INTRODUCTION
Materials are the driving force behind the technological revolutions and are the key ingredients for manufacturing. Materials are everywhere around us, and we use them in one way or the other. The materials and the manufacturing process employed, could be better appreciated if one understands various types of materials and its properties.

PROPERTIES OF MATERIALS
Properties of materials include mechanical properties (such as strength, hardness, toughness), thermal properties (conductivity), optical properties (refractive index), electrical properties (resistance) etc. Here, however, we shall concentrate only on mechanical properties which are most important in manufacturing processes and also in everyday life and we use these terms quite often. To understand the mechanical properties, it is useful to first understand the behaviour of the material when subjected to a force which causes deformation; this could be understood with the ‘stress-strain diagram’.

STRESS-STRAIN DIAGRAM
Consider a rod of initial length $L_0$ and area $A_0$ which is subjected to a load $F$. The stress $\sigma$ is the force per unit area, and strain $\varepsilon$ is the change in length ($\delta$) divided by the initial length. Thus,

\[
\text{Stress } \sigma = \frac{F}{A_0} \\
\text{Strain } \varepsilon = \frac{\delta}{L_0}
\]

The $\sigma$-$\varepsilon$ curve for a material (say mild steel) is shown in the Fig. 1.1. Up to the proportionality point $A$, the stress-strain variation is linear. Up to this point Hooke’s law holds good.

\[
i.e., \quad \sigma \propto \varepsilon \\
\text{or} \quad \sigma = E\varepsilon
\]

where $E$ is the Young’s modulus commonly called modulus of elasticity.

Beyond point $A$ and up to point $B$, material remains elastic $i.e.$, the material returns to its original condition of the forces acting on it is removed.
If the specimen is stressed beyond point B, permanent set takes place and we enter plastic deformation region. In the plastic deformation region, the strain does not get fully removed even with the removal of the force causing it. If the force is increased further, point ‘C’ is reached where the test specimen stretches even when the stress is not increased. This point is called yield point. Infact, there are two yield points C and D which are called upper and lower yield points respectively.

With further straining, the effect of a phenomenon called strain hardening or work hardening takes place.* The material becomes stronger and harder and its load bearing capacity increases. The test specimen is therefore able to bear more stress. On progressively increasing the force acting on the specimen, point E is reached. This point is the highest point in the stress-strain curve and represents the point of maximum stress. It is, therefore, called ultimate tensile stress (UTS) of the material. It is equal to the maximum load applied divided by the original cross-sectional area ($A_0$) of the test specimen.

Here, we must consider the effect of increasing load on the cross-sectional area of the test specimen. As plastic deformation increases, the cross-sectional area of the specimen decreases. However for calculation of the stress in the stress-strain graph, the original cross-sectional area is considered. It is for this reason, that the point of breakage F seems to occur at a lower stress level than the UTS point E. After UTS point E, a sharp reduction in cross-sectional area of the test specimen takes place and a “neck” is formed in the centre of the specimen. Ultimately the test specimen breaks in two pieces as the neck becomes thinner and thinner. The actual breaking stress is much higher than the UTS, if the reduced cross-sectional area of the test specimen is taken into account.

The measure of the strength of a material is the ultimate tensile strength ($\sigma$ at point E). However, from the point of view of a design engineer, the yield point is more important as the structure designed by him should withstand forces without yielding. Usually yield stress ($\sigma$ at point D) is two-thirds of the UTS and this is referred to as yield-strength of the material.

In actual practice, to determine UTS, a tensile test is carried out on a tensile testing or a universal

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*This phenomenon is more fully described in Unit II, Chapter 1.
testing machine. In order that tests conducted in different laboratories on the same material may give identical test results, the test piece used for the tensile test has been standardised. A standard test piece is shown in Fig. 1.2.

![Fig. 1.2 Dimensions of a standard tensile test-piece](image)

**Note:** Gauge, shoulder and overall lengths according to IS : 210-1978.

A stress-strain curve for brittle material is obtained by subjecting a test bar of such material in a tensile testing machine. The tensile load is gradually increased and the extention of the test piece is recorded. The stress-strain curve for a brittle material shows some marked differences as compared to the curve obtained for a ductile material. A typical stress-strain curve for a brittle material is shown in Fig. 1.3.

![Fig. 1.3 Stress-strain curve for brittle material](image)

This curve displays no yield point, and the test specimen breaks suddenly without any appreciable necking or extension. In the absence of a yield point, concept of “proof-stress” has been evolved for measuring yield strength of a brittle material. For example, 0.2% proof-stress indicates the stress at which the test specimen ‘suffers’ a permanent elongation equal to 0.2% of initial gauge length and is denoted by $\sigma_{0.2}$.

The tensile test and the stress-strain curve has been described above in some detail, because a lot of useful information with regard to other properties of material can be gleaned from it. It may be noted that most tensile testing machines are provided with equipment to carry out a compressive strength test as well.
MALLEABILITY AND DUCTILITY

Both these properties relate to the plasticity of the material. Malleability refers to the ability of plastic deformation under compressive loads, while ductility refers to plastic deformation under tensile loads. A malleable material can be beaten into thin sheets and even thinner foils. A ductile material can be drawn into wires.

A measure of ductility is “percentage elongation”. Before the tensile test begins two punch marks are made on the stem of the tensile test piece. Distance between these marks is noted and is known as gauge length \( l_0 \). After the tensile test piece fractures in two pieces, the two pieces are retrieved and placed together as close to each other as possible. Now the distance between the two punch marks is measured and noted again. Let this distance be \( l_1 \). The % elongation is calculated as

\[
\frac{l_1 - l_0}{l_0} \times 100
\]

High values of percentage elongation indicate that material is very ductile. Low values indicate that material is brittle and has low ductility. For mild steel, the percentage elongation usually is 20% or more.

BRITTLENESS

Brittleness can be thought of as opposite of ductility. It is a property which is possessed in great measure by glass and other ceramics. A piece of glass, if dropped on a hard surface shatters and is broken in many pieces. The real cause of brittleness is inability of the material to withstand shock loads. Of course, glass is an extreme case of brittle material.

STIFFNESS AND RESILIENCE

A material with high value of modulus of elasticity is said to be stiff and a material with low value of modulus of elasticity is said to be resilient. Consider a material undergoing tensile stress within the elastic range. If the material possesses a high value of Young’s modulus (which is the modulus of elasticity corresponding to tensile stress), the material will not stretch much. It will behave as a “stiff” material. In this case, the slope of the line OA (Fig. 1.1) will be more. Resilience is a property which is totally opposite to stiffness. A beam made of stiff material will deflect to a lesser extent as compared to another made of resilient material under identical loading condition.

TOUGHNESS AND IMPACT STRENGTH

Toughness and impact strength are allied or similar properties (although these are some differences as mentioned later). They represent the ability of the material to absorb energy before actual failure/fracture occurs. Refer to Fig. 1.1. If the scale of y-axis is changed and if force is plotted on this axis and, if actual elongation is plotted on x-axis instead of strain, we shall obtain a force-elongation curve instead of stress-strain curve. The shape of curve will remain the same; only scales of x and y axes will change. Now the area under this curve will represent energy required to fracture the material. Higher
the energy, higher is the toughness of material. Toughness comes from a combination of strength and percentage elongation. Since this property enables a material to withstand both elastic and plastic strains, it is considered very important.

Higher impact strength goes with higher toughness. In actual impact testing, loads used are dynamic loads and the load is directed to the specimen through a sharp notch. Two tests have been standardised to measure the impact strength of a material (as also its toughness). These tests are called (i) IZOD test, and (ii) Charpy test. IZOD test is described below in brief.

A standardised test specimen is shown below in Fig. 1.4 (a).

This specimen is fixed in the IZOD testing machine in a vertical position as shown in Fig. 1.4 (b). A blow from a swinging pendulum falling from a specified height is then struck on the test specimen 22 mm above the notch. The mass of the pendulum is known. Since height from which pendulum descends down to strike the blow is also known, we know the energy stored in the pendulum (m.g.h.).

After striking the test piece and fracturing it at the notch, the pendulum moves on and the height to which it rises on the otherside of the test piece is noted and measured. Thus the energy still left in the pendulum can be calculated. The difference between the original energy in the pendulum and the energy left over after breaking the test specimen is assumed to have been used up in breaking the test specimen. This is taken as the impact strength of the material of the specimen. A correction factor for friction at pendulum bearing is applied to get accurate result.

A brittle material has low impact strength and poor toughness.

HARDNESS

Hardness is a very important property of materials. Hardness indicates wear-resistance and resistance against abrasion or scratching. A hard material also offers resistance to penetration by another body. In the olden days, a scale of hardness was established and diamond, which is the hardest known material was put on top of this scale. Glass and other materials were put lower down on this scale. The criterion used was a simple scratch test. If a material could scratch another material, then the former was considered harder than the latter material and was placed higher in the scale of hardness.
In modern times, several tests for hardness have been devised. The most popular ones are called (i) Brinell hardness test, (ii) Rockwell hardness test, and (iii) Vicker’s hardness test. All these tests are based on resistance of the material under test against penetration by a specially designed and manufactured “indentor” into the surface of the test specimen under specified load. A harder material offers more resistance and therefore the indentor cannot penetrate its surface to the same depth as it would, if the test specimen were of softer material. Thus the depth of the impression made by the indentor into the test specimen or the area of the impression left by the indentor into the specimen is used to measure the hardness of the material.

It is beyond the scope of this book to give detailed test procedures. However, the essential information is given in Table 1.1.

<table>
<thead>
<tr>
<th></th>
<th>Brinell test</th>
<th>Rockwell test</th>
<th>Vicker’s test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indentor used</td>
<td>Hardened steel ball of 10 mm diameter.</td>
<td>A diamond cone, called braille is used.</td>
<td>A square based diamond pyramid containing an angle of 136° between opposite faces.</td>
</tr>
<tr>
<td>Load applied on the indentor during test</td>
<td>3000 kg for 10–15 seconds</td>
<td>Load is applied in two stages. First a minor load of 10 kg followed by major load of 150 kg, in case of ‘C’ scale.</td>
<td>5 kg–120 kg.</td>
</tr>
<tr>
<td>How is hardness number calculated</td>
<td>$BHN = \frac{\text{Load on ball (kg)}}{\text{Area of ball impression in mm}^2}$</td>
<td>Rockwell hardness No. $= 100 – 500 t$, where $t$ is depth of indentation.</td>
<td>VPN or VHN $= \frac{\text{Load}}{\text{Area of impression}}$</td>
</tr>
<tr>
<td>Special comment</td>
<td>Depending upon material to be tested, dia of ball and load applied may change</td>
<td>1. There are several hardness scales used like A, B, C etc. They are meant for different materials. The major load applied and even the indentor may change. 2. Hardness is never calculated. The hardness no. is read off a graduated dial. 3. For ferrous material we generally use ‘C’ scale.</td>
<td>In practice VPN is not calculated. The indentation left by the diamond pyramid is in the shape of a rectangle. The lengths of its diagonals is measured and VPN directly found from a table against the measured value of diagonal.</td>
</tr>
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</table>

**FRACTURE OF MATERIAL**

If a specimen is subjected to high stress beyond its strength, it fails and ultimately fractures in two or more parts. During the description of the tensile test, we have already come across fractures of ductile and brittle material. The ductile fracture occur after considerable plastic deformation and shows a
characteristic reduction in the cross-sectional area near the fractured portion. Brittle fracture occurs suddenly when a small crack in the cross-section of the material grows resulting in a complete fracture. But such fracture does not show much plastic deformation.

Actually, by a careful examination of the fractured surface and the macro and micro metallurgical examination of the fractured specimen, much interesting information as to the probable cause of its failure can be deduced by an experienced metallurgist.

Apart from the ductile and brittle type of fractures, we also have fractures caused by FATIGUE and CREEP of material.

**FATIGUE FAILURE**

It has been noticed that materials often fail or fracture at a stress level far below their strength, if the stress is either (i) alternating type or (ii) it is varying periodically. What is meant by alternating stress? An example will make this clear. Consider an axle fitted with two wheels. The axle bears the weight of the vehicle and at the same time it rotates along with wheels. Because of weight, the axle undergoes a little deflection causing compressive stress in its top half and tensile stress in bottom half of the cross-section. But since it is rotating, with every 180° rotation, the bottom half becomes the top half and vice versa. Thus the nature of stress at any point in the axle keep alternating between compression and tension due to its rotation.

A varying stress cycle means that the magnitude of the stress keeps reducing and increasing periodically although its sign does not change. If the material is subjected to several million cycles of either the alternating or varying stress, it gets fatigued and fails even though the magnitude of such stresses may be far lower as compared to its strength.

Fortunately, there is a level of alternating and varying stress, which the material is able to withstand without failure even if it is subjected to infinite number of cycles. This is called the ENDURANCE LIMIT. A designer ensures that a component subject to fatigue in service is so designed that its actual stress level remains below the endurance limit.

The visual examination of a fatigue fracture shows three distinct zones. These are:

(i) The point of crack initiation, it is the point from where the crack may have originated e.g. a notch like a key way or some materials defect like an impurity, or even a surface blemish.

(ii) The area of crack propagation during service. This area is usually characterised by circular ring-like scratch marks with point of crack initiation as the centre.

(iii) Remaining area of cross-section showing signs of sudden breakage. As a result of crack propagation with time, a stage comes, when the remaining cross-sectional area becomes too small to sustain the stress and fractures suddenly.

**CREEP FAILURE**

Failure of material can take place even under steady loads within the strength of the material. This happens if the subjected components remain under steady loads for a very longtime especially when they are subjected to high temperature conditions. Some common examples are stays in boilers, steam
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turbine blades, furnace parts etc. Such failures are termed creep-failures due to the fact the material continues to deform plastically under such conditions although at a very very slow rate. But over long periods of time, the effect of creep can become appreciable resulting in ultimate failure of the component.

**QUESTIONS**

1. Draw a stress-strain curve for a ductile material. In what respects, a similar curve for a brittle material will be different?

2. What do you understand by the following terms?
   (i) Limit of proportionality
   (ii) Yield-point
   (iii) Ultimate tensile strength.

3. Explain the meaning of the following terms:
   (i) Stiffness,
   (ii) Toughness, and
   (iii) Hardness.

4. Differentiate between failure of material due to fatigue and creep.

5. What do you understand by percentage elongation? What does a high percentage elongation value signify?

6. Name three common “hardness” tests. Describe anyone of them.