CHAPTER

5

PROPERTIES, TESTING AND INSPECTION OF METALS

5.1 INTRODUCTION

A wide range of materials find use in engineering applications. This includes both, metals as well as non-metals. However, in manufacturing practice metals and their alloys have a wider application, although it is not at all possible to altogether ignore the non-metallic group of materials. With the development of newer non-metallic materials, which have overcome their inherent drawbacks to a considerable extent, there is a tough competition many a times between these two groups while selecting the material for a component. If both are found to be equal in performance requirements it is the cost factor that decides as to which of the two should be selected.

The basic concern of an engineer while selecting the material for a particular component is to match the service requirements of the component with the properties of the material under consideration. As such, in order that an engineer is capable of selecting a proper material for a specific application he should be fully conversant with the different properties found in different materials, methods of determining these properties, procedures for testing them, their limitations, etc. Also, it is well known that a larger part of manufacturing and fabrication activities involves the use of solid materials, especially metals and their alloys. Our discussions in this chapter will, therefore, be in the context of metals and metal alloys.

Further, as started above, materials possess different properties in varying degrees and, therefore, behave in different ways under given conditions. These properties include *mechanical properties, electrical properties, thermal properties, chemical properties, magnetic properties and physical properties*. A design or manufacturing engineer is basically

interested in knowing as to how a particular material will behave under applied loads, *i.e.*, in knowing the *mechanical properties* of the material under consideration. Our discussions in this chapter will, therefore, mainly confine to the review of main mechanical properties of metals and their alloys, although a brief review of other properties will also follow at the end of this chapter.

5.2 STRESS AND STRAIN

When a load is applied to a structure its material may either deform or break. The ultimate result will depend upon the amount of load applied, cross sectional area of the section under load and the nature of the material. Natural tendency of the material is to resist deformation. This resistance against the action of the applied load is offered by the internal reactive forces, called **Stresses**, which are developed in the material when the external load is applied. Mathematically, the *Stress* is expressed as the *Force or Load per unit area of cross-section* of the component, *i.e.*,

$$S = \frac{P}{A}$$

where, S = Stress

P = Load applied

and A = Area of cross section.

Strain represents the deformation caused per unit length of a body, *i.e.*, *the change in length per unit length of the body*. From this, it follows that it is a ratio of change in length of a body to its original length. Since it is a ratio it has no unit. However, it can be expressed in millimeter per metre or as a percentage. Mathematically, it is expressed thus :

$$e = \frac{\Delta L}{L} = \text{longitudinal strain (or unit strain)}$$

where, e = Strain

ΔL = Change in length

and, L = Original length of the body.

The strain caused in a body can be *Lateral Strain* or *Shear Strain* according to the manner in which the load is applied on to the body.

The *stresses* caused in a body and the corresponding *strains* developed are also named according to the nature of loading a body. For example, if a body is subjected to pulls from either end and, it is under tension, *i.e.*, the tendency of the applied load is to elongate the body. The resulting stress in the body is, therefore, known as **Tensile stress**

and the corresponding strain as **Tensile strain**, Similarly, when a body is so loaded that the tendency of the load is to squeeze it, *i.e.*, to shorten it, the stress caused is termed as **Compressive stress** and the corresponding strain as **Compressive strain**. In the same way, if a body is acted upon by two equal and opposite loads, acting upon its opposite surfaces, the tendency of the load will be to make a portion of the body slide over the other, *i.e.*, to shear the body along a common plane. Such a loading will cause a **Shear stress** and the corresponding strain will be known as **Shear strain**.

Let it also be clear that the deformation in the material due to applied load is not necessarily along the length alone. It can be in length, volume or both, which ultimately leads to a change in shape of the body. In order to generalise the above definition of strain we can better say that, *Engineering Strain is the deformation per unit dimension*, If this deformation is along the length then it is called **Longitudinal strain**, if in volume then **Volumetric strain** and when in transverse direction the **Shear strain** or **Transverse strain.**

Hooke's Law

Named after its developer Robert Hooke, this law states that within the *elastic limit, the Stress is directly proportional to the Strain, i.e., the ratio of stress to strain is a constant*. This constant is known as **Young's Modulus of Elasticity** or **Coefficient of Elasticity** and is represented by the letter '*E*'. Mathematically expressing

$$E = \frac{S}{e} = \textbf{constant.}$$

This **Constant of Proportionality** is different for different materials and also different for different types of stresses. In case of tensile and compressive stresses it is known as **Young's Modulus of Elasticity (*E*)**, in case of shear stresses and strains it is known as **Modulus of Rigidity (*G*)** and when volumetric stresses and strains are in play this constant is known as the **Bulk modulus (*K*)**. In general, this constant is known as the **Modulus of Material.**

Poisson's ratio

If a force is applied on a uniform body, say a bar or a test specimen, along its axis, the body is strained both in the direction of application of force as well as in a direction normal to it. The *strain* in the direction of application of force is called *Longitudinal Strain* and that in the direction normal to it the *Lateral Strain*. The ratio between the *lateral strain* and *longitudinal strain* is called **Poisson's ratio**. Its value is constant for a particular material but varies for different materials. For each material it is an important **Elastic Constant**. For most of the materials

commonly used in engineering practice its value ranges between 0.3 to 0.6. Mathematically expressing :

$$\textbf{Poisson's ratio} = \frac{\text{lateral strain}}{\text{longitudinal strain}} = \textbf{Constant.}$$

5.3 STRESS-STRAIN RELATIONSHIP

The relationship between stress and strain can be best understood withe the help of a **Stress-Strain Curve.** This curve can be easily drawn by plotting a graph between the different values of stresses and corresponding strains, obtained during the tensile test of material specimen, stress values being taken along the ordinate and the corresponding strain values along the abscissa.

In order to make it quite clear let us take the example of tensile test performed on a specimen made from a ductile material, say low carbon steel (mild steel). Fig. 5.1 represents the curve plotted from the data obtained during such a test. When engineering stress of different magnitudes are applied to the test specimen they cause corresponding changes in the length of the specimen. Both these readings, *i.e.*, the magnitudes of the applied stresses and the corresponding changes in length, recorded on strain measuring devices, are noted down. By dividing the latter data by the original length of the specimen different values of *Engineering Strains*, corresponding to different values of applied *Engineering Stresses,* are calculated and recorded. A graph is then plotted between the different values of applied loads (stresses) and the corresponding values of resulting strains. By joining these points a curve of the type shown in Fig. 5.1 is obtained.

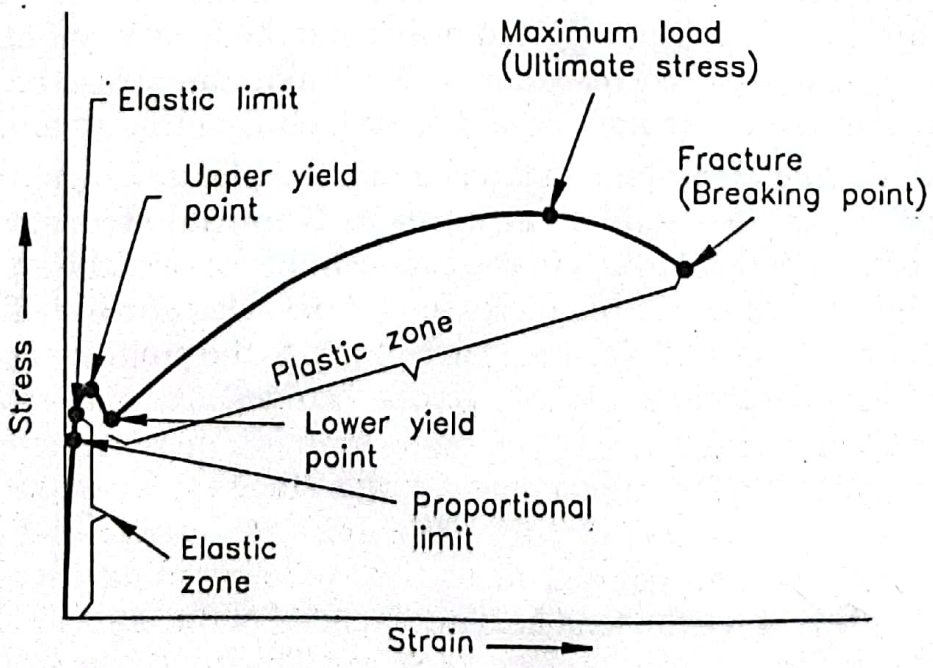

Fig. 5.1. An engineering stress-strain curve for a ductile material.

A close study of the curve reveals that the material elongates elastically in the beginning of the test, *i.e.*, the *strain* increases in direct proportion to the *applied stress*. Obviously, if the load is removed during this range the specimen will automatically return to its original length, *i.e.*, the material will perfectly obey the Hooke's law. This state will continue till the stress-strain values reach a specific common point called the **Limit of proportionality** or simply **Proportional limit**. If the material is loaded beyond this stage, it will not obey the Hooke's law perfectly.

Beyond this point you will notice another point on the curve, called the **Elastic limit**. This point corresponds to the maximum stress value upto which the material will exhibit true elastic behaviour. The region of the curve falling between the 'zero' stress value and the elastic limit is known as **Elastic region** or **Elastic zone**. In some materials the proportional limit and elastic limit are almost identical, but in most of the materials the *Elastic Limit* is slightly higher than the *Proportional Limit*.

If the material is located beyond the elastic limit the applied stresses cause *plastic deformation*, *i.e.*, the material fails to return to its original shape and size or we can say that it retains its elongation permanently even after the loads are removed. Also, beyond the elastic limit the increase in strain does not bear the same direct proportionality with the corresponding stress. In fact, beyond the elastic limit, the strain is found to increase more rapidly than the corresponding stress. This process continues till a point is reached where it is noticed that the strain increases even without any further increase in the stress. At this point the material is found to stretch suddenly. This point is known as **Yield Point**. In case of the material under consideration there are two distinct *yield points*, called the **Upper yield point** and the **Lower yield point**. The *Upper yield point* corresponds to the maximum stress preceding the extensive strain, the *Lower yield point* following this strain.

With further straining of material into the plastic range its *Load-bearing ability* increases. In other words its **Nominal stress**, which is the ratio of applied load to original cross-sectional area of the specimen, increases. The reason for this increase is **Work Hardening**. The load bearing ability of the material is said to be equal to the product of strength and cross-sectional area. Because the cross-sectional area of the specimen decreases during its tensile stretching its strength increases, and so its load-bearing ability. During tensile testing a stage is arrived where the decrease in cross sectional area with increased strain acquires a predominant position compared to the corresponding increase in strength. At this stage the load bearing capacity of the material is at its peak and so is the value of the *Tensile Stress*. This represents the value of the stress at maximum load. It can be found out by dividing the load

at that point by the original cross-sectional area of the specimen and is known as **Ultimate tensile stress** or simply **Ultimate stress** which corresponds to the *Ultimate tensile strength* of the material.

At this point a typical phenomenon works in that the strain continues to increase slowly without any increase in the load, *i.e.*, stress. This phenomenon of slow increase in strain with time without any further increase in stress is called **Creep.** The cross-sectional area of the specimen is the weakest point of the test bar at this stage, which continues to become weaker and weaker as the slow extension continues, and further deformation becomes localised around this weakest point and a **neck** is formed there. The entire further deformation takes place within the neck. Further straining of the material is surprisingly accompanied by a reduction in applied stress and that is why the stress-strain curve falls beyond the point of *ultimate stress*. If straining is continued further the test specimen finally fractures (breaks) at a point where its cross sectional area is minimum. The strength at this point is known as the **Fracture strength** or **Breaking strength**. In ductile materials the fracture strength is less than the **Ultimate tensile strength** and final fracture is always preceded by *necking*. In brittle materials, however, the stress-strain curve is terminated before necking can start and, therefore, fracture takes place without necking.

5.4 ENGINEERING AND TRUE STRESS AND STRAIN

We have seen in the previous article that when a tensile test specimen is loaded it elongates and its cross-sectional area reduces. This reduction, however, is not uniform through the length of the specimen but is confined to a relatively smaller portion somewhere near the middle of the length. It is also seen that the change in cross-sectional area is negligible within the elastic zone, but appreciable beyond the elastic limit. Another notable feature of the test is that one portion of the specimen starts deforming more rapidly than the rest as the test progresses.

The obvious question, therefore, is as to which areas should be considered for computing the stress for a known load, *i.e.*, whether it should be the original area of the specimen or the actual area at the instant when the stress is being calculated. Both these options are used. When the original area is considered for this purpose the stress obtained is known as **Engineering stress** or **Nominal stress** and when the actual area is considered the computed stress is called the **True Stress.** Mathematically expressing :

$$\text{Engineering stress} = \frac{\text{Load}}{\text{Original area}} = \frac{P}{A}$$

$$\text{True stress} = \frac{\text{Instantaneous load}}{\text{Instantaneous area}} = \frac{P}{A_i}$$

Similarly,

$$\text{Engineering strain} = \frac{\text{Change in length}}{\text{Original length}} = \frac{\Delta L}{L}$$

But, as stated above, after the start of necking, one portion of the specimen deforms more rapidly than the rest, *i.e.*, elongation in this portion will be more than the rest of the specimen. It, therefore, follows that the strain will not be homogenous and, as such, it is not logical to consider the entire length of the specimen for finding out the True strain. The strain can be calculated from the following relationships:

$$\text{True strain} = \int_{L_0}^{L_i} \frac{\Delta L}{P}$$

Or, in terms of area,

$$\text{True strain} = \frac{\text{Original area}}{\text{Instantaneous area}}$$

5.5 PRINCIPAL MECHANICAL PROPERTIES

Those characteristics of the materials which describe their behavour under external loads are known as **Mechanical properties** of materials. Since all the engineering components, articles, tools and machinery, structures, etc., manufactured and fabricated through various processes are likely to be subjected to external loading in some way or the other at some stage, specially during use, it is essential that the design and manufacturing engineers possess a sound knowledge of the mechanical properties of materials in order to design and manufacture sound articles, components and structures to avoid failures during use. It is only with the sound knowledge of these properties that the selection of a proper material for a particular part will be possible.

These properties largely depend upon the structure of the material and the various factors contributing to this structure, such as grain size, type of bonding, presence and nature of imperfections, grain boundaries, etc., as explained in the last chapter. A brief review of these properties will follow in this chapter.

5.6 STRENGTH

It can be described as the measure of ability of a material to withstand external forces. In other words, we can say that it is the resistance offered by a material when subjected to external loading. Higher the strength the higher is the resistance offered by the material to deformation and, therefore, higher is the amount of the external load it can withstand without failure.

Depending upon the type of load applied the strength can be *Tensile, Compressive, Shear or Torsional.* The various strengths shown by a material during a tensile test are shown on the curve in Fig. 5.1 and described in Article 5.3. The stress in the material at the *Elastic Limit* is known as **Yield strength** and the maximum stress before the fracture is called **Ultimate strength.** While in tension, the *Ultimate Strength* of the material represents its *tenacity*. Analogous strengths for a material in compression, shear and torsion can also be determined through respective tests.

5.7 ELASTICITY

It is a type of tensile property of a material due to which it resists permanent deformation under applied loads, *i.e.*, the property which enables the material to spring back to its original size and shape as soon as the external loads are removed. It has already been discussed in sufficient detail in Articles 5.2 and 5.3. Also, several related terms like *yield point, proportional limit, elastic zone*, etc. have been fully explained in those articles.

5.8 STIFFNESS

It is also known as **Rigidity**. It is that property of a material due to which it is capable of resisting *deflection* or *elastic deformation* under applied loads. This is very important for those parts or components which are required to remain perfectly aligned under externally applied loads. The degree of stiffness of a material is indicated by the *Young's modulus* if it obeys the Hooke's law, by *Modulus of Elasticity*, in case of tensile and compressive stresses, *Modulus of rigidity* in case of shear stress and *Bulk modulus* in case of volumetric deformation.

5.9 PLASTICITY

It is the property of a material due to which it can undergo permanent deformation without failure or rupture. This property is widely used in several mechanical processes like forming, shaping, extruding, rolling, etc. Due to this property various metals can be transformed into different products of required shapes and sizes. This conversion into

desired shapes and sizes is effected either by the application of pressure, heat, or both. In general, it is found that plasticity increases with increase in temperature.

5.10 MALLEABILITY AND DUCTILITY

Both **Malleability** and **Ductility** in a material are due to *plasticity*. It should be clearly understood that while plasticity is the controlling property *malleability* and *ductility* indicate the ability of the material to undergo specific mechanical working processes without rupture. Some other terms used in the same sense, *i.e.*, to indicate the response of the material to specific mechanical processes are **Formability** and **Workability**.

Coming specifically to the above two main terms, **Malleability** can be defined as the ability of a material for being flattened into sheets without cracking through cold or hot working. **Ductility** of a material relates to its ability to be drawn into wires without rupture and without losing much strength. Some common ductile metals are lead, tin, silver, aluminium, copper, iron, steel, etc.

All the metals are not necessarily both ductile and malleable. For example, *lead* can be easily shaped into sheets by rolling or hammering but cannot be drawn into wires, *i.e.*, while it is *malleable* it is not *ductile*. It is generally reckoned that while *ductility* is a tensile characteristic, *malleability* is a compressive characteristic. *Ductility* of a material is usually indicated by *the percentage elongation prior to necking or the percentage reduction in area in the necked region* during the tensile test of the material.

5.11 BRITTLENESS

A material is said to be *brittle* if it fails with little or no ductility. Thus, it can be considered as the opposite of ductility. But, a brittle material should not be considered as lacking in strength. It only shows the lack of plasticity. To elaborate it further, let us consider the example of cast iron, which is a brittle but sufficiently strong material. It is found to break suddenly as soon as its stress strain curve begins deviating from a straight line.

5.12 TOUGHNESS

It is the property on account of which a material is able to withstand *bending* or *torsion* without fracture and is equal to the work per unit volume needed to fracture the material. In other words, we can say that it indicates the amount of energy absorbed by the material before its actual failure or fracture occurs. One method of determining toughness of a material is to conduct tensile test on its specimen and construct a

stress-strain diagram from the data obtained through the test. The total area under the stress-strain diagram from the data obtained through the test. The total area under the stress-strain curve will represent the *energy* (*work*) required per unit volume to fracture the material. However, in order to get correct values, the variation in temperature and rate of application of load during testing should be taken into account because they can appreciably change the nature of the stress-strain curve and, therefore, the *toughness* value of the material. The work or energy absorbed by the material is usually expressed as **Modulus of Toughness**.

To understand it more clearly, let us compare two different materials, one brittle (say glass) and the other tough (say wrought iron). If sudden load is applied to two pieces, one each of the above materials, the glass piece breaks suddenly while the wrought iron piece will absorb a substantial amount of energy before failing. Accordingly, therefore, wrought iron is supposed to be much tougher than glass. Since this property enables a metal to withstand both elastic and plastic deformations it is of very great significance for design and manufacturing engineers who have to design and manufacture a large number of parts and structures, which are supposed to bear shock loads and vibrations during use. It is, therefore, amply clear that it is commonly associated with shock or impact loading and, hence, to **Impact Strength**.

5.13 RESILIENCE

It is the measure of the capacity of a material to absorb energy within the elastic limit. When a material is extensively loaded within elastic limit it absorbs *Strain Energy*. It is a potential energy and it is released when the applied load is removed. The amount of energy that a unit volume of material can absorb within the elastic range (Fig. 5.1) is known as **Resilience**. The maximum amount of energy that can be stored in a material (body) upto the classic limit is called **Proof Resilience**. The amount of proof resilience per unit volume of the material is known as **Modulus of Resilience**. This property indicates the capacity of a material to withstand shock loads and vibrations.

5.14 HARDNESS

This property is quite closely related to the strength of a material. Although it is a basic and very important property of materials, no precise definition of this property has yet been established. However, a common way of defining this property is in terms of the capacity or ability of a material to resist permanent indentation, such on scratching, wear, prenetration, abrasion, cutting, etc. Several types of tests are used to determine the *hardness* of materials. Of these, the most commonly used

are **Brinell, Rockwell** and **Vickers** hardness tests. These tests will be described in detail later on in this chapter. These tests give numbers which are indicative of the relative hardness of the material under test.

A particular term which often finds use in the description of this property, specially in the context of steel, is *Hardenability*. It is indicative of the degree of hardness that the metal can acquire through the hardening process, *i.e.*, heating and quenching. Not only the degree but even distribution of the indicated hardness in the metal is determined. The more uniformly the induced hardness is distributed throughout the structure of the metal the higher will be the hardenability of the metal concerned.

5.15 IMPACT STRENGTH

This property encompasses both toughness and strength of a material. In short, it can be defined as the resistance of the material to fracture under impact loading, *i.e.*, under quickly applied dynamic loads. Two standard tests are normally used to determine this property (1) The *Load impact test* and (2) The *Charpy test*. Details of these tests will be described later in this chapter.

5.16 FATIGUE

This property of a material decides its behaviour under a particular type of loading, in which a much smaller load than the one required for material failure in a single application is repeatedly applied innumerous times. Thus, the material is subjected to repetitive cycles, in very large number, of *fluctuating stress*. Under such conditions the material fails at a much lower stress than the one required for its failure through fracture under a single application of steady loads. This phenomenon of material failure, under the condition described above, is known as **Fatigue**. The stress at which the material fails due to fatigue is known as **Fatigue Strength**. The fatigue failure always shows a brittle fracture with no appreciable deformation of the material at the fracture. It is also reckoned that in almost all metals there is a well defined value of stress below which the material will not fail due to fatigue even if there is a repeated application of load in the above manner. This value of stress, which is much below the normal yield stress, is known as the **Fatigue Limit** or **Endurance Limit** of the material.

The phenomenon of *fatigue failure* is very important from the point of view of design and manufacture of various components which are supposed to be subjected to repeated or cyclic loading continuously. Some examples of such components are rotating machine parts, motor shafts, gears, components of high speed turbines and aero engines, aircraft

wings, etc. The factors which generally govern the *fatigue strength* of a material are its chemical composition, extent of cold working and grain size. For more metallurgical details about fatigue the readers are advised to refer back to chapter 4.

5.17 CREEP

The property of material due to which it is progressively deformed, at a slow rate with time, at a constant stress is called **Creep.** A large number of components in different engineering applications, such as pressure vessels in high temperature chemical processes, aircrafts, steam and gas turbines, power plants, furnaces, etc., are subjected to constant stresses for long periods. Under such conditions the material undergoes slow deformation over a long period of time, rendering it unserviceable. If this deformation is allowed to continue even after that, it may result in total failure of the structure. It is due to **Creep.**

Most metals show creep at elevated temperatures. *Creep* in materials occurs in three stages, known as *primary, secondary and tertiary*. **Creep strength** is the term used to denote the stress for a definite rate of strain at a constant temperature. For more details about the phenomenon of creep the readers should refer back to chapter 4.

5.18 MACHINABILITY, FORMABILITY AND WELDABILITY

These three terms, instead of being truly the properties of materials, are actually indicative of the response of materials to specific methods of metal processing. For example, the ease with which a material can be cut to provide it the desired shape and size indicates its degree of **Machinability,** which is expressed as a percentage. This percentage, called **Machinability Index** is determined by comparing the metal under consideration with *free cutting steel* of which the machinability rating is assumed to be 100 percent. However, this is not the only aspect that effects the suitability of a material. Several other properties of the material are to be considered to decide upon its suitability, because the type of machining operation, required degree of surface finish, desired tool life, etc., call for specific properties in the material to be machined.

Similarly, **Formability** indicates the response and suitability of the material for plastic deformation processes. Materials, however, behave in different manner at different temperatures and also respond differently to different deforming processes. Some materials may exhibit very good *formability* at high temperature but show a very poor response if deformed at room temperature. Some materials, may readily flow when deformed at slow speed but they will break, as if they are brittle

materials, if higher deformation speeds are employed. So, while deciding the overall *formability* of a material all these aspects should be taken into consideration.

The term **Weldability** of a material indicates its ability to respond to the welding process under given fabrication conditions in order to enable successful fabrication of a well designed structure which, in turn, should successfully render the intended service when put to use.

5.19 TESTING OF METALS

Many types of mechanical tests are conducted on metal specimens in order to ascertain their different mechanical properties and, thus, their suitabilities for specific uses. The data obtained from these tests is of direct use for the design engineers in order to decide as to whether a particular material conforms to the required specifications or not. This helps in the selection of a suitable material for a specific use and also its soundness. All the test procedures have been standardised. The prominent Indian institutions involved in standardising the test procedures, developing standard specifications for materials and standard definitions of the related terms are the **Bureau of Indian Standards (formerly I.S.I.)**, **National Physical Laboratory (NPL)** and the **National Test House (NTH)**. All the mechanical tests can be grouped into two main categories :

1. **Destructive tests.** *Which include Tensile Test, Compression Test, Hardness Tests, Impact Test, Fatigue Test, Creep Test, etc.*
2. **Non-destructive tests.** *Which include Visual examinations, Radiographic test, Ultrasonic test, Penetrating-liquid test, Magnetic particle or Magnetic dust tests, etc.*

These test procedures will now be described in detail in the following articles.

5.20 THE TENSILE TEST

It is a very commonly used test, performed to determine different tensile properties, viz., ultimate tensile strength, yield strength, elastic limit, proportional limit, breaking strength, % elongation, % reduction in area, modulus of elasticity, etc. This test can be performed either on an exclusive **Tensile Testing Machine** or on a **Universal Testing Machine**. The latter type of machine is more commonly preferred because, apart from tensile test , many other types of tests, like compression test, shear test , bending test, etc., can also be performed on this machine, whereas the former type is a single purpose machine. These days **Electronic Universal Testing Machines** with **Microprocessors** are also available in the country. These machines carry high loading efficiency of the order of ± 1% and incorporate digital

readouts, effective safety devices, simple controls, a plotter or printer to draw the graph as the test proceeds, load stabiliser, etc., together with the usual features of the conventional type machines. All these machines carry different replaceable accessories and attachments to enable conductance of different tests on the same machine.

Described below is the procedure for performing *Tensile Test* on mild steel test specimen. The test specimen is made into the shape of a stepped circular bar by machining, or else it may be flat. When circular, it may carry either plain ends (shoulders) or threaded ends. A test specimen with plain ends is shown in Fig. 5.2. with all the essential features indicated on it.

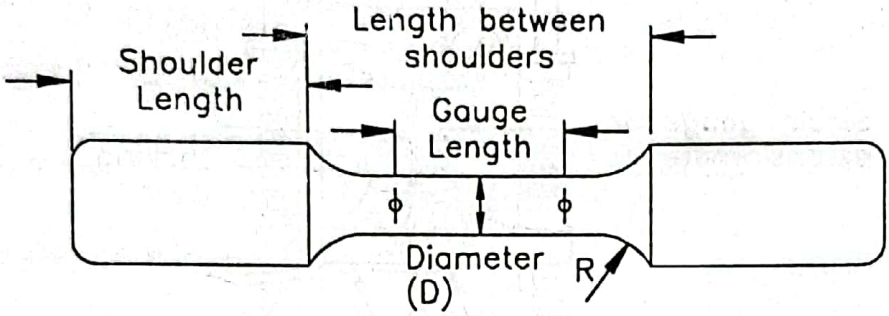

Fig. 5.2. Main parameters of tensile test specimen with plain ends.

An important point to be borne in mind here is that the shape and size of the test specimen do influence the values of the mechanical properties determined through the test. It is, therefore, necessary to use a standard specimen instead of using an arbitrarily shaped and dimensioned test piece. For this purpose many standards are in use, viz., ASTM in U.S.A., B.S. : 18 : 1962 in U.K. and so on. Bureau of Indian Standards (I.S.I.), New Delhi, has also standardised (IS : 210 – 1978) the essential dimensions of tensile test pieces, as shown in Fig. 5.3 and such test pieces are highly recommended for use in our country.

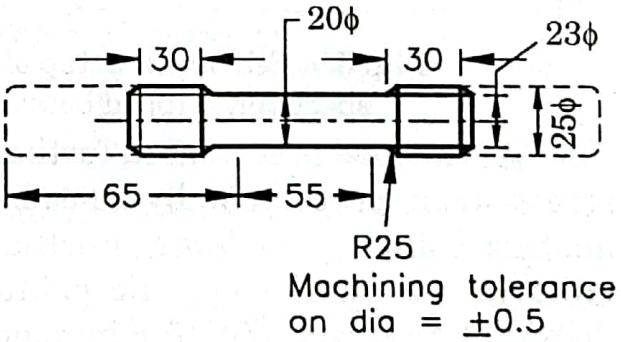

Fig. 5.3. Dimensions of test bars (machined) for tensile tests.

For performing the test, one end of the specimen is gripped in the *upper cross-head* of the machine, which is a fixed head. The other end of the specimen is gripped in the *Adjustable (movable) cross-head*. This set-up is schematically shown in Fig. 5.4. Tensile load is gradually applied to the specimen by means of the loading unit of the machine. In all

modern machines a *hydraulic drive* is used to move the adjustable crosshead downwards to apply the desired tensile load on the test piece. A separate load measuring unit incorporated in the machine shows the magnitude of the applied load. A *Strain gauge* or an *Extensiometer* is attached to the test piece to show the elongation. With increase in load there is a corresponding increase in the length between the two extremities of the gauge length, *i.e.*, there is elongation in the length of test piece. It is, therefore, clear that elongation is obtained as a function of load.

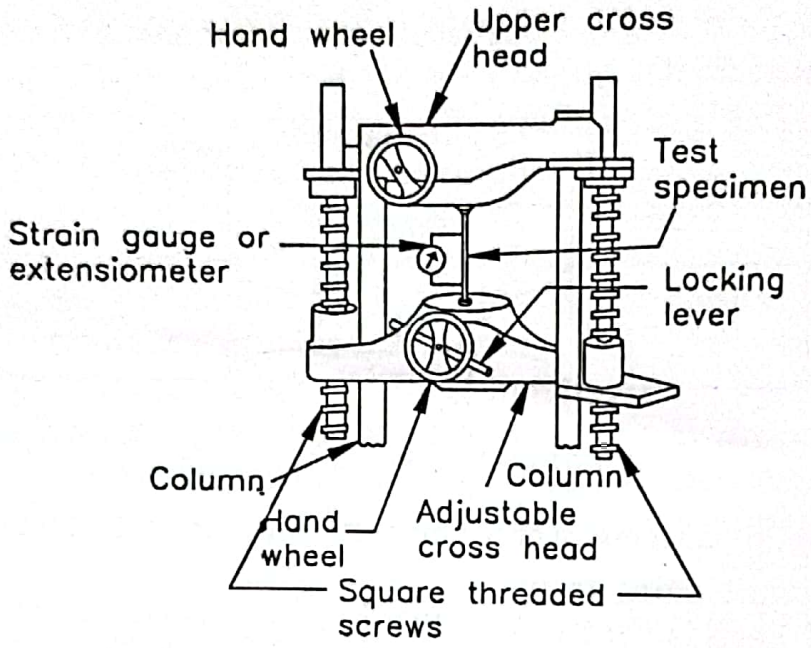

Fig. 5.4. Schematic setup of a U.T.M., showing the test specimen gripped between the two cross heads.

As the load is increased further, a point is arrived after which the stress-strain proportionally is lost but elastic elongation continues upto another point (*elastic limit*). Further loading of the test piece leads the material to another specific point (*yield point*) from where plastic deformation starts. With further addition of load the point of maximum stress (*ultimate stress*) is reached. Here from the test piece starts developing the *neck*. Further deformation of the metal is concentrated on this neck and its area goes on reducing till such time when the specimen breaks. The stress at this point is the **Breaking Stress.**

The two broken portions of the test piece are then joined together, as shown in Fig. 5.5, and the distance between gauge marks and the smallest diameter in the neck found out. The different tensile properties are then calculated from the following relations :

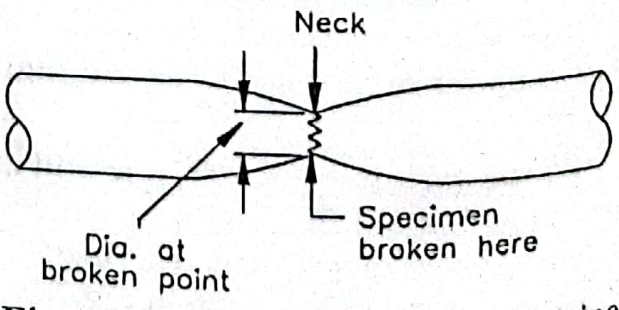

Fig. 5.5. Broken pieces of specimen joined together for final measurements.

Elastic Limit

$$= \frac{\text{Maximum load within the elastic limit}}{\text{Original area of specimen}}$$

Yield Strength

$$= \frac{\text{Load at the yield point}}{\text{Original area of the specimen}}$$

Ultimate Tensile Strength

$$= \frac{\text{Ultimate load}}{\text{Original area of the specimen}}$$

Young's Modulus Of Elasticity

$$(E) = \frac{\text{Stress at a given point within elastic limit}}{\text{Strain at that particular point}}$$

Percentage Elongation

$$= \frac{\text{Final gauge length} - \text{Original gauge length}}{\text{Original gauge length}} \times 100$$

Percentage Reduction In Area

$$= \frac{\text{Original area of specimen} - \text{Final area at broken point}}{\text{Original area of specimen}} \times 100$$

Breaking Strength

$$= \frac{\text{Breaking load}}{\text{Original area of sepcimen}}$$

5.21 COMPRESSION TEST

This test is not very commonly needed for testing metals, of course except some brittle metals, like cast iron, which cannot be subjected to tensile test for testing their strength. The common materials tested in compression include ceramics, mortar, bricks, concrete, etc.

In respect of the direction of application of the axial load it is just reverse of the tensile test. In *Tensile Test* the applied loads tend to pull the specimen apart while in *Compression Test* the applied loads tend to squeeze the test piece between them. The test specimens are normally made as right circular cylinders or prisms with their end faces flat and parallel to each other.

While the tensile test piece is held between the two crossheads on a *Universal Testing Machine* the specimen for compression test is held between the lower crosshead and the table provided on the machine, as

shown in Fig. 5.6. Two **Grip Plates** or **Compression Plates** are provided with the machine for this purpose. One of these is attached to the bottom of the *lower crosshead* and the other to the top surface of the *Table*. After the specimen is correctly placed and firmly gripped the **Strainometer** or **Compressometer**, a *Strain Gauge* specially designed to measure compressive strain, is attached to it. Thereafter, the procedure for conducting the *Compression Test* is similar to that used for conducting the tensile test. Loads are applied at regular intervals and the strain produced is measured. With recorded data a *stress-strain curve* is drawn and various strength values calculated.

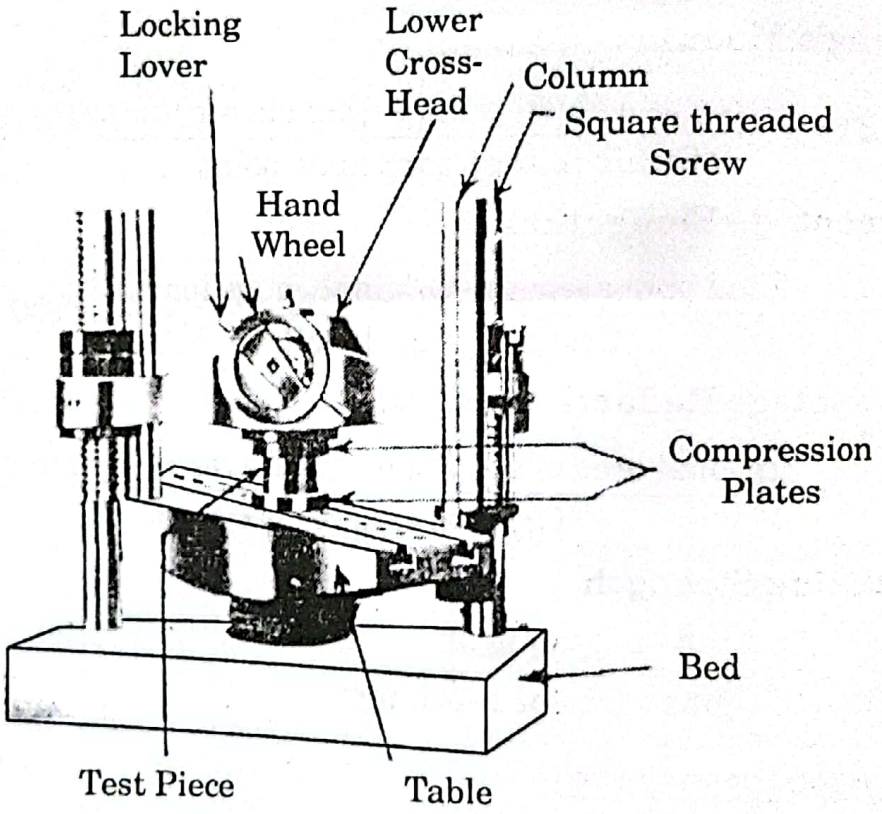

Fig. 5.6. Setup for a compression test on a Universal Testing Machine.

5.22 HARDNESS TESTING

As explained earlier, the hardness of a metal surface is the direct outcome of the interatomic forces working on the metal surface. This is not a basic property of a material but a relative one. However, the most significant aspect of this property is that it appears to have a more or less constant relationship with the tensile strength of the material. Other favourable features with this property are that its testing is simple, quick and of non-destructive nature.

A large number of tests for evaluating hardness of materials have been developed on the basis of material resistance to permanent indentation under static or dynamic loading, resistance to wear,

resistance to scratching, absorption of energy under impact loading, resistance to cutting, etc. However, the most common hardness tests are :

1. Brinell hardness test
2. Rockwell hardness test
3. Vickers hardness test.

These three tests, together with a couple of others in brief, will now be described in the following articles.

5.23 BRINELL HARDNESS TEST

Several different designs of **Brinell Hardness Testing Machines** have been developed, ranging from conventional to those having **Electronic Digital Readouts**. The simplest designs have a manual loading and unloading system while the advanced designs carry a *hydraulic power pack* and *control circuit* for loading and unloading. Some carry only a **Dial Gauge** in front to read the **Ball Penetration** while the more sophisticated designs carry an *Electronic Digital Readout*, on which not only the relevant test data are displayed but also the **Brinell Hardness Number**. All these machines carry a number of accessories with them to facilitate easy and proper testing.

Well, whatever be the design, loading system, reading system and other features of the machine being used, the basic principle of this test is common to all. It involves a prism type test block of the metal being tested, placing the test sample on the table and raising the table to such a position that the top surface of the specimen will just touch the ball. The ball under reference is a *Hardened Steel Ball* (usually of 10 mm ± 0.01 mm diameter). Once that position is reached, the ball is pressed into the surface of the specimen by gradually applying the load either mechanically or hydraulically, depending upon the type of machine. The load is maintained there for about 10 to 15 seconds and then withdrawn. In the meanwhile, the *spherical ball* has made an impression or indentation on the test piece. The diameter of the impression made is measured and the

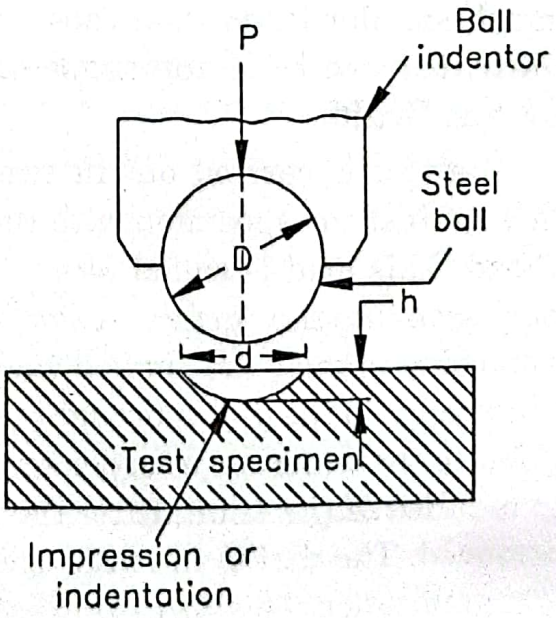

Fig. 5.7. Important parameters of a Brinell hardness test.

Brinell Hardness Number (BHN), which is indicative of the relative hardness of the material being tested, calculated from the following relation (refer to Fig. 5.7).

$$BHN = \frac{\text{Load on ball (in kg)}}{\text{Area of the ball impression (in mm}^2\text{)}}$$

$$= \frac{2P}{\pi D\,(D - \sqrt{(D^2 - d^2)})}$$

where, P = Applied load in kg.

D = Diameter of the spherical ball in mm

d = Diameter of the impression in mm.

The load applied varies from 500 kg to 3000 kg according to the material being tested. The lower values of the load are used in the testing of softer metals and alloys, like brass, while higher values are used for testing of harder materials like steel, steel alloys and cast iron. The magnitude of the **BHN** is indicative of the relative hardness of the material. The *higher* this number the *harder* is the material.

5.24 ROCKWELL HARDNESS TEST

It is a very widely used test because of its speed and also because it is free from personal errors. The **Rockwell Hardness** is determined through an indentation made under a static load and in this sense it is similar to *Brinell Hardness test*. But, it differs from the latter in that it employs the use of much smaller *indentors* (*penetrators*) and application of much smaller loads than those used in Brinell Hardness test. The **Penetrator** can be in the shape of a small ball or a *Diamond Cone*, known as **Brale**.

The test is carried out in two stages. First, the indentor is set firmly against the specimen with the application of a small enough (10 kg) load. This load is called *Minor Load*. This results in a very small penetration into the surface. A *Dial Indicator* is provided on the front of the machine to show the applied load. After the initial small penetration the indicator on the dial is brought to 'zero' reading and a heavier load is applied to the indentor in order to produce a deeper indentation. This load is called *Major Load*. After the indentation is made the major load is removed. The dial then reads 'zero', implying that the minor load is still in application. The *Hardness Test Gauge* then indicates the **Rockwell Hardness Number**, which corresponds to the depth of *permanent penetration* made by the indentor due to the major load.

Fig. 5.8 illustrates the principle of **Rockwell Testing.** The two positions of the indentor shown in dotted represent the position attained by the indentor after the applications of *minor load* and *major load*. The increment (t) in the depth of indentation is a linear measurement and is used as the basis of determining **Rockwell Hardness Number (R).**

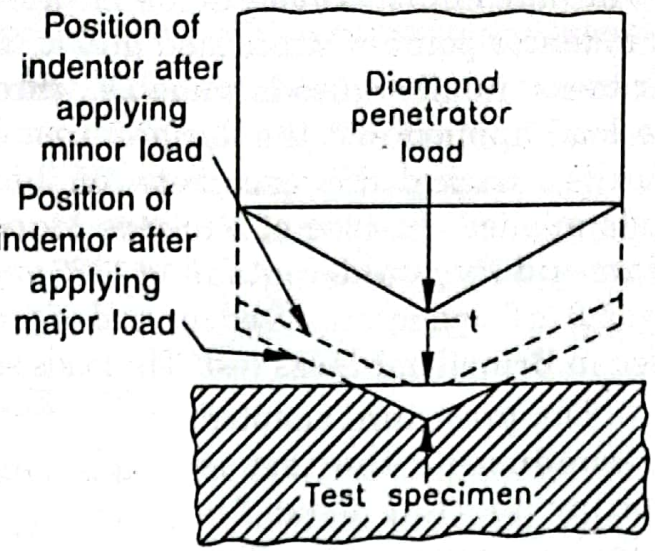

Fig. 5.8. Principle of Rockwell testing.

Mathematically :

$$R = 100 - 500\,t$$

However, no such, calculations are required to be made. The *gauge* fitted on the machine is caliberated to give different values of 'R' corresponding to different values of 't', from where the hardness values can be directly read. Several scales A, B, C, D etc. are provided and each of these scales suits a particular class of material. A *chart* is usually provided with the machines, with the help of which a suitable combination of major load and type of indentor can be selected to suit a material carrying a particular degree of hardness. Out of the many scales available scales ***B*** and ***C*** are most commonly used since they cover most of the commonly used metals, as shown in the table below :

Table 5.1. Use of Rockwell scales

Scale	*Major load*	*Indentor*	*Suited for Rockwell testing of*
A	60	Brale	Hard surfaces like those of case hardened steel,
B	100	Ball	Aluminium, copper, brass, malleable cast iron and grey cast iron.
C	150	Brale	Hardened steel, white cast iron, etc.

Other scales from D onwards are meant for relatively softer and annealed materials. Also, with the help of conversion tables it is possible to convert **Rockwell Hardness Number** into **Brinell Hardness Number (BHN).**

5.25 VICKERS HARDNESS TEST

The test is similar to *Brinell Hardness Test* in the sense that here also an *indentation* is made in the surface of the test specimen by pressing an indentor point at static load into it. The method of determining the hardness number also is same *i.e.*, through the relationship between the load applied and the surface area of the penetration made. But there is a marked difference, between the indentors used and the smaller loads applied. In case of **Vickers Hardness Test** a **Square-Based Diamond Pyramid,** containing 136° angle between opposite faces [see Fig. 5.9 (*a*)], indentor is used instead of the ball type or cone type indentor used in Brinell hardness test. The loads employed vary from 5 kg to 120 kg.

The procedure adopted for conducting the test is similar to that used for Brinell hardness test. The impression made by the indentor on the surface of specimen is as shown in Fig. 5.9 (*b*). The magnitude of the load to be applied depends upon the thickness and hardness of the material. The main advantage of this method over Brinell method lies in the shape of the indentor used which assures a higher accuracy. It is because the diagonals of a square can be measured more accurately than the diameter of a circle. Therefore, the results obtained are more accurate. Another advantage of this method is that plastic deformation is caused even by lighter loads. After indenting, the measurements can be taken and the **Vickers Hardness Number (VHN)** or **Diamond Pyramid Hardness Number (DPN)** can be calculated from the following relationship :

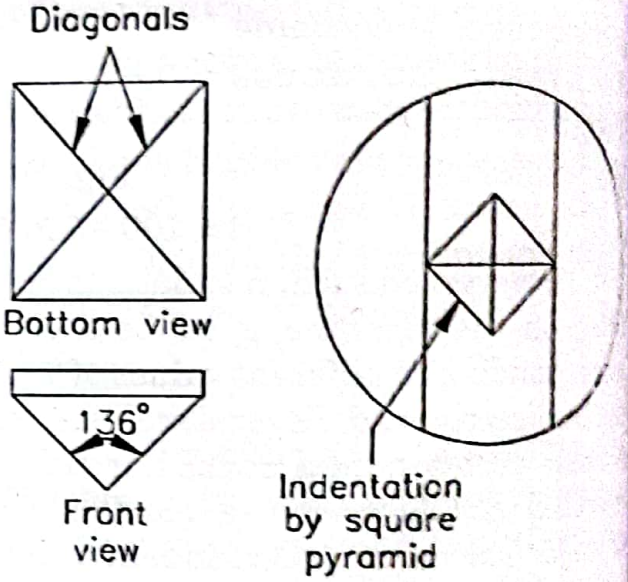

Fig. 5.9. Details of square pyramid and indentation produced during Vickers hardness test.

$$\text{VHN} = \text{DPN} = \frac{\text{Load}}{\text{Area of the impression}}$$

$$= \frac{P}{d^2/2 \sin \theta/2} = \frac{2P \sin \theta/2}{d^2}$$

or

$$= 1.8544 \frac{P}{d^2}$$

where, P = Applied load in kg

d = Average diagonal length in mm

θ = Contained angle between opposite faces = 136°.

In practice, however, the **VHN** can be directly obtained from a standard table against the measured value of the length of diagonal (d). The unit of both **VHN** and **BHN** is same, *i.e.*, kg/mm², and the two hardness numbers are also practically the same upto 400. At hardnesses above this, the VHN is greater than BHN. This method is widely favoured for determining the hardnesses of very thin and hard metals and alloys.

5.26 MICROHARDNESS TESTING

Microhardness Tests are conducted when the requirement is to determine hardness over a very small area of the material. The testing machine most commonly used in this process is known as **Tukon Tester.** The spot, where the test is to be conducted, is carefully selected under high magnification. A special type of indentor, called the **Knoop Indentor** (Fig. 5.10), is used in this test. It is a diamond indentor ground to pyramid shape such that the two diagonals of its cross-section are unequal, as shown in the Fig. The ratio of their length is approximately 1 : 7.

The loads applied in the test are of very small magnitude, ranging from 25 gram to 3600 grams. To obtain correct results it is necessary that the test specimen should possess a perfectly polished surface. For testing the hardness, the indentor is pressed into the surface of the specimen by applying a predetermined load. The hardness number, called the **Knoop Hardness Number,** is then calculated by dividing the load by the projected area of the indentation. This test is also known as **Knoop Hardness Test** after the name of the indenter used.

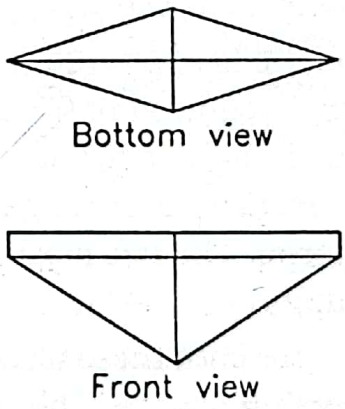

Fig. 5.10. Diamond Knoop indentor used in Knoop hardness test.

5.27 OTHER HARDNESS TESTS

Scratch test. It is a test which determines the ability of a material to resist scratching by other materials having different hardness levels. The test involves filing of the material by different files, possessing different known hardnesses, and observing which file is able to scratch it and which file fails to do so. This indicates the relative hardness level of the material. Although crude, it is quite a useful method for common shop floor purposes.

A more accurate and quantitative method is to measure the hardness on **Mohs Scale**. This scale, devised by a German Scientist Friendrich Mohs, carries 10 numbers (1 to 10), each corresponding to the ability of a particular material for being scratched. Diamond, the hardest material is given No. 10 and Talc No. 1, which happens to be the softest material on the scale. This, however, is not popularly used in engineering practice because of its failure to precisely quantify the hardness of each material.

Rebound test. It is also known as **Scleroscope Test**. The testing equipment used in this test is known as **Shore-Scleroscope**. In this test, a small diamond tipped hammer, normally weighing 1/120 *oz*, is dropped on to the surface of the material from a height of 250 mm. The hammer is enclosed in a glass tube which carries graduations. When the hammer falls on the surface of the material from a height it rebounds and the height of this rebound is noted with the help of the graduations on the glass tube. The relative hardness of the material is measured in terms of the height of the rebound.

5.28 IMPACT TESTS

The **Impact Tests** are performed to determine the resistance to fracture of a material under *impact loading, i.e.*, under suddenly applied dynamic loads. An *Impact Test* measures the *Fracture Energy, i.e.*, the energy required to fracture a standard notched specimen by an impact load. It is measured in kg-m on a scale provided on the machine. The measured energy is indicative of the relative **Toughness** of the material. The two most commonly performed impact tests are **Izod** and **Charpy**.

For both these tests a standard **Pendulum Type Impact Testing Machine** is used. This machine, along with all its parts and controls is shown in Fig. 5.11. Before conducting the tests standard test specimens are prepared. The test specimen is held in the *Specimen Support*, provided on the column, and struck by a load, attached to the *pendulum brake*, suddenly by releasing the pendulum from its stationary position. The striking load provides a heavy impact on the specimen and breaks it in a single blow. The pendulum, after breaking the specimen, continues to swing in the same direction and the ultimate height attained by it at the end of the swing is measured. With the help of this data the energy consumed in breaking the specimen can be calculated. This can also be directly read on the scale provided on the machine.

The pointer on the machine scale, which also moves as the pendulum swings, at the end of the swing not only indicates the energy consumed during the test but also shows the energy remaining unspent.

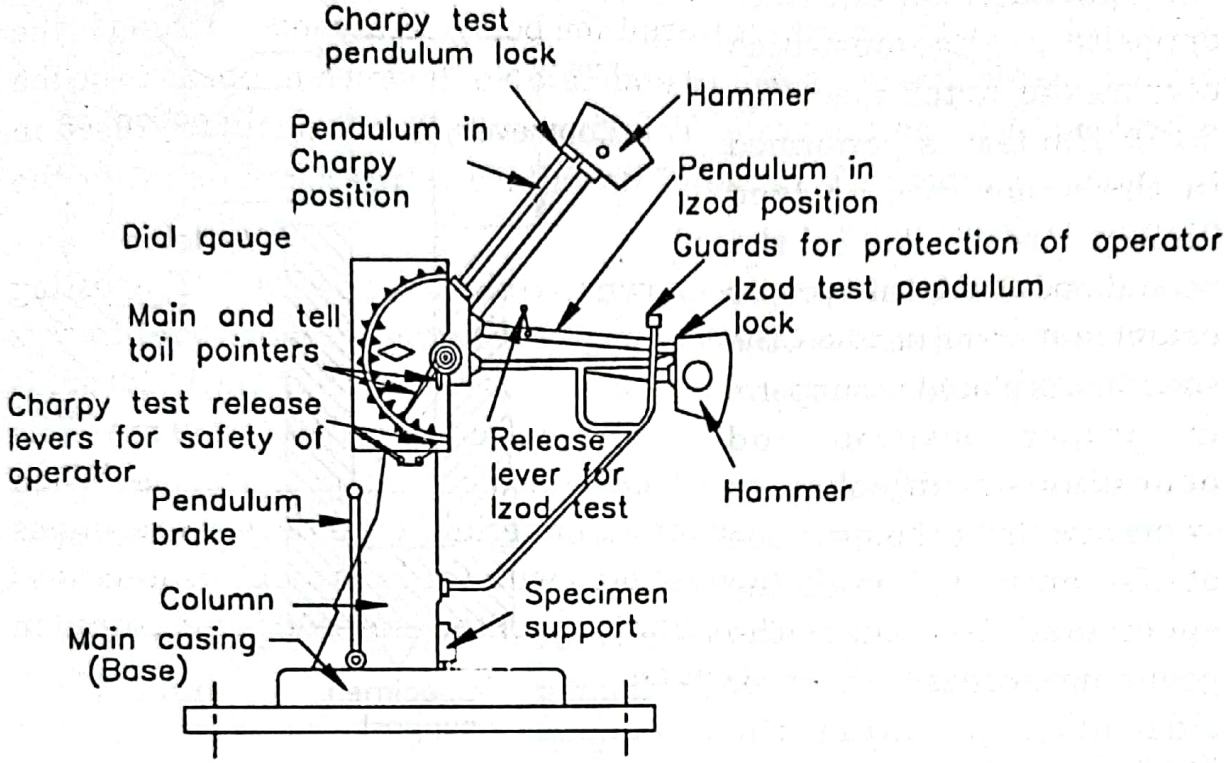

Fig. 5.11. A pendulum type Impact heating machine.

The test specimen used for **Izod Impact Test** is held in the support in a cantilever position, as shown in Fig. 5.13. Dimensions of the specimen are shown in Fig. 5.12. For breaking the specimen during the test the **Swinging Load** strikes it near its upper end, as shown in the diagram.

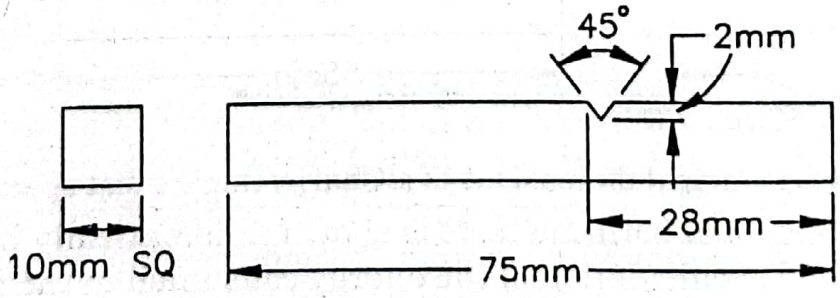

Fig. 5.12. Standard dimensions of an Izod impact test specimen.

The **Charpy Impact** test is another very commonly used test. Its test specimen is similar to the one used in *Izod test* but is shorter in length and the position of '*V*' notch is in centre. A Charpy *test specimen* with its principal dimension is shown in Fig. 5.14. For conducting the test, the specimen is held in the supports as a *simply supported beam.*

The position of the *V*-notch is kept in such a way that the pendulum hammer will strike the specimen on the face opposite to the one which carries the notch (see Fig. 5.15). The test is performed in the same way as Izod impact test, *i.e.*, the pendulum is locked at a proper height in starting position, the specimen is placed in supports in proper position and pendulum is unlocked to swing and strike the specimen at its centre to break the specimen. As usual, the pendulum swings to the other side after breaking the specimen and its final height at the end of the swing is noted.

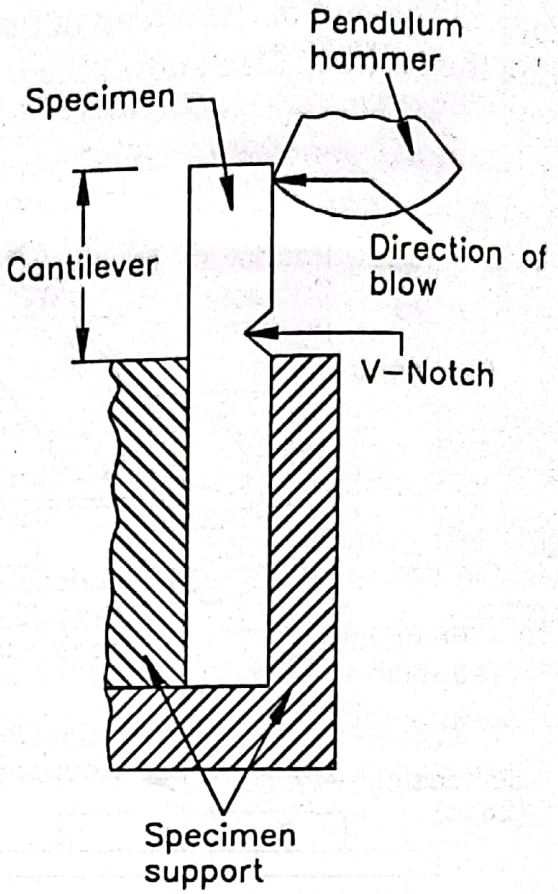

Fig. 51.3. The test specimen held in cantilever position for Izod impact test.

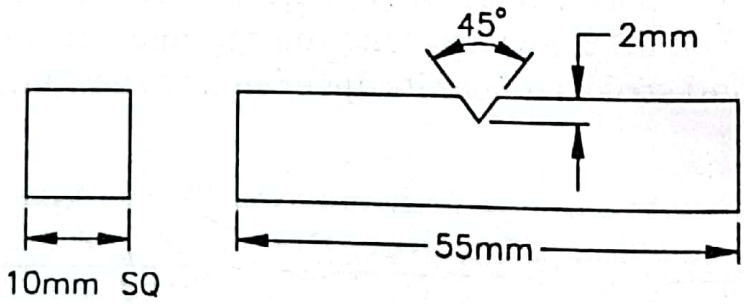

Fig. 5.14. Principal dimensions of a Charpy impact test specimen.

The principle of both the tests is shown schematically in Fig. 5.16 and the method of calculation of the energy consumed in the fracture of the test specimen in either test is as follows :

Initial energy of pendulum = Potential energy at height H

Weight = WH

= Kinetic energy for striking the specimen

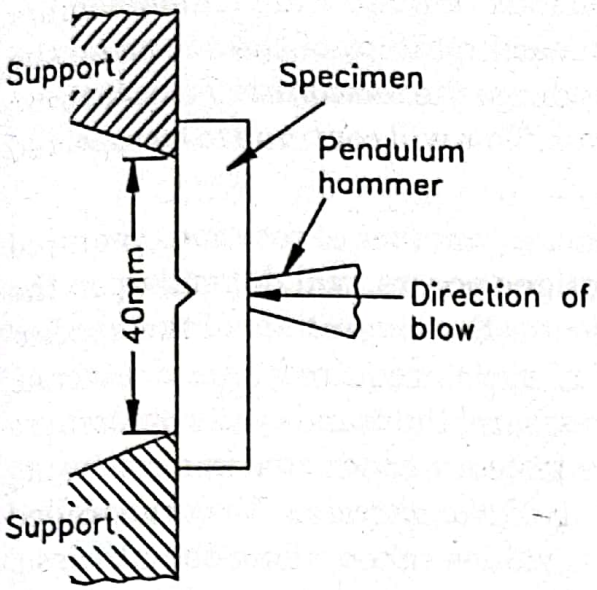

Fig. 15. Charpy test specimen held in supports in proper position for test

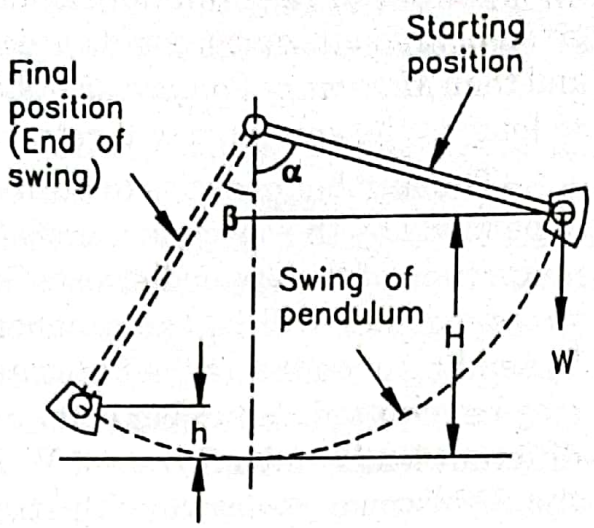

Fig. 5.16. Schematic diagram showing the principle of Izod and Charpy impact tests.

Remaining energy after fracture = Kinetic energy spent in carrying the pendulum weight to a vertical height 'h' after fracture

$= Wh$

$\therefore$ Energy consumed = Initial energy – remaining energy after fracture, in fracture of specimen

$= WH - Wh$

$= W(H - h)$.

5.29 FATIGUE TESTING

Components which have to withstand static loads can be easily designed on the basis of the **yield strengths** of the materials of which these components are to be made. But there are situations in which a component has to withstand cyclic loading, *i.e.*, repeated application of loads. For designing components for such situation, it is necessary to know the behaviour of the component material under dynamic loading, *i.e.*, its fatigue properties including the **Fatigue Strength** or **Endurance Limit**, which are used in the design of such components.

Several different designs of fatigue testing machines are available. The criteria used for classifying these machines are the type and method of application of load. Laboratory tests are usually carried out on a **Constant Load Machine**. The test specimen used looks like the one used in tensile testing. It is loaded in the machine with its both ends being supported. It is loaded at two points just like a simple beam subjected to pure bending. When it is rotated, each point on its

circumference will alternate between maximum tension and maximum compression in each rotation, *i.e.*, in each rotation of the specimen the given point on its surface will once undergo the *Maximum Tensile stress* and then *Maximum Compressive Stress*. This will continue to be repeated so long as the specimen will rotate.

The number of cycles to be used, *i.e.*, number of rotations required to be made by the specimen, until fatigue occurs, will depend upon the magnitude of the applied stress. Greater the *magnitude* of the *applied stress*, smaller will be the number of cycles required and vice versa. Depending upon the amount of stress several thousand cycles per minute may be required. A number of failure tests are conducted in a row using different loads and a *Stress* (*s*) Vs *Log* of *No. of cycles* (*N*) curve, called the ***SN* Curve**, is drawn with stress values taken along the abscissa. The value of stress, below which failure of material will not occur, is known as *Endurance Limit*.

Figures 5.17 and 5.18 below show the *fatigue curves* drawn for two different metals—mild steel and aluminium. It will be observed that the ***S-N* Curve** for mild steel shows a distinct *fatigue limit* or *endurance limit* while that for aluminium does not. This characteristic is found common with most metals in two distinct categories *i.e.*, the *S-N* curves for most *ferrous metals* will show distinct *endurance limit* while those for *non-ferrous* will not.

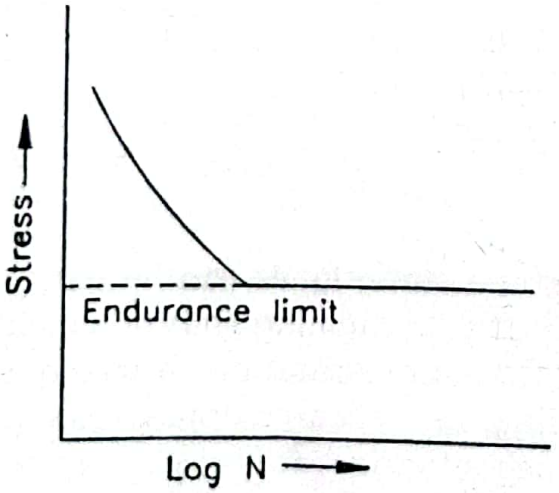

Fig. 5.17. Fatigue (S–N) curve for mild steel

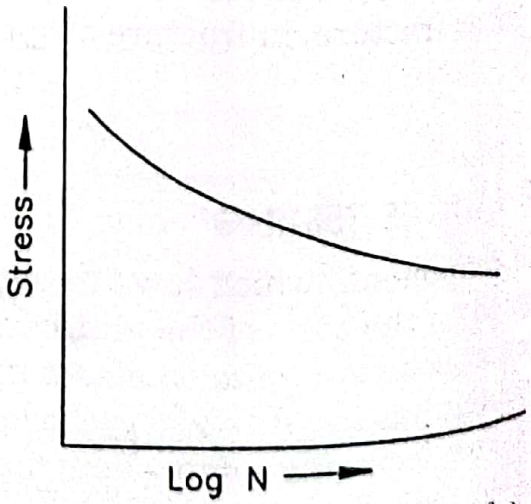

Fig. 5.18. S–N curve for Aluminium.

5.30 CREEP TEST

As already explained in Art. 5.16, and also in Chapter 4, materials (specially metals) under specific service conditions are subjected to steady loads under varying conditions of temperature and pressure for a very long period of time. In such situations, the material continues to deform

slowly until it loses its usefulness. With time, this deformation may grow to such alarming dimensions that it may lead to fracture of the component without any increase in load. This phenomenon is called **Creep.**

Although elongation in metals does not take place at low temperatures it is more pronounced at high temperatures and occurs more rapidly and, therefore, acquires a high significance in that range. A **Creep curve** is obtained by drawing a plot between *percent elongation* (or *percent strain*) and *time* at constant temperature and constant *true stress*. For this, a constant load is applied to a tensile test specimen, maintaining a constant temperature, and the elongation in the specimen, determined as a function of time. A plot is then made from the data obtained and the curve drawn. A typical **Creep Curve** drawn from the data obtained from a *Creep Test* is shown in Fig. 5.19, which clearly indicates the different stages of creep.

As soon as the load is applied, there is an *instantaneous strain* created in the metal. During *primary creep* stage, work hardening takes place due to deformation and the *creep rate* is found to be decreasing. During *secondary creep* stage, the *creep rate* is steady and deformation takes place at almost constant rate. The last stage or **Tertiary Creep Stage** is attained if the applied stress and temperature both are substantially high. This results in an accelerated rate of creep and finally the metal fails.

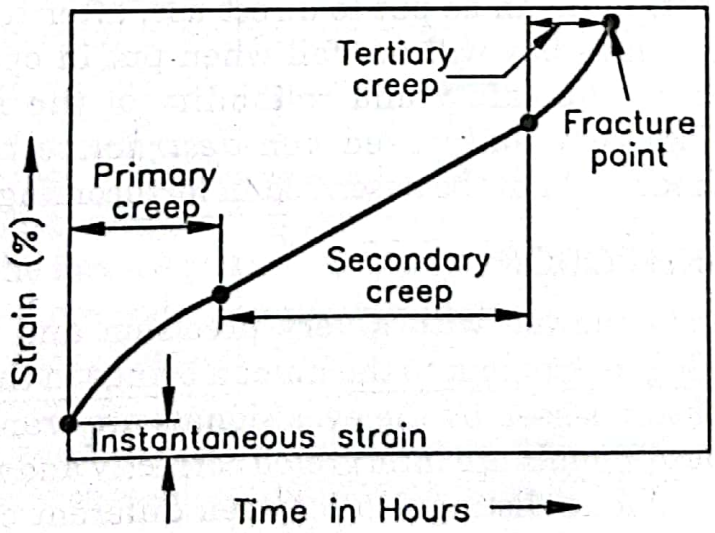

Fig. 5.19. A typical creep curve showing different stages of creep.

In brief, it is commonly noticed that steels with coarse grains are more creep resistant than those with fine grains at elevated temperatures. It is also reckoned that addition of alloying elements like nickel, manganese, tungsten, vanadium, chromium, molybdenum, etc. helps in reducing the creep rate in steels.

Stress-rupture curves. These curves are of great significance for design engineers while designing components for high temperature applications. These curves, called *stress-rupture curves*, are drawn with the help of the data obtained from *stress-rupture tests*. These tests are simply extensions of the creep tests, wherein a test specimen is subjected to a definite applied load at a constant temperature until its failure. A number of such tests under different applied loads and different temperatures are conducted and the rupture-time data collected is plotted to draw a number of *curves* on a single diagram.

5.31 NON-DESTRUCTIVE INSPECTION AND TESTING

It is true that a lot of precautions are taken while designing a product, selecting proper material, its fabrication, heat treatment, etc., and all this is done with a view that a *quality product* is manufactured at a reasonable cost, which will meet the service conditions without failure. However, always there are chances that the product, although apparently looking sound and appealing, may carry some invisible internal defects or flaws which may lead to its failure when put to use. As such, it is necessary to test the product to ensure that it is free of such defects and flaws.

Non-Destructive Testing Methods are used for this purpose. As the name suggests, the material or component tested for its internal soundness through *non-destructive* methods is neither broken nor destroyed. In fact, they can be put to direct use, after testing, with an enhanced surety that they will not fail when put in operation. Thus, these tests add to the safety and reliability of the manufactured components. The commonly used *non-destructive testing* and/or *inspection* methods will now be described in forthcoming articles.

5.32 VISUAL INSPECTION

Nature has endowed with a very precision and accurate non-destructive testing instrument to the human beings in the form of eyes. Whenever an object is seen by the eyes signals are transmitted to the brain, where these signals are interpreted correctly and readily. This is how a person is able to distinguish between different colours, shapes sizes, contours, and what not. This important aspect is taken use of in the first inspection of components, called **Visual Inspection**. The method is simple but widely adopted.

For visual inspection of a component its surface is illuminated and then observed with naked eye. If required, optical aids like magnifying glass, mirror or microscope can also be used to help in minute observation

of the surface to detect the flaws. It is a simple, cheap and easy technique and can be used for inspection of any material, any size or shape, where the surface can be accessed. It can, however, be used for detection of *surface defects* only and the quality of result will solely depend upon the *knowledge* and *skill* of the observer.

5.33 RADIOGRAPHY

The **Radiographic Technique** used for *flaw detection* in materials or components is similar in principle to the one used in medical examination of human bodies. The principle involves penetration of an object by a *radiation* due to *X-rays, gamma rays* or *neutron beams* and creating a shadow on a photographic film or fluorescent screen, depending upon the source of radiation used. The extent to which the radiation is absorbed by the film depends upon atomic structure of the material, its density, variations in the thickness and the presence of flaws or defects in the component being tested.

Both **X-rays** and **Gamma-rays** are short wavelength electromagnetic radiations. These rays are capable of penetrating all materials, which reflect or absorb visible light to varying degrees. **X-rays** are produced by high voltage electrical equipment and the wavelength, energy and penetrating power of the rays will depend on this voltage. The higher the voltage the smaller the wavelength and higher the energy and power of penetration. **Gamma-rays** are also short wavelength radiations, produced from radioactive isotopes, usually of cobalt, and have greater penetrating power than X-rays.

For conducting the test, the X-rays or Gamma-rays are directed on to the component which, after passing through the material, strike on to the photographic film or the fluorescent screen to show an image or a picture there. The photographic film can be developed in the usual way to reveal details of the formed picture, which may consists of darker and lighter areas. Since more radiation can pass through less denser areas like cavities, voids, cracks, blowholes, etc., these defects will be indicated by lighter (less darker) portions on the film. The denser part of the component, through which less radiation can pass, will, therefore, appear darker. Inclusions, if any, will appear darker than the material of the component as well.

Since the penetrating power of *Gamma-rays* is more than that of *X-rays* they are more effective in case of thicker sections. Moreover, it is possible to inspect a number of components simultaneously by *Gamma-rays* applications. Another advantage of this technique is that Gamma

rays are not deflected by magnetic fields. Also, in our country, the ratio isotopes are now easily available at cheaper rates. This also makes this method economically more viable. For all these reasons, this method is now gaining more popularity over X-rays. The technique of performing the test is the same as for X-ray inspection but is quicker than the latter. The main limitation, however, of this method is the difficulty encountered and the high level of precautions required in handling of isotopes.

Both the above methods are commonly used for inspection and determination of internal defects in castings, forgings and components produced through mechanical working processes.

The **Neutron Beam Radiography** is a highly sensitive and accurate method but its application for inspection of metals and alloys is dependent on the extent of radioactive decay occurring in unit time. It is advantageously used for detection of inclusions, concentrations and voids, etc., in aerospace equipment, defence items, explosives, polymers, lubricants, etc. The *neutron beams* used in *radiography* can be derived from radio isotopes or nuclear reactors.

5.34 ULTRASONIC TESTING

The technique of using sound as a basis of judging the soundness of an article is an ancient one. An earthen pot is usually tested by tapping it gently and hearing the sound produced. Similarly, one can see people testing metallic articles for their soundness by striking them with a hammer and hearing the sound produced. If the article is free from internal defects a ringing sound will be produced and if it carries flaws it will not ring true but produce a flat sound. This method is, however, confined to the detection of large internal flaws only. For the detection of very small internal defects **Ultrasonic Inspection** is required. *Ultrasonic* means a sound signal of such a small wavelength that it is beyond the hearing range of human ear.

This technique involves sending of very high frequency vibrations into the material being tested, which is reflected partially or fully after striking the flaw or the other surface of the component. The reflected signal is noted and interpreted to get the result. A **Pulse Oscillator** is used in conjunction with a **Transducer** to convert electrical energy into mechanical vibrations. The *Transducer* carries a *Piezoelectric crystal* which changes the electrical oscillations to mechanical vibrations. The transducer is placed on the top surface of the component and the *Ultrasonic Beam* of vibrations sent into the material. Another transducer, called the **Receiving Transducer,** is used to receive the reflected signals which are then amplified, filtered, processed and displayed on an **Oscilloscope**, which are finally interpreted to get the results. The

system also carries an Electronic *Time Recorder*. The time gap between the initial emission of the pulse and recording of reflected echo forms the basis of detection of the defect, which is indicated by the shorter amplitude of the echo on the screen of the oscilloscope. If the time taken by the reflected echo to reach the receiving transducer is the same, as taken by the emitted vibration to reach the other end of the material, both the amplitudes will be equal indicating that there is no flaw. If the amplitude of the echo is shorter, it indicates that it has been reflected from some point (*location of flaw*) within the material and has failed to reach the other surface of the component.

This is a highly sensitive technique through which internal defects, cracks, voids, etc., can be detected in almost all materials, *viz.*, metals, ceramics, graphite, concrete, rubber, glass, plastics, etc. Also, it is possible to detect the flaw to any depth below a surface because of its high penetration. The test is performed very speedily and it needs access to only one side of the component. Together with location, it indicates the size of flaw as well. It is absolutely free of radiation and presents no safety hazards. It can also be used for measuring thickness and detecting flaws in joints or between adjoining surfaces between materials. However, complicated shapes, rough surfaces, and small and thin articles, create difficulties in its application. Similar difficulties are encountered if the structure of the material is not homogeneous.

5.35 LIQUID PENETRANT TEST

It is a simple test for detecting such flaws or defects which extend upto the surface of the material. As a first step the component is cleaned and dried. Then a liquid material, called *penetrant*, is applied to the surface. The penetrant used should be such that it can be easily drawn into the surface discontinuity by capillary action. It can be applied to the work surface by spraying, brushing or dipping. Usually some bright *colouring dye* is added to the penetrant liquid so as to create a colour contrast. As an alternative, a *fluorescent material* can be added instead of a dye. This material will radiate in ultraviolet light to make the penetrant traces more evident.

Some time is allowed after the application of the penetrant so that it is drawn into the flaw through capillary action. The excess penetrant is then wiped off from the surface. Then an absorbent material, called developer, is applied to the surface. This developer absorbs penetrant traces from the flaw and draws them back onto the surface. The colour contrast between the shining traces of the penetrant and the rest of the surface reveals the presence of defect. After the test, the developer and the penetrant are cleaned away.

It is a very simple and cheap method, which can be applied with equal advantage to all metals and non-metals of any size and shape to detect several types of flaws like porosity; cracks developed during forging, grinding, heat treatment ; cracks occurring due to fatigue, shrinkage, bending, etc., and minor leaks, which are generally likely to be present on various components produced through different processes like forging, casting, welding, machining and hot and cold working of metals. However, it is necessary that the material being tested should not be porous.

5.36 MAGNETIC PARTICLE TEST

This test is widely used for **Non-destructive Testing** of *ferro-magnetic materials*, like iron and steel, but cannot be used for non-magnetic materials like non-ferrous metals and alloys as well as austenitic stainless steel which is not a ferro magnetic alloy. The basic principle involved in this test is that if a magnetic field is passed through a perfectly sound (defect free) component the lines of magnetic flux will be uniform. Against this, if the field is passed through a defective component, the lines of flux will get distorted in the area of defect. An important point to be borne in mind is that this test can be effectively used for detection of such invisible flaws only which are either on or extend upto the surface of the component being tested.

The equipment used in this test is known as **Magnaflux.** For conducting the test the component is first magnetised. It is then dipped in a bath carrying kerosene oil and iron oxide powder. Alternatively, dry powder of iron can be spread over the surface of the magnetised article. The powder particles can also be treated with *fluorescent material* so that they can be more clearly observed under ultraviolet light. If the position of the flaw is across the path of the flux lines then each side of the flaw will become a magnetic pole. This, in turn, will attract the iron powder towards it. Thus, there will be a concentration of the iron particles over that part of the surface where the flaw exists. This will reveal the location of the flaw. It should be noted here that all the components which undergo this test will carry some residual magnetisation. All these components should, therefore, be demagnetised before use or their further processing.

5.37 EDDY CURRENT TESTING

Eddy Currents, also called **Surface Currents**, are produced when an electrical conductor is brought near a coil carrying alternating current. It is because the current flowing through the coil produces an *alternating magnetic field*. The *Eddy Currents* are small currents which are produced as above either on or near the surface of the conductor, as shown in

Fig. 5.20. Separate magnetic fields are generated by these eddy currents. These magnetic fields interact with the alternating magnetic fields produced by alternating current flowing through the *coil*. Consequently, the *impedance* of the current carrying coil is changed. The changes affected in the impedance of the coil are measured. The flaws are then detected by identifying and interpreting the differential characteristic changes in impedance.

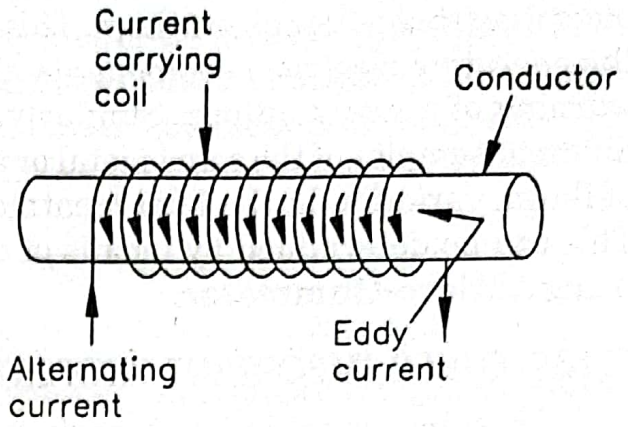

Fig. 5.20. Principle of generation of eddy currents.

The equipment required for conducting the test basically consists of a source of generating eddy currents in the test specimen, a source to sense the changes due to interaction of two types of magnetic fields, a source to detect changes in the impedance, and a source to measure and interpret these changes in the impedance. The method, if required, can be made fully *automatic* with both control and analysis being done by a computer.

This method can be used to detect surface flaws in both ferrous as well as non-ferrous metals. It is a low cost method and prior surface cleaning of the component is not required. However, it can be used only for those materials which are *electric conductors*.

5.38 OTHER TESTING METHODS

A number of other non-destructive testing methods have been developed which, although not very commonly used, can prove very useful under special situations and/or for obtaining specific prior information about the materials and components in use. For example, an **Acoustic Emission Monitoring** technique can be very successfully used to detect the growth of an existing flaw or crack in a structural member under stress or material undergoing deformation. This will help us take corrective measures before a final failure can take place. Similarly, **Holographic Interferometry** can be effectively used to know minute changes taking place in a component under stress.

A **Leak Test** is successfully used to reveal the presence or absence of a leak in an article and also the rate of discharge of the contained material through the leak. A **Strain Sensing** technique can be employed to know the strain and stress distribution in a component by sensing the strains at different locations on the component. Similarly, **Thermal Testing Methods** can be used to determine the soundness of a component

by noting the temperature distribution. If a component is heated, its defective area is found to be hotter than the rest of the component, indicating that a flaw exists there. This test is widely employed for testing the operative electrical components as a means of providing advanced warning of a likely failure. Similarly, variations in the resistivities of different samples of the same metal or alloy are indicative of the presence of flaws, variation in the heat treatment or homogeneity of a weld etc. This can be determined by means of a **Resistivity Test** conducted by using a **Micro-Ohmmeter**.

5.139 OTHER IMPORTANT PROPERTIES OF MATERIALS

In some specific engineering applications several material properties, other than the mechanical properties, can carry more importance. These properties are the following :

Thermal properties. They determine the behaviour of materials under varying temperature conditions in order to evaluate their suitabilities for manufacturing components which are likely to be subjected to either varying temperatures or very high steady temperatures. The properties are :

1. Specific heat
2. Thermal conductivity
3. Coefficient of thermal expansion
4. Melting point.

Electrical properties. These properties determine the ability of a material to allow or resist the flow of electricity through it. The selection of proper material for the manufacture of electrical components is largely governed by these properties. The main properties are :

1. Conductivity
2. Resistivity
3. Dielectric strength
4. Thermoelectric effects
5. Temperature coefficient of resistance.

Magnetic properties. It is important to know the response of different materials to an applied magnetic field in order to assess their suitabilities as commercial magnetic materials and for specific engineering applications. The main magnetic properties of materials are :

1. Permeability
2. Hysteresis
3. Coersive force.

Materials are also sometimes classified as paramagnetic, diamagnetic, ferromagnetic and ferrimagnetic, based upon their magnetic responses.

Chemical properties. These properties indicate the reactions of materials when they come in contact with other substances like water, air, gas, fumes, chemicals, etc., The main chemical properties are :

1. Resistance to corrosion
2. Alkalinity.
3. Acidity
4. Chemical composition.

Other properties. The other properties of engineering importance are :

1. **Technological properties.** The main technological properties are machinability, formability and castability.

2. **Optical properties.** They include absorptivity, reflectivity and refractive index.

3. **Physical properties.** They include density, porosity, structure, etc.

5.40 MATERIAL SELECTION

Selection of a proper material for a product plays a very important role from the point of view of design, processing, economy and the requirements it is expected to meet while in use. The three main considerations in selecting a material for a product are :

1. Property consideration or service requirements. What it means is to consider the various mechanical and other physical properties expected in the material, viz., strength required under operating conditions, type of loadings it is expected to withstand while in use, the mode of likely failure due to overloading if it occurs, expected wear resistance, likely temperatures it has to encounter during service, any electrical or magnetic properties required, chemical and thermal properties requirements, etc. All these considerations will help in selecting a material which will perform the expected functions without failure.

2. Geometrical considerations. That is to consider the shape and size of the product in order to select proper manufacturing methods for making the product. The primary points of consideration are the complexity of shape, uniformity and thicknesses of sections, whether to make it in one or more parts, the degree of precision required in its dimensions, surface characteristics and accuracies, type of finish required on different surfaces, etc.

3. Fabrication considerations. This is another area for consideration which considerably effects the method of fabrication to be used for making the product. The prime considerations are the technological properties like castability, machinability, formability, forgeability, etc. Also to be considered are the number of components required, rate at which they are to be produced, expected requirements of quality control and inspection, mating requirements at assembly, number of the standardised components to be used, expected relative level of quality in comparison to that of similar other products in market

4. Economic considerations. viz., demand prospects, cost considerations, whether a monopoly item or has to compared with other products of the same type, etc.

5. Other important considerations

(*a*) Ease of availability

(*b*) Whether locally produced or available

(*c*) Ease in handling.

5.41 SUGGESTED BIS CODES FOR FURTHER REFERENCE

IS 1408 : 1968, IS 2595 : 1978, IS 2854 : 1964,
IS 1499 : 1977, IS 3766 : 1977, IS 4132 : 1967,
IS 1828 : 1975, IS 4258 : 1982, IS 5069 : 1969,
IS 5242 : 1979, IS 5652 : 1981, IS 6520 : 1972,
IS 6885 : 1973, IS 7096 : 1981, IS 8632 : 1977,
IS 7666 : 1988,
IS 1501 (Pt. 1 and 2) : 1984,IS 1501 (Pt. 3) : 1987, IS 3703 : 1980

TEST QUESTIONS

1. Why it is necessary to know the different properties of materials which are used in engineering ?
2. Define and explain the terms 'Stress' and 'Strain'.
3. Explain the terms : tensile stress, tensile strain, compressive stress, compressive strain, shear stress and shear strain.
4. What is Hooke's law ? Explain the term Poisson's ratio.
5. What is a stress strain curve and why it is important ?
6. Draw a sample stress-strain curve and with its help explain the terms : limit of proportionality, elastic limit, yield point, nominal stress, ultimate stress and breaking strength.
7. Explain the difference between engineering stress and true stress and engineering strain and true strain.

8. What do you understand by the term 'Mechanical properties' of materials ? Why it is necessary to know these properties ? On which factors these properties mainly depend ?
9. What are the main mechanical properties ? Describe each in brief.
10. Differentiate between :
    (*a*) Malleability and ductility
    (*b*) Toughness and stiffness
11. What is resilience ? When is this property is important for a material ?
12. What is the difference between hardness and impact resistance of a material ? Explain the term 'hardenability'.
13. Explain the term 'fatigue'. Also explain the terms 'fatigue strength' and 'fatigue limit' related to fatigue.
14. What do you understand by 'creep' and 'creep strength' ?
15. Explain the terms machinability, formability and weldability.
16. Why are different tests performed to evaluate mechanical properties of materials ? How do you classify these tests ?
17. With the help of suitable diagrams describe the method of 'Tensile testing' of materials. What different tensile properties are determined through this test ?
18. What is a 'compression test' and how is it performed ?
19. With the help of a suitable diagram describe the 'Brinell hardness test'.
20. Explain the process of 'Rockwell hardness testing'. Which Rockwell scales would you use for testing of cemented carbides, aluminium, white cast iron, malleable cast iron and grey cast iron ?
21. What is a 'Vickers hardness test' and how is it performed ? In what ways it is similar to or different from Brinell hardness test ?
22. What is 'Microhardness testing' ? How it is performed using a Knoop indentor ?
23. Briefly describe the 'Scratch test' and 'Rebound test'. What is a Mohs scale ?
24. What is an 'Impact test' ? Describe in detail an Izod Impact Test.
25. What is a 'Charpy Impact Test' ? How it is performed ?
26. Explain the purpose and method of conducting a 'fatigue test'. What is an S–N curve ? Explain.
27. How is a Creep test conducted ? What is a creep curve and what important information does it give ?
28. What do you understand by non-destructive testing ? What for are these tests performed ?
29. Write a short note on 'Visual inspection as a non-destructive test'.
30. Describe the 'Radiography' technique of flaw detection in materials.

31. What is an 'Ultrasonic testing' and how it is used for detection of flaws in materials ?
32. Describe a liquid penetrant test.
33. What is a 'Magnetic particle test' ? How it is performed and what are its limitations ?
34. Explain the principle of 'Eddy current testing'. What are its advantages ?
35. What are the important properties of materials other than the mechanical properties ?
36. What important considerations an engineer is required to make while selecting a material for a product ?