Every designed component has to be made of some material. Now the question arises whether the material used for the designed component will survive when subjected to actual loading conditions. This survival is determined by the properties of the material. In case of components related to a mechanical machine, strength is the most vital among all the properties. Theoretically, strength of a material is determined at nanoscopic level by the inter-atomic bonding forces. However, because of defects in the structure, strength of a material is reduced by several times compared to theoretical strength of the ideal defect-free material i.e., strength predicted at atomic and microscopic level.

2.1 INTRODUCTION

The design of any machine component is based on its capacity to withstand the load. The capacity of machine components is its ability to sustain the loading conditions without changing its configuration which may not allow the components to perform the intended function. The capacity of the components is measured on the basis of the mechanical properties obtained experimentally. The condition maintained during the testing does not exist in actual service conditions. Moreover, the mechanical properties obtained for two standard test specimens of the same material may not result in same values even when they are tested on the same machine. That is why the minimum value or range of strength is given. The selection of appropriate material property data is the responsibility of the designer to ensure the safety of his design. The design case where safety risk is very high, as in the design of aircraft, space vehicles, automobiles etc, the safest approach is to develop the mechanical property data by conducting tests involving actual loading conditions on the prototype manufactured through the specified processes, so as to emulate the actual conditions as accurately as possible during testing.
**Point P: Proportional limit**

The proportional limit (point P) is the point on the stress-strain curve up to which the stress-strain curve follows a straight line. It is the upper limit for which Hooke’s law (stress is directly proportional to strain within the elastic limit; in actual practice stress is proportional to strain within proportional limit) is valid.

**Point E: Elastic limit**

It is the point up to which the material regains its original shape after the load is removed. It may also be defined as the point corresponding to the maximum stress that can be applied to a material without causing permanent deformation. It represents the boundary between the elastic and the plastic behavior of a material. It may be noted that the curve from point P to E is not a straight line and, therefore, the Hooke’s law, which states that stress is proportional to the strain, does not apply from P to E. It is important to observe that a single tensile test cannot determine elastic limit, as the exact determination of the elastic limit needs a repeated loading and unloading of the specimen beyond the proportional limit with incremental step up in the load. Every time, the length is checked after removing the load. The elastic limit is marked when first change in the gauge length is observed after the removal of the load.

**Point Y: Yield strength**

If a slight increase in loading is applied to the elastic limit, the material deforms for the first time without any increase in loading. Referring to the curve will show that its slope is horizontal just beyond the Y. The stress corresponding to this point is known as yield strength.

**Point U: Ultimate strength or tensile strength**

Beyond point Y, the material begins to strain-harden and recovers some of its elastic property. As the deformation (plastic) increases, the metal becomes stronger and thus, greater load is required
for carrying out further deformation. However, this increase in the actual strength of the material is also accompanied by a reduction in the cross-sectional area due to elongation. Eventually, a stage is reached when the loss of strength (i.e., the load carrying capacity) due to reduction in cross-sectional area of the specimen under test dominates the gains due to strain-hardening of the material. Obviously, the load supported by the specimen is maximum at this point. The load reaches this maximum value at point U and the stress at this point is called the ultimate or tensile strength ($S_{ut}$). It is characterized by the beginning of necking. This point represents the maximum tensile stress or ultimate strength.

**Point F: Fracture strength**

Beyond U, the cross-section of the specimen goes on decreasing rapidly with drop in the load and this continues until the specimen fractures at point F. The stress at point F is called the fracture strength ($S_F$). The fact that the nominal strength at F is less than the ultimate strength at U is somewhat misleading. In fact, the cross-section of the specimen between U and F goes on decreasing and if tensile load is divided by the reduced cross-sectional area, the actual stress developed in the specimen would be higher. The stress-strain curve obtained in the case when instantaneous area is used for stress computation is called *true stress-strain* curve as shown by dotted line UF' in Figure 2.2. However, the solid line represents the engineering stress-strain diagram. The fracture strength has little design significance because no component is designed to be loaded till fracture point.

### 2.3 MORE ON TENSILE TEST

For most of the design applications, yield strength acts as a basis of design. Hence, measurement of the yield strength of materials is highly important. Different materials yield in a different ways. Structural steel or low carbon steels (soft steels) are the only materials which exhibit pronounced yield point (Figure 2.2). The material properties are affected by alloying, heat treatment, and the manufacturing process used as shown in the stress-strain curves of pure iron and of three different grades of steel (Figure 2.3).

![Stress-strain curve for different ferrous alloys](image-url)
It is noted from the curves that there is no actual dip in the curves as observed for soft steels. The yield strength, for the materials which do not exhibit a well defined yield phenomenon or yield point, is measured as the stress required to produce a small amount of permanent deformation. It implies that as the load is removed, the specimen will not regain its original shape and a permanent strain or elongation will set in it. The term yield strength for such material is also referred to as proof stress or offset yield strength. It is the stress at which the permanent elongation or the total elongation is equal to the specified value and in general it is taken as 0.2%. To mark the yield point, strain equal to 0.002 is marked (OB) on the abscissa of the stress-strain curve and a line parallel to the initial slope is drawn to intersect the curve at Y. This is shown in Figure 2.4. The additional information that can be obtained from the stress-strain curve is given in the following sections.

![Stress-Strain Diagram](image)

**Fig. 2.4  Proof stress**

**Modulus of elasticity or Young's modulus**

The slope of the straight line is known as modulus of elasticity as shown in Figure 2.4.

\[ E = \frac{\sigma}{\varepsilon} = \frac{HA}{OH} \]

It is a measure of stiffness of the material. The modulus of elasticity is one of the most structure insensitive mechanical properties. It is slightly affected by alloying, heat treatment or cold working as indicated by same initial line of the Figure 2.3. However, increase in the temperature decreases the modulus of elasticity.

**Poisson's ratio**

Poisson’s ratio (\(v\)) is a measure of the unit strain of a material in the direction normal to the applied load. It is defined as the ratio of lateral strain to longitudinal strain.

\[ v = - \frac{\text{lateral strain}}{\text{longitudinal strain}} \quad \text{...(2.2)} \]
Its value ranges between 0 and 0.5. \( v = 0.5 \) implies that material is incompressible and operating in plastic range.

For a uniaxial loading along x-direction,

\[
\varepsilon_x = \frac{\sigma_x}{E}; \quad \varepsilon_y = \varepsilon_z = -v \frac{\sigma_x}{E}
\]

**Shear modulus of elasticity or modulus of rigidity**

Modulus of rigidity \( (G) \) is defined as the ratio of shear stress \( (\tau) \) to shear strain \( (\gamma) \) within elastic range and it represents the resistance offered by a material to geometric distortion.

\[
G = \frac{\tau}{\gamma}
\] ...(2.3)

The relationship between shear modulus and Young’s modulus is given below

\[
G = \frac{E}{2(1+v)}
\] ...(2.4)

**Bulk modulus**

Bulk modulus is a measure of the elastic volume change in a material and is defined as

\[
K = \frac{\text{Hydrostatic stress}}{\text{Volumetric strain}}
\]

The bulk modulus and Young’s modulus are related as

\[
K = \frac{E}{3(1-2v)}
\] ...(2.5)

Reciprocal of the bulk modulus is called compressibility.

**Elongation and reduction of area**

The elongation is the difference between original gauge length and the length of specimen after rupture and the reduction of area is the difference between the original cross-section area and the least area after fracture. Both are expressed as percentage of original gauge length and original area. These are used as a measure of ductility. The two materials having same strength can have different abilities to absorb overloads due to different ductility. Percentage reduction in area is given by

\[
\% \text{ reduction in area} = \frac{dA}{A_o} \times 100 = \frac{A_o - A_F}{A_o} \times 100
\] ...(2.6)

where \( A_o \) is the original area and \( A_F \) is the area at fracture.
**True strain or logarithmic strain**

True strain or logarithmic strain is the sum of each incremental elongation divided by the instantaneous length \((l)\) of the specimen, mathematically, it is given by,

\[
e = \int_{l_0}^{l} \frac{dl}{l} = \ln \frac{l}{l_0}
\]

...(2.7)

**Resilience**

When the material undergoes elastic deformation under the application of load, positive work is done on the material, which equals the average load and total change in length. This work is stored in the material in the form as strain energy (just as a spring stores strains energy). Again, when the load is reduced, it does negative work and in turn, the stored strain energy is released by the material. This ability of a material to absorb energy when deformed elastically and release the energy when unloaded is known as resilience. The modulus of resilience is defined as the area under the stress-strain curve till elastic limit or the yield point (Figure 2.5). The measurement of stress corresponding to elastic limit is difficult and we know that the yield point and elastic point are practically close. Therefore, modulus of resilience is the strain energy stored per unit volume of the material till yield point.

\[
\text{Modulus of resilience} = \frac{S_y^2}{2E}
\]

...(2.8)

This property is desirable for the components which should not undergo permanent deformation i.e., these materials must have high strength and low modulus of elasticity such as that observed for spring materials.

![Fig. 2.5 Modulus of resilience](image1)

![Fig. 2.6 Modulus of toughness](image2)
Toughness

Toughness is a measure of the ability of a material to absorb energy in plastic range i.e. the ability of a material to withstand occasional stress above yield strength without failure. As energy absorbed equals the work done in deforming the material, which in turn equals the product of load and change in length, the area under stress-strain curve till fracture point is a measure of modulus of toughness (Figure 2.6).

\[
\text{Modulus of toughness} = \frac{1}{2} (S_y + S_u) \varepsilon_f \quad \text{for ductile material} \quad \ldots (2.9a)
\]

\[
= \frac{2}{3} S_u \varepsilon_f \quad \text{for brittle material} \quad \ldots (2.9b)
\]

\(\varepsilon_f\) is the strain at fracture point. This property is desirable in the components such as freight car, gears, crane hooks etc, where shock loading is present.

Behavior of material: ductile or brittle

The classification of material such as ductile and brittle is done on the basis of their behavior under the application of load. A ductile material has the ability to undergo appreciable plastic deformation when loaded beyond the elastic limit. A completely brittle material fractures at the elastic limit although some brittle materials like white cast iron show a little plasticity before fracture. A material is accepted as ductile if it shows more than 5 percent elongation at fracture. Ductility is the most desirable property for the operations like bending, drawing, forming etc. The ductility and brittleness of a material may also be affected due to manufacturing process e.g. the casting of a material is less ductile than the cold/hot working of the same material. In general, the tendency of a material to be brittle increases with decrease in temperature; increases with rate of loading; and changes in state of stress from uniaxial to triaxial tension.

Tensile fracture of specimen

When a ductile material is fractured under tension, the necking (local reduction in cross-section due to sudden flow of material) occurs and leads to a most popularly known cup and cone fracture as shown in Figure 2.7(a). Unlike ductile material, a brittle material does not exhibit any necking before fracture. The typical brittle fracture of a brittle material under tension is shown in Figure 2.7(b).

Fig. 2.7 Fractured tensile test specimens (a) ductile material (b) brittle material
2.4 COMPRESSION TEST DATA

It is an usual assumption that materials are equally strong in tension and compression. This is specifically true for a wide variety of steels. Generally, the strength of the material in compression is higher than that observed in tension. Due to the above mentioned reason, apart from the fact that yield strength is one of the important mechanical properties in the design of machine components where yielding is undesirable, the other tests though required but detailed discussion of these tests is not needed. Hence, we shall discuss the results of other mechanical tests in brief.

The proportional limit, the elastic limit and the ultimate strength of the material in compression can be obtained from the compression test. The definitions of all these properties are analogous to those defined for tension but the exact determination of the ultimate strength of a ductile material in compression is difficult. The brittle materials shatter at the compressive fracture whereas ductile materials do not and hence a particular degree of distortion is considered an indicative of ultimate point, i.e. material failure.

The initial regions of stress strain diagrams in compression and tension are more or less similar for ductile materials such as steel, aluminium and copper. However, after yielding compressed ductile material bulges outward and flattened out with increase in load. This increases the resistance to compression. Since the actual cross-sectional area of a specimen tested in compression is larger than the initial area, the true stress in compression test is smaller than the nominal stress.

2.5 TORSION AND OTHER TESTS DATA

Torsional properties evaluate the behavior of materials for engineering application involving shear stress. Torsion test can determine the proportional limit, the elastic limit, the shear yield strength, shear ultimate strength and modulus of rigidity. All the definitions are analogous to the corresponding properties defined for tension test. The modulus of rigidity (G) is the ratio of shear stress within the proportional limit to the corresponding shear (angular) strain in radians. In most of the cases, the properties of a material in shear are not available, so we can use the following empirical relation to obtain the shear data for practical purposes to be used in the design of machine elements:

\[ S_{us} = 0.8S_{ut} \quad \text{for steel} \]
\[ S_{us} = 0.75S_{ut} \quad \text{non-ferrous ductile material} \]
\[ S_{sy} = 0.577S_{y} \quad \text{according to maximum distortion energy theory} \]

The shear fracture is quite different from those observed in tension or compression. In case of shear test, no reduction of area or elongation is observed in specimen, and the fracture has distinct texture characteristics of the twisting effect. The typical fractured specimens of cast iron and mild steel are shown in Figure 2.8.

**Hardness test**

Hardness test is conducted to measure the ability of material to resist scratching, abrasion, deformation, indentation or penetration when it is indented by another material of higher
hardness. It is usually expressed by Brinell, Rockwell or Vickers hardness numbers. In either of these tests the resistance to plastic deformation is measured directly or indirectly after indenting the specimen with either a steel ball or diamond indenter. Different indenters, scales and loads are generally employed to suit different materials and component thicknesses. It is a common practice to use Rockwell hardness test for semi-finished or finished products whereas Brinell test is used for testing raw materials such as bars, rods, plates, forgings and castings etc.

The Rockwell C scale and Brinell hardness number are related as,

\[ RC = 88(BHN)^{0.162} - 192 \]

Brinell hardness is expressed in terms of a number known as Brinell Hardness Number given by:

\[ BHN = \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})} \]

where, \( d \) is the diameter (mm) of the impression created by a load \( F \) (kg) on the surface of a material by a steel ball indenter of diameter \( D \).

The ultimate strength or tensile strength and BHN of plain carbon steel are related as

\[ \sigma_u = (3.45) \text{ (BHN)} \text{ N/mm}^2 \]

Vickers hardness is particularly suited for hard and thin materials. In this case a square shaped pyramid diamond indenter with an apex angle of 136° is used. The Vickers hardness is given as

\[ V = 1.854 \frac{F}{D} \]

where, \( D \) (mm) is the average length of the two diagonals of the impression and \( F \) is the load applied in kg.

**Fatigue test**

All the above tests discussed are conducted under static loading whereas most of the machine components are subjected to loads that are varying with time and are called dynamic load. Therefore, the properties obtained from these tests are used to design the machine elements subjected to static loading only. In designing components subjected to dynamic loading, the properties obtained from static test are not directly used. It is fatigue strength which comes into picture for designing components subjected to varying (dynamic) load. The fatigue test
experimentally determines the endurance limit of the material and has been discussed in detail in Chapter 6.

**Creep test**

The variation in stress and strain with time is known as creep. It is a time dependent deformation or strain under constant stress and generally occurs at absolute temperatures above half the melting point for a given material. Accordingly, creep is present even at room temperature for materials like aluminum and copper, while for ferrous alloys, it occurs in disks and blades of steam or gas turbine, which are subjected to centrifugal stress along with high temperature.

A specimen is loaded with a constant force and the variation of its length at a fixed temperature is observed. A typical creep curve for steel is shown in Figure 2.9. As can be seen from the curve, the strain grows rapidly at the start (primary creep), followed by a slow increase at a constant rate (secondary creep) and finally, a rapid increase (tertiary creep) as the specimen begins to neck down. The basic mechanical characteristics of a material under creep deformation are the *creep-rupture strength* and *creep limit*. Creep-rupture strength is defined as the ratio of load, at which a tension specimen fails in given length of time, to the original cross-sectional area. The creep limit is defined as the stress at which plastic strain reaches a given value in a given time. The creep properties decrease with increase in temperature.

![Creep curve](image)

**Fig. 2.9 Creep curve**

### 2.6 DESIGNING WITH BRITTLE MATERIALS

The design for brittle material is more complicated than the ductile material as the mechanical properties are not precisely available. Under these circumstances, the following guidelines must be followed when the design involves brittle materials:

- Increase operating temperature as brittleness decreases with temperature.
- Apply gradual load to increase its ability to absorb deformation.
- Avoid direct tensile loading.
- Reduce stress raisers (viz. notches, sudden changes in cross-section, defects etc.).
- Use smaller parts to have higher fracture strength.
- Align the components properly.
2.7 DESIGNING WITH FERROUS MATERIALS

This section is devoted to refresh the student’s knowledge about the materials and not to build the basic concepts of materials. It is presumed that the readers have a basic understanding of the different terms related to materials. Materials Science is itself a separate course or even a discipline. Here, we shall be too brief with an advice to the reader that they may refer to any standard text for further detail.

Iron is the main constituent (up to 99%) of any ferrous material together with small amounts of C, Mn, Si, Mg, Ni, Cr, Co, V, S and P. Small variations in the amount of carbon change the properties of these materials drastically and may even change its category e.g. steel to cast iron. We shall divide the ferrous materials into three different categories—wrought iron, cast iron and steel. Figure 2.10 shows iron-iron carbide diagram representing different equilibrium phases of iron alloy and important temperatures. It does not provide any information regarding the nons-
**White Cast Iron (WCI)**

This cast iron has less percentage of free carbon which is due to lesser amounts of silica and increased cooling rate. Therefore, it contains hard cementite (Fe₃C) phase and is harder than GCI. It is called white cast iron because of its silver white fracture surface. It is more wear resistant than GCI but the impact resistance is lesser. The carbon content is about 2.5% and silicon about 1.5%. It is used for rail-car wheels, cams, valve seats, small pulleys, rollers and gears etc.

**Malleable Cast Iron (MCI)**

If the WCI is reheated to about (870°C) for a long period (40 – 80 hours) in the presence of oxides, the cementite decomposes into ferrite and free carbon which on cooling forms small compact particles of graphite. The free carbon thus produced in the structure, is referred to as temper carbon and called ferritic malleable cast iron. Addition of manganese and proper control of this heat treatment process results in matrix of pearlite and therefore, called pearlitic malleable cast iron. The mechanical properties of MCI are superior to grey cast iron. The castings made up of MCI are strong and malleable to withstand vibrations, hence used for machine structures, crank cases, pump bodies, manifolds, large cylinders and cylinder heads, compressor parts etc.

The MCI is designated by a symbols BM, PM or WM followed by its tensile strength in kg/mm², e.g.

BM 35 for Black hearth malleable cast iron with tensile strength of 35 kg/mm²
PM 70 for Pearlitic malleable cast iron with tensile strength of 70 kg/mm²
WM 42 for White hearth malleable cast iron with tensile strength of 42 kg/mm²

**Nodular Cast Iron**

The carbon forms into spheres when cerium, magnesium or sodium is added to low sulphur content melt of iron. This cast iron possesses high tensile strength with improved toughness and shock resistance.

The applications and mechanical properties of GCI and MCI are shown in Table 2.2 and 2.3.

**Table 2.2** Grades and application of cast iron castings

<table>
<thead>
<tr>
<th>ISI Grade</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCI 15</td>
<td>Where bending stress &lt; 10 N/mm²; pressure &lt; 5 N/mm²: columns, pedestals, beds, covers, housings, arms, Sliding tables</td>
</tr>
<tr>
<td>GCI 20</td>
<td>Where bending stress &lt; 30 N/mm²; pressure &lt; 100 N/mm²: beds, columns, gears, guide ways, pulleys</td>
</tr>
<tr>
<td>GCI 25</td>
<td>Bending stress &lt; 50 N/mm²; pressure &lt; 200 N/mm² columns, chucks, gears, ways, hydraulic cylinders, pump body, HP valves, work table, flywheels.</td>
</tr>
<tr>
<td>Malleable CI</td>
<td>Face plate, chuck body, vices, clamps, levers, hand wheels turret body, tool post.</td>
</tr>
</tbody>
</table>
Table 2.3 Properties and applications of cast iron

<table>
<thead>
<tr>
<th>Cast Iron</th>
<th>$S_{ut}$ MPa</th>
<th>$S_{uc}$ MPa</th>
<th>$S_{yt}$ MPa</th>
<th>$E$ GPa</th>
<th>$G$ GPa</th>
<th>BHN</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray CI 4.5% C</td>
<td>170</td>
<td>655</td>
<td>–</td>
<td>69</td>
<td>28</td>
<td>110-150</td>
<td>General industrial castings, pumps, cylinders</td>
</tr>
<tr>
<td>Malleable CI 2% C</td>
<td>345</td>
<td>620</td>
<td>230</td>
<td>165</td>
<td>65</td>
<td>100-140</td>
<td>Automobile parts etc.</td>
</tr>
</tbody>
</table>

Note: The properties of some material varies greatly because of different manufacturing processes, chemical composition, internal defects, temperature, measuring errors and many other factors. Consequently, catalogues of manufacturer of the material should be consulted for precise value of the properties.

2.7.3 Designing with Steels

Steel is the designer’s servant. It is obedient too. This is because we use steel in most of the engineering applications and its properties can be modified as per requirement. It works according to designer’s desire. Steels can be classified as plain carbon steels and alloy steels based on their chemical composition. On the basis of their applications, they can be classified as structural steels, tool steels and special purpose steels. Some authors also classify steel as plain carbon steels, alloy steels and special purpose steels. Special purpose steels are produced to get some desired properties for use and manufacturing such as free cutting, heat resistance, corrosion resistance, impact resistance and tool steels. Alloy steel is produced by alloying some specific alloying element in excess of a specified quantity. Steel which is neither special purpose nor alloy steel comes under the category of plain carbon steel.

Killed steel

Killed steel has been processed to remove or bind the oxygen that saturates the molten steel prior to solidification. It is defined as deoxidized steel and produced either by addition of strong deoxidizing agents or by vacuum treatment to reduce the oxygen content to such a level that no reaction occurs between carbon and oxygen during solidification. Semi-killed steel is incompletely deoxidized, and may also be specified. The benefit of killing is to reduce the number of gas pockets present in the steel, which can adversely affect the mechanical properties of the steel, including ductility and toughness, as well as reduce the number of oxide-type inclusions in the steel. Most commonly, killing is done using additions of silicon, but may also be done with aluminum or manganese. Killed steels often have silicon levels in the range of 0.10% to 0.30%, but may also be higher.

Plain carbon steels

It is mainly alloy of iron and carbon containing less than 2.0% carbon, with a small amount of impurities such as sulphur, manganese, phosphorus and silicon. The carbon content generally varies from 0.05 to 1.0 percent. The plain carbon steel is classified on the basis of carbon percentage as low carbon steel (upto 0.3% C), medium carbon steel (between 0.3 to 0.7% C) and high carbon steel above 0.7% C. Low carbon steel is very soft and ductile with good machinability and weldability. It is less responsive to heat treatment due to less carbon content. High carbon steel, though, responds well to heat treatment process but becomes brittle and difficult to weld.
The medium carbon steel does not lose its ductility when heat treated. There are many merits of plain carbon steel. It is cheap; readily available; it has wide range of mechanical properties; heat treatment can ensure the desired combination of strength and ductility; it has good machinability and weldability; mechanical properties can be improved by proper alloying. Typical applications and properties of plain carbon steel are given in Table 2.4.

<table>
<thead>
<tr>
<th>Designation</th>
<th>$S_{ut}$ MPa</th>
<th>$S_{yt}$ MPa</th>
<th>% elong</th>
<th>BHN</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>C07</td>
<td>314-392</td>
<td>196</td>
<td>27</td>
<td>—</td>
<td>Cold forming and deep drawing, Rimming quality used for Automobile bodies and rivets, killed quality used for forgings</td>
</tr>
<tr>
<td>C10</td>
<td>333-412</td>
<td>206</td>
<td>26</td>
<td>—</td>
<td>Cam shafts, cams, light duty gears, worms, gudgeon pins, spindles, ratchets, chain wheels, tappets etc.</td>
</tr>
<tr>
<td>C14</td>
<td>363-441</td>
<td>216</td>
<td>26</td>
<td>137</td>
<td>Cold worked-rivets, General purpose-low stresses components</td>
</tr>
<tr>
<td>C15</td>
<td>363-481</td>
<td>233</td>
<td>25</td>
<td>137</td>
<td>Cold formed levers, Hardened and tempered tie rods, cables, sprockets, hubs and bushes, steel tubes etc.</td>
</tr>
<tr>
<td>C20</td>
<td>432-510</td>
<td>245</td>
<td>24</td>
<td>156</td>
<td>Low stressed components, automobile tubes and fasteners</td>
</tr>
<tr>
<td>C25</td>
<td>432-520</td>
<td>275</td>
<td>27</td>
<td>170</td>
<td>Low stressed parts, cycle and motor frame tubes, fish plates for rails and fasteners</td>
</tr>
<tr>
<td>C25Mn75</td>
<td>461-560</td>
<td>275</td>
<td>22</td>
<td>207</td>
<td>Crank shafts, shafts, spindles, axle beams, push rods, connecting rods, studs, bolts, gears etc</td>
</tr>
<tr>
<td>C30</td>
<td>490-588</td>
<td>294</td>
<td>21</td>
<td>179</td>
<td>Shafts, bolts, gears and spindles of machine tools</td>
</tr>
<tr>
<td>C35</td>
<td>510-608</td>
<td>304</td>
<td>20</td>
<td>187</td>
<td>Shafts, keys, cylinders, hardened stock for worms and worm gears</td>
</tr>
<tr>
<td>C35Mn75</td>
<td>540-637</td>
<td>314</td>
<td>20</td>
<td>223</td>
<td>Rail steel, bolts, gear shafts, rocking levers and cylinder liners</td>
</tr>
<tr>
<td>C40</td>
<td>570-667</td>
<td>324</td>
<td>18</td>
<td>217</td>
<td>Keys, crank shafts, cylinders, cams, gears, sprockets, parts requiring moderate wear resistance</td>
</tr>
<tr>
<td>C45</td>
<td>618-696</td>
<td>353</td>
<td>15</td>
<td>229</td>
<td>Locomotive carriage and wagon tyres, engine valve springs, washers and thin stamped parts</td>
</tr>
<tr>
<td>C50</td>
<td>647-765</td>
<td>373</td>
<td>13</td>
<td>241</td>
<td>Not applicable</td>
</tr>
<tr>
<td>C50Mn1</td>
<td>706(min)</td>
<td>392</td>
<td>11</td>
<td>255</td>
<td>Not applicable</td>
</tr>
<tr>
<td>C55Mn75</td>
<td>706(min)</td>
<td>392</td>
<td>13</td>
<td>265</td>
<td>Not applicable</td>
</tr>
<tr>
<td>C65</td>
<td>736(min)</td>
<td>422</td>
<td>10</td>
<td>255</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

**Note:** The properties of same material vary greatly because of different manufacturing processes, chemical composition, internal defects, temperature, measuring errors and many other factors. Consequently, catalogues of manufacturer of the material should be consulted for precise value of the properties.

The steels with carbon content ranging from 0.05 to 0.5% carbon are very commonly used for building structures, doors, windows, nuts, bolts, washers, grill works etc., and hence are also called *Structural steel.*

The structural steel with carbon percentage of about 0.25% is used for bridges, boilers, chemical and nuclear plants. The ductility is essential in various ways for the proper functioning
of steel structures and is particularly important in the behavior of connections. Structural steel undergoes sizeable permanent (plastic) deformations before fracture. It can be classified as follows:

1. **Structural carbon steel** with a specified yield strength between 228 and 248 MPa.
2. **High-strength steel** with a specified yield strength between 290 and 345 MPa.
3. **High-strength low-alloy steels** with a specified yield strength ranging from 276 to 448 MPa.
4. **Quenched and tempered carbon steel** with a specified yield strength between 345 and 414 MPa.
5. **Quenched and tempered alloy steel** with a specified yield strength between 621 and 689 MPa.

Steel castings are more difficult to produce than cast iron castings and are more expensive but are stronger and tougher. They are used for machine members of intricate shape that require high strength and impact resistance such as IC engine frames etc.

### IS designation of plain carbon steels

Plain carbon steels are designated as $A C Y Z$

where

- $A$ average carbon content in percent $\times 100$
- $C$ stands for carbon
- $Y$ average manganese content in percent $\times 10$
- $Z$ stands for special characteristics

For example, 20 C 8 means steel is containing average 0.2 percent carbon and 0.8 percent of manganese.

### Alloy steels

Alloy steel may be defined as carbon steel to which one or more elements are added to improve certain mechanical property. Following are the most commonly used alloying elements with the influence on the properties of steel. **Sulphur** when added up to 0.33%, increase machinability in free cutting steel. Such steels become hot embrittle (tendency to crack at rolling and forging temperatures). **Phosphorus** up to 0.12% is added to low carbon steel to increase strength, hardness and resistance to corrosion. It also improves machinability. Phosphorus causes **cold shortness** (reduction in impact strength at low temperature) in high strength high carbon steel. **Silicon** increases strength and hardness keeping ductility intact. It acts as a deoxidizer when 0.1 to 0.3 percent is added. It gives strength and soundness to a casting if added amount is 0.3 to 0.5 percent. It is added up to 5% in magnetic materials used in transformers as it increases permeability and reduces iron losses.

Addition of 12 to 14% of manganese produces extremely tough, wear resistant and non-magnetic steel called hadfield steel. **Nickel** provides hardness, strength and toughness without sacrificing the ductility. It is corrosion resistant and increases hardenability. An amount of 5% nickel induces high static and impact strength at low temperature. **Chromium** provides high hardness, strength and wear at elevated temperature. It resists corrosion if more than 4% is added.
### Table 2.5  Properties of Alloy Steel

<table>
<thead>
<tr>
<th>ISI Grade</th>
<th>$S_{ut} \ N/mm^2$</th>
<th>$S_{yt} \ N/mm^2$</th>
<th>Min % Elongation</th>
<th>BHN</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 Mn 2</td>
<td>588 – 736</td>
<td>432</td>
<td>18</td>
<td>170 – 217</td>
</tr>
<tr>
<td></td>
<td>687 – 834</td>
<td>490</td>
<td>16</td>
<td>201 – 248</td>
</tr>
<tr>
<td>37 Mn 2</td>
<td>588 – 736</td>
<td>432</td>
<td>18</td>
<td>170 – 217</td>
</tr>
<tr>
<td></td>
<td>687 – 834</td>
<td>530</td>
<td>18</td>
<td>201 – 248</td>
</tr>
<tr>
<td></td>
<td>785 – 932</td>
<td>588</td>
<td>16</td>
<td>229 – 277</td>
</tr>
<tr>
<td></td>
<td>882 – 1030</td>
<td>687</td>
<td>15</td>
<td>255 – 311</td>
</tr>
<tr>
<td>35 Mn 2 Mo 28</td>
<td>687 – 834</td>
<td>530</td>
<td>18</td>
<td>201 – 248</td>
</tr>
<tr>
<td></td>
<td>785 – 932</td>
<td>588</td>
<td>16</td>
<td>229 – 277</td>
</tr>
<tr>
<td></td>
<td>882 – 1030</td>
<td>687</td>
<td>15</td>
<td>255 – 311</td>
</tr>
<tr>
<td>35 Mn 2 Mo 45</td>
<td>785 – 932</td>
<td>588</td>
<td>16</td>
<td>229 – 277</td>
</tr>
<tr>
<td></td>
<td>882 – 1030</td>
<td>687</td>
<td>15</td>
<td>255 – 311</td>
</tr>
<tr>
<td></td>
<td>981 – 1128</td>
<td>785</td>
<td>13</td>
<td>285 – 341</td>
</tr>
<tr>
<td>35 Mn 2 Mo 45</td>
<td>785 – 932</td>
<td>588</td>
<td>16</td>
<td>229 – 277</td>
</tr>
<tr>
<td></td>
<td>882 – 1030</td>
<td>687</td>
<td>15</td>
<td>255 – 311</td>
</tr>
<tr>
<td></td>
<td>981 – 1128</td>
<td>785</td>
<td>13</td>
<td>285 – 341</td>
</tr>
<tr>
<td>40 Cr 1</td>
<td>687 – 834</td>
<td>530</td>
<td>18</td>
<td>201 – 248</td>
</tr>
<tr>
<td></td>
<td>785 – 932</td>
<td>588</td>
<td>16</td>
<td>229 – 277</td>
</tr>
<tr>
<td></td>
<td>882 – 1030</td>
<td>687</td>
<td>15</td>
<td>255 – 311</td>
</tr>
<tr>
<td>40 Cr 1 Mo 28</td>
<td>687 – 834</td>
<td>530</td>
<td>18</td>
<td>201 – 248</td>
</tr>
<tr>
<td></td>
<td>785 – 932</td>
<td>588</td>
<td>16</td>
<td>229 – 277</td>
</tr>
<tr>
<td></td>
<td>882 – 1030</td>
<td>687</td>
<td>15</td>
<td>255 – 311</td>
</tr>
<tr>
<td>15 Cr 3 Mo 55</td>
<td>687 – 834</td>
<td>530</td>
<td>18</td>
<td>201 – 248</td>
</tr>
<tr>
<td></td>
<td>785 – 932</td>
<td>588</td>
<td>16</td>
<td>229 – 277</td>
</tr>
<tr>
<td>40 Cr 3 Mo 1 V 20</td>
<td>1324 min</td>
<td>1098</td>
<td>8</td>
<td>363 min</td>
</tr>
<tr>
<td></td>
<td>1520 min</td>
<td>1275</td>
<td>8</td>
<td>444 min</td>
</tr>
<tr>
<td>40 Cr 2 A1 1 Mo 18</td>
<td>687 – 834</td>
<td>530</td>
<td>18</td>
<td>201 – 248</td>
</tr>
<tr>
<td></td>
<td>785 – 932</td>
<td>588</td>
<td>16</td>
<td>229 – 277</td>
</tr>
<tr>
<td></td>
<td>882 – 1030</td>
<td>687</td>
<td>15</td>
<td>255 – 311</td>
</tr>
<tr>
<td>40 Ni 3</td>
<td>785 – 932</td>
<td>588</td>
<td>16</td>
<td>229 – 277</td>
</tr>
<tr>
<td></td>
<td>882 – 1030</td>
<td>687</td>
<td>15</td>
<td>255 – 311</td>
</tr>
<tr>
<td>35 Ni 1 Cr 60</td>
<td>687 – 834</td>
<td>530</td>
<td>18</td>
<td>201 – 248</td>
</tr>
<tr>
<td></td>
<td>785 – 932</td>
<td>588</td>
<td>16</td>
<td>229 – 277</td>
</tr>
<tr>
<td></td>
<td>882 – 1030</td>
<td>687</td>
<td>15</td>
<td>255 – 311</td>
</tr>
<tr>
<td>30 Ni 4 Cr 1</td>
<td>1520 min</td>
<td>1275</td>
<td>8</td>
<td>444 min</td>
</tr>
<tr>
<td>40 Ni 1 Cr 1 Mo 15</td>
<td>785 – 932</td>
<td>588</td>
<td>16</td>
<td>229 – 277</td>
</tr>
<tr>
<td></td>
<td>882 – 1030</td>
<td>687</td>
<td>15</td>
<td>255 – 311</td>
</tr>
<tr>
<td></td>
<td>981 – 1128</td>
<td>785</td>
<td>13</td>
<td>285 – 341</td>
</tr>
<tr>
<td></td>
<td>1080 – 1226</td>
<td>863</td>
<td>11</td>
<td>311 – 363</td>
</tr>
<tr>
<td>31 Ni 3 Cr 65 Mo 55</td>
<td>1200 min</td>
<td>1000</td>
<td>10</td>
<td>444 min</td>
</tr>
</tbody>
</table>

**Note:** The properties of same material varies greatly because of different manufacturing processes, chemical composition, internal defects, temperature, measuring errors and many other factors. Consequently, catalogues of manufacturer of the material should be consulted for precise value of the properties.
Molybdenum and tungsten increase hardenability, red hardness and wear resistance. Molybdenum reduces temper brittleness and reduces softening during tempering. Tungsten, due to its heat resistant property is used in tool steel. Vanadium provides highest hardness and improves fatigue resistance. Titanium imparts red hot hardness. Chromium when added with molybdenum improves strength at high temperature and when alloyed with nickel gives superior mechanical properties. The properties of some alloy steels are given in Table 2.5.

**IS designation of alloy steels**

In case of alloy steels first number represents the 100 times the carbon content and then alloying element followed by a number as $A \ AE1 \ Y1 \ AE2 \ Y2 \ .... \ so \ on$

where

\[
A \quad \text{average carbon content in percent} \times 100 \\
AE1 \quad \text{chemical formula of alloying element 1} \\
Y1 \quad \text{average content in } \% \times 4 \text{ if } AE1 \text{ is } \text{Cr, Co, Ni, Mn, Si and W} \\
Y1 \quad \text{average content in } \% \times 10 \text{ if } AE1 \text{ is } \text{Al, V, Pb, Cu, Ti, Mo, Zr} \\
Y1 \quad \text{average content in } \% \times 100 \text{ if } AE1 \text{ is } P, S, N \\
AE2 \quad \text{chemical formula of alloying element 2} \\
Y2 \quad \text{average content in } \% \times 4 \text{ if } AE2 \text{ is } \text{Cr, Co, Ni, Mn, Si and W} \\
Y2 \quad \text{average content in } \% \times 10 \text{ if } AE2 \text{ is } \text{Al, V, Pb, Cu, Ti, Mo, Zr} \\
Y2 \quad \text{average content in } \% \times 100 \text{ if } AE2 \text{ is } P, S, N
\]

For example 40 Cr 4 Mo 2 means alloy steel containing average 0.4 percent of carbon, 1.0 percent of chromium and 0.2 percent of molybdenum.

**2.8 DESIGNING WITH NON-FERROUS ALLOYS**

The strength of copper is less as compared to steel but it is tough, ductile and malleable. The properties of copper depend largely on the mechanical treatment. The cold working increases the strength and brittleness. Copper in its purest form is used for castings where resistance to corrosion and heat conductivity are of prime consideration, such as in condenser tubes, water pipes, automobile radiators, heat-exchangers, sheet metal parts etc., but has very limited application in machine design.

Copper alloys are widely used in machines to have good friction and corrosion resistance. Three groups of copper alloys used in machine design are brasses, bronzes and Monel metal. Copper when alloyed with zinc is called brass and any other copper alloy is called bronze. Brasses contain 45 to 90 percent copper and up to 50 percent zinc with small amount of iron, lead and tin as impurities. Brasses have good resistance to corrosion, high electrical conductivity, sufficient strength and especially good processing properties. Brasses can be cast, cold worked and even machined at high speed with very good surface finish.

The bronzes are classified as tin, lead, aluminium, beryllium and silicon bronzes according to the main alloying element other than copper. In general, bronzes have high antifriction properties; high corrosion resistance and they are conducive to several processing methods, such
• Heating the steel to austenizing temperature (upper critical temperature)
• Steel is held at that temperature for some time called soaking period. This is also called homogenization.
• It is then cooled back to room temperature at the required cooling rate depending upon the properties desired.
• If necessary, steel may be reheated again to a temperature (lower than upper critical temperature), held and cooled again, this process is called tempering.

The events of heat treatment cycle are shown in Figure 2.11. Heating is generally done slowly to ensure uniformity; soaking is holding the alloy at a given temperature for a specified period of time; and cooling or returning the metal to room temperature, sometimes rapidly, sometimes slowly. It is also important to note here that cooling may also be done in steps i.e. there may be more than one soaking period depending on the change in the cooling rate during heat treatment cycle. Slow heating results in nearly uniform heating. Thermal conductivity, hardness/softness, prestressing, size and cross-section have their influence on selecting the rate of heating. After uniform heating, the alloy must be held at that temperature to ensure that the microstructural changes have sufficient time to take place. This holding period (soaking period) depends on the composition, size, geometry and mass of the part. Cooling the heated alloy rapidly is called quenching and oil, water, brine, or other media are used as quenching medium. In most of instances, quenching is associated with hardening. Brine and water cool metals quickly as compared to oil. Carbon steels are considered water hardened and alloy steels oil hardened whereas nonferrous metals are usually quenched in water. In practice, steel is first slowly heated to temperature just below \( A_3 \) or \( A_{1,3} \), and then held at this temperature until heat is absorbed throughout the metal. This process is called preheating and is indicated in Figure 2.11 by dotted lines. The steel is then heated to the final temperature quickly. Preheating helps uniform heating, avoids distortion and cracking. Preheating can also be done at more than one temperature depending on the complexity of the geometry to prevent cracking and excessive warping. Also, heating of steel is done to a temperature above \( A_3 \) which is a austenite phase field and hence this process of heating is also called austenitization. There are different types of heat treatment process

![Fig. 2.11 Heat treatment process](image-url)
associated with the heat treatment of steel. The selection of a particular heat treatment process depends on the application of the steel component and the carbon content of the steel.

**Annealing**

Annealing consists of heating the metal in the furnace to a temperature slightly above the upper critical temperature and cooling slowly in the furnace, after it is shut off. It produces an even grain structure, reduces hardness and increases ductility usually at a reduction of strength.

**Normalizing**

Normalizing is heating of metal in the furnace to a temperature slightly above the upper critical temperature and then cooled in still air. Normalizing is done to remove the effect of any previous heat treatment and to produce uniform grain structure before other heat treatments are applied. Normalized steel will have higher hardness and more strength than annealed steel.

![Stress-strain curve for steel after heat treatment](image)

**Fig. 2.12** Stress-strain curve for steel after heat treatment

**Quenching**

Unlike annealing and normalizing, the metal is cooled rapidly in water or in any suitable medium after heating the metal above the lower critical temperature. It is basically a pure hardening process. Hardness achieved during the quenching process depends on the amount of carbon content and cooling rate. Different cooling rates can be achieved by using different cooling medium such as water, oil, hot oil, etc. Quenching increases hardness and wear resistance and the steel becomes brittle and reduces ductility.

**Tempering**

Tempering is reheating the quenched component below the critical temperature to regain some ductility and reduces the brittleness. Increased toughness is obtained at the expense of strength. The desired properties can be obtained by controlling the temperature and tempering time.