4-1- What is Material Property?

It is a factor that influences qualitatively or quantitatively the response of a given material to impose stimuli & constraints, e.g., forces, temperature, etc. Properties render a material suitable or unsuitable for a particular use in industry.

4-2- PROPERTIES OF METALS

Metals are elements that have atoms arranged in rows. The electrons are easily released from metal atoms so that layers of metal atoms exist in a 'sea' of electrons. Examples of Metals are gold, copper, lead, zinc, iron, magnesium, sodium, calcium and mercury.

A steel ruler is easy to bend elastically—‘elastic’ means that it springs back when released. Its elastic stiffness (here, resistance to bending) is set partly by its shape—thin strips are easy to bend—and partly by a property of the steel itself: its elastic modulus, \( E \). Materials with high \( E \), like steel, are intrinsically stiff; those with low \( E \), like polyethylene, are not. Figure 1.2(b) illustrates the consequences of inadequate stiffness. The steel ruler bends elastically, but if it is a good one, it is hard to give it a permanent bend. Permanent deformation has to do with strength, not stiffness.

The ease with which a ruler can be permanently bent depends, again, on its shape and on a different property of the steel—its yield strength, \( \sigma_y \). Materials with large \( \sigma_y \), like titanium alloys, are hard to deform permanently even though their stiffness, coming from \( E \), may not be high; those with low \( \sigma_y \), like lead, can be deformed with ease. When metals deform, they generally get stronger (this is called ‘work hardening’), but there is an ultimate limit, called the tensile strength, \( \sigma_{ts} \), beyond which the material fails (the amount it stretches before it breaks is called the ductility). Figure 1.2(c) gives an idea of the consequences of inadequate strength. So far so good. One more. If the ruler were made not of steel but of glass or of PMMA (Plexiglas, Perspex), as transparent rulers are, it is not possible to bend it permanently at all. The
ruler will fracture suddenly, without warning, before it acquires a permanent bend. We think of materials that break in this way as brittle, and materials that do not as tough. There is no permanent deformation here, so σ_y is not the right property. The resistance of materials to cracking and fracture is measured instead by the fracture toughness, K_{1c}. Steels are tough—well, most are (steels can be made brittle)—they have a high K_{1c}. Glass epitomizes brittleness; it has a very low K_{1c}. Figure 1.2(d) suggests consequences of inadequate fracture and toughness.

We started with the material property density, mass per unit volume, symbol ρ. Density, in a ruler, is irrelevant. But for almost anything that moves, weight carries a fuel penalty, modest for automobiles, greater for trucks and trains, greater still for aircraft, and enormous in space vehicles. Minimizing weight has much to do with clever design—we will get to that later—but equally to choice of material. Aluminum has a low density, lead a high one. If our little aircraft were made of lead, it would never get off the ground at all (Figure 1.2(e)). These are not the only mechanical properties, but they are the most important ones.

### 4-3 - TYPES OF MATERIAL PROPERTIES:

There are two major classes of material properties:

1- **Fundamental**: can be measured directly: Mechanical properties, Thermal properties, Electrical properties, Magnetic properties, Chemical properties, Optical properties, Physical properties, Acoustical properties, Radiological properties. They generally have the advantage that they can be used directly in design calculations.

2- **Ranking**: These generally do not measure single fundamental properties and can only be used to rank materials in order of superiority. They cannot be used directly in design calculations, but could be used in formalized selection procedures. A combination of several fundamental and generally more subjective. These known as manufacturing properties e.g. formability, machinability. Other takes a figure or order of merit such as hardenability.
Manufacturing properties: these properties are desire properties a material should have and needed in fabrication and manufacturing process, like Castability, Hardenability, Machinability, Malleability and ductility.

Physical Properties of Metals: Physical Properties of Metals include shiny luster, greyish-silver colour, good heat and electricity conductivity, high melting and boiling points. Some of metals - sodium and calcium (very soft), gold and copper (yellowish colour), and mercury (low melting and boiling points).

Table () some of Materials properties

<table>
<thead>
<tr>
<th>Category</th>
<th>Typical desirable properties</th>
<th>Main applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Strength, Toughness, Stiffness</td>
<td>Machinery, Load-bearing structures</td>
</tr>
<tr>
<td>Chemical</td>
<td>Oxidation resistance, Corrosion resistance, UV radiation resistance</td>
<td>Chemical plant, Power plant, Marine structures, Outdoor structures</td>
</tr>
<tr>
<td>Physical</td>
<td>Density</td>
<td>Aerospace, outer space, Reciprocating and rotating machinery</td>
</tr>
<tr>
<td></td>
<td>Thermal conductivity, Electrical conductivity, Magnetic properties</td>
<td>Power transmission, Instrumentation, Electrical machinery, Electronics</td>
</tr>
</tbody>
</table>

A. Chemical Properties of Metals: Some metals are more reactive than others. This is because very reactive metals lose electrons easily. Metals such as sodium are very reactive and are explosive in air. Metals such as gold are very unreactive, and therefore do not corrode or tarnish in air.

B. Mechanical Properties: These include those characteristics of material that describe its behaviour (response) under the action of external forces (loads). Can be
determined by conducting experimental tests on the material specimen. **Strength**, Hardness, Toughness, Britteness, Ductility, Malleability, Elasticity, Plasticity, Rigidity, Resilience, Fatigue, Creep…

1) **STRENGTH** It is the ability of a material to resist deformation under the action of tensile, compressive or shear force. The strength of a component is usually based on the maximum load that can be borne before failure is apparent. The most common measure of strength is the yield strength.

2) **HARDNESS** It is the ability of a material to offer resistance to penetration or indentation. It is also the ability to resist wear, abrasion, scratch or cutting.

3) **TOUGHNESS** It describes a material’s resistance to fracture under impact loading. It is often expressed in terms of the amount of energy a material can absorb before fracture. Toughness is not a single property but rather a combination of strength and ductility.

4) **BRITTLENESS**: It is that property by virtue of which a material breaks easily under action of shock loads without appreciable amount. It indicates the lack of ductility. For example glass, ceramics and cast iron are brittle materials.

5) **DUCTILITY**: It is a measure of the amount of deformation of a material can withstand before breaking. It is also the ability of a material by which it can be drawn into wires.

6) **MALLEABILITY**: It is the ability of a material by which it can be rolled into sheets. Malleability is the ability of a material to exhibit large deformation subjected to compressive force whereas ductility is the ability of a material to deform upon the application of tensile force. Aluminum, Copper and gold have good malleability.

7) **ELASTICITY**: It is the property of a material to regain its original shape after the removal of load. When a material is subjected to an external load of such magnitude that deformation continues only with increase in load, and on
removing the load it regains its original shape, then the material is said to have elasticity.

8) **PLASTICITY** It is the property of a material by virtue of which it undergoes permanent deformation. When a material is subjected to an external load of such magnitude that deformation continues with no apparent further increase in load, the material is said to have become plastic. In this region the material experiences permanent deformation and does not return to its original shape when the load is removed.

9) **RIGIDITY** : It is also known as stiffness. It is the property of a material by virtue of which the material resists elastic or plastic deformation under applied loads.

10) **MACHINABILITY** It refers to the ease with which a material can be removed during various machining operations. It describes the property of a material when it is cut. Materials with good machinability require less power to cut, resulting in good surface finish and longer cutting tool life.
11) HARDENABILITY It indicates the degree of hardness that a material can acquire through a hardening process. It is the capability of a material to get hardened by heat treatment. It determines the depth and distribution of hardness induced by quenching.

12) RESILIENCE It is the property of a material to absorb energy when it is deformed elastically and then, upon unloading, to have this energy recovered. In other words, it is the maximum energy per volume that can be elastically stored.

13) FATIGUE It is the strength of the materials when subjected to cyclic or rapid fluctuating load conditions. Owing to fatigue a material fails at a stress level much below that under static loads. The maximum stress to which the material can be subjected without fatigue failure is known as the endurance limit.

14) CREEP It is the progressive deformation of a material under a constant static load maintained for a long period of time. It is a slow, temperature-aided, time-dependent deformation. It occurs in three stages known as primary, secondary and tertiary stage.

Figure 4.2 - Thermal properties.
4-4 – 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), it may oxidize, degrade or decompose. Figure 4.2 (a) This means that there is a limiting temperature called the maximum service temperature, \( T_{\text{max}} \), above which its use is impractical. Stainless steel has a high \( T_{\text{max}} \) —it can be used up to 800°C; most polymers have a low \( T_{\text{max}} \) and are seldom used above 150°C. Most materials expand when they are heated, but by differing amounts depending on their thermal expansion coefficient, \( \alpha \). The expansion is small, but its consequences can be large. If, for instance, a rod is constrained, and then heated, expansion forces the rod against the constraints, causing it to buckle. Railroad track buckles in this way if provision is not made to cope with it.

Some materials—metals, for instance—feel cold; others—like woods—feel warm. This feel has to do with two thermal properties of the material: thermal conductivity and heat capacity. The first, thermal conductivity, \( \lambda \), measures the rate at which heat flows through the material when one side is hot and the other cold. Materials with high \( \lambda \) are what you want if you wish to conduct heat from one place to another, as in cooking pans, radiators and heat exchangers; Figure 4.4 (c) suggests consequences of high and low \( \lambda \) for the cooking vessel. But low \( \lambda \) is useful too—low \( \lambda \) materials insulate homes, reduce the energy consumption of refrigerators and freezers, and enable space vehicles to re-enter the earth’s atmosphere.

These applications have to do with long-time, steady, heat flow. When time is limited, that other property—heat capacity, \( C_p \) matters. It measures the amount of heat that it takes to make the temperature of material rise by a given amount. High heat capacity materials—copper, for instance—require a lot of heat to change their temperature; low heat capacity materials, like polymer foams, take much less. Steady heat flow has, as we have said, to do with thermal conductivity. There is a subtler property that describes what happens when heat is first applied. Think of lighting the gas under a cold slab of material with a bowl of ice-cream on top (here, lime ice-cream) as in Figure 1.3(d). An instant after ignition, the bottom surface is hot but the rest is cold. After a while, the middle gets hot, then later still, the top begins to warm up and the ice-cream first starts to melt. How long does this take? For a given thickness of slab,
the time is inversely proportional to the thermal diffusivity, \( a \), of the material of the slab. It differs from the conductivity because materials differ in their heat capacity—in fact, it is proportional to \( \lambda/C_p \). There are other thermal properties.

**Electrical, magnetic and optical properties**

We start with electrical conduction and insulation (Figure 1.4(a)). Without electrical conduction we would lack the easy access to light, heat, power, control and communication that—today—we take for granted. Metals conduct well—copper and aluminum are the best of those that are affordable. But conduction is not always a good thing. Fuse boxes, switch casings, the suspensions for transmission lines all require insulators, and in addition those that can carry some load, tolerate some heat and survive a spark if there were one. Here the property we want is resistivity, \( \rho_e \), the inverse of electrical conductivity \( \kappa_e \). Most plastics and glass have high resistivity (Figure 1.4(a))—they are used as insulators—though, by special treatment, they can be made to conduct a little. Figure 1.4(b) suggests further electrical properties: the ability to allow the passage of microwave radiation, as in the radome, or to reflect them, as in the passive reflector of the boat. Both have to do with dielectric properties, particularly the dielectric constant \( \varepsilon_D \). Materials with high \( \varepsilon_D \) respond to an electric field by shifting their electrons about, even reorienting their molecules; those with low \( \varepsilon_D \) are immune to the field and do not respond.

Electricity and magnetism are closely linked. Electric currents induce magnetic fields; a moving magnet induces, in any nearby conductor, an electric current. The response of most materials to magnetic fields is too small to be of practical value.

But a few—called ferromagnets and ferrimagnets—have the capacity to trap a magnetic field permanently. These are called ‘hard’ magnetic materials because, once magnetized, they are hard to demagnetize. They are used as permanent magnets in headphones, motors and dynamos. Here the key property is the remanence, a measure of the intensity of the retained magnetism. A few others—‘soft’ magnet materials—are easy to magnetize and demagnetize. They are the materials of transformer cores and the deflection coils of a TV tube. They have the capacity to conduct a magnetic
field, but not retain it permanently (Figure 1.4(c)). For these a key property is the saturation magnetization, which measures how large a field the material can conduct.

Materials respond to light as well as to electricity and magnetism—hardly surprising, since light itself is an electromagnetic wave. Materials that are opaque reflect light; those that are transparent refract it, and some have the ability to absorb some wavelengths (colors) while allowing others to pass freely (Figure 1.4(d)).

**Chemical properties**

Products often have to function in hostile environments, exposed to corrosive fluids, to hot gases or to radiation. Damp air is corrosive, so is water; the sweat of your hand is particularly corrosive, and of course there are far more aggressive environments than these. If the product is to survive for its design life it must be made of materials—or at least coated with materials—that can tolerate the surroundings in which they operate. Figure 1.5 illustrates some of the commonest of these: fresh and salt water, acids and alkalis, organic solvents, oxidizing flames and ultraviolet radiation. We regard the intrinsic resistance of a material to each of these as material properties, measured on a scale of 1 (very poor) to 5 (very good).
Figure 1.5 Chemical properties: resistance to water, acids, alkalis, organic solvents, oxidation and radiation.

From x-eng. Materials / Ashby
Material Testing:

In general, the behavior of Materials under loads can be determined through standard tests, which shows the relevant Mechanical Properties. There are three types of material deformation and the corresponding mechanical properties can be summarized as follows:

- **Elastic material properties**: They govern the so-called elastic deformations where upon removal of the applied loads, the material returns to its original state (recoverable deformation),

- **Plastic material properties**: They govern the response of materials in plastic deformations where upon removal of the applied load, the material does not return to its original state (non-recoverable deformation), and finally

- **Fracture properties**: They define the laws that are associated with the separation of the material in two or more pieces after the application of some forces.
Concepts of Stress and Strain (tension and compression)

To compare specimens of different sizes, the load is calculated per unit area.

**Engineering stress:** $\sigma = \frac{F}{A_0}$

$F$ is load applied perpendicular to specimen crosssection; $A_0$ is cross-sectional area (perpendicular to the force) before application of the load.

**Engineering strain:** $e = \frac{\Delta l}{l_0} (\times 100 \%)$

$\Delta l$ is change in length, $l_0$ is the original length.

These definitions of stress and strain allow one to compare test results for specimens of different cross-sectional area $A_0$ and of different length $l_0$.

**Stress and strain are positive for tensile loads, negative for compressive loads**

**Elastic deformation**

Reversible: when the stress is removed, the material returns to the dimension it had before the loading.

Usually strains are small (except for the case of plastics).

**Plastic deformation**

Irreversible: when the stress is removed, the material does not return to its previous dimension.

**Nonlinear elastic behavior**

In some materials (many polymers, concrete...), Elastic deformation is not linear, but it is still reversible.

**Plastic deformation:**

- Stress and strain are not proportional
- The deformation is not reversible
- Deformation occurs by breaking and re-arrangement of atomic bonds (in crystalline materials primarily by motion of dislocations).
Chapter four  
Selection of Materials and processes  
Fourth class - 2013-2014  
Dep. of Production Eng. And Metallurgy  
Dr. May George Amin  
industrial Engineering

**Tensile Strength**

If stress = tensile strength is maintained then specimen will eventually break

Fracture Strength

"Necking"

Tensile strength: maximum stress (~100 - 1000 MPa)

For structural applications, the yield stress is usually a more important property than the tensile strength, since once it is passed, the structure has deformed beyond acceptable limits.

**Tensile properties: Yielding**

Yield stress $\sigma_y$ is chosen as that causing a permanent strain of 0.002

Yield point $P$ - the strain deviates from being proportional to the stress (the proportional limit)

The yield stress is a measure of resistance to plastic deformation

For a low-carbon steel, the stress vs. strain curve includes both an upper and lower yield point. The yield strength is defined in this case as the average stress at the lower yield point.

**Tensile properties: Ductility**

Ductility is a measure of the deformation at fracture

Defined by percent elongation

$$\% EL = \left( \frac{L_f - L_0}{L_0} \right) \times 100$$
Toughness = the ability to absorb energy up to fracture = the total area under the strain-stress curve up to fracture. Can be measured by an impact test (Units: the energy per unit volume, e.g. J/m³)

Note:

The yield strength and tensile strength vary with prior thermal and mechanical treatment, impurity levels, etc. This variability is related to the behavior of dislocations in the material. But elastic module is relatively insensitive to these effects. The yield and tensile strengths and modulus of elasticity decrease with increasing temperature, ductility increases with temperature.
**True Stress and Strain**

True stress is the load divided by the actual area in the necked-down region ($A_i$):

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

Sometimes it is convenient to use true strain defined as:

$$\varepsilon_T = \ln\left(\frac{l_i}{l_0}\right)$$

True stress continues to rise to the point of fracture, in contrast to the engineering stress.

If no volume change occurs during deformation, $A_i l_i = A_0 l_0$ and the true and engineering stress and strain are related as:

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

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

---

**Typical mechanical properties of metals**

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

Hardness is a measure of the material’s resistance to localized plastic deformation

A qualitative Moh’s scale, determined by the ability of a material to scratch another material: from 1 (softest = talc) to 10 (hardest = diamond).

Different types of quantitative hardness test have been designed (Rockwell, Brinell, Vickers, etc.). Usually a small indenter (sphere, cone, or pyramid) is forced into the surface of a material under conditions of controlled magnitude and rate of loading. The depth or size of indentation is measured. The tests somewhat approximate, but popular because they are easy and non-destructive (except for the small dent).
Table (4-1) properties comparison between the four basic material groups.

<table>
<thead>
<tr>
<th>Property</th>
<th>Alloys (Metals)</th>
<th>Ceramics</th>
<th>Polymers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>(2-16) ρ average ≈ 8</td>
<td>(2-17) ρ average ≈ 5</td>
<td>(1-2) ρ average ≈ 1.2</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>L – H (50-3400) °C</td>
<td>M – H 4000</td>
<td>Low :Less than 400</td>
</tr>
<tr>
<td>Hardness</td>
<td>L – H In general M</td>
<td>M – H</td>
<td>Low</td>
</tr>
<tr>
<td>Tensile strength (Mpa)</td>
<td>(0 – 5000) L- H</td>
<td>(20 – 500) L-M</td>
<td>V.L – M Less than 120</td>
</tr>
<tr>
<td>Compression (Mpa)</td>
<td>L – H (10-5000)</td>
<td>M-H (200-5000)</td>
<td>L – M Less than 350</td>
</tr>
<tr>
<td>E (G Pa)</td>
<td>L – H (40-400) Mg w</td>
<td>M-H (150-450)</td>
<td>V.L (0.001-3.5)</td>
</tr>
<tr>
<td>Creep resist</td>
<td>Poor – medium &lt; 1050 °C Pure Metal ≈ 0.3 Tm Special Separately(0.6-0.7) Tm, for must alloys =0.4 Tm</td>
<td>Good – Excellent</td>
<td>V.L</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>M-H</td>
<td>L-H</td>
<td>V.H 2-20 times greater than steel</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>M-H</td>
<td>M (but decease rapidly with increasing temp.)</td>
<td>V.L</td>
</tr>
<tr>
<td>Thermal shock</td>
<td>Good</td>
<td>Generally poor</td>
<td></td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>M-H</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Oxidation resistance</td>
<td>Poor (except Co, Ni alloys)</td>
<td>Excellent</td>
<td></td>
</tr>
<tr>
<td>Machineability</td>
<td>M-H</td>
<td>Generally poor</td>
<td>Generally M</td>
</tr>
<tr>
<td>Castability</td>
<td>M-H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formability</td>
<td>Generally good (except for specific sys. Such as refractory metals)</td>
<td>Generally good for thermoplastic</td>
<td></td>
</tr>
<tr>
<td>Joinability (weldability)</td>
<td>M-H</td>
<td>V. poor</td>
<td>H</td>
</tr>
<tr>
<td>Heat Treatability</td>
<td>M-H</td>
<td>M-H</td>
<td></td>
</tr>
</tbody>
</table>
Table (4-2) properties comparison rating between the four basic material groups.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Formability</th>
<th>Durability</th>
<th>Density</th>
<th>Cost</th>
<th>Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymers</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>Ceramics</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>L</td>
</tr>
<tr>
<td>Metals &amp; Alloys</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>H</td>
</tr>
<tr>
<td>Semiconductor</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Composites</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>L</td>
</tr>
</tbody>
</table>

Table (4-3) properties comparison between the four material groups.

<table>
<thead>
<tr>
<th>Plastics</th>
<th>Metals</th>
<th>Ceramics</th>
<th>Composites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak Compliant</td>
<td>Strong</td>
<td>Strong</td>
<td>Strong</td>
</tr>
<tr>
<td>Tough</td>
<td>Stiff</td>
<td>Brittle</td>
<td>Stiff</td>
</tr>
<tr>
<td>Electrically conducting</td>
<td>Durable</td>
<td>Durable</td>
<td>Low density</td>
</tr>
<tr>
<td>Electrically insulating</td>
<td>High thermal conductivity</td>
<td>Refractory</td>
<td>Anisotropic</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
What are the limits of “safe” deformation?

**Design stress:** \( \sigma_d = N' \sigma_c \) where \( \sigma_c \) = maximum

Anticipated stress, \( N' \) is the “design factor” \( > 1 \). Want to make sure that \( \sigma_d < \sigma_y \)

**Safe or working stress:** \( \sigma_w = \sigma_y/N \) where \( N \) is “factor of safety” \( > 1 \).

### 3-5- Effect of shape on materials selection

**Shape factors**

- Occasionally, section shape is not a factor in designing a component and design optimised solely by material choice.
- More generally, design combines section shape with material choice and so shape factors are required.
- Need to consider macroscopic shape factors: overall bulk shape of a section
- Microscopic shape factors: structural anisotropy within a bulk section
3-6- A General approach for Failure analysis
The Aims are to
  • find the primary cause of failure
  • Initiate corrective action to prevent repetition.
Method
  a- Field assessment
    ▪ obtain samples & controls
    ▪ record background data (plus service history)
    ▪ preliminary examination of failed part
    ▪ reconstruction of events
  b- Initial assessment
    ▪ non-destructive evaluation
    ▪ macroscopic examination (fracture surfaces, cracks)
    ▪ microscopic examination (including micro-hardness)
    ▪ collection of information on (history of) suspect components
  c- Detailed assessment:
    ▪ mechanical testing
    ▪ chemical analysis (bulk, local, surface, corrosion/wear products)
    ▪ test under simulated service conditions
  d- Diagnosis: ensure data are self consistent
  e- Report:
    ▪ analysis of all data
    ▪ suggestions for the future
  f- Action:
    ▪ Implementation of report (no action, modifications, withdrawal).

2-6- Reasons for failure
a. design deficiency
b. material's problem
c. overload (abuse)
d. Failure to observe specification.

History of component
  1) design criteria: specifications - codes of practice, and safety factor
  2) materials selection: specifications, and substitution
  3) manufacturing practice: codes of practice, and records
  4) service history:
    a. Loads
    b. Displacements
    c. Temperature
d. Environment

5) **Statistical data.**

**Failure in service**
Since one of the aims of manufacture is to ensure that failure does not occur in service, it is necessary to be clear concerning the possible mechanisms of failure. Broadly, in engineering components, failure occurs either mechanically or by some form of corrosive attack.
There are three main ways in which a component can fail mechanically:

1. Ductile collapse because the material does not have a yield stress high enough to withstand the stresses imposed. The fracture properties of the material are not important here and the failure is usually the result of faulty design or (especially in the case of high-temperature service) inadequate data.
2. Failure by a fatigue mechanism as a result of a component being subject to repeated loading which initiates and propagates a fatigue crack.
3. Catastrophic or brittle failure, with a crack propagating in an unstable and rapid manner. Any existing flaw, crack or imperfection can propagate if the total energy of the system is decreased, i.e. if the increase in energy to form the two new surfaces and consumed in any plastic work involved is less than the decrease in stored elastic energy caused by the growth of the crack. The significance of ductile yield in blunting cracks and reducing elastic stress concentration is immediately apparent. Beware, then, materials where there is little difference between the yield stress and the maximum stress.
Fatigue (Failure under fluctuating / cyclic stresses)

Fatigue: Cyclic Stresses (I)

- **Periodic and symmetrical about zero stress**
- **Periodic and asymmetrical about zero stress**
- **Random stress fluctuations**
Fatigue

(Failure under fluctuating / cyclic stresses)

Under fluctuating / cyclic stresses, failure can occur at loads considerably lower than tensile or yield strengths of material under a static load: **Fatigue**

Estimated to cause 90% of all failures of metallic structures (bridges, aircraft, machine components, etc.)

**Fatigue failure is brittle-like** (relatively little plastic deformation) - even in normally ductile materials. Thus sudden and catastrophic!

Applied stresses causing fatigue may be axial (tension or compression), flexural (bending) or torsional (twisting).

Fatigue failure proceeds in three distinct stages: crack initiation in the areas of stress concentration (near stress raisers), incremental crack propagation, final catastrophic failure.

**Fatigue: Cyclic Stresses (II)**

Cyclic stresses are characterized by maximum, minimum and mean stress, the range of stress, the stress amplitude, and the stress ratio

Mean stress:

\[ \sigma_m = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} \]

Range of stress:

\[ \sigma_r = \sigma_{\text{max}} - \sigma_{\text{min}} \]

Stress amplitude:

\[ \sigma_a = \sigma_r / 2 = \frac{\sigma_{\text{max}} - \sigma_{\text{min}}}{2} \]

Stress ratio:

\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \]

*Remember the convention that tensile stresses are positive, compressive stresses are negative*
Fatigue: $S — N$ curves (I)  
(stress — number of cycles to failure)

Fatigue properties of a material ($S$-$N$ curves) are tested in rotating-bending tests in fatigue testing apparatus:

Result is commonly plotted as $S$ (stress) vs. $N$ (number of cycles to failure)

Low cycle fatigue: high loads, plastic and elastic deformation

High cycle fatigue: low loads, elastic deformation ($N > 10^5$)

Fatigue: $S—N$ curves (II)

Fatigue limit (endurance limit) occurs for some materials (e.g. some Fe and Ti alloys). In this case, the $S—N$ curve becomes horizontal at large $N$. The fatigue limit is a maximum stress amplitude below which the material never fails, no matter how large the number of cycles is.
In most alloys, $S$ decreases continuously with $N$. In this cases the fatigue properties are described by

**Fatigue strength**: stress at which fracture occurs after a specified number of cycles (e.g. $10^7$)

**Fatigue life**: Number of cycles to fail at a specified stress level

**Fatigue: Crack initiation and propagation (I)**

Three stages of fatigue failure:

1. crack initiation in the areas of stress concentration (near stress raisers)
2. incremental crack propagation
3. final rapid crack propagation after crack reaches critical size

The total number of cycles to failure is the sum of cycles at the first and the second stages:

$$N_f = N_i + N_p$$

$N_f$: Number of cycles to failure
$N_i$: Number of cycles for crack initiation
$N_p$: Number of cycles for crack propagation

High cycle fatigue (low loads): $N_i$ is relatively high. With increasing stress level, $N_i$ decreases and $N_p$ dominates
Fatigue: Crack initiation and propagation (II)

- Crack initiation at the sites of stress concentration (microcracks, scratches, indents, interior corners, dislocation slip steps, etc.). Quality of surface is important.

- Crack propagation
  - Stage I: initial slow propagation along crystal planes with high resolved shear stress. Involves just a few grains, and has flat fracture surface
  - Stage II: faster propagation perpendicular to the applied stress. Crack grows by repetitive blunting and sharpening process at crack tip. Rough fracture surface.

- Crack eventually reaches critical dimension and propagates very rapidly

Factors that affect fatigue life

- Magnitude of stress (mean, amplitude...)
- Quality of the surface (scratches, sharp transitions).

Solutions:

- Polishing (removes machining flaws etc.)
- Introducing compressive stresses (compensate for applied tensile stresses) into thin surface layer by “Shot Peening”- firing small shot into surface to be treated. High-tech solution - ion implantation, laser peening.
- Case Hardening – create C- or N- rich outer layer in steels by atomic diffusion from the surface. Makes harder outer layer and also introduces compressive stresses
- Optimizing geometry - avoid internal corners, notches etc.
Factors that affect fatigue life: environmental effects

- **Thermal Fatigue.** Thermal cycling causes expansion and contraction, hence thermal stress, if component is restrained.

**Solutions:**

- eliminate restraint by design
- use materials with low thermal expansion coefficients

- **Corrosion fatigue.** Chemical reactions induce pits which act as stress raisers. Corrosion also enhances crack propagation.

**Solutions:**

- decrease corrosiveness of medium, if possible
- add protective surface coating add residual compressive stresses

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**Creep**

Creep is a *time-dependent and permanent* deformation of materials when subjected to a constant load at a high temperature ($> 0.4 \ T_m$). Examples: turbine blades, steam generators.

**Creep testing:**
1. **Instantaneous deformation**, mainly elastic.

2. **Primary/transient creep**. Slope of strain vs. time decreases with time: work-hardening

3. **Secondary/steady-state creep**. Rate of straining is constant: balance of work-hardening and recovery.

4. **Tertiary**. Rapidly accelerating strain rate up to failure: formation of internal cracks, voids, grain boundary separation, necking, etc.

**Parameters of creep behavior**

The stage of secondary/steady-state creep is of longest duration and the **steady-state creep rate** \( \dot{\varepsilon}_s = \Delta \varepsilon / \Delta t \) is the most important parameter of the creep behavior in long-life applications.

Another parameter, especially important in short-life creep situations, is **time to rupture**, or the **rupture lifetime**, \( t_r \).
Creep: stress and temperature effects

With increasing stress or temperature:
➢ The instantaneous strain increases
➢ The steady-state creep rate increases
➢ The time to rupture decreases
Creep: stress and temperature effects

The stress/temperature dependence of the steady-state creep rate can be described by

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

where $Q_c$ is the activation energy for creep, $K_2$ and $n$ are material constants.

(Remember the Arrhenius dependence on temperature for thermally activated processes that we discussed for diffusion)

Alloys for high-temperature use in (turbines in jet engines, hypersonic airplanes, nuclear reactors, etc.)

Creep is generally minimized in materials with:

- High melting temperature
- High elastic modulus
- Large grain sizes (inhibits grain boundary sliding)

Following alloys are especially resilient to creep:

- Stainless steels
2-7 Failure in Service

INTRODUCTION

The service behaviour of a material is governed not only by its inherent properties but also by the stress system acting on it and the environment in which it is operating. Components fail in service when the incorrect material has been selected for their manufacture, or when the service conditions are more severe than those anticipated by the designer. Manufacturing defects also account for a considerable proportion of cases of failure.

Anticipating the different ways in which a product could fail is an important factor that should be considered, when selecting a material or a manufacturing process for a given application. The possibility of failure of a component can be analysed by studying on the job material characteristics, the stresses and other environmental parameters that will be acting on the component, and the possible manufacturing defects that can lead to failure.

This technique is called failure analysis and can be carried out in the following ways:

1. By an environment profile that provides a description of the expected service conditions. These include operating temperature and atmosphere, radiation, presence of contaminants and corrosive media. Other materials in contact with the component and the possibility of galvanic corrosion, and lubrication conditions.

2. By fabrication and process flow diagrams that provide an account of the effect of the various stages of production on the material properties, and of the...

Refractory metals (containing elements of high melting point, like Nb, Mo, W, Ta)
“Super alloys” (Co, Ni based: solid solution hardening and secondary phases)
possibility of quality control. Certain processes can lead to undesirable directional properties, internal stresses, cracking, or structural damage, which could lead to unsatisfactory component performance and premature failure in service.

3. **By failure models** that describe all the possible types of failure and the conditions that can lead to them. Failure due to chemical causes occurs when corrosion, chemical reaction or oxidation are so excessive that it becomes hazardous for the component to remain in service. Electrical failures occur in insulating materials when the applied voltage exceeds the breakdown voltage of the material. Or when flash-over takes place. Mechanical failures are more varied and represent a serious threat to all load bearing components and will be discussed in more detail in this chapter.

### 2-10- TYPES OF MECHANICAL FAILURE

Generally, a component can be considered to have failed when it does not perform its intended function with the required efficiency. The general types of mechanical failure encountered in practice are:

1. **Yielding of the component material under static loading.** Yielding causes permanent deformation which could result in misalignment or hindrance to mechanical movement.

2. **Buckling,** which takes place in slender columns when they are subjected to compressive loading, or in thin-walled tubes when subjected to torsional loading.

3. **Creep failure,** which takes place when the creep strain exceeds allowable tolerances and causes interference of parts. In extreme cases failure can take place through rupture of the component subjected to creep. In bolted joints and similar applications failure can take place when the initial stressing has relaxed below allowable limits, so that the joints become loose or leakage occurs.
4. **Failure due to excessive wear**, which can take place in components where relative motion is involved. Excessive wear can result in unacceptable play in bearings and loss of accuracy of movement. Other types of wear failure are galling and seizure of parts.

5. **Failure by fracture due to static overload**. This type of failure can be considered as an advanced stage of failure by yielding. Fracture can be either ductile or brittle.

6. **Failure by fatigue fracture due to overstressing**, material defects or stress raisers. Fatigue fractures usually take place suddenly without apparent visual signs.

7. **Failure due to the combined effect of stresses and corrosion**, which usually takes place by fracture due to cracks starting at stress concentration points, for example, caustic cracking around rivet holes in boilers.

8. **Fracture due to impact loading**, which usually takes place by cleavage in brittle materials, for example in steels below brittle-ductile transition temperature.

Of the above types of mechanical failure, the first four do not usually involve actual fracture, and the component is considered to have failed when its performance is below acceptable levels. On the other hand, the latter four types involve actual fracture of the component, and this could lead to unplanned load transfer to other components and perhaps other failures.

This can be avoided by careful design and the selection of the appropriate factor of safety as discussed in the following section.

**2-11-Failure: How do Materials Break?**

- **Ductile vs. brittle fracture**
- **Principles of fracture mechanics**
  - Stress concentration
- **Impact fracture testing**
- **Fatigue** (cyclic stresses)
  - Cyclic stresses, the S—N curve
  - Crack initiation and propagation
- Factors that affect fatigue behavior
  - Creep (time dependent deformation)
    - Stress and temperature effects
    - Alloys for high-temperature use

Fracture
Fracture: separation of a body into pieces due to stress, at temperatures below the melting point.

Steps in fracture:
- crack formation
- crack propagation

Depending on the ability of material to undergo plastic deformation before the fracture two fracture modes can be defined - ductile or brittle
- **Ductile fracture** - most metals (not too cold materials percentage):
  - Extensive plastic deformation ahead of crack
  - Crack is “stable”: resists further extension unless applied stress is increased
- **Brittle fracture** - ceramics, ice, cold metals:
  - Relatively little plastic deformation
  - Crack is “unstable”: propagates rapidly without increase in applied stress (Ductile fracture is preferred in most applications).
- **Ductile materials** - extensive plastic deformation and energy absorption (“toughness”) before fracture.
- **Brittle materials** - little plastic deformation and low energy absorption before fracture.
A. Very ductile, soft metals (e.g. Pb, Au) at room temperature, other metals, polymers, glasses at high temperature.

B. Moderately ductile fracture, typical for ductile metals

C. Brittle fracture, cold metals, ceramics.

(a) Necking
(b) Formation of micro voids
(c) Coalescence of micro voids to form a crack
(d) Crack propagation by shear deformation
(e) Fracture
Brittle Fracture (Limited Dislocation Mobility)

- No appreciable plastic deformation
- Crack propagation is very fast
- Crack propagates nearly perpendicular to the direction of the applied stress
- Crack often propagates by cleavage – breaking of atomic bonds along specific crystallographic planes (cleavage planes).

Brittle Fracture

A. Transgranular fracture: Fracture cracks pass through grains. Fracture surface have faceted texture because of different orientation of cleavage planes in grains.

B. Intergranular fracture: Fracture crack propagation is along grain boundaries (grain boundaries are weakened or embrittled by impurities segregation etc.)
Stress Concentration

Fracture strength of a brittle solid is related to the cohesive forces between atoms. One can estimate that the theoretical cohesive strength of a brittle material should be \( \approx E/10 \). But experimental fracture strength is normally \( E/100 - E/10,000 \). This much lower fracture strength is explained by the effect of stress concentration at microscopic flaws. The applied stress is amplified at the tips of micro-cracks, voids, notches, surface scratches, corners, etc. that are called stress raisers. The magnitude of this amplification depends on micro-crack orientations, geometry and dimensions.

For a long crack oriented perpendicular to the applied stress the maximum stress near the crack tip is:

\[
\sigma_{m} \approx 2\sigma_{0}\left(\frac{a}{\rho_{t}}\right)^{1/2}
\]

where \( \sigma_{0} \) is the applied external stress, \( a \) is the half-length of the crack, and \( \rho_{t} \) the radius of curvature of the crack tip. (note that \( a \) is half-length of the internal flaw, but the full length for a surface flaw).

The stress concentration factor is:

\[
K_{t} = \frac{\sigma_{m}}{\sigma_{0}} \approx 2\left(\frac{a}{\rho_{t}}\right)^{1/2}
\]
Cracks with sharp tips propagate easier than cracks having blunt tips

\[ \sigma_{in} \approx 2\sigma_0 \left(\frac{a}{\rho_t}\right)^{1/2} \]

In ductile materials, plastic deformation at a crack tip “blunts” the crack.

**Impact Fracture Testing**
(testing fracture characteristics under high strain rates)

Two standard tests, the **Charpy** and **Izod**, measure the impact energy (the energy required to fracture a test piece under an impact load), also called the **notch toughness**.

Energy \(\sim h - h'\)
Ductile-to-brittle transition

As temperature decreases a ductile material can become brittle - ductile-to-brittle transition

Alloying usually increases the ductile-to-brittle transition temperature. FCC metals remain ductile down to very low temperatures. For ceramics, this type of transition occurs at much higher temperatures than for metals.

The ductile-to-brittle transition can be measured by impact testing: the impact energy needed for fracture drops suddenly over a relatively narrow temperature range – temperature of the ductile-to-brittle transition.

2-12- FACTOR OF SAFETY

In designing a component for a given application two types of service conditions have to be specified:

1- Normal working conditions which the component has to endure during its intended service life; and

2- Limit working condition's, such as overloading. Which the component is only intended to endure on exceptional occasions, and which if repeated frequently could cause premature failure of the component. In a mechanically loaded, component, the
stress levels corresponding to both normal and limit working conditions can be determined from a duty cycle.

The normal duty cycle for an airframe, for example, includes towing and ground handling, engine run, take-off, climb, normal gust loadings at different altitudes, kinetic and solar heating, descent and normal landing. Limit conditions can be encountered in abnormally high gust loadings or emergency landings. Analyses of the different loading conditions in the duty cycle lead to determination of the maximum load that will act on the component. This maximum load value can be used to determine the maximum stress, or damaging stress, which if exceeded would render the component unfit for service before the end of its normal expected life.

The life of a component can be estimated according to safe-life or fail-safe criteria. The safe-life criterion can be applied to components in which an undetected crack or other defect could lead to catastrophic structural failure, and a life limitation must therefore be imposed on their use. The failsafe criterion can be applied to structures in which there is sufficient tolerance of a failure to permit continuous service until discovered by routine inspection procedure, or by obvious functional deficiencies. The majority of engineering components can be designed according to the failsafe criterion. Even a critical component can be designed according to the fail-safe criterion if failure is detectable by the maintenance programs, which must define both the timing and the methods of inspection to be applied. Redistributing the load into sufficiently robust adjacent components if failure occurs is an added safety precaution. If the use of a safe-life component is unavoidable, its safe service life must be established by testing, and its replacement life calculated by applying an appropriate factor of safety.

The factor of safety can be taken as the ratio of the damaging stress to the design stress. If the exact service loading conditions and the exact performance of the component can be determined, a factor of safety approaching unity can be employed. In
practice, the designer usually uses factors of safety from 1.2 to 20. Higher values of factor of safety are used when the material properties are not homogeneous, with the possibility of finding inclusions and porosity. Inaccuracies in determining the stress distribution in the component, and the presence of internal stresses and stress concentrations, call for a higher factor of safety. Common values of the factor of safety range from 1.5 to 10.

For ductile metallic materials, under static loading, the yield strength can be taken as the damaging stress; but for brittle materials the ultimate strength is usually taken as the damaging stress. Under fatigue conditions, the endurance limit is the damaging stress. Unless exceptionally severe overloads are encountered, components do not usually fail through tension or shear. On the other hand fatigue failures account for about 8000 of machine part failures, because the stresses required to produce them are much lower than the static strength of the material, as will be discussed in the following section. Failures due to lack of impact toughness of materials also occur in certain mechanical application

2-13- SELECTION OF MATERIALS AND PROCESSES FOR RESISTANCE TO FATIGUE

Besides the factors that have been discussed, the fatigue performance of a component is largely influenced by the type of material and the processes used in making it. Steels are the most widely used structural materials for fatigue applications as they offer high fatigue strength and good of exhibiting an endurance limit which enables them to perform indefinitely, without failure, if the applied stresses do not exceed this limit. The endurance limit is roughly equal to 0.4 to 0.6 of the ultimate tensile strength of steels up to UTS of about 1100 MN/m2. With stronger steels, the scatter in fatigue strength becomes wide and the endurance ratio can become less than 0.30.