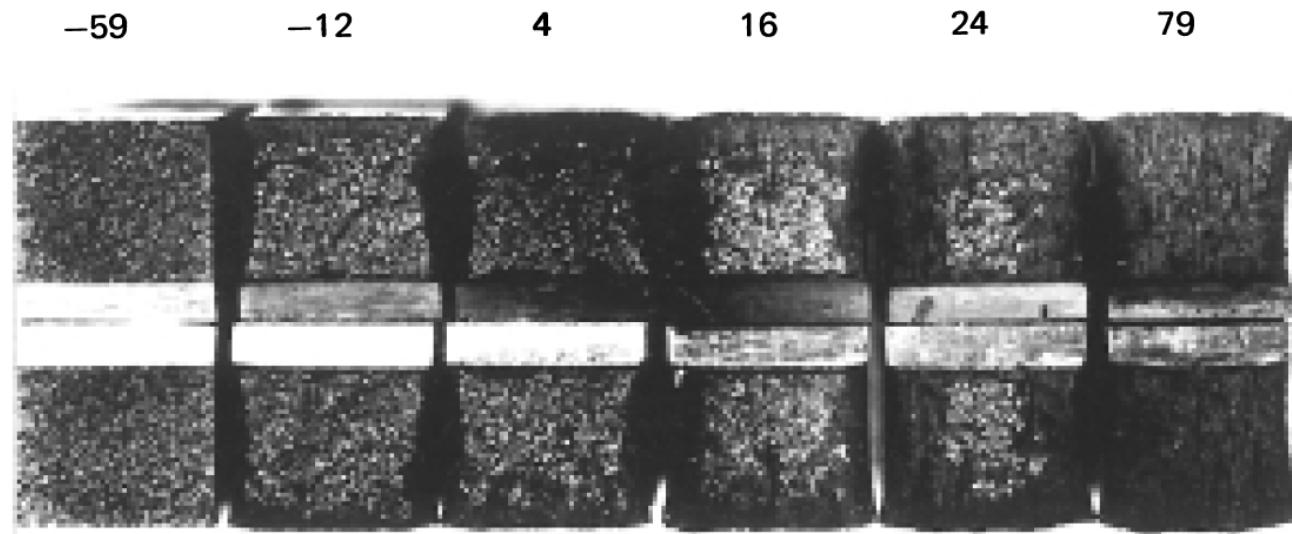
- The load is applied as an impact blow from a weighted pendulum hammer that is released from a held position at a fixed height h .
- Upon release, a knife edge mounted on the pendulum strikes and fractures the specimen at the notch, which acts as a point of stress concentration for this high velocity impact blow.
- The pendulum continues its swing, rising to a maximum height h' , which is lower than h .
- The energy absorption, computed from the difference between h and h' , is a measure of the impact energy.
- The results of the impact tests are qualitative and are of little use for design purposes.

Charpy Test (Movie)



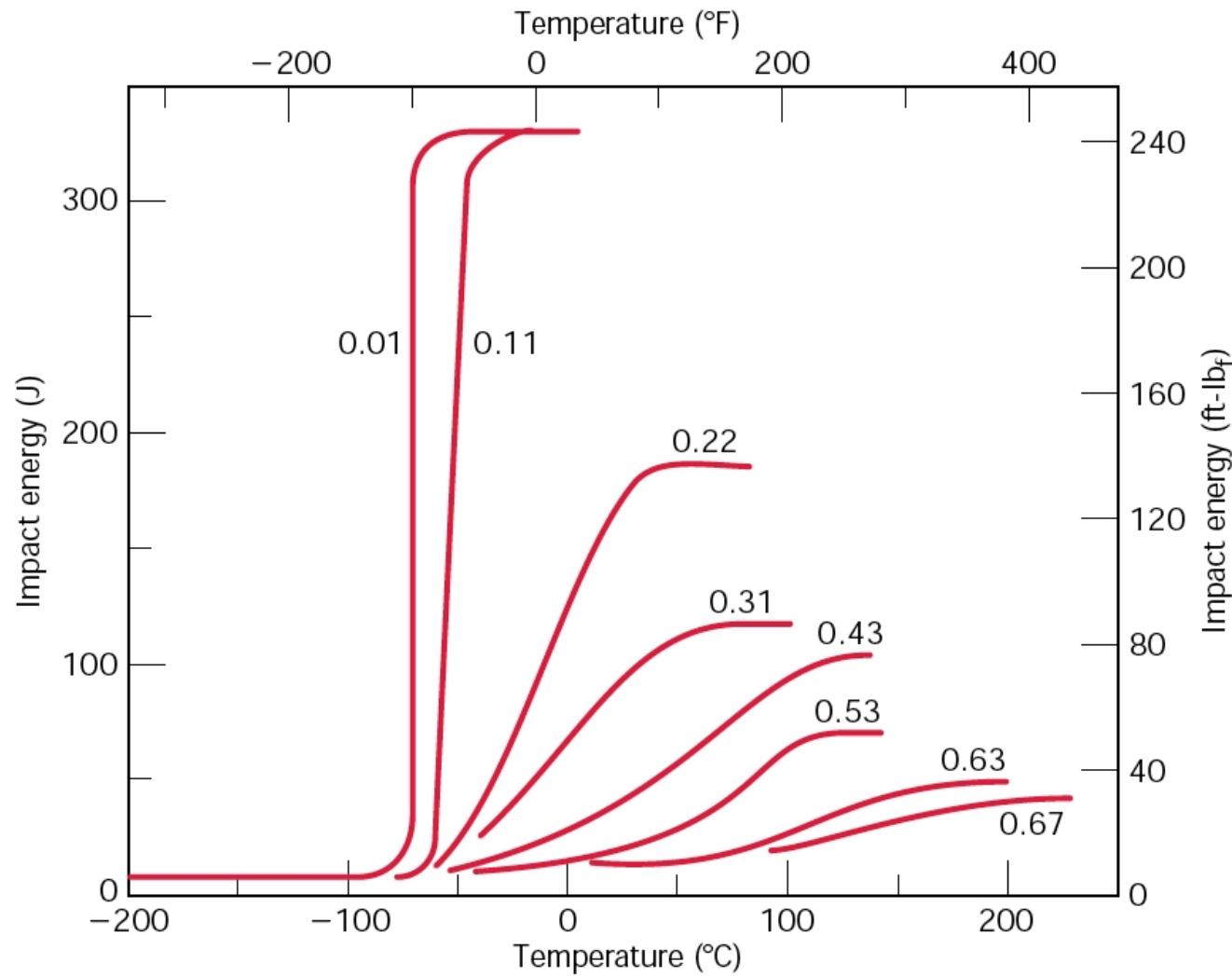
The Ductile-to-Brittle Transition

- One of the primary functions of Charpy and Izod tests is to determine whether or not a material experiences a **ductile-to-brittle transition** with decreasing temperature.
- The ductile-to-brittle transition is related to the temperature dependence of the measured impact energy absorption.



Images show fractured steel impact specimens as a function of temperature.

Influence of Carbon Content on Fracture of Steel

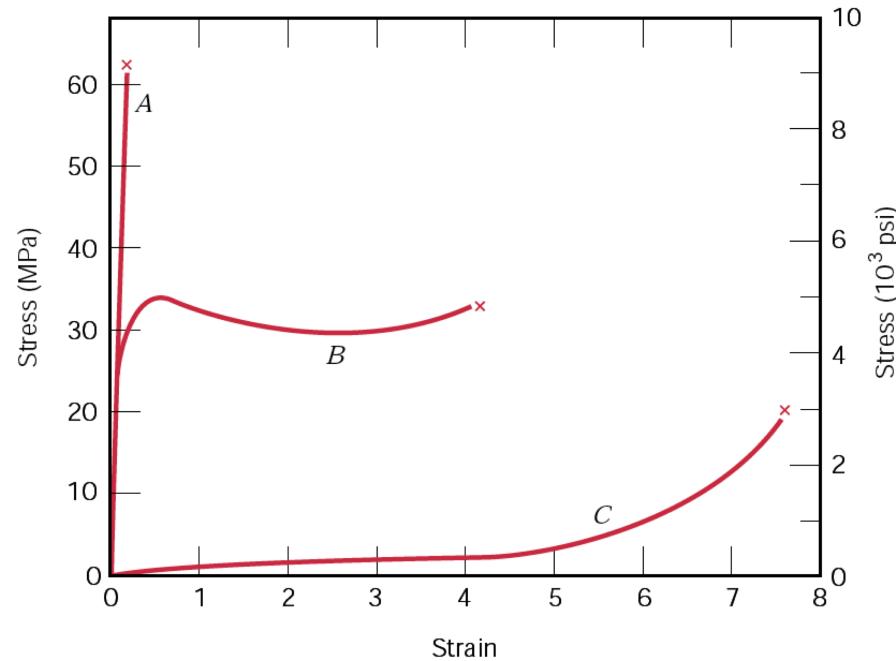


Mechanical Properties of Polymers

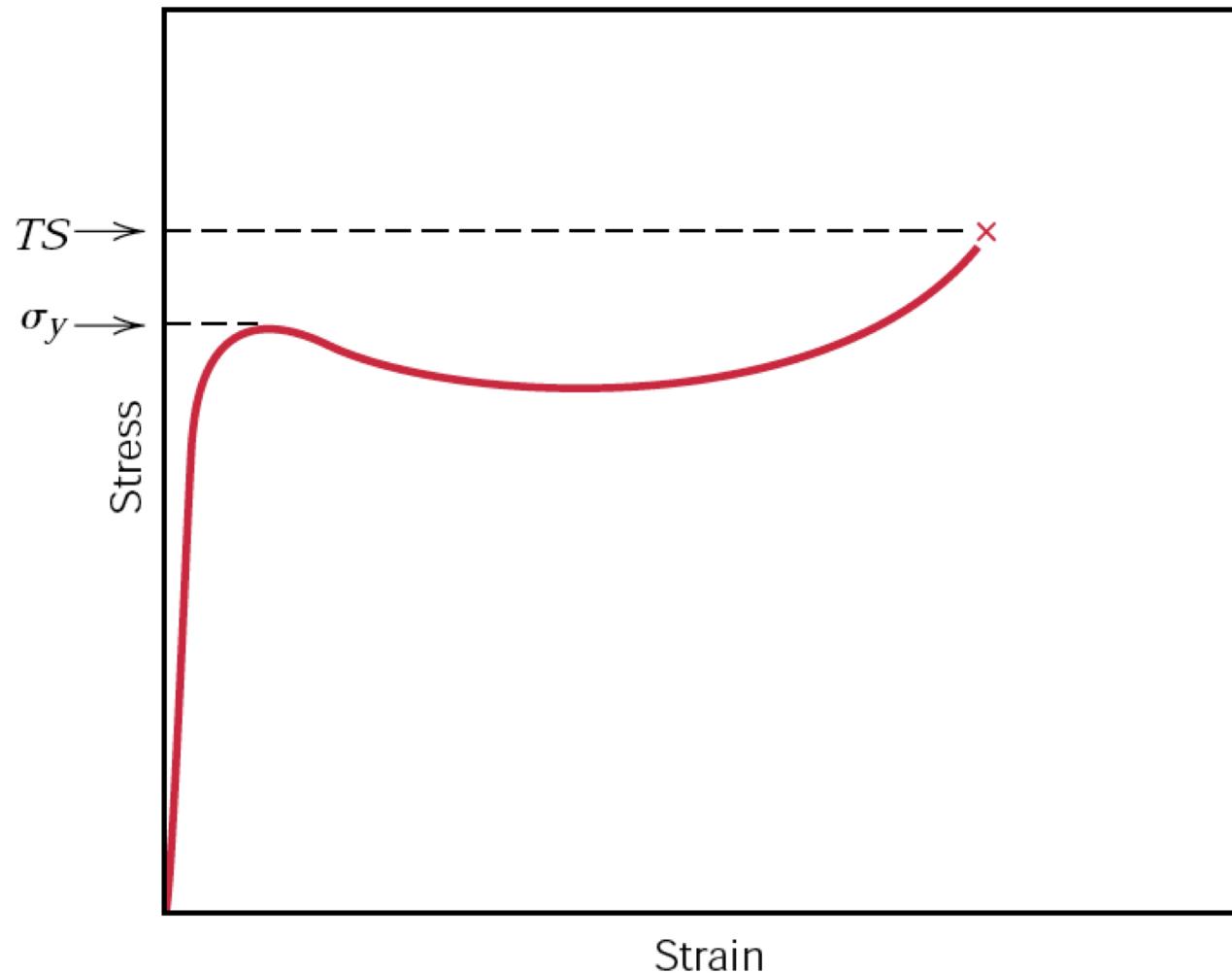
- The mechanical properties of polymers are specified with many of the same parameters that are used for metals. i.e.:
 - Modulus of elasticity, E
 - Yield strength
 - Tensile strength
- For many polymeric materials, the simple stress-strain test is employed for the characterization of some of these mechanical parameters.
- The mechanical characteristics of polymers, for the most part, are highly sensitive to:
 - Rate of deformation (strain rate).
 - Temperature.
 - Chemical nature of the environment (the presence of water, oxygen, organic solvents, etc.).

Tensile Behaviour

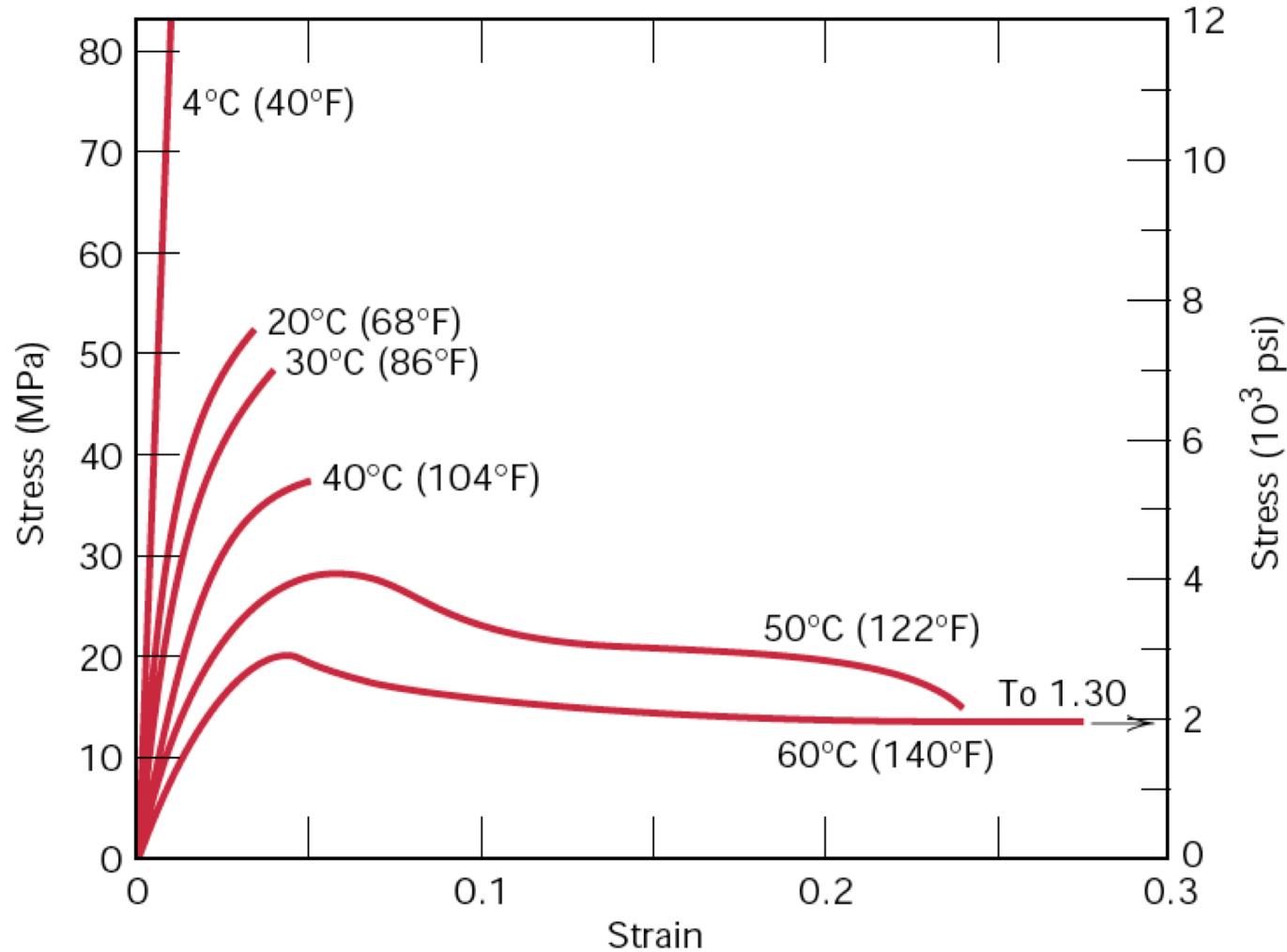
- Three typically different types of stress-strain behavior are found for polymeric materials, depending on whether the material is:
 - Brittle—mainly found in thermosets.
 - Plastic—mainly found in thermoplastics
 - Highly elastic—mainly found in elastomers



Determination of Yield and Tensile Strengths in Plastic Polymers



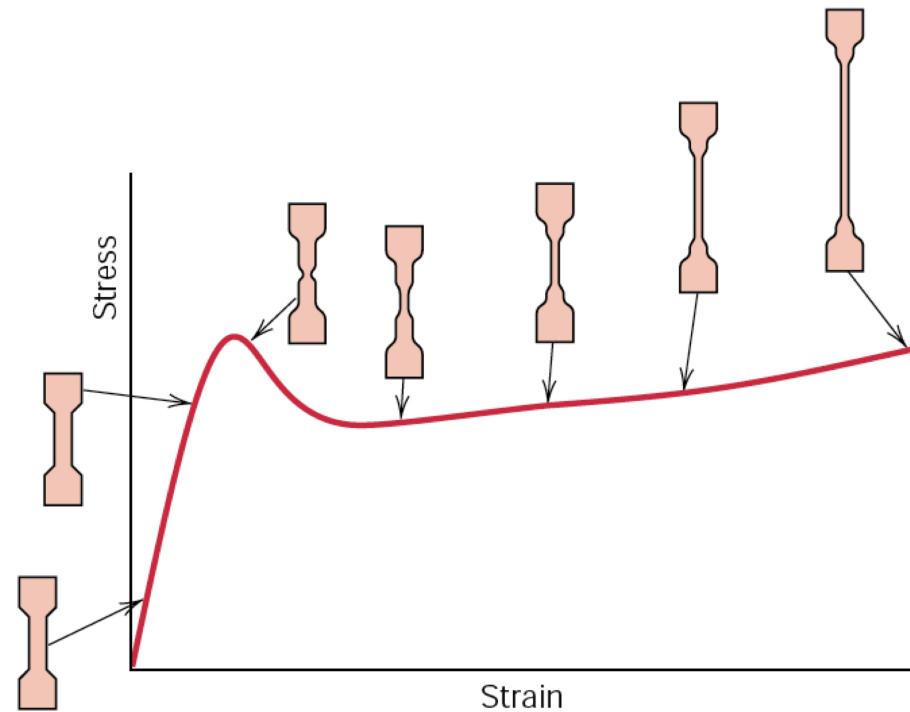
Influence of Temperature on Tensile Behaviour



Stress-strain characteristics of PMMA.

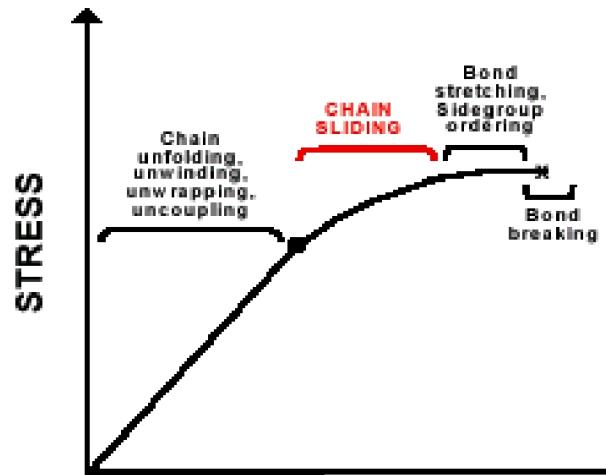
Necking in Polymers

- When necking occurs in many thermoplastics, there is localised strengthening in the region of the neck.
- This contrasts with metals where all plastic deformation is confined to the neck region once necking has initiated.



Strain Mechanisms in Polymers

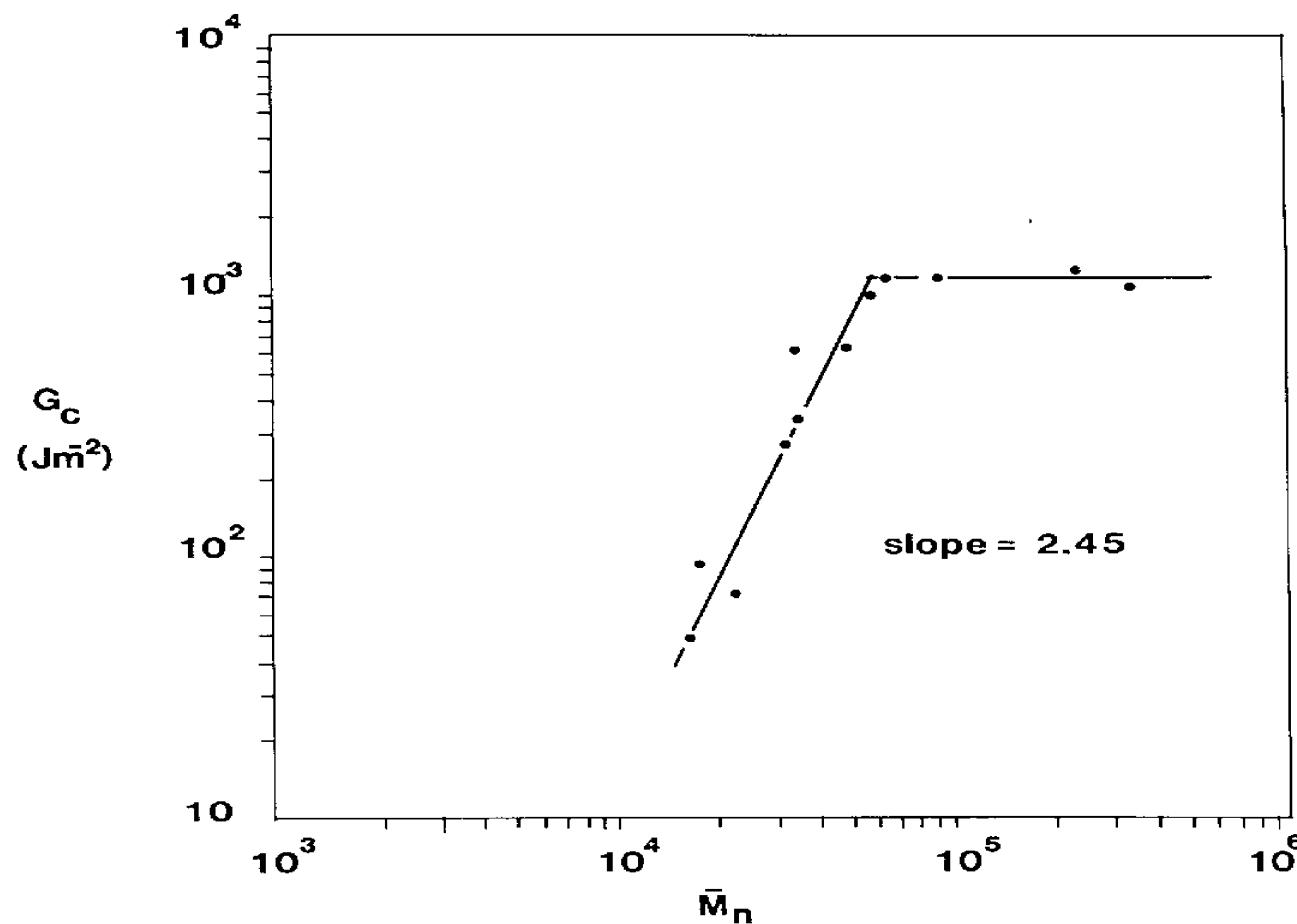
- Low energy
 - Chain unfolding, unwinding, unwrapping, or uncoupling.
 - **Chain sliding**
- High Energy
 - Bond stretching, Side-group ordering
 - Bond breaking



Molecular Weight Effects

Fracture properties of PMMA

(PRENTICE, Journal of materials science (1985) 20 4, 1445 -1454)



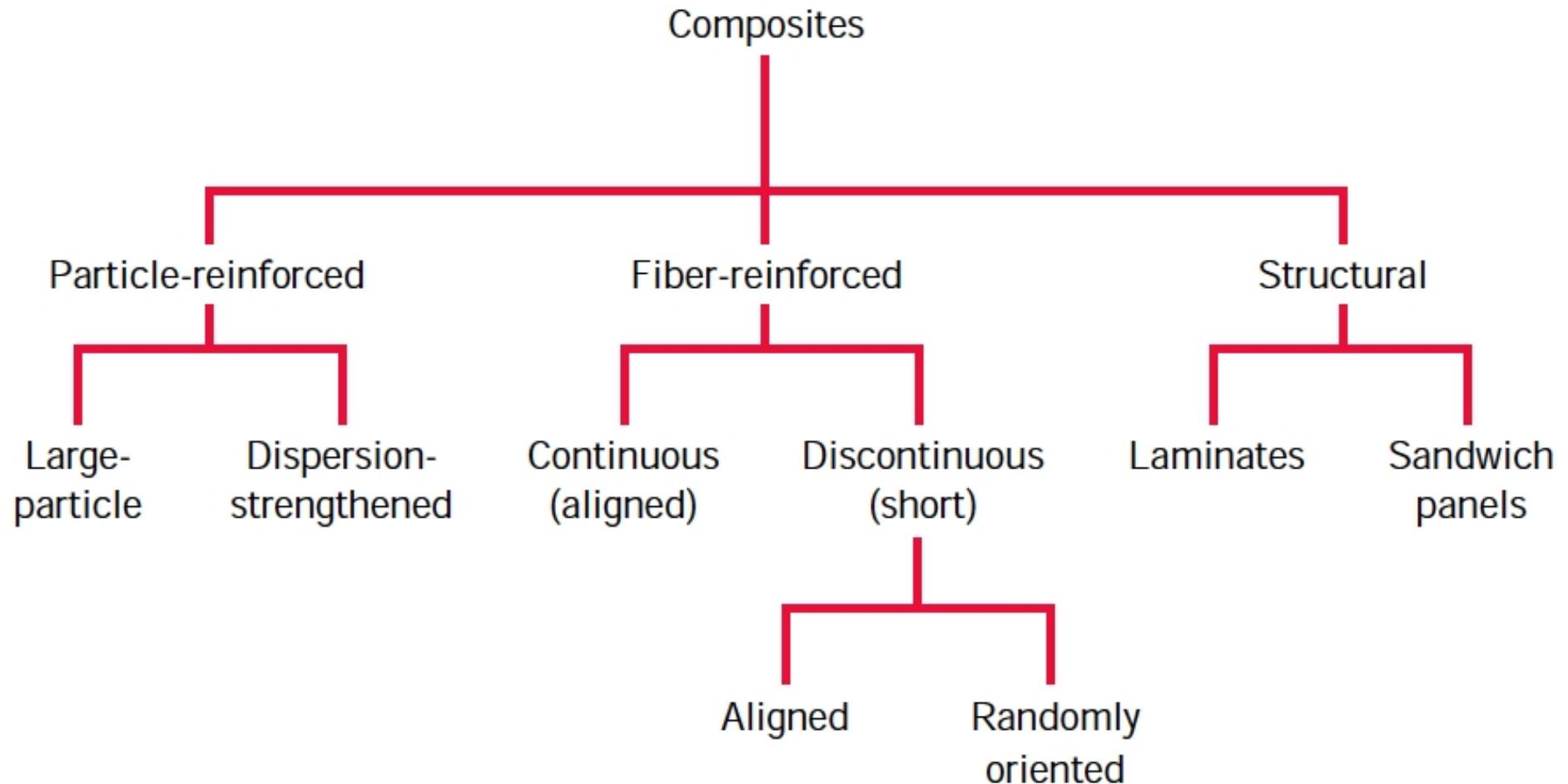
Composite Materials

- A **composite** is considered to be any multiphase material that exhibits a significant proportion of the properties of both constituent phases such that a better combination of properties is realised.
- According to this **principle of combined action**, better property combinations are fashioned by the judicious combination of two or more distinct materials.
- A composite, in the present context, is a multiphase material that is **artificially made**, as opposed to one that occurs or forms naturally.
 - In addition, the constituent phases must be **chemically dissimilar** and separated by a **distinct interface**.
 - Thus, most metallic alloys and many ceramics do not fit this definition because their multiple phases are formed as a consequence of natural phenomena.

Composite Phases

- Many composite materials are composed of just two phases:
 - The **matrix**, which is continuous and surrounds the other phase.
 - The **dispersed** or **reinforcement** phase.
- The properties of composites are a function of the properties of the constituent phases, their relative amounts, and the geometry of the dispersed phase.
- The dispersed phase may be a fibre, a whisker, a particle or a layer.
- Both the matrix and dispersed phases may be metals, polymers or ceramics.

Composite Classification



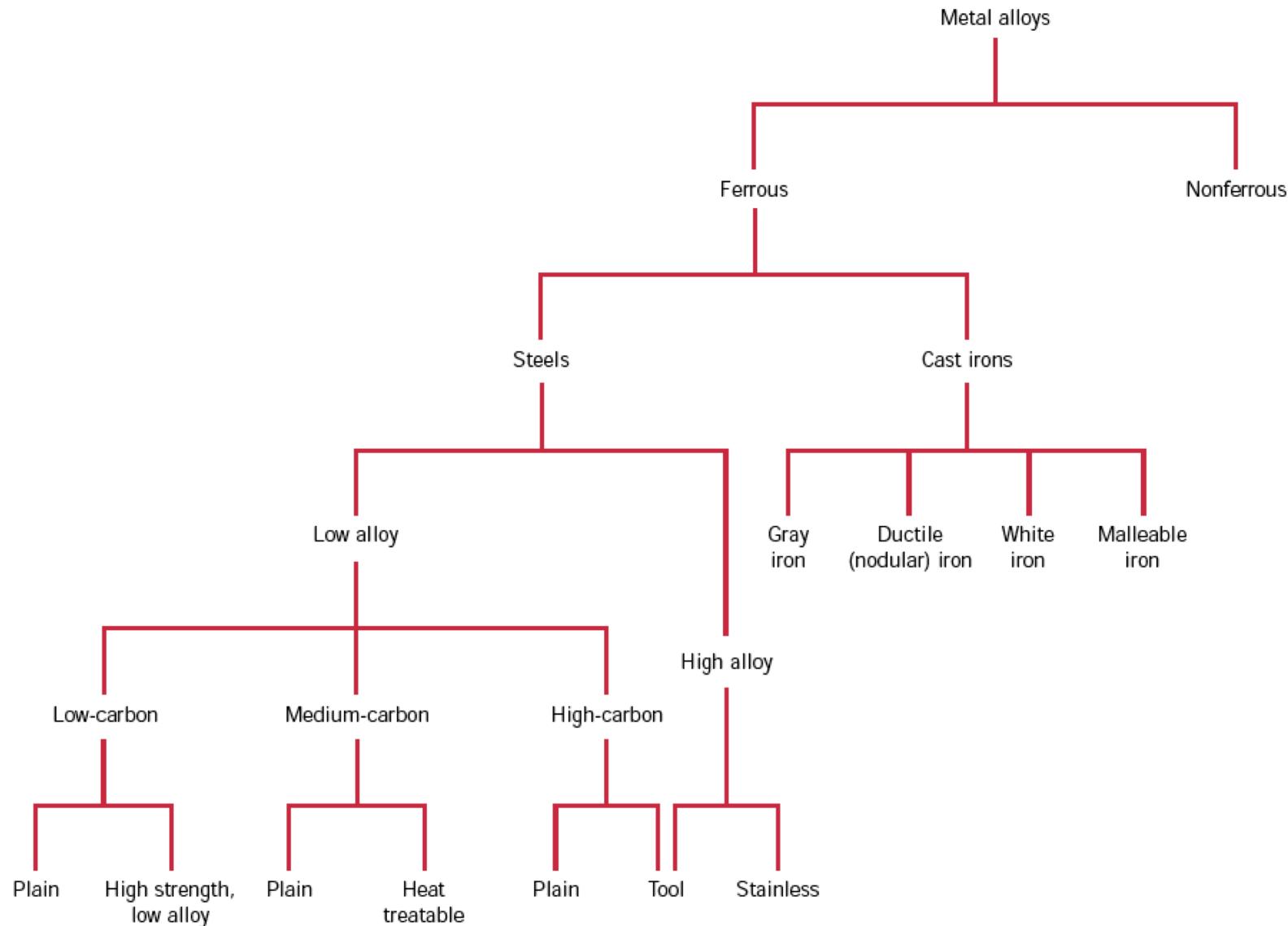
Composite Mechanical Properties

- The strengths of continuous and unidirectional fibrous composites are highly anisotropic. Such composites are normally designed to be loaded along the high-strength, longitudinal direction.
- Transverse tensile loads may also be present. Under these circumstances, premature failure may result inasmuch as transverse strength is usually extremely low—it sometimes lies below the tensile strength of the matrix. Thus, in actual fact, the reinforcing effect of the fibers is a negative one.

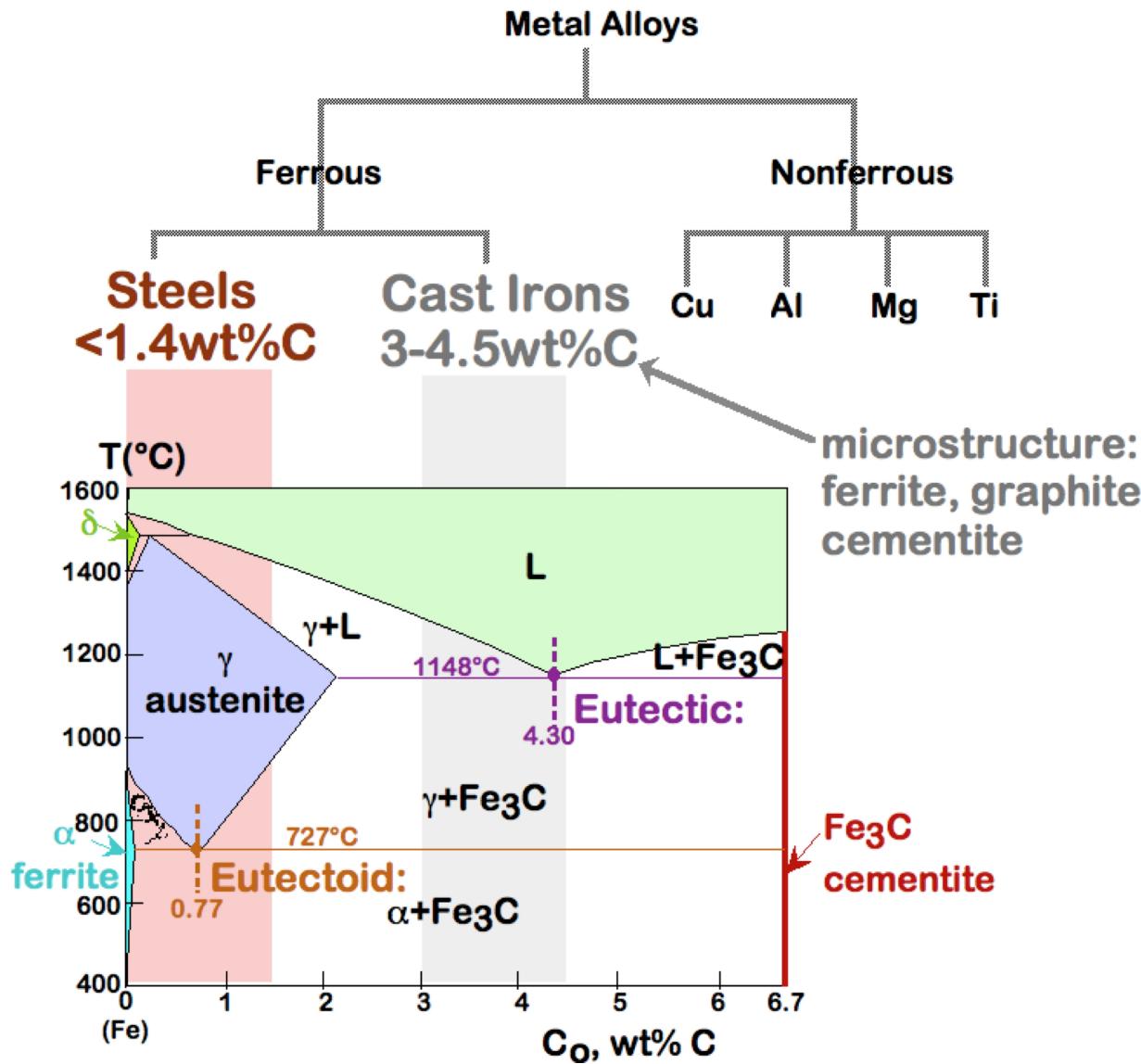
Material	Longitudinal Tensile Strength (MPa)	Transverse Tensile Strength (MPa)
Glass–Polyester	700	20
Carbon (High Modulus)–Epoxy	1000	35
Kevlar–Epoxy	1200	20

Source: D. Hull and T. W. Clyne, *An Introduction to Composite Materials*, 2nd edition, Cambridge University Press, 1996, p. 179.

Classification of Metals



Classification of Ferrous Alloys



Classification of Steels

	Low Alloy			High Alloy	
	low carbon <0.25wt%C	med carbon 0.25-0.6wt%C	high carbon 0.6-1.4wt%C		
Name	plain	HSLA	plain	heat treatable	plain
Additions	none	Cr, V Ni, Mo	none	Cr, Ni Mo	none
Example	1010	4310	1040	4340	1095
Hardenability	0	+	+	++	++
TS	-	0	+	++	+
EL	+	+	0	-	-
Uses	auto struc. sheet	bridges towers press.	crank shafts bolts	pistons gears wear hammers applic.	wear applic. blades
					drills saws dies
					high T applic. turbines furnaces V. corros. resistant

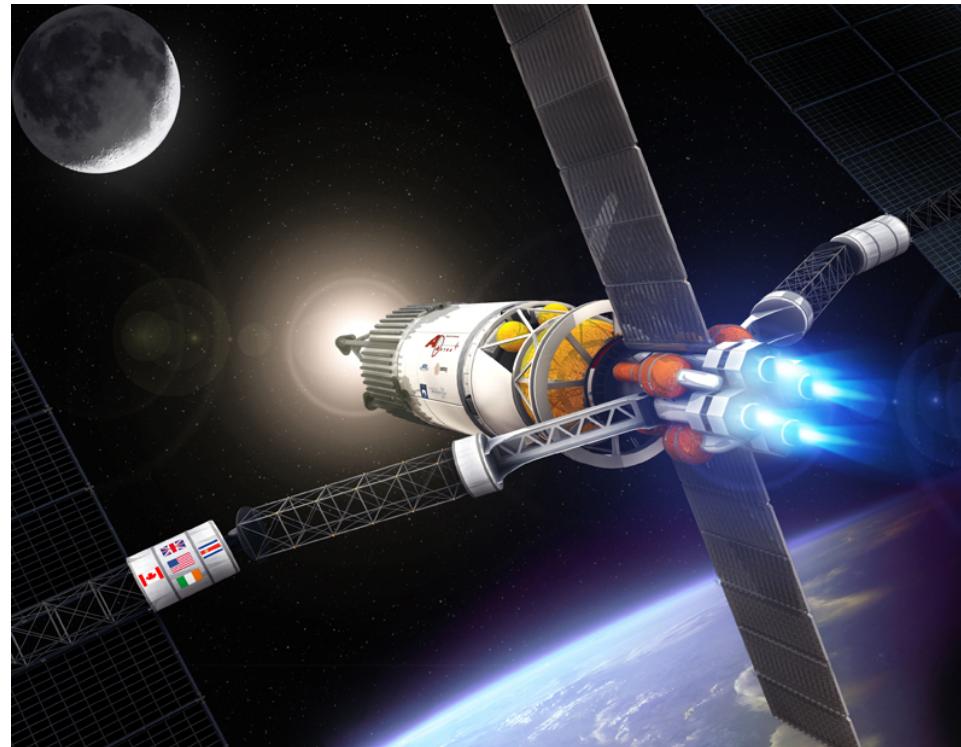
→ increasing strength, cost, decreasing ductility

Thermal Properties (1)

- Materials selection decisions for components that are exposed to **elevated/subambient temperatures, temperature changes, and/or thermal gradients** require the design engineer to have an understanding of the thermal responses of materials.
- The “**thermal properties**” of a material are its responses to the application of heat.
- As a solid absorbs energy in the form of heat, its temperature rises and its dimensions increase.
- The energy may be transported to cooler regions of the specimen if temperature gradients exist, and ultimately, the specimen may melt.

Thermal Properties (2)

- The properties that are often critical in the practical utilization of solids are:
 - **Heat capacity**
 - **Thermal expansion**
 - **Thermal conductivity**



Heat Capacity

- A solid material, when heated, experiences an **increase in temperature** signifying that some **energy has been absorbed**.
- **Heat capacity** is a property that is indicative of a materials ability to absorb heat from the external surroundings; it represents the amount of energy required to produce a unit temperature rise.
- The heat capacity C is expressed as follows:

$$C = \frac{dQ}{dT} \quad (1)$$

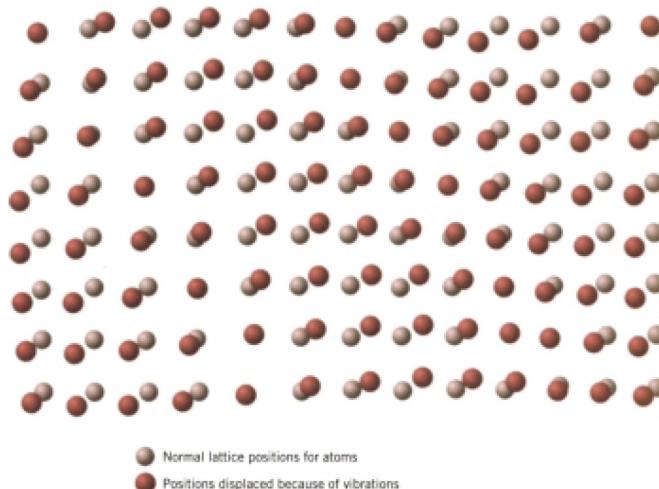
where dQ is the energy required to produce a dT temperature change.

- Ordinarily, *specific* heat capacity is specified per mole⁶ of material: e.g., J/mol-K, or cal/mol-K.

⁶Concentration of liquid solutions is often expressed in terms of molarity, M , the number of moles of solute per million cubic millimeters (10^6mm^3 , or 1000cm^3) of solution.

The Physical Basis for Heat Capacity

- In most solids the principal mode of thermal energy assimilation is by the increase in vibrational energy of the atoms.
 - **In a material heat is atomic vibration.**
- Atoms in solid materials are constantly vibrating at very high frequencies and with relatively small amplitudes.
- The vibrations of adjacent atoms are coupled by virtue of the atomic bonding.



Phonons

- These vibrations are coordinated in such a way that **traveling lattice waves** are produced:
 - These may be thought of as elastic waves or simply sound waves, having short wavelengths and very high frequencies, which propagate through the crystal at the velocity of sound.
 - The **vibrational thermal energy** for a material consists of a series of these elastic waves, which have a range of distributions and frequencies.
- Only certain energy values are allowed (the energy is said to be quantized), and a single quantum of vibrational energy is called a **phonon**.
- The thermal scattering of free electrons during **electronic conduction** is by these vibrational waves, and these elastic waves also participate in the transport of energy during **thermal conduction**.

Thermal Expansion (1)

- Accurate knowledge of thermal expansion coefficients at elevated temperatures is critical for material processing and prediction of thermal stresses for mechanical design.
- The rate of change of specific volume of most materials typically increases with increasing temperature, leading to increasing issues of thermal stress at elevated temperatures.
- The dilation of a material with temperature may be characterised by the rate of change of a linear dimension of the material, referred to the instantaneous length of that dimension, termed the *true instantaneous* coefficient of thermal expansion, α' (COTE) such that:

$$\alpha' = \frac{1}{L_T} \frac{\partial L}{\partial T} \quad (2)$$

where L_T is the length of the specimen at temperature T .

Thermal Expansion (2)

- A more commonly used procedure is to express thermal dilation as the rate of change of linear dimension with temperature, referred to the specimen's linear dimension at some reference temperature, such as 0° or 25° :

$$\alpha = \frac{1}{L_0} \frac{\partial L}{\partial T} \quad (3)$$

where L_0 is the linear dimension at the reference temperature.

- As the absolute change in dimension of the specimen will be very small, the instantaneous COTE referred to a reference temperature (α) will be an excellent approximation to the true instantaneous COTE (α').

Thermal Expansion (3)

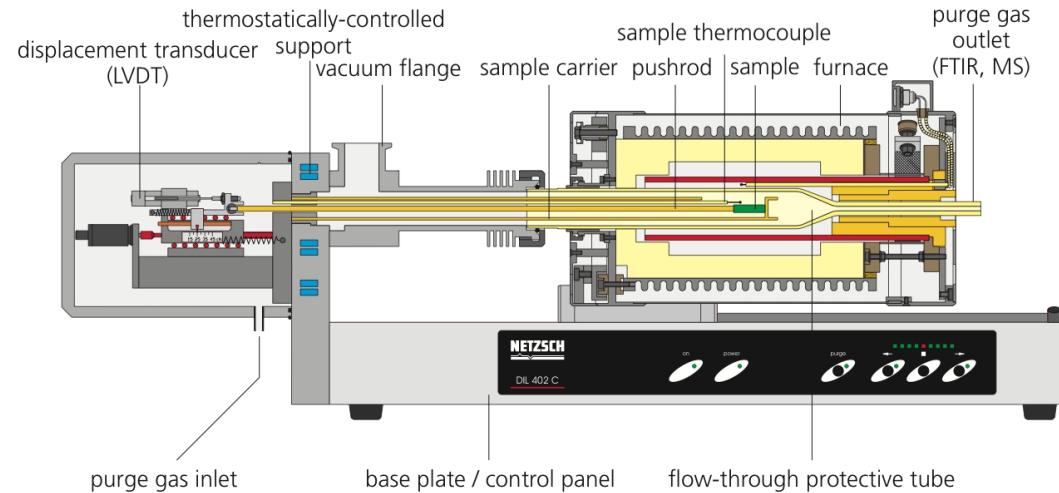
- Thermal dilation is also commonly expressed as an average coefficient of thermal expansion between a reference temperature, such as 0° or 25°, and a specified higher temperature:

$$\bar{\alpha} = \frac{1}{L_0} \frac{L - L_0}{T - T_0} \quad (4)$$

where L_0 is the linear dimension at the reference temperature T_0 .

- Care must be taken when dealing with COTE data, to distinguish between instantaneous and average values.
- Precise experimental values are obtained using a **dilatometer**.

Dilatometry



www.netzsch-thermal-analysis.com Accessed 05/01/2011.

Thermal Conductivity

- Thermal conduction is the phenomenon by which heat is transported from high to low-temperature regions of a substance.
- The property that characterizes the ability of a material to transfer heat is the **thermal conductivity**.
- It is best defined in terms of the expression:

$$q = -k \frac{dT}{dx} \quad (5)$$

where q is the *heat flux*, or heat flow, per unit time per area (where the area is perpendicular to the direction of heat flow), k is the thermal conductivity and dT/dx is the *temperature gradient* through the conducting medium.

- The units of q and k are W/m^2 and $\text{W/m}\cdot\text{K}$, respectively.
- Equation 5 is valid only for steady-state heat flow: i.e. for situations in which the heat flux does not change with time.
- The minus sign in the expression indicates that the direction of heat flow is from hot to cold, or down the temperature gradient.

Mechanisms of Heat Conduction

- Heat is transported in solid materials by both lattice vibration waves (**phonons**) and **free electrons**.
- A thermal conductivity is associated with each of these mechanisms, and the total conductivity is the sum of the two contributions, or:

$$k = k_l + k_e \quad (6)$$

where k_l and k_e are the lattice vibration and electron thermal conductivities, respectively (and usually one of these dominates).

- The k_l contribution results from a net movement of phonons from high- to low-temperature regions of a body across which a temperature gradient exists.

Mechanisms of Heat Conduction: Free Electron Contribution

- Free or conducting electrons participate in **electronic thermal conduction**.
- A gain in kinetic energy is imparted to the free electrons in a hot region of the specimen.
- They then migrate to colder areas, where some of this kinetic energy is transferred to the atoms themselves (as vibrational energy) as a consequence of collisions with phonons or other imperfections in the crystal.
- The relative contribution of k_e to the total thermal conductivity increases with increasing free electron concentrations, since more electrons are available to participate in this heat transference process.

Conductivities of Materials Types

Metals In high-purity metals, the electron mechanism of heat transport is much more efficient than the phonon contribution because electrons are not as easily scattered as phonons and have higher velocities. Furthermore, metals are extremely good conductors of heat because relatively large numbers of free electrons exist that participate in thermal conduction.

Ceramics Nonmetallic materials are thermal insulators inasmuch as they lack large numbers of free electrons. Thus the phonons are primarily responsible for thermal conduction: k_e is much smaller than k_l .

Polymers For these materials, energy transfer is accomplished by the vibration and rotation of the chain molecules. Polymers are often utilized as thermal insulators because of their low thermal conductivities. As with ceramics, their insulative properties may be further enhanced by the introduction of small pores, which are ordinarily introduced by foaming during polymerization. Foamed polystyrene (Styrofoam) is commonly used for drinking cups and insulating chests.