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Engineering Materials

Introduction:-

Materials science, also commonly known as materials science and engineering, is an interdisciplinary field which deals with the discovery and design of new materials. This relatively new scientific field involves studying materials through the materials paradigm (synthesis, structure, properties and performance). It incorporates elements of physics and chemistry, and is at the forefront of nano science and nanotechnology research. In recent years, materials science has become more widely known as a specific field of science and engineering.

Importance of Materials:-

A material is defined as a substance (most often a solid, but other condensed phases can be included) that is intended to be used for certain applications. There are a myriad of materials around us—they can be found in anything from buildings to spacecrafts. Materials can generally be divided into two classes: crystalline and non-crystalline. The traditional examples of materials are metals, ceramics and polymers. New and advanced materials that are being developed include semiconductors, nano materials, biomaterials etc.

Why Study Materials Science and Engineering :-

• To be able to select a material for a given use based on considerations of cost and performance.

• To understand the limits of materials and the change of their properties with use.

• To be able to create a new material that will have some desirable properties.

All engineering disciplines need to know about materials. Even the most immaterial like software or system engineering depend on the development of new materials,

which in turn alter the economics, like software-hardware trade-offs. Increasing applications of system engineering are in materials manufacturing (industrial engineering) and complex environmental systems.

Classification of Engineering material

The factors which form the basis of various systems of classifications of materials in material science and engineering are:

(i)   the chemical composition of the material,

(ii) the mode of the occurrence of the material in the nature,

(ii)   the refining and the manufacturing process to which the material is subjected prior it acquires the required properties,

(iv) the atomic and crystalline structure of material and

(v) the industrial and technical use of the material.

Common engineering materials that fall within the scope of material science and engineering may be classified into one of the following six groups:

(1) Metals (ferrous and non-ferrous) and alloys

(2) Ceramics

(3i) Polymers

(4) Composites

Why Material Science & Engineering is important to technologists?

• Mechanical engineers search for high temp material so that gas turbines, jet engines etc can operate more efficiently and wear resistance materials to manufacture bearing materials

• Electrical engineers search for materials by which electrical devices or machines can be operated at a faster rate with minimum power losses

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• Aerospace & automobile engineers search for materials having high strength-toweight

ratio

• Electronic engineers search for material that are useful in the fabrication & miniaturization of electronic devices

• Chemical engineers search for highly corrosion-resistant materials

PROPERTIES OF MATERIALS:-

Different materials possess different properties in varying degree and therefore behave in different ways under given conditions. These properties include Mechanical properties, Electrical properties, Thermal properties, Chemical properties, Magnetic properties and Physical properties. A design engineer is interested in the behavior of materials under load which is mechanical in nature, for the design of machines & structures. Any material subjected to a load either deforms, yield, or break, depending upon the magnitude of the load. We are basically interested in knowing as to how a particular material will behave under applied load i.e. in knowing the mechanical properties.

Properties of Engineering Materials

It is possible to classify material properties as follows - :

1- Physical properties:

Density, specific gravity, porosity, water absorption, etc....

2- Mechanical properties:

Tensile strength, compressive strength, rigidity, hardness. Creep, fatigue ...... etc.

3- Thermal properties:

Thermal conductivity, thermal expansion and other.......

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4- Chemical properties:

Resistance to acids, alkalis, brines and oxidation.

5- Electrical properties
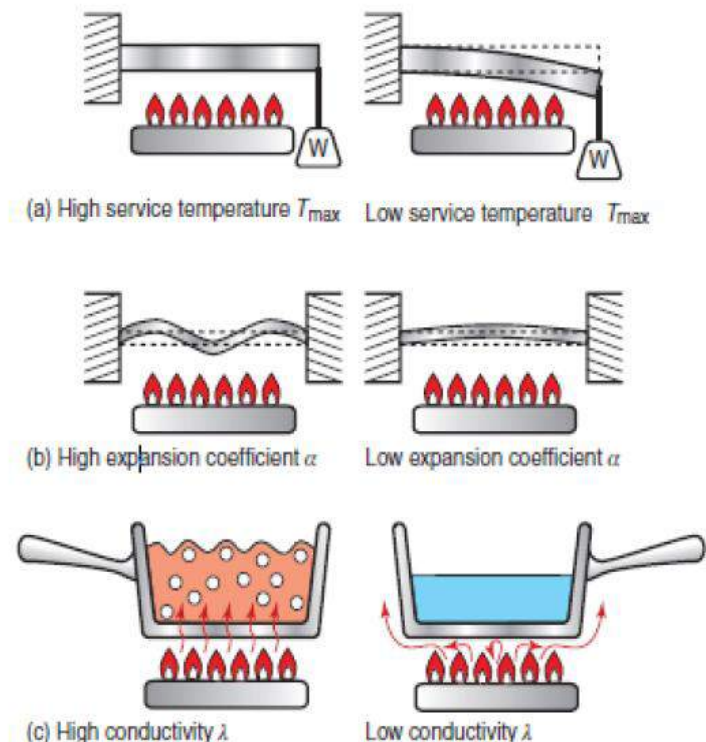
6- Magnetic properties

7- Economic characteristics:

Cost savings

8- Aesthetic properties:

Color, surface smoothness, the reflection of light

Thermal properties

The properties of a material change with temperature, usually for the worse. Its strength falls, it starts to 'creep' (to sag slowly over time), and it may oxidize, degrade or decompose (Figure). This means that there is a limiting temperature called the *maximum service temperature*, Tmax, above which its use is impractical. Stainless steel has a high Tmax—it can be used up to 800°C; most polymers have a low Tmax and are seldom used above 150°C.

(a) High service temperature T_{max} Low service temperature T_{max}

(b) High expansion coefficient α Low expansion coefficient α

(c) High conductivity λ Low conductivity λ

MECHANICAL PROPERTIES:-

Those characteristics of the materials which describe their behavior under external loads are known as Mechanical Properties. The most important and useful mechanical properties are:
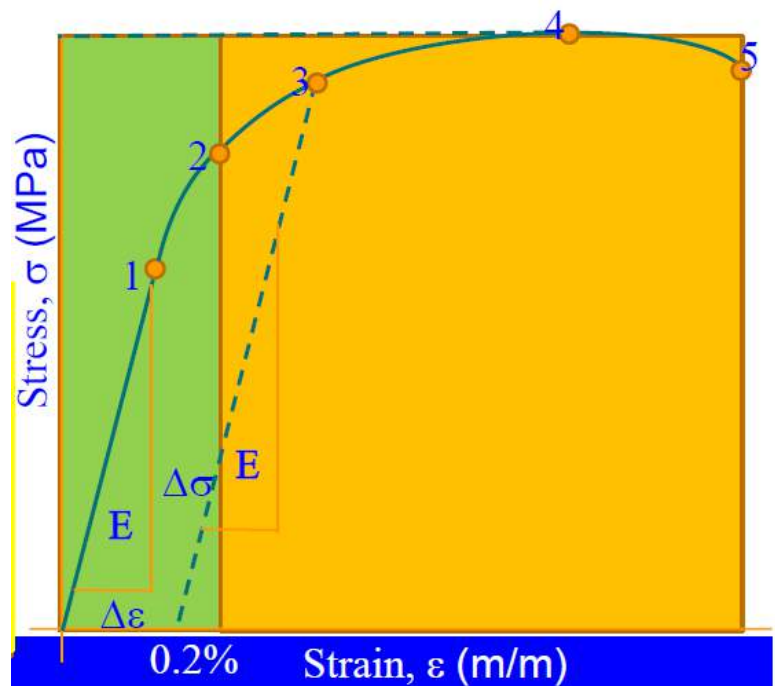
Stress-Strain Curves

Strength:-

It is the resistance offered by a material when subjected to external loading. So, stronger the material the greater the load it can withstand. Depending upon the type of load applied the strength can be tensile, compressive, shear or torsion. The maximum stress that any material will withstand before destruction is called its ultimate strength. (Point d)

Elasticity:-

Elasticity of a material is its power of coming back to its original position after deformation when the stress or load is removed. Elasticity is a tensile property of its material. The greatest stress that a material can endure without taking up some permanent set is called elastic limit. (Point a).

Stiffness (Rigidity):-

The resistance of a material to deflection is called stiffness or rigidity. Steel is stiffer or more rigid than aluminum. Stiffness is measured by Young's modulus E. The higher the value of the Young's modulus, the stiffer the material. E is the ratio of stress over strain and is given by the slope of line 0-a.

Plasticity:-

The plasticity of a material is its ability to undergo some degree of permanent deformation without failure. Plastic deformation will take place only after the elastic range has been exceeded, beyond point b. Plasticity is an important property and widely used in several mechanical processes like forming, shaping, extruding and many other hot and cold working processes. In general, plasticity increases with increasing temperature and is a favorable property of material for secondary forming Processes.

Due to these properties various metals can be transformed into different products of required shape and size. This conversion into desired shape and size is effected either by the application of pressure, heat or both.

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Ductility:-

Ductility of a material enables it to draw out into thin wire on application of the load. Mild steel is a ductile material. The wires of gold, silver, copper, aluminum, etc. are drawn by extrusion or by pulling through a hole in a die due to the ductile property. The ductility decreases with increase of temperature. The per cent elongation and the reduction in area in tension is often used as empirical measures of ductility.

Malleability:-

Malleability of a material is its ability to be flattened into thin sheets without cracking by hot or cold working. Aluminum, copper, tin, lead, steel, etc. are malleable metals. Lead can be readily rolled and hammered into thin sheets but can not be drawn into wire. Ductility is a tensile property, whereas malleability is a compressive property. Malleability increases with increase of temperature.

Brittleness:-

The brittleness of a material is the property of breaking without much permanent distortion. There are many materials, which break or fail before much deformation take place. Such materials are brittle e.g., glass, cast iron. brittle materials is only a fraction of their compressive strength. A brittle material should not be considered as lacking in strength. It only shows the lack of plasticity. On stress-strain diagram, these materials don't have yield point and value of E is small.

Toughness:-

The toughness of a material is its ability to withstand both plastic and elastic deformations. It is a highly desirable quality for structural and machine parts to

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withstand shock and vibration. Manganese steel, wrought iron, mild steels are tough materials. For Ex: If a load is suddenly applied to a piece of mild steel and then to a piece of glass the mild steel will absorb much more energy before failure occurs. Thus, mild steel is said to be much tougher than a glass.

Toughness is a measure of the amount of energy a material can absorb before actual fracture or failure takes place. "The work or energy a material absorbs is called modulus of toughness" Toughness is also resistance to shock loading. It is measured by a special test on Impact Testing Machine.

Hardness:-

Definition Hardness is a resistance to deformation. (for people who are concerned with mechanics of materials, hardness is more likely to mean the resistance to indentation)
Hardness tests can be used for many engineering applications to achieve the basic

requirement of mechanical property.

• For examples

 surface treatments where surface hardness has been much improved.

   Powder metallurgy

 Fabricated parts: forgings, rolled plates, extrusions, machined parts.

Hardness is closely related to strength. It is the ability of a material to resist scratching, abrasion, indentation, or penetration. It is directly proportional to tensile strength and is measured on special hardness testing machines by measuring the resistance of the material against penetration of an indenter of special shape and material under a given load. The different scales of hardness are Brinell hardness, Rockwell hardness, Vicker's hardness, etc.

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Hardness of a metal does not directly relate to the hardenability of the metal. Hardenability is indicative of the degree of hardness that the metal can acquire through the hardening process. i.e., heating or quenching.
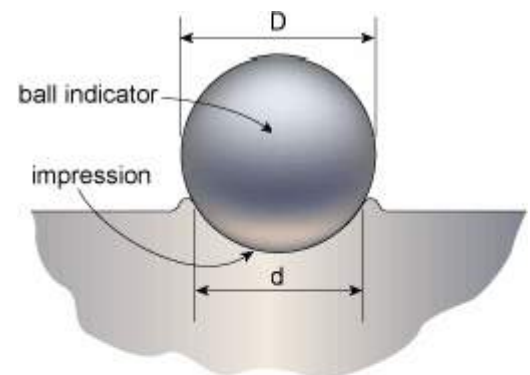
Briinell hardness

• J.A. Brinell introduced the first standardised indentation-hardness test in 1900. The Brinell hardness test consists in indenting the metal surface with a 10-mm diameter steel ball at a load range of 500-3000 kg, depending of hardness of particular materials.

• The load is applied for a standard time (~30 s), and

the diameter of the indentation is measured.

giving an average value of two readings of the diameter of the indentation at right angle.

• The Brinell hardness number (BHN or HB) is expressed as the load P divided by surface area of the indentation

(a) Brinell indentation
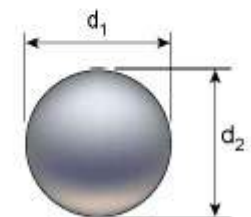
(b) measurement of impression diameter

$$BHN = \frac{P}{(\pi D / 2)\left(D - \sqrt{D^2 - d^2}\right)} = \frac{P}{\pi D t}$$

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Where :-

P : is applied load, kg

D : is diameter of ball, mm

D : is diameter of indentation, mm

T : is depth of the impression, mm

Advantages and disadvantages of Brinell hardness test

• Large indentation averages out local heterogeneities of microstructure.

• Different loads are used to cover a wide rage of hardness of commercial metals.

• Brinell hardness test is less influenced by surface scratches and roughness than other hardness tests.

• The test has limitations on small specimens or in critically stressed parts where indentation could be a possible site of failure.
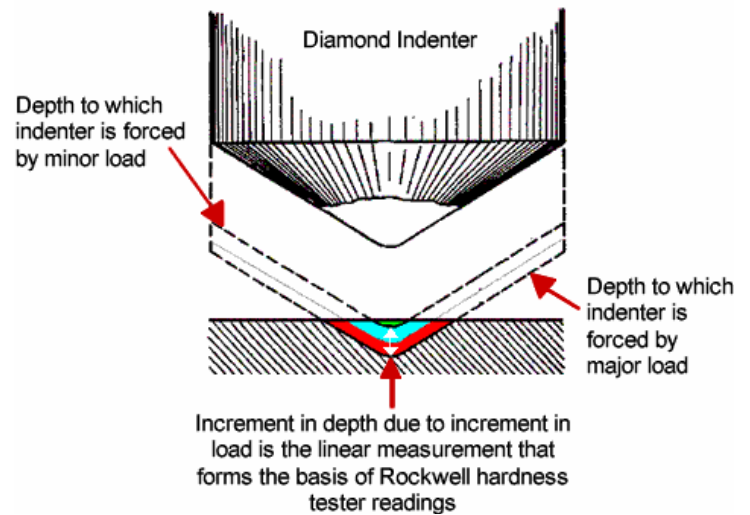
$$HB = \frac{2F}{\pi D (D - \sqrt{D^2 - d^2})}$$
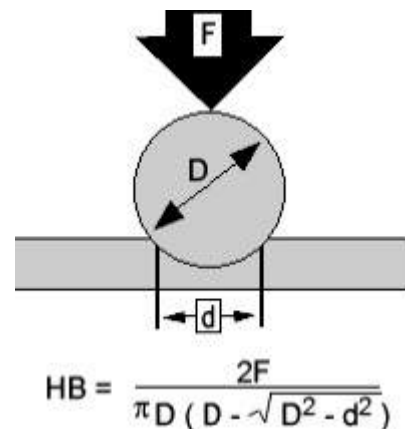
## Rockwell hardness test:-

Principal of the Rockwell Test

• Position the surface area to be measured close to the indenter.

• Applied the minor load and a zero reference position is established

• The major load is applied for a specified time period (dwell time) beyond zero

• The major load is released leaving the minor load applied.

The Rockwell number represents the difference in depth from the zero reference position as a result of the applied major load. Deeper indentation

Depth to which indenter is forced by minor load

Diamond Indenter

Depth to which indenter is forced by major load

Increment in depth due to increment in load is the linear measurement that forms the basis of Rockwell hardness tester readings

Rockwell hardness scale:-

Rockwell hardness number (RHN) represents in different scale, A, B, C,.. depending on types of indenters and major loads used
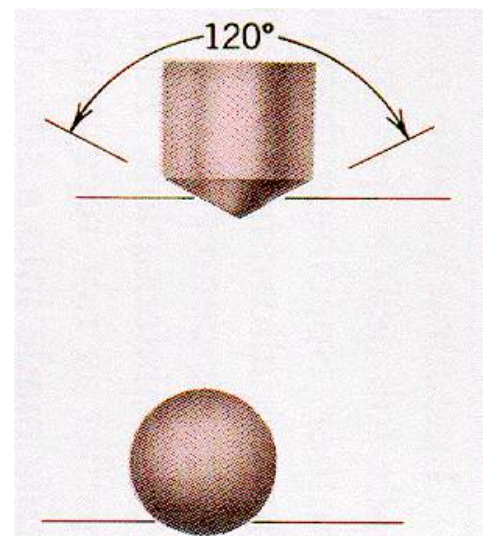
Scale	Indenter	Load (kg.f)	Scale
A	Brale	60	HRA
B	1/16'' steel ball	100	HRB
C	Brale	150	HRC

• The Hardened steel is tested on the C scale with Rc20-70.

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• Softer materials are tested on the B scale with Rb30-100.

Vickers hardness :-

Vickers hardness test uses the loads ranging from 1-120 kgf, applied for between 10 and 15 seconds.

• Provide a fairly wide acceptance for research work because it provides a continuous scale of hardness, for a given load.

• VHN = 5-1,500 can be obtained at the same load level   easy

Impressions made by Vickers hardness

• A perfect square indentation (a) made with a perfect diamond pyramid indenter would be a square.

• The pincushion indentation (b) is the result of sinking in of the metal around the flat faces of the pyramid. This gives an overestimate of the diagonal length (observed in annealed metals).

• The barrel-shaped indentation (c) is found in cold-worked metals, resulting from ridging or piling up of the metal around the faces of the indenter. Produce a low value of contact area   giving too high value

Microhardness:-

Determination of hardness over very small areas for example individual constituents, phases, requires hardness testing machines in micro or sub-micro scales.

- Vickers hardness can also be measured in a microscale, which is based on the same fundamental method as in a macroscale.

- The Knoop indenter (diamondshape) is used for measuring in a small

area, such as at the cross section of the heat-treated metal surface.

- The Knoop hardness number (KHN) is the applied load divided by the

unrecovered projected area of the indentation

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Fatigue of metals

Fatigue : failure under applied cyclic stress. Fatigue failures are widely studies because it accounts for 90% of all service failures due to mechanical causes. Fatigue failures occur when metal is

subjected to a repetitive or fluctuating stress and will fail at a stress much lower than its tensile strength.

• Fatigue failures occur without any plastic deformation (no warning).

• Fatigue surface appears as a smooth region, showing beach mark or origin of fatigue crack.

Factors causing fatigue failure:-

Basic factors

- 1) A maximum tensile stress of sufficiently high value.

- 2) A large amount of variation or fluctuation in the applied stress.

- 3) A sufficiently large number of cycles of the applied stress.

Additional factors

- Stress concentration

- Corrosion

- Temperature

- Overload

- Metallurgical structure

- Residual stress

- Combined stress

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- Fatigue is an important form of behaviour in all materials including metals, plastics, rubber and concrete.

- All rotating machine parts are subjected to alternating stresses.

- Example: aircraft wings are subjected to repeated loads, oil and gas pipes are often subjected to static loads but the dynamic effect of temperature variation will cause fatigue.

- There are many other situations where fatigue failure will be very harmful.

- Because of the difficulty of recognizing fatigue conditions, fatigue failure comprises a large percentage of the failures occurring in engineering.

- To avoid stress concentrations, rough surfaces and tensile residual stresses, fatigue specimens must be carefully prepared

Stress cycles:

Types of fatigue loading:
- **1.Completely reversed cycle of stress:**
- **2. repeated stress cycles**
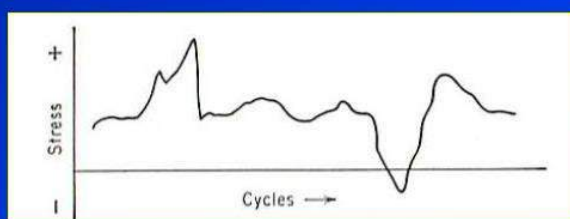- **3. irregular or random stress cycle:**

Different types of fluctuating stress
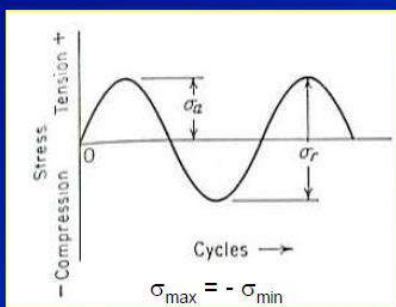
(a) Completely reversed cycle of stress (sinusoidal)
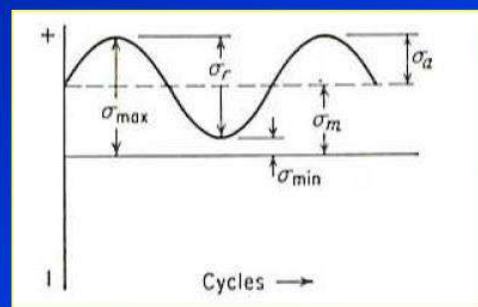
(b) Repeated stress cycle

Tensile stress +

Compressive stress -

Completely reversed cycle of stress:

Illustrates the type of fatigue loading where a member is subjected to opposite loads alternately with a means of zero.

For example bending of steel wire continuously in either direction leads to alternate tensile and compressive stresses on its surface layers and failure fatigue.

If the applied load changes from any magnitude in one direction to the same magnitude in the opposite direction, the loading is termed completely reversed Repeated stress cycles

Repeated stress cycles

Type of fatigue loading where a member is subjected to only tension but to various degrees.

A spring subjected to repeated tension as in a toy would lead to fatigue failure

Irregular or random stress cycle:

•   **This type of fatigue loading where a member could be subjected to**

   irregular loads just as in

   the case of an aircraft wing subjected to wind loads

   i.e if the load changes from one magnitude to another (the direction does not necessarily change), the load is said to be *fluctuating load*

CRACK INITIATION AND PROPAGATION

The process of fatigue failure is characterized by three distinct steps: (1) crack initiation, wherein a small crack forms at some point of high stress concentration; (2) crack propagation, during which this crack advances incrementally

with each stress cycle; and (3) final failure, which occurs very rapidly once the advancing crack has reached a critical size. Cracks associated with fatigue failure almost always initiate (or nucleate) on the surface of a component at some point of stress concentration. Crack nucleation sites include surface scratches, sharp fillets, keyways, threads, dents, and the like. In addition, cyclic loading can produce microscopic surface discontinuities resulting from dislocation slip steps that may also act as stress raisers, and therefore as crack initiation sites. The region of a fracture surface that formed during the crack propagation step may be characterized by two types of markings termed beach marks and striations. Both of these features indicate the position of the crack tip at some point in time and appear as concentric ridges that expand away from the crack initiation site(s), frequently in a circular or semicircular pattern. Beachmarks (sometimes also called "clamshell marks") are of macroscopic dimensions (Figure),
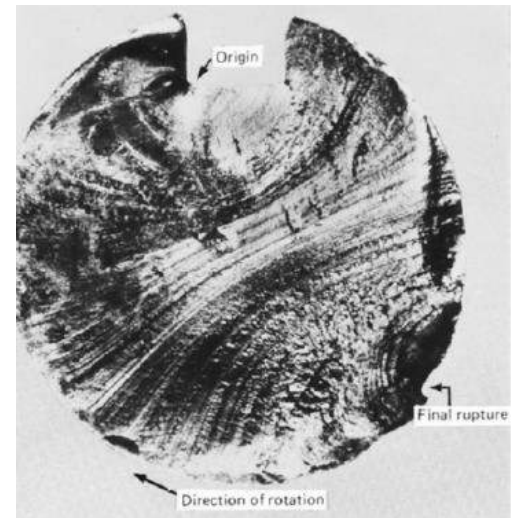
and may be observed with the unaided eye. These markings are found for components that experienced interruptions during the crack propagation stage—for example, a machine that operated only during normal work-shift hours. Each beachmark band represents a period of time over which crack growth occurred. On the other hand, fatigue striations are microscopic in size and subject to observation with the electron microscope (either TEM or SEM). Figure

an electron fractograph that shows this feature. Each striation is thought to represent the advance distance of a crack front during a single load cycle. Striation width depends on, and increases with, increasing stress range. At this point it should be emphasized that although both beachmarks and striations are fatigue fracture surface features having similar appearances, they are nevertheless different, both in origin and size. There may be literally thousands of striations within a single beachmark. Often the cause of failure may be deduced after examination of the failure surfaces. The presence of beachmarks and/or striations on a fracture surface confirms that the cause of failure was fatigue. Nevertheless, the absence of either or both does not exclude fatigue as the cause of failure. One final comment regarding fatigue failure surfaces: Beachmarks and striations will not appear on that region over which the rapid failure occurs. Rather, the rapid failure may be either ductile or brittle; evidence of plastic deformation will be present for ductile, and absent for brittle, failure. This region of failure may be noted in Figure

Region of slow crack propagation

2 cm

Region of rapid failure
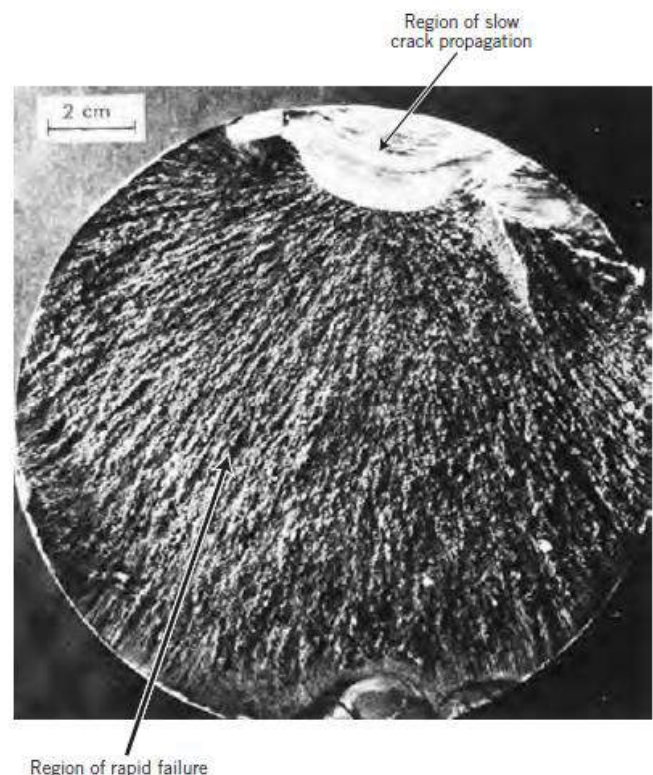
Definitions: Stress Ratios

The stress amplitude alternates about a mean stress σ_m, defined as the average of the maximum and minimum stresses in the cycle, or

Mean stress for cyclic loading—dependence on maximum and Minimum stress levels

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2}$$

Furthermore, the *range of stress* σ_r is just the difference between σ_{max} and σ_{min}— namely,

Computation of range of stress for cyclic loading

$$\sigma_r = \sigma_{max} - \sigma_{min}$$

Stress amplitude σ_a is just one half of this range of stress, or

Computation of stress amplitude for cyclic loading

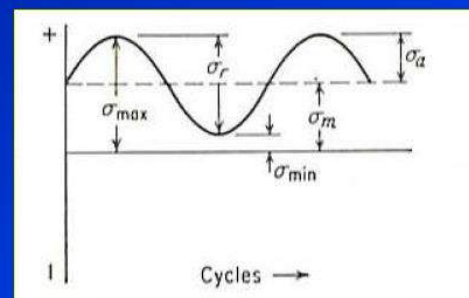$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{max} - \sigma_{min}}{2}$$

Finally, the stress ratio R is just the ratio of minimum and maximum stress amplitudes
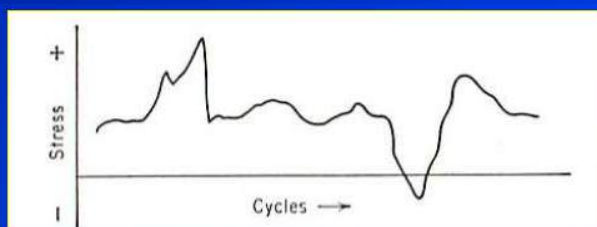
Computation of stress ratio

$$R = \frac{\sigma_{min}}{\sigma_{max}}$$
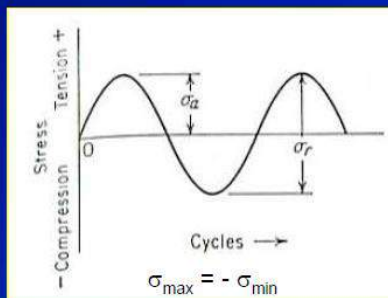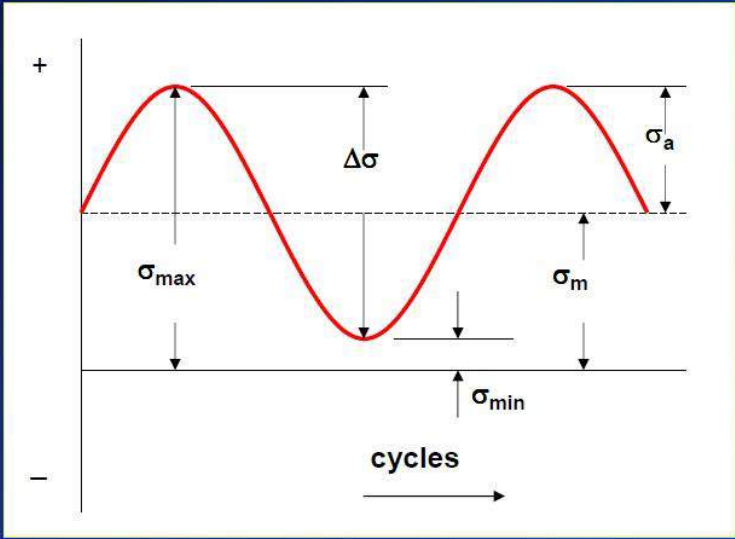

(a) Completely reversed cycle of stress (sinusoidal)

(b) Repeated stress cycle

(c) Irregular or random stress cycle

Tensile stress +

Compressive stress -

Nomenclature of stress parameter in fatigue loading

Maximum stress, σ_{max}

Minimum stress, σ_{min}

Stress range

$$\Delta\sigma \ \ or \ \ \sigma_r = \sigma_{max} - \sigma_{min} \qquad Eq.1$$

Alternating stress

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{max} - \sigma_{min}}{2} \qquad Eq.2$$

Mean stress

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \qquad Eq.3$$

Stress ratio

$$R = \frac{\sigma_{min}}{\sigma_{max}} \qquad Eq.4$$
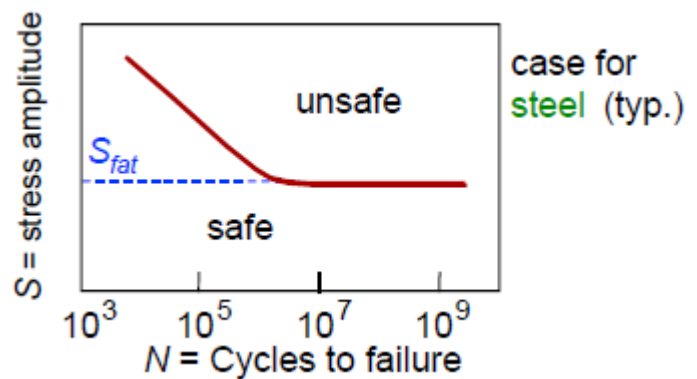
Amplitude ratio

$$A = \frac{\sigma_a}{\sigma_m} = \frac{1-R}{1+R} \qquad Eq.5$$
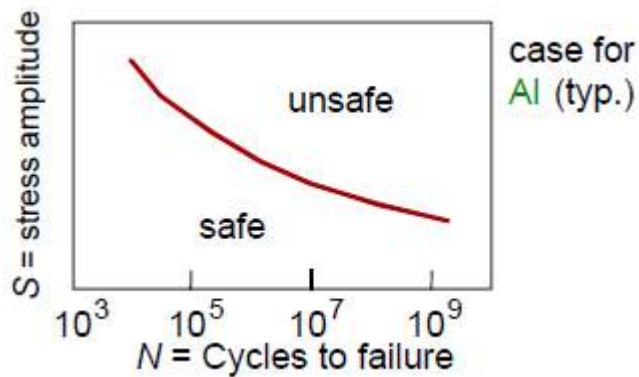
Fatigue stress cycle

The S-N curve

Engineering fatigue data is normally represented by means of S-N curve, a plot of stress S against the number of cycle, N.

• Stress can be _σa, σmax, σmin

• σm , R or A should be mentioned.

• S-N curve is concerned chiefly with fatigue failure at high numbers of cycles (N > 105 cycles) _ high cycle fatigue (HCF).

• N < 104 or 105 cycles _ low cycle fatigue (LCF).

• N increases with decreasing stress level.

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• Fatigue limit or endurance limit is normally defined at 107 or 108 cycles. Below this limit, the material presumably can endure an infinite number of cycle before failure.

• Nonferrous metal, i.e., aluminum, do not have fatigue limit _ fatigue strength is defined at ~ 108 cycles.

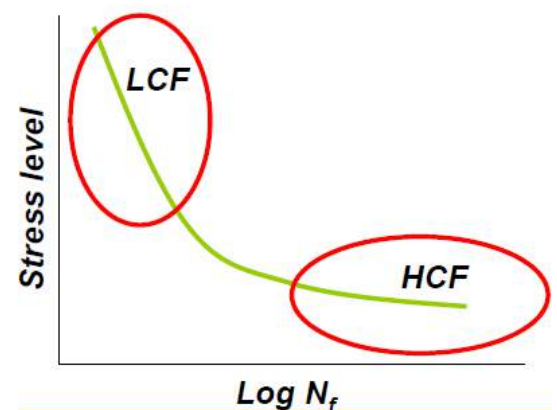## Basquin equation:-

The S-N curve in the high-cycle region is sometimes described by The Basquin equation

$$N\sigma_a^p = C$$

Where σ_a is the stress amplitude

p and C are empirical constants

HCF is High cycle (low strain) fatigue.

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**LCF** is Low cycle (high strain) fatigue

Construction of S-N curve:-

The construction of S-N curve normally requires ~ 8-12 specimens by first testing at a high level of stress ~ 2/3 of the tensile strength of the material.

• The test is then carried out at lower levels of stress until run out.

The data obtained is normally scattered at the same stress level by using several specimens.

• This requires statistic approach to define the fatigue limit
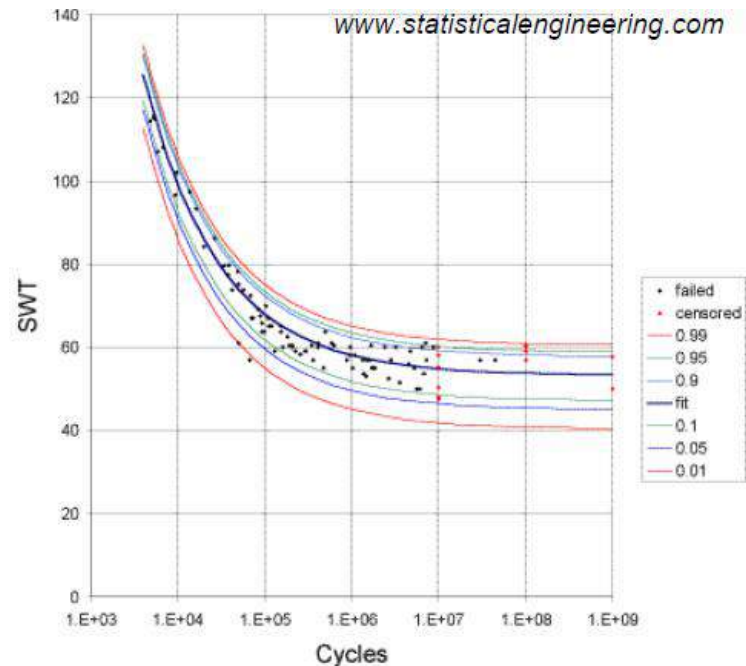
Statistical nature of fatigue:-

Because the S-N fatigue data is normally scattered, it should be therefore represented on a probability basis.

• Considerable number of specimens are used to obtain statistical parameters.

• At σ1, 1% of specimens would be expected to fail at N1 cycles.

• 50% of specimens would be expected to fail at N2 cyc

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For engineering purposes, it is sufficiently accurate to assume a logarithmic normal distribution of fatigue life in the region of the probability of failure of P = 0.10 to P = 0.90.

Note: The S-N fatigue data is more scattered at lower stress levels. Each specimen has its own fatigue limit
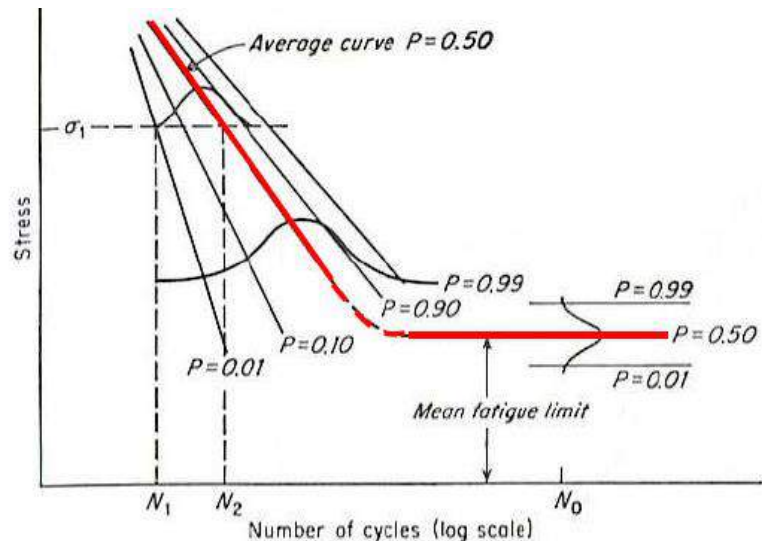
Effect of Mean Stress on Fatigue Life:

The mean stress σ_m can have an important effect on the fatigue strength of a material. For a given stress amplitude $\si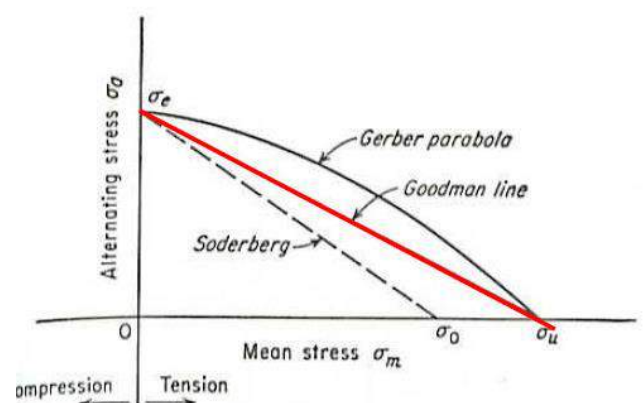gma_a$, as the mean stress increases, the fatigue life decreases Various empirical expressions have been proposed which take into account the effect of mean stress on fatigue life. Some of these are the following:

Haig-Solderberg diagram:-

In Haig-Solderberg diagram is a plot of alternating stress σ_a and mean stress σ_m.

• The Goodman relationship may be expressed by

Where x = 1 for the Goodman line,

x = 2 for the Gerber parabola,

σ_e = the fatigue limit for completely reversed loading.

• If the design is based on the yield strength

σ_o, (based on Solderberg line), then the σ_u is

replaced by σ_o in this equation

$$\sigma_a = \sigma_e\left[1 - \left(\frac{\sigma_m}{\sigma_u}\right)^x\right]$$

Classical Fatigue

The classical approach to fatigue, also referred to as Stress Controlled Fatigue or High Cycle Fatigue (HCF), through S/N or Wohler diagrams

In order to determine the strength of materials under the action of fatigue loads, specimens with polished surfaces are subjected to repeated or varying loads of specified magnitude while the stress reversals are counted up to the destruction point.

The number of the stress cycles to failure can be approximated by the

WOHLER or S-N DIAGRAM

Fatigue properties:

•　 Fatigue life (N): it is total number of cycles are required to bring about

final fracture in a specimen at a given stress.

- Fatigue life for a given condition is a property of the individual specimen

- and is arrived at after testing a number of specimens at the same stress.

Fatigue life for P % survival (N_p)

It is fatigue life for which P percent of samples tested have a longer life than the rest.

- For example, N_{90} is the fatigue life for which 90% of the samples would be expected to survive

and 10% to fail at a particular stress.

Median fatigue life:

- it is fatigue life for which 50 % of the population of samples fail

and the other 50 % survive at a particular stress

Fatigue strength (σ_n)

- It is stress at which a material can withstand repeatedly N number of

cycles before failure.

- OR it is the strength of a material for a particular fatigue life.

Fatigue limit or Endurance limit (σE):

- it is stress below which a material will not fail for any number of cycles.

- For ferrous materials it is approximately half of the ultimate tensile strength.

- For non-ferrous metal since there is no fatigue limit.

Endurance limit

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is taken to be the stress at which it endures, N number of cycles without failure

.N is usually taken as 5×10^8 cycles for non-ferrous metals.

Ex1/ fatigue test was conducted in which the m ean stress was 50 MPa and the stress amplitude was 225 MPa

  (a) Compute the maximum and minimum stress levels.

  (b) Compute the stress ratio.

  (c) Compute the magnitude of the stress range.

Solution

  (a) Given the values of σ_m (50 MPa) and σ_a (225 MPa) we are asked to compute σmax and σmin.

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} = 50 \text{ MPa}$$

$$\sigma_{max} + \sigma_{min} = 100 \text{ MPa}$$

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} = 225 \text{ MPa}$$

$$\sigma_{max} - \sigma_{min} = 450 \text{ MPa}$$

$$\sigma_{max} = 275 \text{ MPa}$$
$$\sigma_{min} = -175 \text{ MPa}$$

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$$R = \frac{\sigma_{min}}{\sigma_{max}} = \frac{-175 \ \text{MPa}}{275 \ \text{MPa}} = -0.64$$

$$\sigma_r = \sigma_{max} - \sigma_{min} = 275 \ \text{MPa} - (-175 \ \text{MPa}) = 450 \ \text{MPa} \ (65,500 \ \text{psi})$$

Ex2/ A cylindrical 1045 steel bar is subjected to repeated compression-tension stress cycling along its axis. If the load amplitude is 22,000 N, compute the minimum allowable bar diameter to en sure that fatigue failure will not occur. Assume a factor of safety of 2.0.

From the Tables , the fatigue limit stress amplitude for this alloy is

310 MPa (Stress is defined in Equation . $\sigma = \dfrac{F}{A_0}$. For a cylindrical bar

$$\sigma = \frac{F}{A_0} = \frac{F}{\pi \left(\dfrac{d_0}{2}\right)^2} = \frac{4F}{\pi d_0^2}$$

We now solve for d_0, taking stress as the fatigue limit divided by the factor of safety. Thus

$$d_0 = \sqrt{\frac{4F}{\pi \left(\dfrac{\sigma}{N}\right)}}$$

$$= \sqrt{\frac{(4)(22,000 \ \text{N})}{(\pi)\left(\dfrac{310 \times 10^6 \ \text{N/m}^2}{2}\right)}} = 13.4 \times 10^{-3} \ \text{m} = 13.4 \ \text{mm} \ (0.53 \ \text{in.})$$

Q1/ An 8.0 mm diameter cylindrical rod fabricated from a red brass alloy is subjected to reversed tension-compression load cycling along its axis. If the maximum tensile and compressive loads are +7500 N and - 7500 N respectively, determine .

(a) the maximum and minimum stress levels.

(b) the stress ratio.

(c) the magnitude of the stress range.

Q2/ Three identical fatigue specimens (denoted A, B, and C) are fabricated from a nonferrous alloy. Each is subjected to one of the maximum-minimum stress cycles listed below; the frequency is the same for all three tests

Specimen	σ_{max} (MPa)	σ_{min} (MPa)
A	+450	−350
B	+400	−300
C	+340	−340

(a) Rank the fatigue lifetimes of these three specimens from the longest to the shortest.
(b) Now justify this ranking using a schematic S–N plot.

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, and high-pressure steam lines). 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). Amorphous polymers, which include plastics and rubbers, are especially sensitive

to creep deformation .

WHAT IS CREEP

All materials under constant stress and temperature will exhibit an increase of strain with time called creep.

Creep is strain with time at constant load and temperature (time dependent strain).

Metals usually creep at temperature above 0.3 to 0.4 Tm, where Tm is the absolute melting temperature of the metal.

WHERE CREEP IS IMPORTANT:-

1-When a metal is subjected to high temperature, the creep is an important design

consideration.

2- In many mechanical application, like turbine blades, boiler, reactors, engine,

a designer must consider the creep
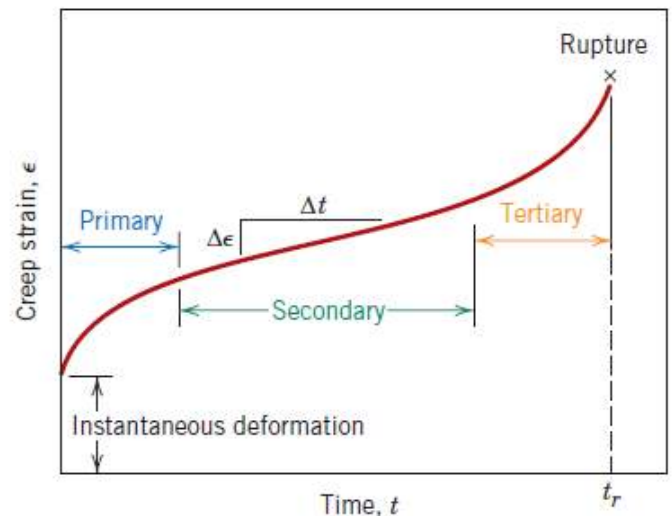
CREEP CURVE
1. Stage I: Primary Creep
   - _ Strain rate decreases as strain increases.Resistance to plastic deformation: strain hardening
2. Stage II: Secondary (steady-state) Creep *(used as design tool)*
   - Strain rate _ Strain rate minimum and constant _ Balance between recovery = strain hardening. Fracture will not occur.
3. Stage III: Tertiary Creep *(failure-rupture)_*
   - Strain rate increases. reduction in cross section al area due to voids, necking reduce

Creep Curve

• The slope of creep curve is referred to 'creep rate' $(d\varepsilon/dt)$

• instantaneous deformation : elastic deformation due to applied load and occurs at $T < 0.4\ T_m$.

• During the creep test, applied load is constant, thus the specimen will elongate and it cross sectional area will decrease.

1. Stage I: Primary Creep
 — Strain rate decreases as strain increases. Resistance to plastic deformation: strain hardening
 ➤ deformation becomes more difficult as the material is strained.

2. Stage II: Secondary (steady-state) Creep *(used as design tool)*
 — Strain rate minimum and constant
 — Balance between recovery = strain hardening. Fracture will not occur. The materials become softer and retains its ability to experience deformation

3. Stage III: Tertiary Creep *(failure-rupture)*
 — Strain rate increases. reduction in cross-sectional.
 — Failure, due to microstructure and/or metallurgical changes e.g. grain boundary separation and the formation of internal cracks, cavities and voids.

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Figure typical creep curve of strain versus time at constant stress and constant Elevated temperature. The minimum creep rate is the $\Delta\epsilon/\Delta t$ slope of the linear segment in the secondary region. Rupture lifetime t_r is the total time to rupture

STRESS AND TEMPERATURE EFFECTS

Both temperature and the level of the applied stress influence the creep characteristics (Figure follows). At a temperature substantially below $0.4T_m$, and after the Initial deformation, the strain is virtually independent of time. With either increasing Stress or temperature, the following will be noted: (1) the instantaneous strain At the time of stress application increases, (2) the steady-state creep rate is increased, And (3) the rupture lifetime is diminished
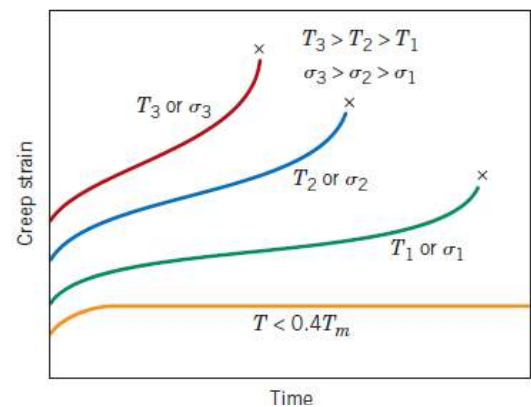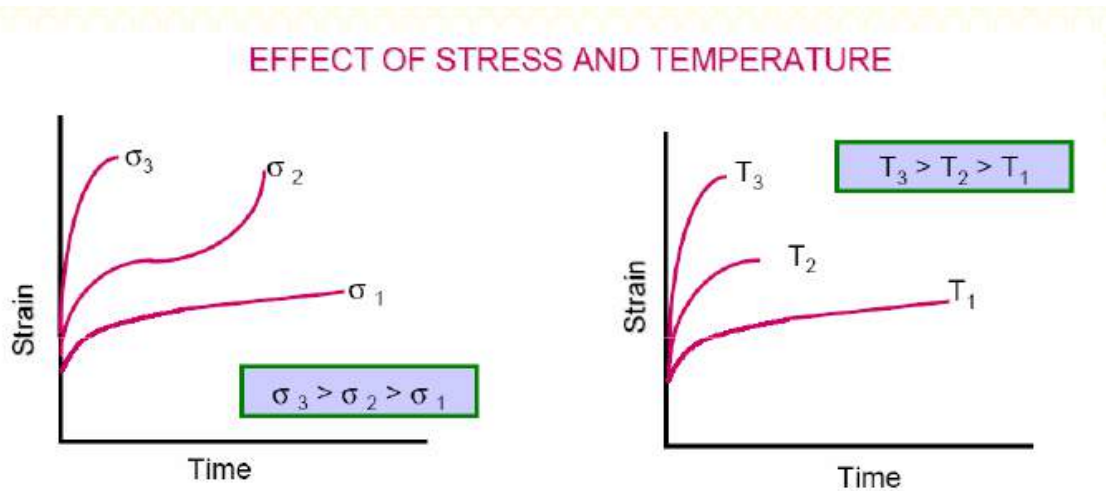
Figure Influence of stress δ and temperature T on creep behavior. The results of creep rupture tests are most commonly presented as the logarithmof stress versus the logarithm of rupture lifetime. Figure follows is one such plot for a nickel alloy in which a linear relationship can be seen to exist at each temperatur e.

EFFECT OF STRESS AND TEMPERATURE

For some alloys and over relatively large stress ranges, nonlinearity in these curves is observed.

Empirical relationships have been developed in which the steady-state creep rate as a function of stress and temperature is expressed. Its dependence on stress can be written

Dependence of creep strain rate on stress

$$\dot{\epsilon}_s = K_1 \sigma^n$$

Where K_1 and n are material constants. A plot of the logarithm of $\dot{\epsilon}_s$ versus the logarithm of σ yields a straight line with slope of n; this is shown in Figure 8.31 for a nickel alloy at three temperatures. Clearly, a straight line segment is drawn at each temperature.

Now, when the influence of temperature is included

Dependence of creep strain rate on stress and Temperature (in K)

$$\dot{\epsilon}_s = K_2 \sigma^n \exp\left(-\frac{Q_c}{RT}\right)$$

where K_2 and Q_c are constants; Q_c is termed the activation energy for creep.

Figure Stress (logarithmic scale) versus rupture lifetime (logarithmic scale) for a low carbon–nickel alloy at three temperatures.
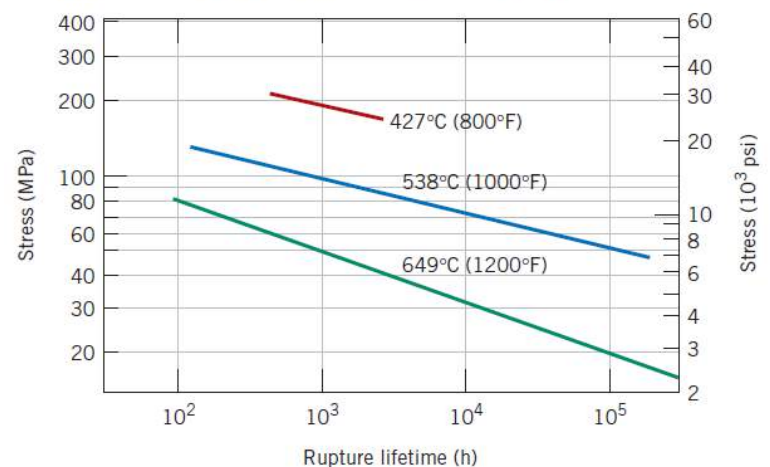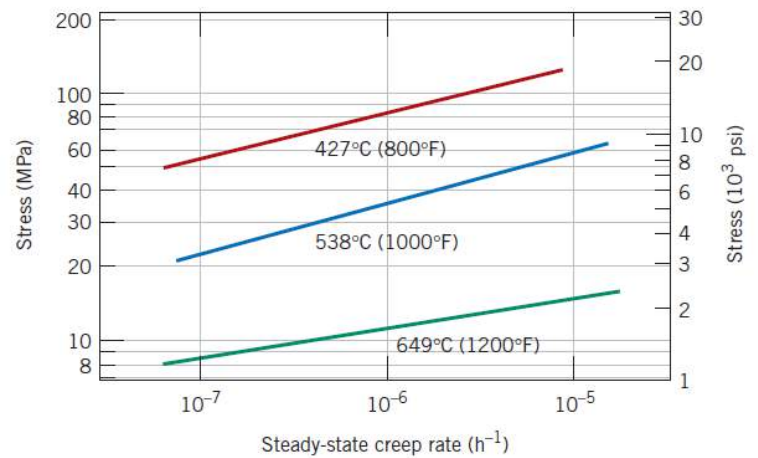
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Figure Stress (logarithmic scale) versus steady-state creep rate (logarithmic scale) for a low carbon–nickel alloy at three temperatures


DATA EXTRAPOLATION METHODS:-

The need often arises for engineering creep data that are impractical to collect from Normal laboratory tests. This is especially true for prolonged exposures (on the order of years). One solution to this problem involves performing creep and/or creep rupture tests at temperatures in excess of those required, for shorter time periods, and at a comparable stress level, and then making a suitable extrapolation to the in-service condition. A commonly used extrapolation procedure employs the Larson–Miller parameter, defined as

The Larson–Miller parameter—in terms of temperature and rupture lifetime

$$T(C + \log t_r)$$

where C is a constant (usually on the order of 20), for T in Kelvin and the rupture lifetime t_r in hours. The rupture lifetime of a given material measured at some specific stress level will vary with temperature such that this parameter remains constant. Or, the data may be plotted as the logarithm of stress versus the Larson–Miller parameter, as shown in Figure. Utilization of this technique is demonstrated in the following design example

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Figure Logarithm stress versus the Larson–Miller parameter for an S-590 iron. (From F. R. Larson and J. Miller, Trans. ASME, 74, 765, 1952. Reprinted by permission of ASME.)

$10^3\, T(20 + \log t_r)(°R–h)$

$10^3\, T(20 + \log t_r)(K–h)$
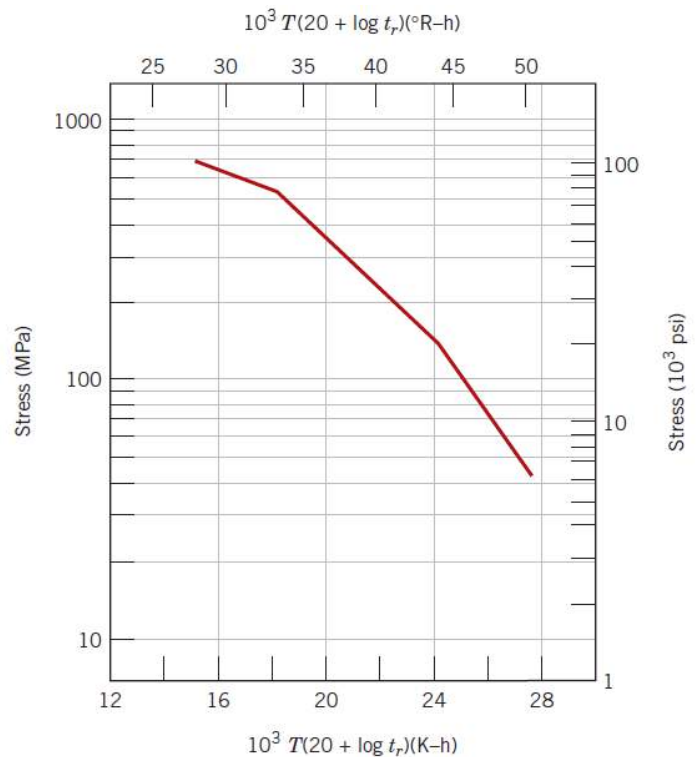
DESIGN EXAMPLE

Rupture Lifetime Prediction

Using the Larson–Miller data for S-590 iron shown in Figure 8.32, predict the time to rupture for a component that is subjected to a stress of 140 MPa (20,000 psi) at 800°C (1073 K).

Solution

From Figure 8.32, at 140 MPa (20,000 psi) the value of the Larson–Miller parameter is 24.0×10^3, for T in K and t_r in h; therefore,

$$24.0 \times 10^3 = T(20 + \log t_r)$$
$$= 1073(20 + \log t_r)$$

and, solving for the time,

$$22.37 = 20 + \log t_r$$
$$t_r = 233\,\text{h}\ (9.7\,\text{days})$$

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Corrosion of Metals:-

Corrosion is defined as the destructive and unintentional attack of a metal; it is electrochemical and ordinarily begins at the surface. The problem of metallic corrosion is one of significant proportions; in economic terms, it has been estimated that approximately 5% of an industrialized nation's income is spent on corrosion prevention and the maintenance or replacement of products lost or contaminated as a result of corrosion reactions. The consequences of corrosion are all too common. Familiar examples include the rusting of automotive body panels and radiator and exhaust components
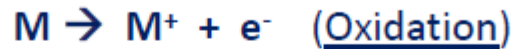
Corrosion processes are occasionally used to advantage. For example, etching procedures, as discussed in Section 4.10, make use of the selective chemical reactivity of grain boundaries or various microstructural constituents.

Corrosion Mechanism:-

Corrosion Mechanism is the destructive attack, or deterioration, of a metal by chemical or electrochemical reaction with its environment. Corrosive attack of metals is an electrochemical process. In a galvanic cell, two dissimilar metals (e.g., iron and copper) are placed in electrical contact in the presence of oxygen and moisture. Separate chemical reactions take place at the surfaces of the two metals, creating a flow of electrons through the connecting wire
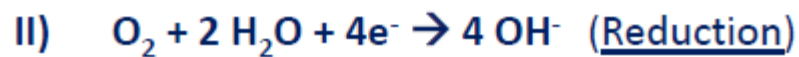
$$M \longrightarrow M^{n+} + ne^-$$

$$Fe \longrightarrow Fe^{2+} + 2e^-$$
$$Al \longrightarrow Al^{3+} + 3e^-$$

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Generic chemical formula for **anodic** metal loss:

$$M \rightarrow M^+ + e^- \quad \text{(Oxidation)}$$

The produced **electrons** are consumed at the **cathodic** side:
→ 2 possibilities in aqueous solution:

I) $\quad 2H^+ + 2e^- \rightarrow H_2$ (Reduction)

II) $\quad O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ (Reduction)

FORMS OF CORROSION

- Corrosion may be   classified in different ways
- Wet / Aqueous corrosion & Dry Corrosion
- Room Temperature/ High Temperature Corrosion

CORROSION

WET CORROSION | DRY CORROSION

CORROSION

ROOM TEMPERATURE CORROSION | HIGH TEMPERATURE CORROSION

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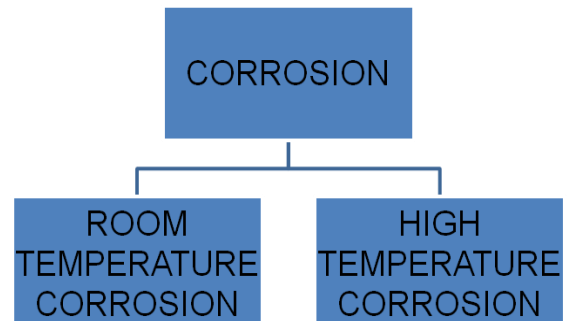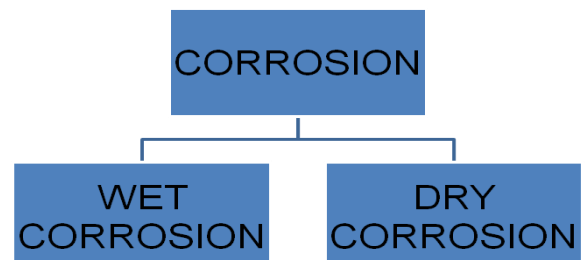
WET & DRY CORROSION

- Wet / aqueous corrosion is the major form of corrosion which occurs at or near room temperature and in the presence of water
- Dry / gaseous corrosion is significant mainly at high temperatures

WET / AQUEOUS CORROSION

Based on the appearance of the corroded metal, wet corrosion may be classified as:

- Uniform or General
- Galvanic or Two-metal
- Pitting
- Environment-assisted cracking
- Intergranular
- Crevice
- Velocity-assisted
- Dealloying
- Fretting

Corrosion penetration rate (CPR)

where W is the weight loss after exposure time t; ρ and A represent the density and exposed specimen area, respectively, and K is a constant, its magnitude depending

$$CPR = \frac{KW}{\rho At}$$

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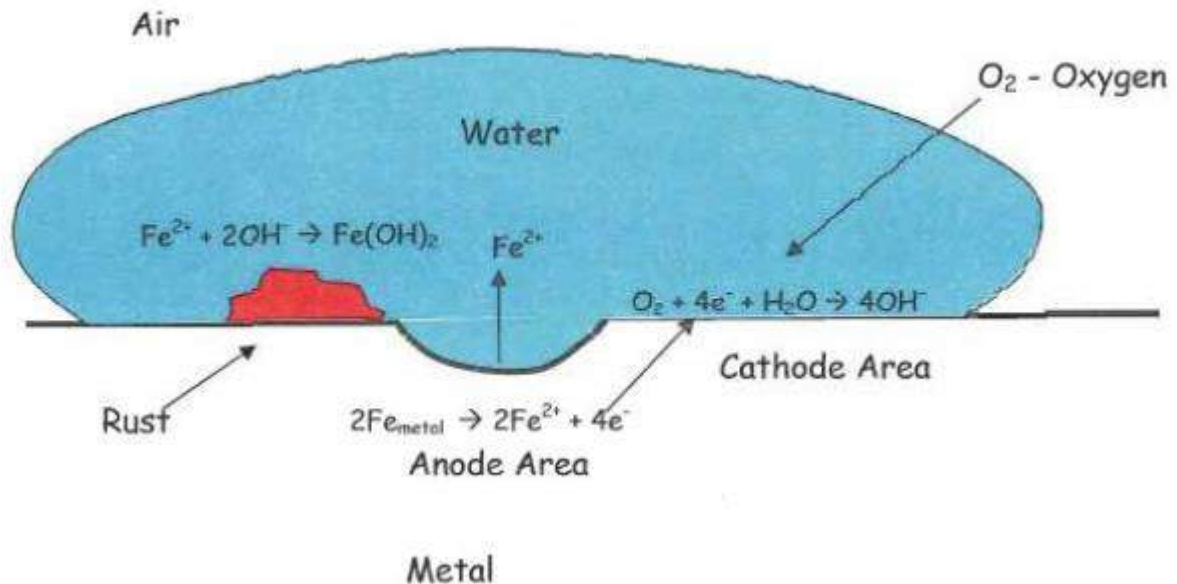
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on the system of units used

Uniform Corrosion

- This one is common in steel that is unprotected by any surface coating. Most noticeable. Surface effect, leaving rust on the surface.
- The good thing about this, if there is one, is that the corrosion is widely spread around.
- Corrosion over the entire exposed surface at a uniform rate. e.g.. Atmospheric corrosion.
- Maximum metal loss by this form. Not dangerous, rate can be measured in the laboratory

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Corrosion of iron (Fe) :

Air

Water

O_2 - Oxygen

$Fe^{2+} + 2OH \rightarrow Fe(OH)_2$ Fe^{2+}

$O_2 + 4e^- + H_2O \rightarrow 4OH^-$

Cathode Area

Rust

$2Fe_{metal} \rightarrow 2Fe^{2+} + 4e^-$

Anode Area

Metal

Prevention of Uniform Corrosion

1. Proper material selection

2. Change the environment (add inhibitors)

3. Cathodic protection Source: corrosion-doctors.org General (Uniform) corrosion

Cathodic protection

• Cathodic protection (CP) is a technique to control the corrosion of a metal surface by making it work as a cathode of an electrochemical cell.

• This is achieved by placing in contact with the metal to be protected another more easily corroded metal to act as the anode of the electrochemical cell.

Pipeline

Electrons

Magnesium
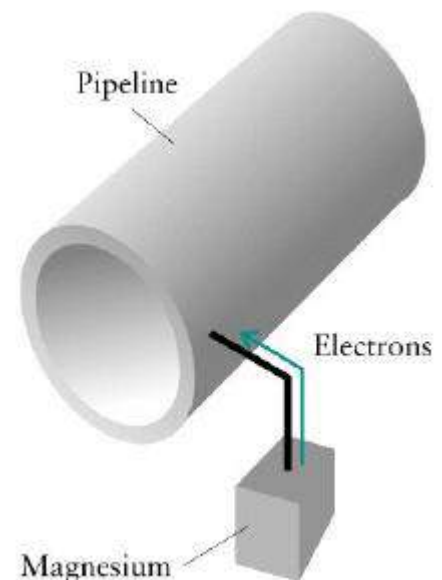
• Cathodic protection systems are most commonly used to protect steel, water or fuel pipelines and storage tanks, steel pier piles, ships, offshore oil platforms and onshore oil well casings
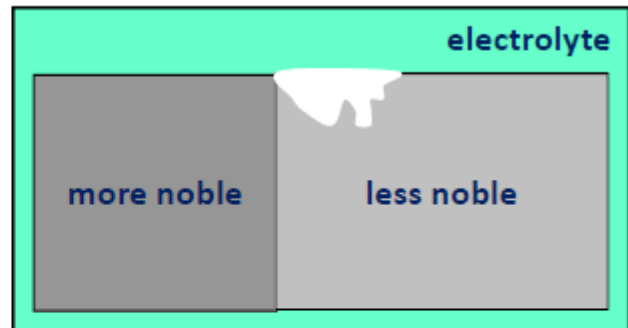
Galvanic Corrosion

- Possibility when two dissimilar metals are electrically connected in an electrolyte*

- Results from a difference in oxidation potentials of metallic ions between two or more metals. The greater the difference in oxidation potential, the greater the galvanic corrosion.

- Refer to Galvanic Series

- The less noble metal will corrode (i.e. will act as the anode) and the more noble metal will not corrode (acts as cathode).

- Perhaps the best known of all corrosion types is galvanic corrosion, which occurs at the contact point of two metals or alloys with different electrode potentials.

- When two dissimilar metals are joined together and exposed, the more active of the two metals corrode faster and the nobler metal is protected. This excess corrosion is due to the galvanic current generated at the junction

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→ **dissimilar conducting materials are connected electrically and exposed to an electrolyte**

preconditions:
- electrochemically dissimilar metals
- metals are in electrical contact
- metals are exposed to an electrolyte

metals in electrolyte → different corrosion potentials of different metals
→ potential difference = driving force for galvanic current flow

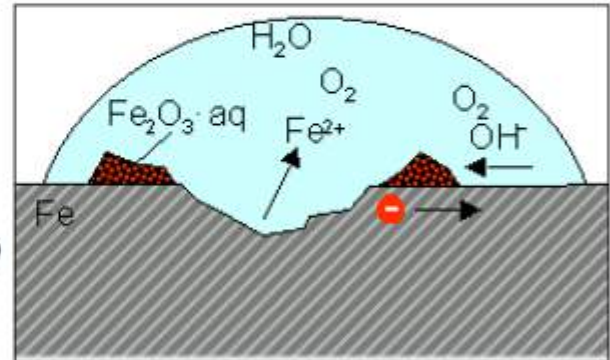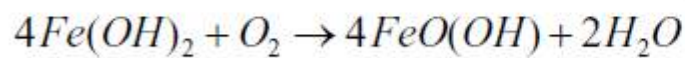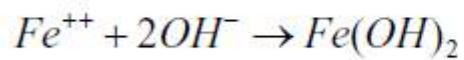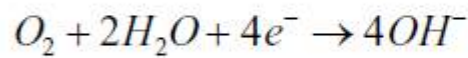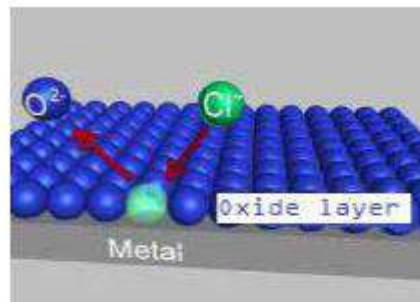| less noble material | = anode | → acceleration of corrosion |
| more noble material | = cathode | → reduction of corrosion |

Pitting corrosion

- It is based on low oxygen concentration at the bottom of the pit.
- This is very common in materials that protect themselves with a passive layer, i.e. stainless steel and aluminum.

→ Kathodic reaction at the periphery of the drop

→ Passivation of border area by increasing pH

→ Low pH & low O_2-concentration in the middle → dissolving of ion

→ around anodic area: formation of rust

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

$$Fe^{++} + 2OH^- \rightarrow Fe(OH)_2$$

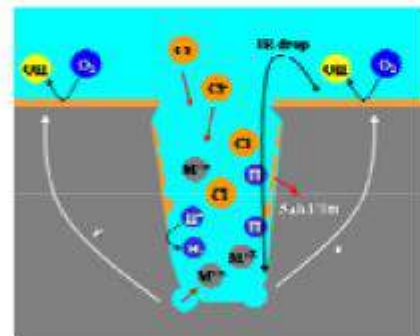$$4Fe(OH)_2 + O_2 \rightarrow 4FeO(OH) + 2H_2O$$

↑**Corrosion** with ↓O_2 **concentration**

Initiation:
Oxide layer
breakup

Processes in
the pit

pitting corrosion on
surface of cast iron bathtub

$FeCl_2 + H_2O \rightarrow FeClOH + H^+ + Cl^-$

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- Erosion corrosion: when subjected to high - velocity liquids, undergo a pitting type of corrosion called *impingement attack,* or *erosion corrosion.*

  Copper and brass condenser tubes, for example, are subject to this type of Attack
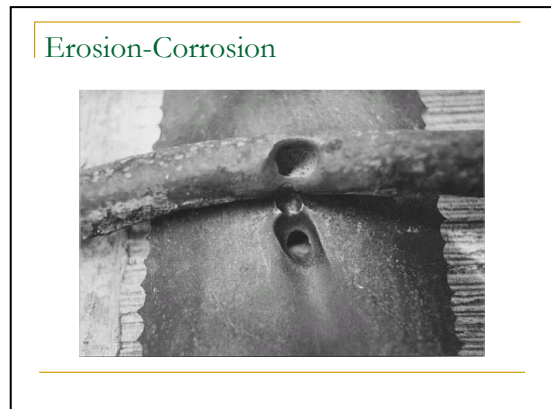
  Erosion-Corrosion

- Fretting corrosion , which results from slight relative motion (as in vibration) of two substances in contact, one or both being metals, usually leads to a series of pits at the metal interface. Metal - oxide debris usually fills the pits so that only after the corrosion products are removed do the pits become visible

  Fretting Corrosion
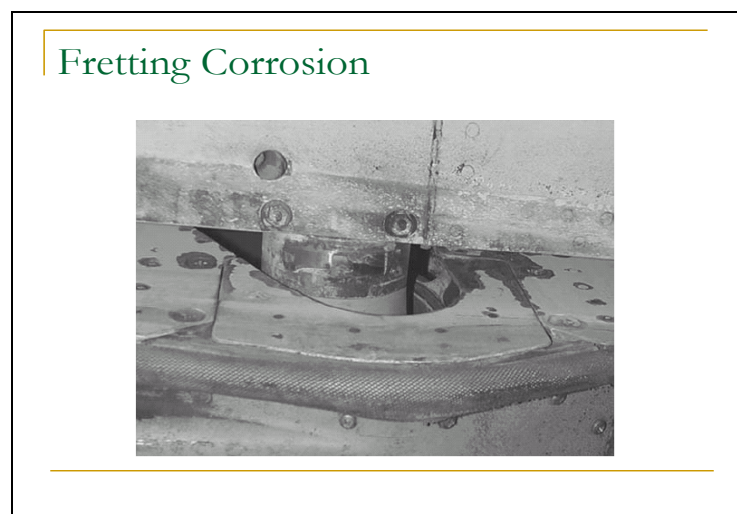
CLASSIFICATION OF MATERIALS

Solid materials have been conveniently grouped into three basic classifications: metals, ceramics, and polymers. This scheme is based primarily on chemical makeup and atomic structure, and most materials fall into one distinct grouping or another, Although there are some intermediates. In addition, there are the composites, combinations of two or more of the above three basic material classes. A brief explanation of these material types and representative characteristics is offered next .Another classification is advanced materials—those used in high-technology applications— viz. semiconductors, biomaterials, smart materials, and nanoengineered materials;
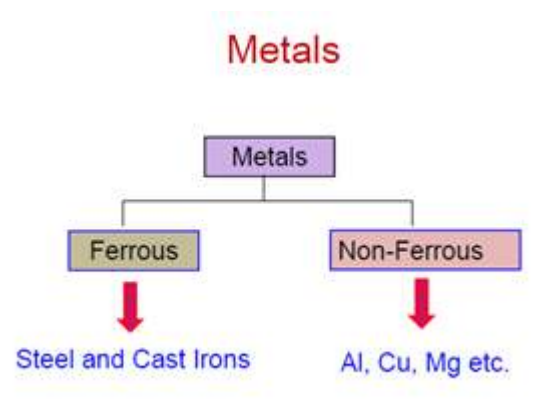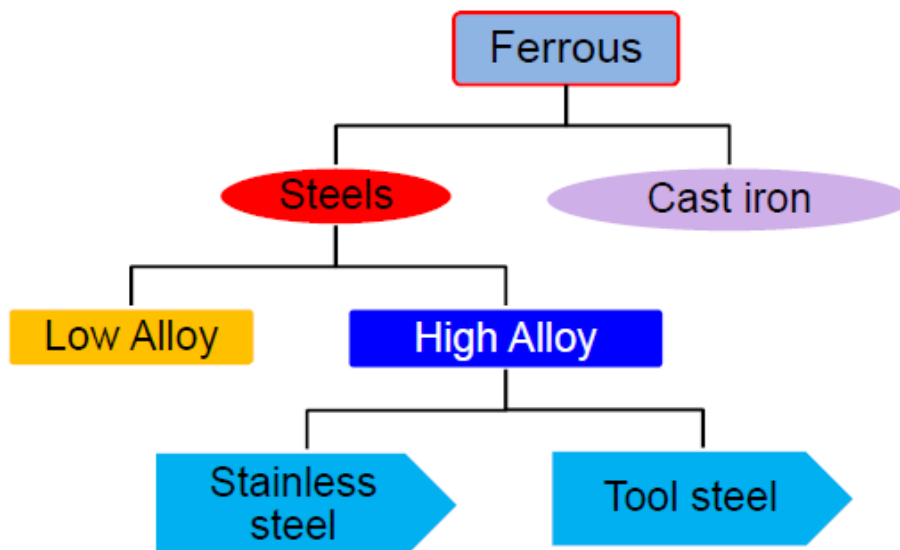
Classification of Materials
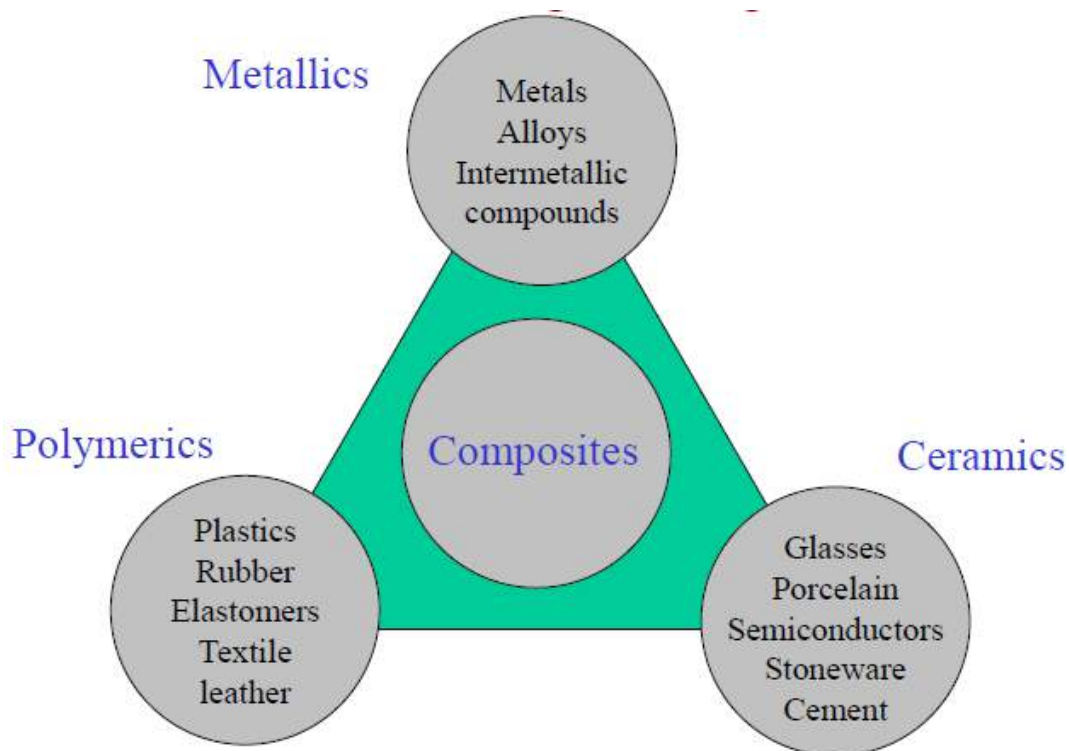
Metal Alloys:-

Most engineering metallic materials are alloys. Metals are alloyed to enhance their properties, such as strength, hardness or corrosion resistance, and to create new properties, such as superconductivity and shape memory effect. Engineering metal alloys can be broadly divided into

1-Ferrous Alloys and

2-Non-ferrous Alloys

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Ferrous Materials - Steels

- Steels - alloys of iron-carbon. May contain other alloying elements.
- Several grades are available.
- Low Alloy (<10 wt%)
  - Low Carbon (<0.25 wt% C)
  - Medium Carbon (0.25 to 0.60 wt%)
  - High Carbon (0.6 to 1.4 wt%)
- High Alloy
  - Stainless Steel (> 11 wt% Cr)
  - Tool Steel

Steels

Low alloy → Low Carbon, Medium Carbon, High Carbon

High alloy → Stainless, Tool
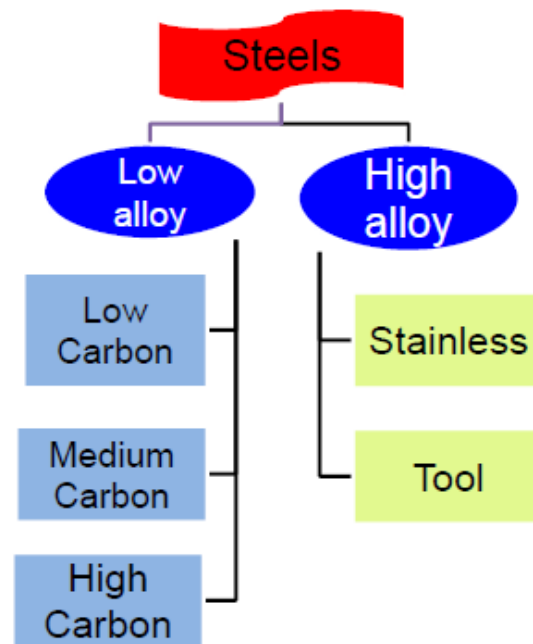
Low Carbon Steel

-Plain carbon steels - very low content of alloying elements and small amounts of Mn.

-Most abundant grade of steel is low carbon steel – greatest quantity produced; least expensive.

-Not responsive to heat treatment; cold working needed to improve the strength.

-Good Weldability and machinability

-High Strength, Low Alloy (HSLA) steels - alloying elements (like Cu, V, Ni and Mo) up to 10 wt %; have higher strengths and may be heat treated.

Medium Carbon Steel

-Carbon content in the range of 0.3 – 0.6%.

-Can be heat treated - austenitizing, quenching and then tempering.

-Most often used in tempered condition – tempered martensite

-Medium carbon steels have low hardenability

-Addition of Cr, Ni, Mo improves the heat treating capacity

-Heat treated alloys are stronger but have lower ductility

-Typical applications – Railway wheels and tracks, gears, crankshafts..

High Carbon Steel

High carbon steels – Carbon content 0.6 – 1.4%

-High C content provides high hardness and strength. Hardest and least ductile.

-Used in hardened and tempered condition

-Strong carbide formers like Cr, V, W are added as alloying elements to from carbides of these metals.

-Used as tool and die steels owing to the high hardness and wear resistance property

Stainless steel

•Stainless steels - A group of steels that contain at least 11% Cr. Exhibits extraordinary corrosion resistance due to formation of a very thin layer of Cr2O3 on the surface.

-Categories of stainless steels:

-Ferritic Stainless Steels – Composed of α ferrite (BCC)

-Martensitic Stainless Steels – Can be heat treated.

-Austenitic Stainless Steels – Austenite γ phase field is extended to room temperature.

Most corrosion resistant.

-Precipitation-Hardening (PH) Stainless Steels – Ultra high strength due to precipitation hardening.

-Duplex Stainless Steels – Ferrite + Austenite

Composition and Properties of some stainless steels are given in the next slide

Cast Irons

Carbon 2.1- 4.5 wt% and Si (normally 1-3 wt%).

-Lower melting point (about 300 °C lower than pure iron) due to presence of eutectic point at 1153 °C and 4.2 wt% C.

-Low shrinkage and good fluidity and casting ability.

-Types of cast iron: grey, white, nodular, malleable and compacted graphite

Nonferrous Metals

Copper

Copper is one of the earliest metals discovered by man.

- The boilers on early steamboats were made from copper.

- The copper tubing used in water plumbing in Pyramids was found in serviceable condition after more than 5,000 years.

- Cu is a ductile metal. Pure Cu is soft and malleable, difficult to machine.

- Very high electrical conductivity – second only to silver.

- Copper is refined to high purity for many electrical applications.

- Excellent thermal conductivity – Copper cookware most highly regarded – fast and uniform heating.

- Electrical and construction industries are the largest users of Cu

-The second largest use of Cu is probably in coins.

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-The U.S. nickel is actually 75% copper. The dime, quarter, and half dollar coins contain 91.67% copper and the Susan B Anthony dollar is 87.5% copper.

-The various Euro coins are made of Cu-Ni, Cu-Zn-Ni or Cu-Al-Zn-Sn alloys

Copper Alloys

- Brasses and Bronzes are most commonly used alloys of Cu. Brass is an alloy with Zn. Bronzes contain tin, aluminum, silicon or beryllium.
- Other copper alloy families include copper-nickels and nickel silvers. More than 400 copper-base alloys are recognized.

Copper Alloys - Brass

- Brass is the most common alloy of Cu – It's an alloy with Zn
- Brass has higher ductility than copper or zinc.
- Easy to cast - Relatively low melting point and high fluidity
- Properties can be tailored by varying Zn content.
- Some of the common brasses are yellow, naval and cartridge.
- Brass is frequently used to make musical instruments (good
- ductility and acoustic properties)

Aluminum

- Aluminum is a light metal (· = 2.7 g/cc); is easily machinable; has wide variety of surface finishes; good electrical and thermal conductivities; highly reflective to heat and light.
- Versatile metal - can be cast, rolled, stamped, drawn, spun, roll-formed, hammered, extruded and forged into many shapes.
- Aluminum can be riveted, welded, brazed, or resin bonded.

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- Corrosion resistant - no protective coating needed, however it is often anodized to improve surface finish, appearance.
- Al and its alloys - high strength-to-weight ratio (high specific strength) owing to low density.
- Such materials are widely used in aerospace and automotive applications where weight savings are needed for better fuel efficiency and performance.
- Al-Li alloys are lightest among all Al alloys and find wide applications in the aerospace industry.

Aluminum Alloys

-Aluminum alloys are classified into two categories – Cast and Wrought alloys.
-Wrought alloys can be either heat-treatable or non-heat treatable.
-Alloys are designated by a 4 digit number. Wrought – the 1st digit indicates the major alloying element. Cast – The last digit after the decimal indicates product from (casting - 0 or ingot -1)

The main properties of it:-

1. The usually have a crystalline structure and are good thermal and electrical conductors.
2. Many metals have high strength and high elastic module.
3. They maintain their good strength at high and low temperature.
4. They also have sufficient ductility which is important for many engineering applications.
5. The can be strengthened by alloying and heat treatment.
6. They are last resistant to corrosion.

Polymers:-

Are bound by covalent forces and also by weak van der Waals forces, and usually based on H, C and other non-metallic elements. They decompose at moderate temperatures (100– 400 C), and are lightweight. Other properties vary greatly. Examples: plastics (nylon, Teflon, polyester) and rubber. Other categories are not based on bonding. A particular microstructure identifies

-Polymers – Chain of H-C molecules. Each repeat unit of H-C is a monomer e.g. ethylene (C_2H_4), Polyethylene – ($-CH_2 - CH_2$)n

-Polymers: Thermosets – Soften when heated and harden on cooling – totally reversible. Thermoplasts – Do not soften on heating

-Plastics – moldable into many shape and have sufficient structural rigidity. Are one of the most commonly used class of materials.

-Are used in clothing, housing, automobiles, aircraft, packaging, electronics, signs, recreation items, and medical implants.

-Natural plastics – hellac, rubber, asphalt, and cellulose

Elastomers

- ❖ **Elastomer** – a polymer with rubber-like elasticity.
- ❖ Each of the monomers that link to form the polymer is usually made of carbon, hydrogen, oxygen and/or silicon.
- ❖ Cross-linking in the monomers provides the flexibility.
- ❖ Glass transition temperature, T_g, is the temperature at which transition from rubbery to rigid state takes place in polymers.

❖ Elastomers are amorphous polymers existing above their T_g. Hence, considerable segmental motion exists in them.

❖ Their primary uses are in seals, adhesives and molded flexible parts

Liquid Crystal Polymers (LCP)

-LCPs are a group of chemically complex structure having unique properties. Primarily used in LCDs (liquid crystal displays) on watches, flat panel computer monitors, televisions and clocks.

-Advantages - LCDs are thinner and lighter and consume much less power than cathode ray tubes (CRTs).

-The name "liquid crystal" arises out of their characteristics. It takes a fair amount of heat to change a suitable substance from a solid into a liquid crystal, and it only takes a little more heat to turn the liquid crystal into a real liquid.

-LCDs use these liquid crystals because they react predictably to electric current in such a way as to control light passage.

-A particular sort of nematic liquid crystal, called twisted nematics (TN), is naturally twisted. Applying an electric current to these liquid crystals will untwist them to varying degrees, depending on the applied electrical potential.

Advanced Polymers

Ultrahigh Molecular Weight Polyethylene (UHMWPE)

❑ Molecular weight ca. 4×10^6 g/mol
❑ Outstanding properties
  ▪ high impact strength
  ▪ resistance to wear/abrasion
  ▪ low coefficient of friction
  ▪ self-lubricating surface
❑ Important applications
  ▪ bullet-proof vests
  ▪ golf ball covers
  ▪ hip implants (acetabular cup) ➡

UHMWPE

The main properties of it:-

1. Most polymers are non-crystalline but some consist of both crystalline and non-crystalline regions.

2. The generally have low densities and low rigidity.

3. Their mechanical properties may very considerably.

4. Most polymers are poor electrical conductors due to the nature of the atomic bonding.

5. Most of them are corrosion resistant but cannot be used at high temperature.

6. They generally have a good strength to weight ratio.

Ceramics Materials

Ceramics and glass:

Atoms behave mostly like either positive or negative ions, and are bound by Coulomb forces between them. They are usually combinations of metals or semiconductors with

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oxygen, nitrogen or carbon (oxides, nitrides, and carbides).Examples: glass, porcelain, many minerals

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                    ┌─────────────┐
                    │  Ceramics   │
                    └─────────────┘
           ┌──────────┬─────┴─────┬──────────┐
    ┌────────────┐ ┌──────────┐ ┌───────┐ ┌────────────┐
    │ Refractory │ │ Abrasives│ │ Glass │ │  Advanced  │
    │  Materials │ │          │ │       │ │  Ceramics  │
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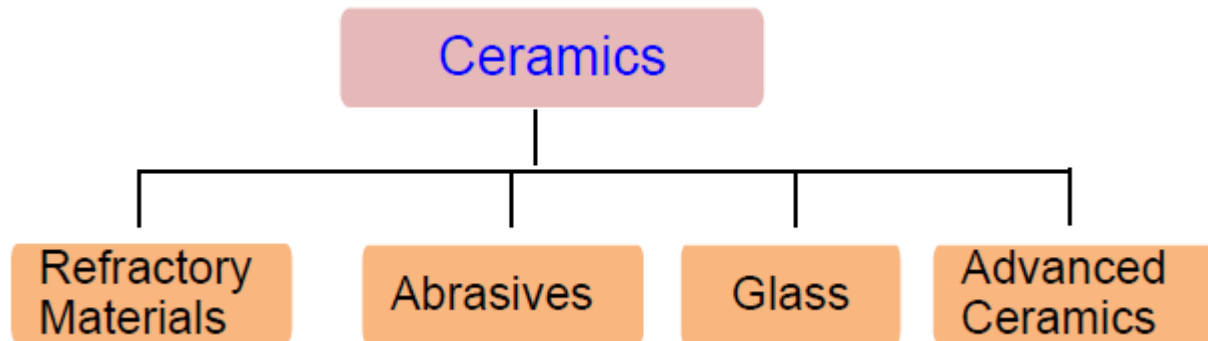
Refractory Materials

- Refractory - retains its strength at high temperatures > 500°C.
- Must be chemically and physically stable at high temperatures. Need to be resistant to thermal shock, should be chemically inert, and have specific ranges of thermal conductivity and thermal expansion.
- Are used in linings for furnaces, kilns, incinerators, crucibles and reactors.
- Aluminium oxide (alumina), silicon oxide (silica), calcium oxide (lime) magnesium oxide (magnesia) and fireclays are used to manufacture refractory materials.
- Zirconia - extremely high temperatures.
- SiC and Carbon – also used in some very severe temperature conditions, but cannot be used in oxygen environment, as they will oxidize and burn

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Advanced Ceramics: Automobile Engine parts

Advantages:
Operate at high temperatures – high efficiencies; Low frictional losses; Operate without a cooling system; Lower weights than current engines

Disadvantages:
Ceramic materials are brittle; Difficult to remove internal voids (that weaken structures); Ceramic parts are difficult to form and machine

Potential materials: Si_3N_4 (engine valves, ball bearings), SiC (MESFETS), & ZrO_2 (sensors),
Possible engine parts: engine block & piston coatings

Microelectromechanical systems (MEMS)

❖ MEMS – These micron-sized structures such as beams, cantilevers, diaphragms, valves, plates and switches that can function as tiny sensors and actuators.

❖ Fabricated by integrated circuit (IC) manufacturing processes: bulk and surface micromachining.

❖ Thousands of micromachines can be fabricated on a single silicon wafer with supporting circuits integrated on the chip. Can be mass produced in the millions at low prices.

❖ Low-cost, commercial MEMS devices developed for: Corrosion detectors and monitors; Instrumentation for automotive and aerospace; Biological and medical

devices; Chemical and environmental sensors; Manufacturing and process control devices ;Virtual reality systems

Abrasive Ceramics

❖Abrasives are used in cutting and grinding tools.

❖Diamonds - natural and synthetic, are used as abrasives, though relatively expensive. Industrial diamonds are hard and thermally conductive. Diamonds unsuitable as gemstone are used as industrial diamond

❖Common abrasives – SiC, WC, Al_2O_3 (corundum) and silica sand.

❖Either bonded to a grinding wheel or made into a powder and used with a cloth or paper.
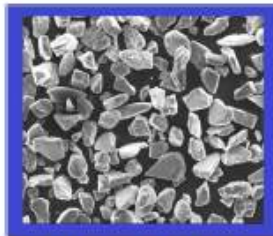
Silicon carbide

Glass

Glass - inorganic, non-crystalline (amorphous) material.

- Range - soda-lime silicate glass for soda bottles to the extremely high purity silica glass for optical fibers.

- Widely used for windows, bottles, glasses for drinking, transfer piping and receptacles for highly corrosive liquids, optical glasses, windows for nuclear applications.

- The tuent of glass is silica (SiO_2). The most common form of silica used in glass is sand.

- Sand fusion temp to produce glass - 1700 °C. Adding other chemicals to sand can considerably reduce the fusion temperature.

- Sodium carbonate (Na_2CO_3) or soda ash, (75% SiO_2 + 25% Na_2O) will reduce the fusion temperature to 800 °C.

- Other chemicals like Calcia (CaO) and magnesia (MgO) are used for stability. Limestone ($CaCO_3$) and dolomite ($MgCO_3$) are used for this purpose as source of CaO and MgO.

.**The main properties of it:-**

1. The can be crystalline (Ceramics) non crystalline (glass) or mixture of both (glass – Ceramics) .

2. Generally they have high melting points and high chemical stabilities.

3. The have high hardness high module and high temperature strength.

4. But since they are very brittle the cannot be used as good as metals.

5. Ceramics are usually poor electrical conductors.

6. Ceramics have high strength on corrosion.

Composites:-

A materials system composed of two or more physically distinct phases whose combination produces aggregate properties that are different from those of its constituents.

1. Why Composites are Important

- Composites can be very strong and stiff, yet very light in weight, so ratios of strength-to-weight and stiffness-to-weight are several times greater than steel or aluminum

- Fatigue properties are generally better than for common engineering metals

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- Toughness is often greater too
- Composites can be designed that do not corrode like steel
- Possible to achieve combinations of properties not attainable with metals, ceramics, or polymers alone

Disadvantages and Limitations of Composite Materials:-

- Properties of many important composites are anisotropic - the properties differ depending on the direction in which they are measured – this may be an advantage or a disadvantage
- Many of the polymer-based composites are subject to attack by chemicals or solvents, just as the polymers themselves are susceptible to attack
- Composite materials are generally expensive
- Manufacturing methods for shaping composite materials are often slow and costly

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Terminology/Classification

- Composites:
  -- Multiphase material w/significant proportions of each phase.
- Matrix:
  -- The continuous phase
  -- Purpose is to:
    - transfer stress to other phases
    - protect phases from environment
  -- Classification: MMC, CMC, PMC

  metal   ceramic   polymer

- Dispersed phase:
  -- Purpose: enhance matrix properties.
    MMC: increase σ_y, TS, creep resist.
    CMC: increase K_c
    PMC: increase E, σ_y, TS, creep resist.
  -- Classification: Particle, fiber, structural
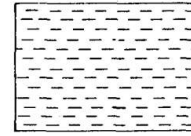
woven fibers

0.5 mm

cross section view

0.5 mm
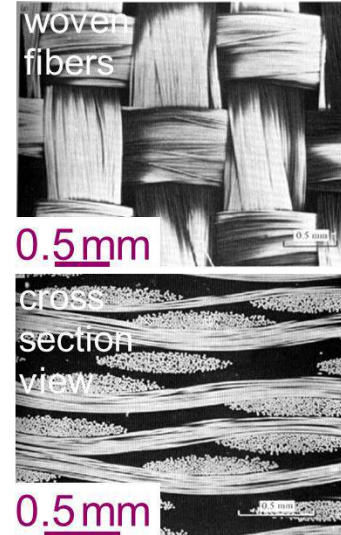
Types of Composite Materials

There are five basic types of composite materials: Fiber, particle, flake, laminar or layered and filled composites.
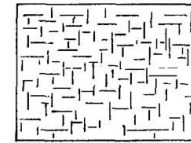
1. Fiber Composites:-

In fiber composites, the fibers reinforce along the line of their length. Reinforcement may be mainly 1-D, 2-D or 3-D. Figure shows the three basic types of fiber orientation.
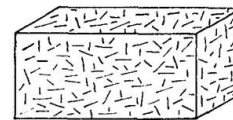
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◆ 1-D gives <u>maximum</u> strength in one direction.

ONE-DIMENSIONAL REINFORCEMENT

◆ 2-D gives strength in two directions.

TWO-DIMENSIONAL REINFORCEMENT

◆ Isotropic gives strength equally in all directions.


ISOTROPIC REINFORCEMENT

The mechanical characteristics of a fiber-reinforced composite depend not only on the properties of the fiber, but also on the degree to which an applied load is transmitted to the fibers by the matrix phase. Important to the extent of this load transmittance is the magnitude of the interfacial bond between the fiber and matrix phases. Under an applied stress, this fiber–matrix bond ceases at the fiber ends, yielding a matrix deformation pattern as shown schematically in Figure
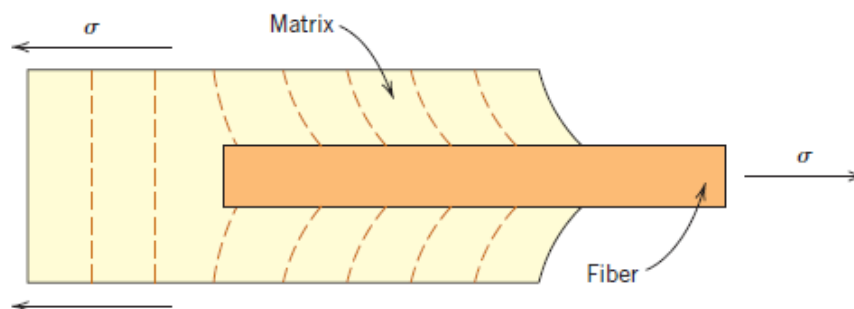
in other words, there is no load transmittance from the matrix at each fiber extremity. Some critical fiber length is necessary for effective strengthening and stiffening of the composite material. This critical length (l_c) is dependent on the fiber diameter (d) and its ultimate (or tensile) strength σf^{*} and on the fiber–matrix bond strength (or the shear yield strength of the matrix, whichever is smaller) T_c according to

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$$l_c = \frac{\sigma_f^* d}{2\tau_c}$$

Continuous and Aligned Fiber Composites

Tensile Stress–Strain Behavior—Longitudinal Loading

Mechanical responses of this type of composite depend on several factors to include the stress–strain behaviors of fiber and matrix phases, the phase volume fractions, and, in addition, the direction in which the stress or load is applied. Furthermore, the properties of a composite having its fibers aligned are highly anisotropic, that is, dependent on the direction in which they are measured.
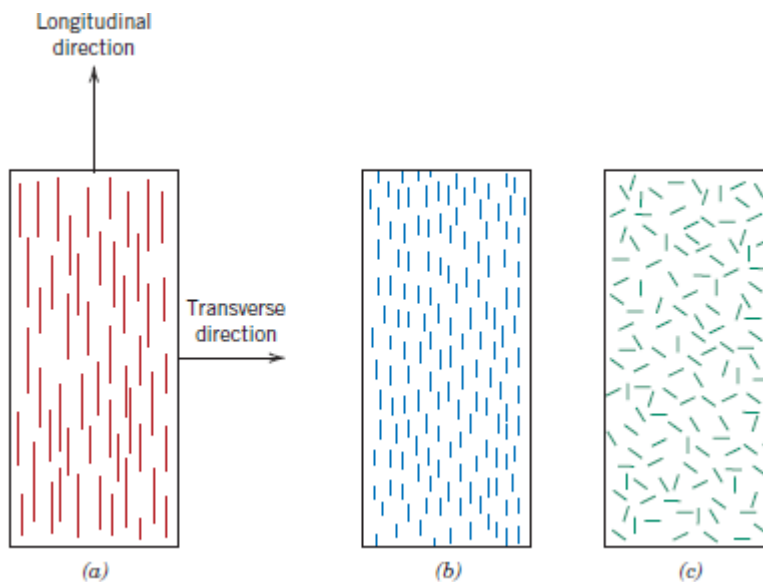

Figure Schematic representations of (*a*) continuous and aligned, (*b*) discontinuous and aligned, and (*c*) discontinuous and randomly oriented fiberreinforced composite

Elastic Behavior—Longitudinal Loading

Let us now consider the elastic behavior of a continuous and oriented fibrous composite that is loaded in the direction of fiber alignment. First, it is assumed that the

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fiber–matrix interfacial bond is very good, such that deformation of both matrix and fibers is the same (an *isostrain* situation). Under these conditions, the total load sustained by the composite (F_c) is equal to the sum of the loads carried by the matrix phase (F_m)and the fiber phase (F_f).

$$F_c = F_m + F_f$$

From the definition of stress, F=σA, and thus expressions for(F_c), (F_m) and (F_f) in terms of their respective stresses σ_c, σ_m and σ_f and cross-sectional areas A_c, A_m and A_f are possible. Substitution of these into Equation.

$$\sigma_c A_c = \sigma_m A_m + \sigma_f A_f$$

and then, dividing through by the total cross-sectional area of the composite A_c , we have

$$\sigma_c = \sigma_m \frac{A_m}{A_c} + \sigma_f \frac{A_f}{A_c}$$

The previous assumption of an isostrain state means that

$$\epsilon_c = \epsilon_m = \epsilon_f$$

$$\frac{\sigma_c}{\epsilon_c} = \frac{\sigma_m}{\epsilon_m} V_m + \frac{\sigma_f}{\epsilon_f} V_f$$

The modulus of elasticity of a continuous and aligned fibrous composite in the direction of alignment

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$$E_{cl} = E_m V_m + E_f V_f$$

$$E_{cl} = E_m(1 - V_f) + E_f V_f$$

It can also be shown, for longitudinal loading, that the ratio of the load carried by the fibers to that carried by the matrix is

$$\frac{F_f}{F_m} = \frac{E_f V_f}{E_m V_m}$$

EXAMPLE PROBLEM

Property Determinations for a Glass Fiber-Reinforced Composite—Longitudinal Direction

A continuous and aligned glass fiber-reinforced composite consists of 40 vol% of glass fibers having a modulus of elasticity of 69 GPa (10×10^6 psi) and 60 vol% of a polyester resin that, when hardened, displays a modulus of 3.4 GPa (0.5×10^6 psi).

(a) Compute the modulus of elasticity of this composite in the longitudinal direction.

(b) If the cross-sectional area is 250 mm² (0.4 in.²) and a stress of 50 MPa (7250 psi) is applied in this longitudinal direction, compute the magnitude of the load carried by each of the fiber and matrix phases.

(c) Determine the strain that is sustained by each phase when the stress in part (b) is applied.

Solution

(a) The modulus of elasticity of the composite is calculated using Equation 16.10a:

$$E_{cl} = (3.4 \text{ GPa})(0.6) + (69 \text{ GPa})(0.4)$$
$$= 30 \text{ GPa} (4.3 \times 10^6 \text{ psi})$$

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(b) To solve this portion of the problem, first find the ratio of fiber load to matrix load, using Equation 16.11; thus,

$$\frac{F_f}{F_m} = \frac{(69 \text{ GPa})(0.4)}{(3.4 \text{ GPa})(0.6)} = 13.5$$

or $F_f = 13.5 \, F_m$.

In addition, the total force sustained by the composite F_c may be computed from the applied stress σ and total composite cross-sectional area A_c according to

$$F_c = A_c\sigma = (250 \text{ mm}^2)(50 \text{ MPa}) = 12{,}500 \text{ N } (2900 \text{ lb}_f)$$

However, this total load is just the sum of the loads carried by fiber and matrix phases; that is,

$$F_c = F_f + F_m = 12{,}500 \text{ N } (2900 \text{ lb}_f)$$

Substitution for F_f from the above yields

$$13.5 \, F_m + F_m = 12{,}500 \text{ N}$$

or

$$F_m = 860 \text{ N } (200 \text{ lb}_f)$$

whereas

$$F_f = F_c - F_m = 12{,}500 \text{ N} - 860 \text{ N} = 11{,}640 \text{ N } (2700 \text{ lb}_f)$$

Thus, the fiber phase supports the vast majority of the applied load.

(c) The stress for both fiber and matrix phases must first be calculated. Then, by using the elastic modulus for each (from part a), the strain values may be determined.

For stress calculations, phase cross-sectional areas are necessary:

$$A_m = V_m A_c = (0.6)(250 \text{ mm}^2) = 150 \text{ mm}^2 \ (0.24 \text{ in.}^2)$$

and

$$A_f = V_f A_c = (0.4)(250 \text{ mm}^2) = 100 \text{ mm}^2 \ (0.16 \text{ in.}^2)$$

Thus,

$$\sigma_m = \frac{F_m}{A_m} = \frac{860 \text{ N}}{150 \text{ mm}^2} = 5.73 \text{ MPa } (833 \text{ psi})$$

$$\sigma_f = \frac{F_f}{A_f} = \frac{11{,}640 \text{ N}}{100 \text{ mm}^2} = 116.4 \text{ MPa } (16{,}875 \text{ psi})$$

Finally, strains are computed as

$$\epsilon_m = \frac{\sigma_m}{E_m} = \frac{5.73 \text{ MPa}}{3.4 \times 10^3 \text{ MPa}} = 1.69 \times 10^{-3}$$

$$\epsilon_f = \frac{\sigma_f}{E_f} = \frac{116.4 \text{ MPa}}{69 \times 10^3 \text{ MPa}} = 1.69 \times 10^{-3}$$

Therefore, strains for both matrix and fiber phases are identical, which they should be, according to Equation 16.8 in the previous development.

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Elastic Behavior—Transverse Loading

A continuous and oriented fiber composite may be loaded in the **transverse direction;** that is, the load is applied at 90° a angle to the direction of fiber alignment as shown in Figure *a*. For this situation the stress **σ** to which the composite as well as both phases are exposed is the same, or

$$\sigma_c = \sigma_m = \sigma_f = \sigma$$

This is termed an isostress state. Also, the strain or deformation of the entire composite ϵ_c is

$$\epsilon_c = \epsilon_m V_m + \epsilon_f V_f$$

but, since $\epsilon = \sigma/E$,

$$\frac{\sigma}{E_{ct}} = \frac{\sigma}{E_m} V_m + \frac{\sigma}{E_f} V_f$$

where E_{ct} is the modulus of elasticity in the transverse direction. Now, dividing through by **σ** yields

$$\frac{1}{E_{ct}} = \frac{V_m}{E_m} + \frac{V_f}{E_f}$$

which reduces to

$$E_{ct} = \frac{E_m E_f}{V_m E_f + V_f E_m} = \frac{E_m E_f}{(1 - V_f)E_f + V_f E_m}$$

Above e quation is analogous to the lower-bound expression for particulate composites

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EXAMPLE PROBLEM

Elastic Modulus Determination for a Glass Fiber-Reinforced Composite—Transverse Direction

Compute the elastic modulus of the composite material described in Example Problem 16.1, but assume that the stress is applied perpendicular to the direction of fiber alignment.

Solution

According to Equation 16.16,

$$E_{ct} = \frac{(3.4 \text{ GPa})(69 \text{ GPa})}{(0.6)(69 \text{ GPa}) + (0.4)(3.4 \text{ GPa})}$$
$$= 5.5 \text{ GPa } (0.81 \times 10^6 \text{ psi})$$

This value for E_{ct} is slightly greater than that of the matrix phase but, from Example Problem 16.1a, only approximately one-fifth of the modulus of elasticity along the fiber direction (E_{cl}), which indicates the degree of anisotropy of continuous and oriented fiber composites.

RULE OF MIXTURES

For fiber reinforced composites, the rule of mixtures predicts the density of the composite as well as electrical and thermal conductivity along the direction of the fibers if they are continuous and unidirectional. Density, r, is given as a fraction, f, as:

$$\rho_c = f_m \rho_m + f_f \rho_f \qquad \text{Note that } f_m = 1 - f_f$$

For thermal conductivity:

$$K_c = f_m K_m + f_f K_f$$

For electrical conductivity:

$$\sigma_c = f_m \sigma_m + f_f \sigma_f$$

Thermal and electrical energy can be transferred through the composite at a rate that is proportional to the volume fraction, f of the conductive material

Example :-

Estimate the maximum and minimum thermal conductivity values for a cermet that contains 85 vol% titanium carbide (TiC) particles in a cobalt matrix. Assume thermal conductivities of 27 and 69 W/m-K for TiC and Co, respectively.

Solution

This problem asks for the maximum and minimum thermal conductivity values for a TiC-Co cermet. Using a modified form of Equation 16.1 the maximum thermal conductivity k_{max} is calculated as

$$k_{max} = k_m V_m + k_p V_p = k_{Co} V_{Co} + k_{TiC} V_{TiC}$$

$$= (69 \text{ W/m-K})(0.15) + (27 \text{ W/m-K})(0.85) = 33.3 \text{ W/m-K}$$

Using a modified form of Equation 16.2, the minimum thermal conductivity k_{min} will be

$$k_{min} = \frac{k_{Co} k_{TiC}}{V_{Co} k_{TiC} + V_{TiC} k_{Co}}$$

$$= \frac{(69 \text{ W/m-K})(27 \text{ W/m-K})}{(0.15)(27 \text{ W/m-K}) + (0.85)(69 \text{ W/m-K})}$$

$$= 29.7 \text{ W/m-K}$$

2. Particle Composites:-

◆ **Particles** usually reinforce a composite equally in all directions (called *isotropic*). *Plastics*, *cermets* and *metals* are examples of particles.

◆ **Particles** used to strengthen a matrix do not do so in the same way as fibers. For one thing, particles *are not directional like fibers. Spread at random through out a matrix, particles tend to reinforce in all directions equally.*

☞ Cermets

(1) Oxide–Based cermets

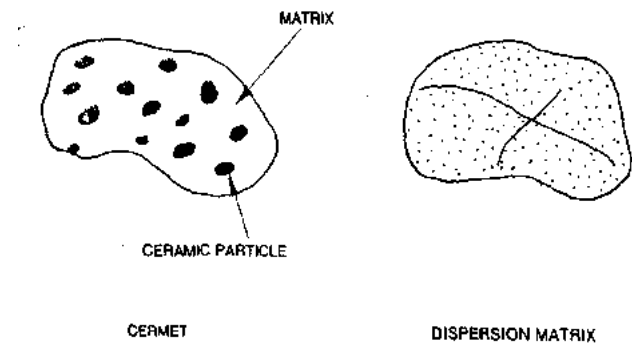(e.g. Combination of Al2O3 with Cr)

(2) Carbide–Based Cermets

(e.g. Tungsten–carbide, titanium–carbide)

☞ Metal–plastic particle composites

(e.g. Aluminum, iron & steel, copper particles)

☞ Metal–in–metal Particle Composites and Dispersion Hardened Alloys

(e.g. Ceramic–oxide particles)

Particles can have quite a variety of geometries, but they should be of approximately the same dimension in all directions (equiaxed).For effective reinforcement, the particles should be small and evenly distributed throughout the matrix. Furthermore, the volume fraction of the two phases influences the behavior; mechanical properties are enhanced with increasing particulate content. Two mathematical expressions have been formulated for the dependence of the elastic modulus on the volume fraction of

the constituent phases for a two-phase composite. These **rule of mixtures** equations predict that the elastic modulus should fall between an upper bound represented by

$$E_c(u) = E_m V_m + E_p V_p$$

Figure Modulus of elasticity versus volume percent tungsten for a composite of tungsten particles dispersed within a copper matrix. Upper and lower bounds are according to Equations
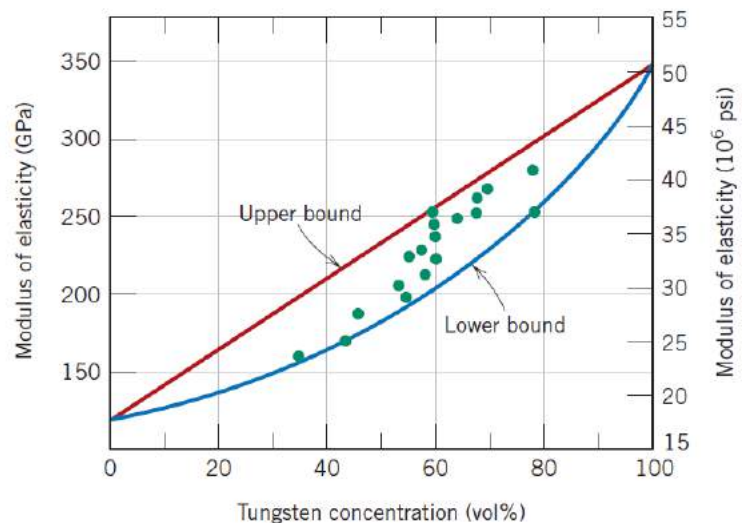
$$E_c(l) = \frac{E_m E_p}{V_m E_p + V_p E_m}$$

Example :-

A large-particle composite consisting of tungsten particles within a copper matrix is to be prepared. If the volume fractions of tungsten and copper are 0.60 and 0.40, respectively, estimate the upper limit for the specific stiffness of this composite given the data that follow.

	Specific Gravity	Modulus of Elasticity (GPa)
Copper	8.9	110
Tungsten	19.3	407

Solution

Given the elastic moduli and specific gravities for copper and tungsten we are asked to estimate the upper limit for specific stiffness when the volume fractions of tungsten and copper are 0.60 and 0.40, respectively. There are two approaches that may be applied to solve this problem. The first is to estimate both the upper limits of elastic modulus [$E_c(u)$] and specific gravity (ρ_c) for the composite,

$$E_c(u) = E_{Cu}V_{Cu} + E_W V_W$$

$$= (110 \ GPa)(0.40) + (407 \ GPa)(0.60)$$

$$= 288 \ GPa$$

$$\rho_c = \rho_{Cu}V_{Cu} + \rho_W V_W$$

$$= (8.9)(0.40) + (19.3)(0.60) = 15.14$$

$$\text{Specific Stiffness} = \frac{E_c(u)}{\rho_c} = \frac{288 \ GPa}{15.14} = 19.0 \ GPa$$

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$$\text{Specific Stiffness} = \frac{E_{Cu}}{\rho_{Cu}} V_{Cu} + \frac{E_W}{\rho_W} V_W$$

$$= \frac{110\ \text{GPa}}{8.9}(0.40) + \frac{407\ \text{GPa}}{19.3}(0.60) = 17.6\ \text{GPa}$$

Q1/ Compute the longitudinal tensile strength of an aligned glass fiber-epoxy matrix composite in which the average fiber diameter and length are 0.010 mm and 2.5 mm respectively, and the volume fraction of fibers is 0.40. Assume that (1) the fiber matrix bond strength is 75 MPa (2) the fracture strength of the fibers is 3500 MPa , and (3) the matrix stress at fiber failure is 8.0 MPa .

Q2/ In an aligned and continuous glass fiber reinforced nylon 6,6 composite, the fibers are to carry 94% of a load applied in the longitudinal direction. (a) Using the data provided, determine the volume fraction of fibers that will be required. (b) What will be the tensile strength of this composite? Assume that the matrix stress at fiber failure is 30

	Modulus of Elasticity [GPa (psi)]	Tensile Strength [MPa (psi)]
Glass fiber	72.5 (10.5×10^6)	3400 (490,000)
Nylon 6,6	3.0 (4.35×10^5)	76 (11,000)

*Q3 /*For a continuous and oriented fiber-reinforced composite, the moduli of elasticity in the longitudinal and transverse directions are 19.7 and 3.66 GPa , respectively. If the volume fraction of fibers is 0.25, determine the moduli of elasticity of fiber and matrix phases.

Q4/ A large-particle composite consisting of tungsten particles within a copper matrix is to be prepared. If the volume fractions of tungsten and copper are 0.60 and 0.40,

respectively, estimate the upper limit for the specific stiffness of this composite given the data that follow.

	Specific Gravity	Modulus of Elasticity (GPa)
Copper	8.9	110
Tungsten	19.3	407

MATERIALS SELECTION

The basic question is how do we go about selecting a material for a given part? This may seem like a very complicated process until we realize than we are often restrained by choices we have already made. For example, if different parts have to interact then material choice becomes limited.

When we talk about choosing materials for a component, we take into account many different factors. These factors can be broken down into the following areas.

➢ Materials selection is an important part of a larger process of creating new solutions to problems. This larger process is called "Engineering Design"

➢ Design of engineering components is limited by the available materials, and new designs are made possible by new materials

➢ To see how important is the material selection in the design, consider

the definition of "engineering" used by ABET in the U.S.A

Factors Influencing Materials Selection

Issues include

- **Properties**
  - Physical & Mechanical

- **Manufacturing considerations**
  - Castability / formability
  - Machinability / Coatability
  - Heat treatment / Weldability
  - Failure & repairability

- **Cost analysis**
  - Availability
  - Materials life & maintenance

- **Environmental issues**
  - Ergonomic & safety
  - Recycling

A number of questions need to be answered before a decision can be made as to the specification required of a material and hence a decision as to the optimum material for a particular task. The questions can be grouped under four general headings:

 1. What properties are required?

2. What are the processing requirements and their implications for the choice of material?

3. What is the availability of materials?

4. What is the cost

Processing Parameters:

1. Are there any special processing requirements which will limit the choice of material? For example, does the material have to be cast or perhaps extruded?

2. Are there any material treatment requirements?

For example, does the material have to be annealed or perhaps solution hardened?

1. Are there any special tooling requirements?

2. For example, does the hardness required of a material mean special cutting tools are required?

Availability:

1. Is the material readily available?

Is it, for example, already in store, or perhaps quickly obtainable from normal suppliers?

2. Are there any ordering problems for that material?

Is the material only available from special suppliers? Is there a minimum order quantity?

3. What form is the material usually supplied in?

For example, is the material usually supplied in bars or perhaps sheet? This can affect the processes that can be used.

Cost:

1. What is the cast of the raw material?

Could a cheaper material be used?

2. What quantity is required?

What quantity of product is to be produced per week, per month, per year?

What stocking policy should be adopted for the material?

3. What are the cost implications of the process requirements?

Does the process require high initial expenditure? Are the running costs high

or low? Will expensive skilled labor be required?

4. What are the cost penalties for over specification?

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If the material is, for example stronger than is required, will this significantly increase the cost? If the product is manufactured to higher quality than is required, what will be the cost implications?

Which Material ?
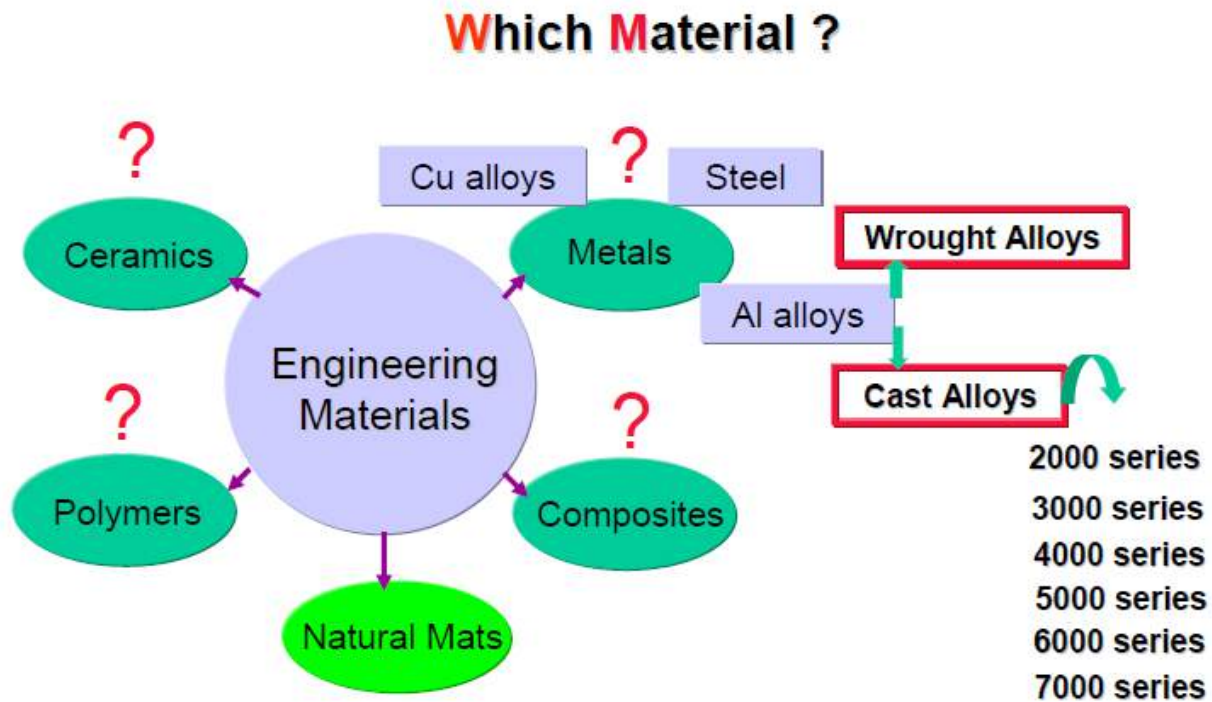
Why do we need to select a new Material

1.. When the product is new (never produced before), the decision to select a new material is obvious

2. With existing products (Material Substitution), selecting a new material is due to the following:

- Reduce materials cost
- Reduce production cost
- Accommodate some changes in function
- Solve some materials processing problems

- Take advantage of new materials or processing methods

- Incorporate failure analysis recommendations
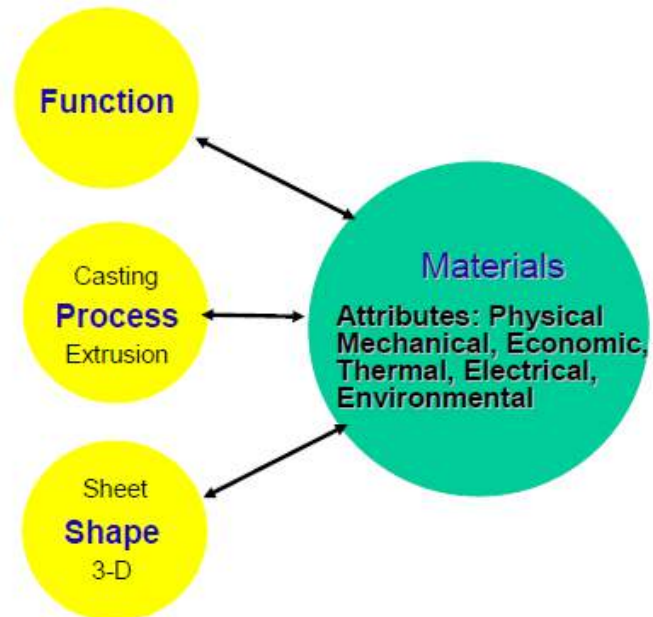
The selection of the material is done with all 3 criteria considered at the same time with the PERFORMANCE & COST as the most important factor

1. Properties profile

• Material selection based on properties profile is the process of matching the numerical values of the properties of the material to the requirements and constraints

2. Processing profile:

• Material selection based on processing profile is aimed at identifying the process that will form the material into the desired final shape including joining and finishing at the minimum cost

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3. Environmental profile:

• Relates to the impact of the material (its manufacture, use, reuse and disposal) on the environment. This added constraint increases the cost of the product

• Designing for the environment is an excellent philosophy because it can be a good marketing tool to environment conscious customers

• Assessment of the impact of materials on the environment is done by several approaches. The most popular is the "life-cycle analysis" or "LCA"

Materials Selection Methodology

• Translate the design requirements into materials specifications.It should take into consideration the design objectives, constraints and free variables. OR (express design requirements as constraints and objectives)

• Screening out of materials that fail the design constraints, OR (eliminate materials that cannot do the job).

• Ranking the materials by their ability to meet the objectives. (Material Indices). OR (find materials that best do the work using performance indices)

•Search for supporting information for the material candidates.

1. Defining the Design requirements

Function: What does the component do?

Objective: What essentials conditions must be met?

Constraints: What is to be maximized or minimized?

Free Variables: Identify which design variables are free?

•Which can be modified?

•Which are desirable?

Function	*Objective*	*Constraint*
"What does component do?"	*"What is to be maximized or minimized?"*	*"What specific requirements must be met?"*
Any engineering component has one or more functions (to support a load, to contain a pressure, to transmit heat, etc.).	The designer has an objective (to make it as cheap as possible, or as light as possible, or as safe as possible or some combination of these).	The objective must be achieved subject to constraints (e.g. the dimensions are fixed; the component must carry the given load without failure, it should function in a certain temperature range, etc.

Screening

Eliminate materials that cannot do the job

Need an effective way to evaluate a large range of material properties and classes.

•Methods to evaluate materials

–Material Bar Charts

–Material Property Charts

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Ranking

find the materials that do the job best

•What if multiple materials remain after screening?

•Which one is best?

•What if there are multiple material parameters for evaluation?

Use the Material Performance Index

Example 1: Strong and light tie-rod
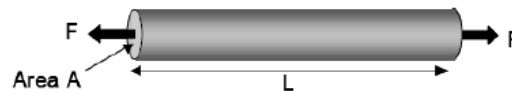
| Function | Support a tensile load |

| Objective | Minimize mass | $m = AL\rho$ |

Constraints	The length (L) is specified
	Must not fail under load
	Must have adequate fracture toughness

$$\frac{F}{A} \leq \sigma_y$$

| Free Variables | Materials choice |
| | Section Area (A) – eliminate using above equations |

$$m = AL\rho = FL\left(\frac{\rho}{\sigma_y}\right)$$

Minimize mass , hence, choose materials with smallest $\dfrac{\rho}{\sigma_y}$

Example: material for stiff, light beam

•Function:

Support a bending load

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•Objective

Minimize mass

•Constraints

Length

Carry load F with minimal deflection

•Free Variables

Cross-sectional area

Material

Example 2: Stiff and light beam

Function	Beam of solid square section
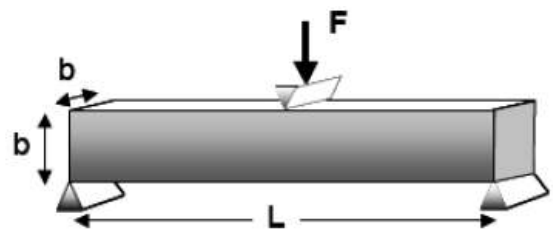
Objective	Minimize mass $\quad m = b^2 L \rho$

Constraints	The beam must be stiff, i.e. small deflection (C is a constant)

$$\delta_{Max} = \frac{FL^3}{48EI} \qquad F = (Stiffness)\delta_{Max}$$

$$Stiffness\_S = \frac{CEI}{L^3} = \frac{C_1 E b^4}{L^3}$$

Free Variables	Materials choice

Dimension *b* – eliminate using above equations

$$m = \left(\frac{SL^3}{C_1 E}\right)^{\frac{1}{2}} L\rho = \left(\frac{SL^5}{C_1}\right)^{\frac{1}{2}} \left(\frac{\rho}{E^{\frac{1}{2}}}\right)$$

Minimize mass , choose materials with smallest $\dfrac{\rho}{E^{\frac{1}{2}}}$

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Example 3: Stiff, light panel

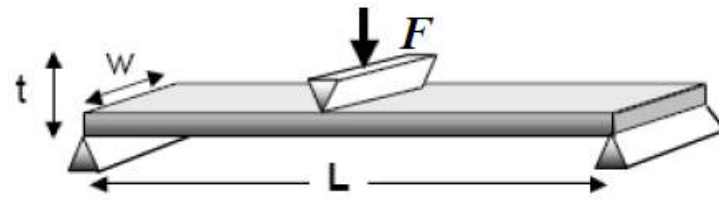| Function	Panel with given width (w) and length (L)
Objective	Minimize mass
Constraints	The panel must be stiff, i.e. small deflection (C is a constant)
Free Variables	Materials choice
	Dimension t – eliminate using above equations

$$m = twL\rho \qquad t = \text{thickness}$$

$$F = (Stiffness)\delta_{Max}$$

$$Stiffness\_S = \frac{CEwt^3}{L^3}$$

$$m = \left(\frac{SL^3}{CEw}\right)^{\frac{1}{3}} wL\rho = \left(\frac{SL^6w^2}{C}\right)^{1/3}\left(\frac{\rho}{E^{1/3}}\right)$$
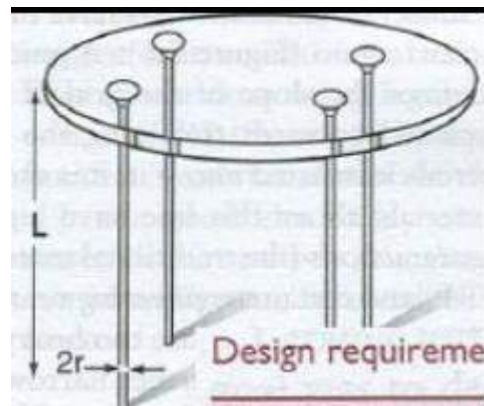
Minimize mass, choose materials with smallest $\dfrac{\rho}{E^{1/3}}$

Materials for Table legs

Design a slender, light table legs that will support the applied design load and will not fracture if struck

Function
Column, supporting compressive loads

L

2r

Design requireme

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Objective	Minimize mass and maximize slenderness
Constraints	Specified length, Must not buckle Must not fracture if struck
Free Variables	Diameter of the legs Choice of materials

mass: $\quad m = \pi r^2 L\rho \quad$ (1)

Maximum elastic buckling load:

$$F_{crit} = \frac{\pi^2 EI}{L^2} = \frac{\pi^3 Er^4}{4L^2} \quad where \quad I = \frac{\pi r^4}{4} \quad (2)$$

Solving for r

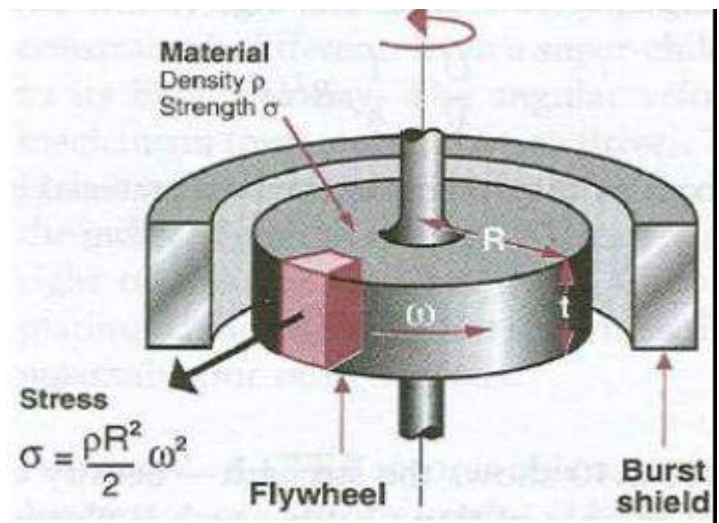$$m \geq \left(\frac{4F}{\pi}\right)^{1/2} L^2 \left(\frac{\rho}{E^{1/2}}\right) \quad (3)$$

The weight is minimized by selecting materials with the greatest value of the materials index:

$$M_1 = \left(\frac{E^{1/2}}{\rho}\right) \quad (4)$$

Inverting equation (2) gives and equation for the thinnest legs which will not buckle:

$$r \geq \left(\frac{4F}{\pi^3}\right)^{1/4} L^{1/2} \left(\frac{1}{E}\right)^{1/4} \quad (5)$$

to yield the second materials index (maximize): $\quad M_2 = E \quad$ (6)

Materials for Flywheels

Flywheels are rotating devices that store rotational energy in applications such as automotive transmissions. An efficient flywheel stores maximum energy per unit volume/mass at a specified angular velocity.

Material
Density ρ
Strength σ

Stress

$$\sigma = \frac{\rho R^2}{2} \omega^2$$

Flywheel

Burst shield

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The kinetic energy the device can the device can store is limited store is limited by the material by the material strength.

| Function | Flywheel for energy storage. |

| Objective | Maximize kinetic energy per unit mass. |

Mass of the disc $\quad m = \pi R^2 t \rho$

Kinetic energy (J is the mass moment of inertia) $\quad KE = \dfrac{1}{2} J w^2$

For a solid round disc J around its rotation axis

$$J = \frac{1}{2} m R^2 \qquad KE = \frac{1}{4} m R^2 w^2$$

The quantity to be maximized is the energy per unit mass

$$\frac{KE}{m} = \frac{1}{4} R^2 w^2$$

| Constraints | The outer radius is fixed.
It must not burst.
It must have adequate toughness (crack tolerance) |

| Free Variables | Choice of materials |

The maximum radial stress (principal stress) is given by the equation:

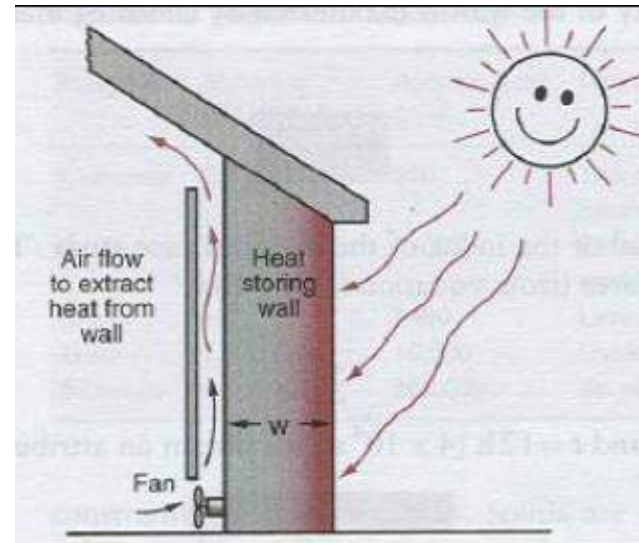$$\sigma_{r,Max} = \frac{3+\upsilon}{8} \rho \omega^2 R^2 \cong \frac{\rho \omega^2 R^2}{2}$$

The stress must not exceed the yield stress:

$$\frac{KE}{m} = \frac{1}{2} \left(\frac{\sigma_y}{\rho} \right)$$

Hence, the material index to maximize is:

$$M = \frac{\sigma_y}{\rho}$$

Materials for Passive Solar Heating

A simple way of storing solar energy for residential heating is by heating the walls during the day and transferring heat to the interior via forced convection at night. Need to diffuse heat from the outer to inner surface in 12h. For architectural reasons, the wall thickness (W) cannot exceed 0.5

Function	Heat storage medium
Objective	Maximize thermal energy storage per unit material cost.
Constraints	Heat diffusion time through wall time (t) ~12h Wall thickness w<0.5m Working temperature T_{Max} ~ 100^oC
Free Variables	Wall thickness w. Choice of materials

What material will maximize the thermal energy captured by the wall while retaining the required heat diffusion time of up to 12h?

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The heat capacity of the wall is maximized by choosing a material with a high value of:

$$\frac{\lambda}{\sqrt{D}}$$

The restriction on the wall thickness (w) and diffusion time (t) yield the constraint:

$$D \leq \frac{w^2}{2t} \leq 3 \times 10^{-6} \, m^2\!/\!s$$

Material Indices

For a wall of thickness w, the heat (Q) per unit area of wall heated through ΔT is given by:

$$Q = w\rho c_p \Delta T$$

For the heat diffusion distance in time t:

$$w = \sqrt{2Dt}$$

where Δ is the thermal diffusivity, λ is the thermal conductivity and ρ is the density

$$D = \frac{\lambda}{\rho c_p}$$

$$Q = \sqrt{2t}\,\rho c_p D^{1/2} \Delta T = \sqrt{2t}\,\Delta T \left(\frac{\lambda}{\sqrt{D}} \right)$$

Material Indices (MI) are groups of material properties (including cost) which are useful metrics for comparison of materials

•Better materials have higher MI's

•The form of the MI depends on the functional requirements (F) and geometry (G).

Materials indices are specific functions derived from design equations that involve only materials properties that can be used in conjunction with materials selection charts

- e.g. strong, light tie rod in tension–minimize ρ/σ_y
- e.g. stiff, light beam in bending –minimize $\rho/E^{1/2}$
- e.g. stiff, light panel in bending -minimize $\rho/E^{1/3}$

Derivation of MI's

This is a good moment to describe the method in more general terms. Structural elements are components that perform a physical function: they carry loads, transmit heat, store energy, and so on: in short, they satisfy functional requirements. The functional requirements are specified by the design: a tie must carry a specified tensile load; a spring must provide a given restoring force or store a given energy, a heat exchanger must transmit heat a given heat flux, and so on. The performance of a structural element is determined by three things: the functional requirements, the geometry and the properties of the material of which it is made.3 The performance P of the element is described by an equation of the form

$$P = \left[\left(\begin{array}{c} \text{Functional} \\ \text{requirements, } F \end{array} \right), \left(\begin{array}{c} \text{Geometric} \\ \text{parameters, } G \end{array} \right), \left(\begin{array}{c} \text{Material} \\ \text{properties, } M \end{array} \right) \right]$$

OR $P = f(F, G, M)$

where P, the *performance metric*, describes some aspect of the performance of the component: its mass, or volume, or cost, or life for example; and "*f*" means "*a function of*". *Optimum design* is the selection of the material and geometry that maximize or minimize P, according to its desirability or otherwise.

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The three groups of parameters in equation are said to be separable when the equation can be written

$$P = f_1(F) \cdot f_2(G) \cdot f_3(M)$$

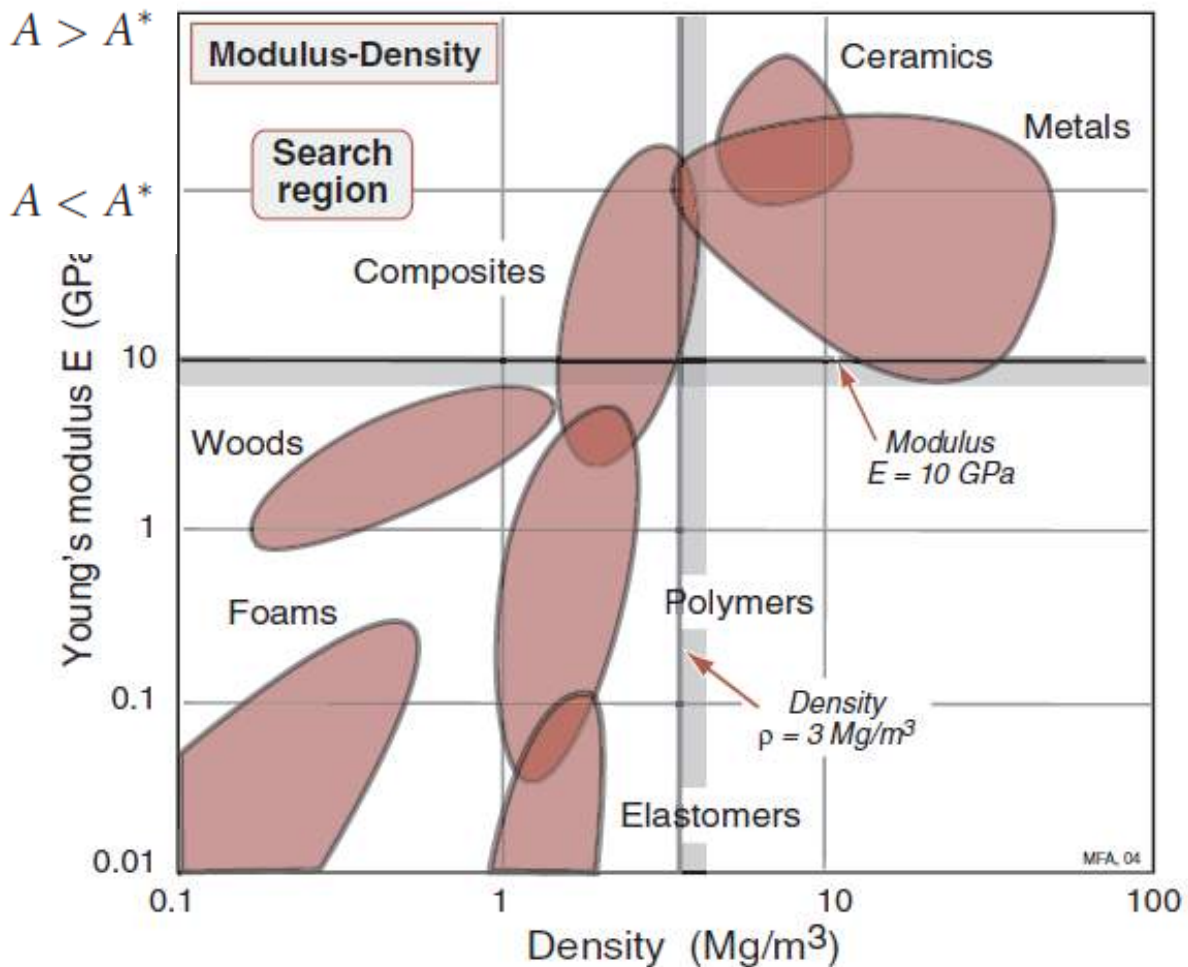where f_1, f_2, and f_3 are separate functions that are simply multiplied together. When the groups are separable, as they frequently are, the optimum choice of material becomes independent of the details of the design; it is the same for all geometries, G, and for all values of the function requirement, F. Then the optimum subset of materials can be identified without solving the complete design problem, or even knowing all the details of F and G. This enables
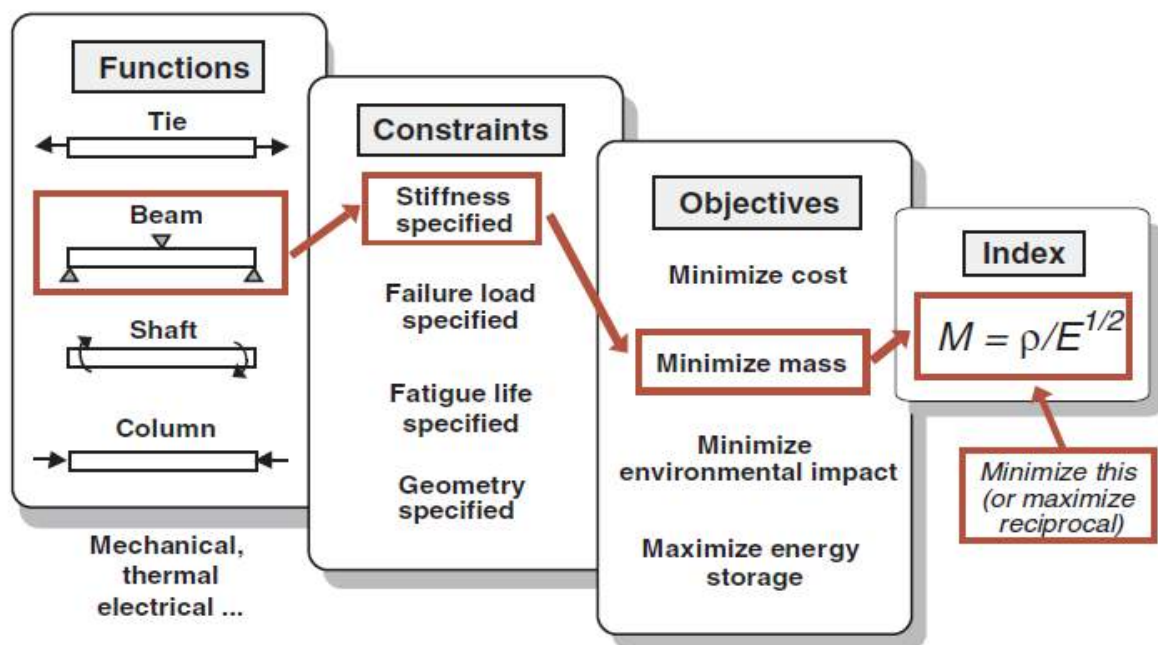
Screening applying attribute limits :-

Any design imposes certain non-negotiable demands ("constraints") on the material of which it is made. We have explained how these are translated into attribute limits. Attribute limits plot as horizontal or vertical lines on material selection charts, illustrated in Figure. It shows a

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schematic E-ρ chart, We suppose that the design imposes limits on these of

$E > 10\,\mathrm{GPa}$ and $\rho < 3\,\mathrm{Mg/m^3}$, shown on the figure. The optimizing search is restricted to the window boxed by the limits, labeled "Search region". Less quantifiable properties such as corrosion resistance, wear resistance or form-ability can all appear as primary limits, which take the form

$$A > A^*$$

$$A < A^*$$

where A is an attribute (service temperature, for instance) and A^* is a critical value of that attribute, set by the design, that must be exceeded, or (in the case of corrosion rate) must *not* be exceeded.

One should not be too hasty in applying attribute limits; it may be possible to engineer a route around them. A component that gets too hot can be cooled; one that corrodes can be coated with a protective film. Many designers apply attribute limits for fracture toughness, K_{1C} and ductility ε_f insisting on materials with, as rules of thumb, $K_{1C} > 15\,\text{MPa.m}^{1/2}$ and $\varepsilon_f > 2\%$ in order to guarantee adequate tolerance to stress concentrations. By doing this they eliminate materials that the more innovative designer is able to use to good purpose (the limits just cited for K_{1C} and ε_f eliminate all polymers and all ceramics, a rash step too early in the design). At this stage, keep as many options open as possible.

Ranking: indices on charts

The next step is to seek, from the subset of materials that meet the property limits, those that maximize the performance of the component. We will use the design of light, stiff components as an example; the other material indices are used in a similar way.

Figure shows, as before, modulus E, plotted against density ρ , on log scales. The material indices $E/\rho,\ E^{1/2}/\rho,$ and $E^{1/3}/\rho$ be plotted onto the figure. The condition

$$\frac{E}{\rho} = C$$

or, taking logs,

$$\text{Log}(E) = \text{Log}(\rho) + \text{Log}(C)$$

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is a family of straight parallel lines of slope 1 on a plot of Log(E) against Log(ρ)
each line corresponds to a value of the constant C. The condition
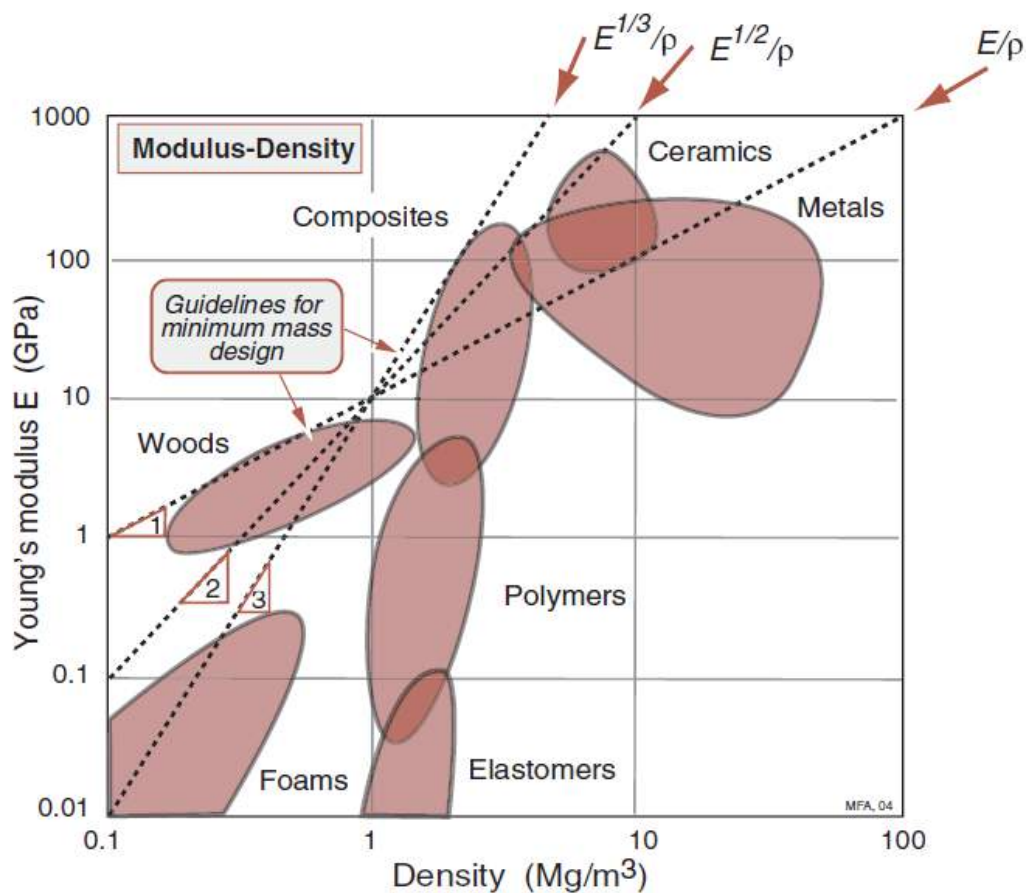
$$\frac{E^{1/2}}{\rho} = C$$

or, taking logs again,

$$Log(E) = 2\,Log(\rho) + 2\,Log(C)$$

gives another set, this time with a slope of 2; and

$$\frac{E^{1/3}}{\rho} = C$$

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gives yet another set, with slope 3. We shall refer to these lines as selection guidelines. They give the slope of the family of parallel lines belonging to that index. Where appropriate the charts of Chapter 4 show the slopes of guidelines like these.
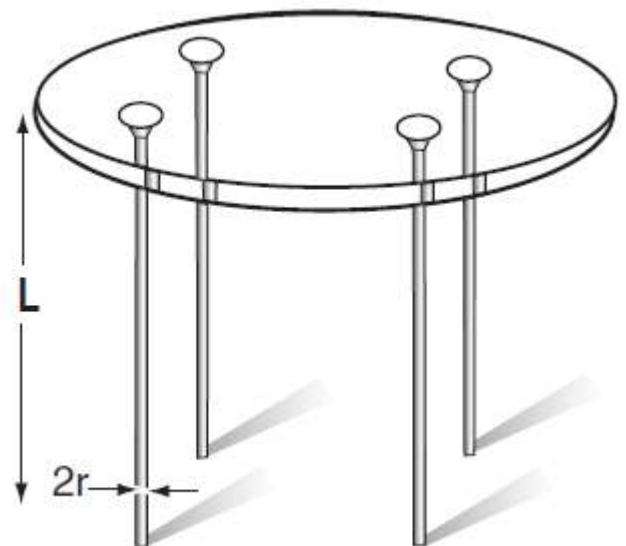
It is now easy to read off the subset materials that optimally maximize performance for each loading geometry. All the materials that lie on a line of constant $E^{1/2}/\rho$ perform equally well as a light, stiff beam; those above the line are better, those below, worse. Figure 5.12 shows a grid of lines corresponding to values of $E^{1/2}/\rho$ from 0.1 to 3 in units of $GPa^{1/2}/(Mg/m^3)$. A material with $M=1$ in these units gives a beam that has one tenth the weight of one with $M=0.1$. The subset of materials with particularly good values of the index is identified by picking a line that isolates a search area containing a reasonably small number of candidates, as shown schematically in Figure 5.13 as a diagonal selection line. Attribute limits can be added, narrowing the search window: that corresponding to $E>50\,GPa$ is shown as a horizontal line. The short-list of candidate materials is expanded or contracted by moving the index line.
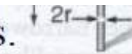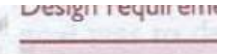
<u>Case 1</u>: Materials for Table legs Design a slender, light table legs that will support the applied design load and will not fracture if struck.

Luigi Tavolino, furniture designer, conceives of a light-weight table of daring simplicity: a flat sheet of toughened glass supported on slender, un-braced, cylindrical legs (Figure). The legs must be solid (to make them thin) and as light as possible (to make the table easier to move).

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Function	Column, supporting compressive loads.
Objective	Minimize mass and maximize slenderness
Constraints	Specified length, Must not buckle, Must not fracture if struck
Free Variables	Diameter of the legs, Choice of materials

mass: $\quad m = \pi r^2 L \rho \qquad (1)$

Maximum elastic buckling load:

$$F_{crit} = \frac{\pi^2 EI}{L^2} = \frac{\pi^3 E r^4}{4L^2} \quad where \quad I = \frac{\pi r^4}{4} \qquad (2)$$

Solving for r

$$m \geq \left(\frac{4F}{\pi}\right)^{1/2} L^2 \left(\frac{\rho}{E^{1/2}}\right) \qquad (3)$$

The weight is minimized by selecting materials with the greatest value of the materials index:

$$M_1 = \left(\frac{E^{1/2}}{\rho}\right) \qquad (4)$$

Inverting equation (2) gives and equation for the thinnest legs which will not buckle:

$$r \geq \left(\frac{4F}{\pi^3}\right)^{1/4} (L)^{1/2} \left[\frac{1}{E}\right]^{1/4}$$

The thinnest leg is that made of the material with the largest value of the material index

$$M_2 = E$$

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The selection. We seek the subset of materials that have high values of $E^{1/2}/\rho$ and E. We need the $E - \rho$ chart again (Figure 6.6). A guideline of slope 2 is drawn on the diagram; it defines the slope of the grid of lines for values of $E^{1/2}/\rho$. The guideline is displaced upwards (retaining the slope) until a reasonably small subset of materials is isolated above it; it is shown at the position $M_1 = 5 \, \text{GPa}^{1/2}/(\text{Mg/m}^3)$. Materials above this line have higher values of M_1. They are identified on the figure: *woods* (the traditional material for table legs), *composites* (particularly CFRP) and certain *engineering ceramics*. Polymers are out: they are not stiff enough; metals too: they are too heavy (even magnesium alloys, which are the lightest). The choice is further narrowed by the requirement that, for slenderness, E must be large. A horizontal line on the diagram links materials with equal values of E; those above are stiffer. Figure 6.6 shows that placing this line at $M_1 = 100 \, \text{GPa}$ eliminates woods and GFRP. If the legs must be really thin, then the short-list is reduced to CFRP and ceramics: they give legs that weigh the same as the wooden ones but are barely half as thick. Ceramics, we know, are brittle: they have low values of fracture toughness.