UNIT 1 INTRODUCTION TO MECHANICAL DESIGN

Structure

1.1 INTRODUCTION

Design is a process that ends in creation of something which will satisfy some need of a person, group of persons or society. The homes and buildings in which we reside, the dams which store water for irrigation or generation of electricity, an engine which is used for pumping water or a hoist for lifting loads are the things that are designed before they are made. The design does not pertain to a single device, structure or product or even something which can be seen to exist. The process of design can achieve a system, which can be identified by its physical entity or by service, which is rendered by the system.

The process of design will take into consideration all the factors that are likely to affect the performance of the end system. The constraints in respect of materials to be used, the processes for changing shapes and size, the personnel to be employed, the cost of components and personnel, transportation of final product or establishment of final system, etc. will be brought under consideration in the design process. If the end result is the product then its disposal after it has served its purpose is also to be considered during design.

Mechanical design is one of several design processes, which ends in systems that provide for doing certain mechanical work or creating certain desired motion and often both. Such devices will need enough strength or capacity to bear forces, which result from doing work and creating motion. The possibility of adopting most economic and convenient process of shaping material to build the device or system will always be the priority of design. Keeping the cost low at every step to make end product most economic. Creating such designs will require designer to have some specified knowledge and experience. In this text we will try to generate requisite knowledge. Some experience may be gained through solving problems.

Objectives

After studying this unit, you should be able to

- explain what is design?
- describe the machine and its designer,
- illustrate the procedure of design,
- know materials used in mechanical design, and
- understand the considerations for manufacturing.

1.2 THE PROCEDURE OF DESIGN

The process of design which encompasses design of mechanical systems or machines consists of a few steps to be followed in order. The discrete steps are :

Recognition

The first step is to recognize the need, i.e. what is the need to be fulfilled. All designs require that the need should be properly and fully defined and described. This description may become the statement of the problem.

Synthesis

This step involves identifying all possible solutions and making a list. In case of mechanical design the step may consist in selecting mechanism or group of mechanisms which will result in desired motion or group of motions and transmission of forces.

Analysis

The best solution is chosen based upon knowledge and experience. The chosen solution is analysed to see the effects of all factors. In case of mechanical design in which each element is required to transmit some force and has definite motion will be analysed to determine force to be transmitted and size of element. The motion will also be analysed.

Material Selection

The analysis will be based upon important information of strength of material, which will be used to transmit force. The material is selected upon the basis of strength, and also its ability to undergo process of manufacture.

Calculation

The limits or permissible values of forces or stresses are immediately known if material is selected. The background knowledge of stress analysis or relationship between forces and deformations are used to determine the sizes which could be cross-sectional dimension and length.

Revision and Modification

The availability of material in certain sizes and shapes, and joining of elements for perfect fit has resulted into standardizations. Such standards are available from professional institutions, government organisations and manufactures of standard elements. Therefore, the results of calculations are to be checked against information from the relevant source or sources. The dimension may be modified to suit standard.

Report

After a design process has been completed the outcome may be a system which would satisfy the needs as described in the first step. If the design is mechanical, the sizes of end connection between the elements would have been decided. The materials would be known and the type of manufacturing methods would have been selected. A complete report on the problem has to be prepared. The mechanical designs are best reported by drawings and standard methods for specifying material and special manufacturing process on the drawing are well known practices.

1.3 THE MACHINE AND ITS DESIGNER

A machine is understood to be a device which transmits motion and force in a controlled manner. A machine is made up of several elements in such a way that each element will move in coherence with other and force will be transmitted from element to element. The motion and force at various points will constitute mechanical work or energy. Hence, the prime function of machine can also be regarded as receiving energy at input point and transmit it to some other body at output point. Between the input and output points the form of energy may or may not change. For example, an internal combustion engine is a machine. It receives thermal energy at the top of piston in the cylinder and delivers kinetic energy at the crank shaft. A milling machine or a lathe machine receives mechanical energy and transmits mechanical energy to work piece through removal of material at cutting point.

In fact, in machine designing we divide activity in the separate steps. One in which only motion is considered and analyzed without considering forces that may be the cause of motion. For this step the elements of machines are regarded as rigid or non-deforming. In the second step the elements are regarded as stationary and forces that are transmitted from connecting link or created due to motion are considered to be acting on the element. The element is supposed to be deforming and hence internal resistance called stress is considered for calculating the size of the element. The subject of **Mechanical Design**, **Design of Machine Elements**, **Machine Design** or **Mechanical Engineering Design** often deals with second step. The first step as included in design procedure at steps 2 and 3 is often taken separately which is outside the purview of the subject of Machine Design.

Designing will appear as a decision making process in which the sizes of various elements will be decided. In simpler designs, enough background information and knowledge are available by way of which a particular element may be regarded to be loaded purely axially, as a beam or as a shaft. Some may be under combined loading when all three or two of these load conditions may exist. A designer's capability is tested by the fact that he creates a similarity between a machine element and any of the standard loading conditions. For examples treating a gear tooth, as a cantilever beam can be an example of ingenuity of the designer or regarding belt to be bent like a beam over pulley could be another such example. In the present we will be considering several such examples in which similarity between a machine member and another loaded in a standard fashion (i.e. axially, bending, torsion or combination thereof) will be brought out. And then the standard formulae of the subject of **Strength of Materials** or **Mechanics of Solids** may be used. The designer will have to be sensitive to determination of forces that may arise from any source. For example, a steam turbine is designed thermodynamically for its major purpose of converting thermal energy into mechanical energy or design of a hydraulic turbine will use principles of **Fluid Mechanics** but a designer of machine will be concerned with the forces that arise from flow of steam or water upon the elements like blades and rotors. Needless to say that designer will find it difficult to visualise all the forces comprehensively if he does not possess comprehensive knowledge of thermodynamics and Fluid Mechanics. We may end up by collecting various characteristics a designer must possess.

(a) He should have sound and comprehensive knowledge in particular field of engineering to which the design belongs (like Thermodynamics, Fluid Mechanics, Refrigeration, etc.)

(b) He invariably should be conversant with Mechanics, Mechanisms, Structures, Engineering Materials and Manufacturing Processes.

(c) Comprehensive knowledge of Mechanics of Solids for correlating stress, deformation, forces (loads) and geometry is a must but in certain cases where the element may not find a parallel in any of standard strength of Material solution the designer may be required to use advanced techniques of Theory of elasticity. The expertise in this area is an added feature.

(d) Some situations which are out of the purview of Strength of Material may require experimental methods like Strain Gauge Survey or Photo-elasticity. With the advent of fast computers the Numerical Technique of Finite Elements has become a handy and strong tool in the hands of designer of machines.

(e) The national and international standards and professional codes make the job of designing much easier. Many times they are essentially to be followed under orders of government or by law. Such standards are helpful in infusing safety of operation and economy. It is thus imperative that a designer is well versed with standards and codes.

(f) A designer must be able to use his knowledge and experience and must always be ready to learn from his own experiences and those of others. Thus, a constant touch with current literature is required.

(g) The ease of operation, safety during operation and convenient repairs and maintenance along with the cost of equipment are such factors, which are related to ultimate user. The designer must make himself aware of human nature and preferences so that his design may be acceptable and remains safe in all aspects of operation, repair, maintenance and final disposal.

(h) The appearance of the product should be attractive to buyers with whose needs in mind the design was made. The designer should have understanding of aesthetics to make the product attractive.

1.4 MECHANICAL PROPERTIES

Properties are quantitative measure of materials behaviour and mechanical properties pertain to material behaviours under load. The load itself can be **static** or **dynamic**. A gradually applied load is regarded as static. Load applied by a universal testing machine upon a specimen is closet example of gradually applied load and the results of tension test from such machines are the basis of defining mechanical properties. The dynamic load is not a gradually applied load – then how is it applied. Let us consider a load *P* acting at the center of a beam, which is simply supported at its ends. The reader will feel happy to find the stress (its maximum value) or deflection or both by using a formula from Strength of Materials. But remember that when the formula was derived certain assumptions were made. One of them was that the load *P* is gradually applied. Such load means that whole of *P* doest not act on the beam at a time but applied in instalments. The instalment may be, say *P*/100 and thus after the 100^{th} instalment is applied the load *P* will be said to be acting on the beam. If the whole of *P* is placed upon the beam, then it comes under the category of the dynamic load, often referred to as **Suddenly Applied Load**. If the load *P* falls from a height then it is a **shock load**. A fatigue load is one which changes with time. Static and dynamic loads can remain unchanged with time after first application or may alter with time (increase or reduce) in which case, they are fatigue load. A load which remains constantly applied over a long time is called creep load.

All Strength of Material formulae are derived for static loads. Fortunately the stress caused by a suddenly applied load or shock load can be correlated with the stress caused by gradually applied load. We will invoke such relationships as and when needed. Like stress formulae, the mechanical properties are also defined and determined under gradually applied loads because such determination is easy to control and hence economic. The properties so determined are influenced by sample geometry and size, shape and surface condition, testing machines and even operator. So the properties are likely to vary from one machine to another and from one laboratory to another. However, the static properties carry much less influence as compared to dynamic (particularly fatigue) properties. The designer must be fully aware of such influences because most machines are under dynamic loading and static loading may only be a dream.

It is imperative at this stage to distinguish between **elastic constants** and mechanical properties. The elastic constants are dependent upon type of material and not upon the sample. However, strain rate (or rate of loading) and temperature may affect elastic constants. The materials used in machines are basically **isotropic** (or so assumed) for which two independent elastic constants exist whereas three constants are often used in correlating stress and strains. The three constants are Modules of Elasticity (E), Modulus of Rigidity (G) and Poisson's Ratio (v). Any one constant can be expressed in terms of other two.

An isotropic material will have same value of E and G in all direction but a natural material like wood may have different values of E and G along fibres and transverse to fibre. Wood is non-isotropic. Most commonly used materials like iron, steel, copper and its alloys, aluminum and its alloys are very closely isotropic while wood and plastic are non-isotropic. The strength of material formulae are derived for isotropic materials only.

The leading mechanical properties used in design are ultimate tensile strength, yield strength, percent elongation, hardness, impact strength and fatigue strength. Before we begin to define them, we will find that considering tension test is the most appropriate beginning.

1.5 TENSION TEST

The tension test is commonest of all tests. It is used to determine many mechanical properties. A cylindrical machined specimen is rigidly held in two jaws of universal testing machine. One jaw is part of a fixed cross-head, while other joins to the part of moving cross-head. The moving cross-heads moves slowly, applying a gradually applied load upon the specimen.

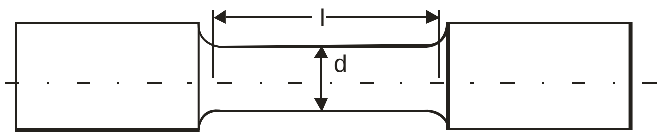


Figure 1.1 : Tension Test Specimen

The specimen is shown in Figure 1.1. The diameter of the specimen bears constant ratio with the gauge length which is shown is Figure 1.1 as distance between two gauge points marked at the ends of uniform diameter length. In a standard specimen $\frac{l}{d} = 5$. The diameter, *d*, and gauge length, *l*, are measured before the specimen is placed in the machine. As the axial force increases upon the specimen, its length increases, almost imperceptibly in the beginning. But if loading continues the length begins to increase perceptibly and at certain point reduction in diameter becomes visible, followed by great reduction in diameter in the local region of the length. In this localised region the two parts of the specimen appear to be separating as the machine continues to operate but the load upon the specimen begins to reduce. Finally at some lesser load the specimen breaks, with a sound, into two pieces. However, the increase in length and reduction of load may not be seen in all the materials. Specimens of some materials show too much of extension and some show too little. The reader must be conversant with the elastic deformation, which is recoverable and plastic deformation, which is irrecoverable. Both type of deformations occur during the test. The appearance of visible decrease in the diameter in the short portion of length (called necking) occurs when the load on the specimen is highest. The machines of this type have arrangement (devices) for the measurement of axial force, *P*, and increase in length, δ. The values of force, *P* and extensions, δ can be plotted on a graph. Many machines have *x*-*y* recorder attached and direct output of graph is obtained. The stress is denoted by σ and calculated as $\frac{P}{A}$ where *A* is the original area of cross-section. Although the area of cross-section of specimen begins to change as the deformations goes plastic, this reduction is seen at and after the maximum load. The separation or fracture into two pieces can be seen to have occurred on smaller diameter. Yet, the stress all through the test, from beginning to end, is represented by $\sigma = \frac{P}{A}$. The strain is defined as the ratio of change in length at any load *P* and original length *l* and represented by ε, i.e. $\varepsilon = \frac{\delta}{l}$ at all loads. Since *A* and *l* are constants hence nature of graph between *P* and δ (load-extension) or between σ and ε (stress-strain) will be same. Figure 1.2 shows a stress-strain diagram, typically for a material, which has extended much before fracture occurred.

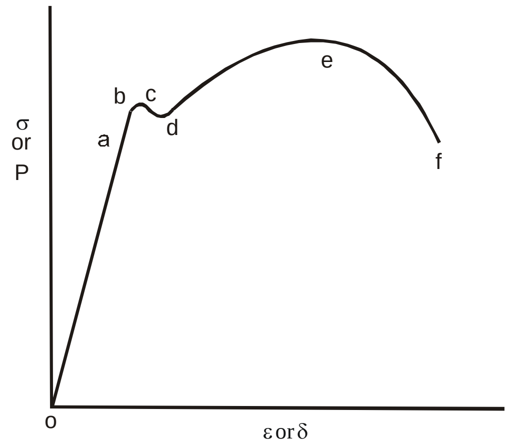


Figure 1.2 : Typical σ – ε Diagram

At first we simply observe what this diagram shows. In this diagram *o* is the starting point and *oa* is straight line. Along line *oa*, stress (σ) is directly proportional to strain (ε). Point *b* indicates the elastic limit, which means that if specimen is unloaded from any point between *o* and *b* (both inclusive) the unloading curve will truly retrace the loading curve. Behaviour of specimen material from point *b* to *c* is not elastic. In many materials all three points of *a*, *b* and *c* may coincide. At *c* the specimen shows deformation without any increase in load (or stress). In some materials (notably mild or low carbon steel) the load (or stress) may reduce perceptibly at *c*, followed by considerable deformation at the reduced constant stress. This will be shown in following section. However, in most materials *cd* may be a small (or very small) region and then stress starts increasing as if the material has gained strength. Of course the curve is more inclined toward ε axis. This increase in stress from *d* to *e* is due to strain hardening. Also note again that *ob* is elastic deformation zone and beyond *b* the deformation is elastic and plastic – meaning that it is part recoverable and part irrecoverable. As the deformation increases plastic deformation increases while elastic deformation remains constant equal to that at *b*. If the specimen is unloaded from any point in the plastic deformation region the unloading curve will be parallel to elastic deformation curve as shown in Figure 1.3.

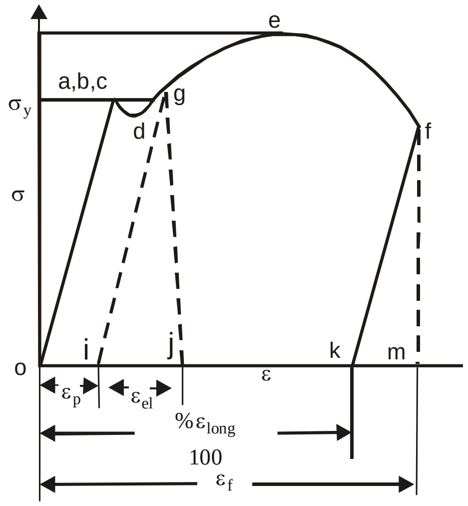


Figure 1.3 : σ – ε Diagram for a Ductile Material

Percent Elongation

From any point *g* the unloading will be along *gi* where *gi* is parallel to *oa*. *oi* is the strain which remains in the specimen or the specimen is permanently elongated by $l\,\varepsilon_p$. The total strain at *g* when the specimen is loaded is $oj = \varepsilon_p + \varepsilon_{el}$ where ε_{el} is recoverable part. At fracture, i.e. at point *f*, if one is able to control and unload the specimen just before fracture, the unloading will follow *f k*. The strain *ok* is an important property because deformation is defined as percent elongation. Hence, *ok* = % elongation/100. Percent elongation is important property and is often measured by placing two broken pieces together and measuring the distance between the gauge points. You can easily see that after the fracture has occurred, the specimen is no more under load, hence elastic deformation (which is equal to km) is completely recovered. However, in a so-called ductile material *km* << *om*. If the distance between gauge points measured on two broken halves placed together is l_f, then

$$\%\ \text{Elongation} = \frac{l_f - l}{l} \times 100$$

The gauge length has pronounced effect on % elongation. Since the major amount of deformation occurs locally, i.e. over very small length smaller gauge length will result in higher % elongation. After $\frac{l}{d} > 5$ the % elongation becomes independent of gauge length. % elongation is an indication of very important property of the material called **ductility**. The ductility is defined as the property by virtue of which a material can be drawn into wires which means length can be increased and diameter can be reduced without fracture. However, a ductile material deforms plastically before it fails. The property opposite to ductility is called **brittleness**. A brittle material does not show enough plastic deformation. Brittle materials are weak under tensile stress, though they are stronger than most ductile materials in compression.

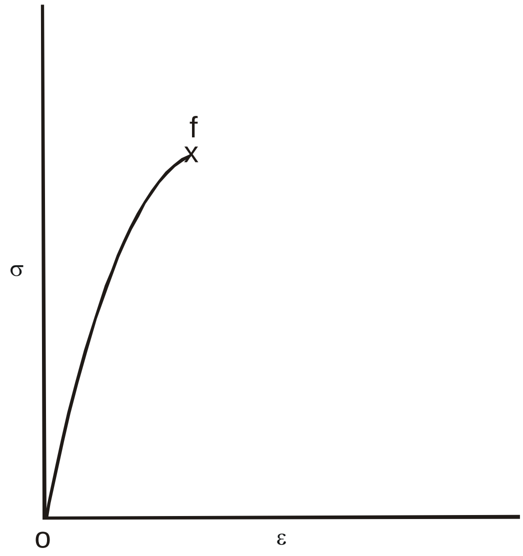


Figure 1.4 : σ – ε Diagram for a Brittle Material

A typical diagram for a brittle material is shown in Figure 1.4. The definitions like too much and too small % elongation fail to give numerical indication. Hence engineers regard all those materials as brittle, which show a % elongation less than 5%. Others are regarded as ductile. Most steels low in carbon and medium carbon range are ductile by this definition. Cast iron is a typical brittle material. Concrete is another example of a brittle material. The failures in engineering structures and machine elements always take place due to tensile stress and hence brittle materials are not used for making such elements. Such components like beds of machines and foundations can be made in cast iron. If tensile stress carrying members have to be made in *C*.1 then they have to be made heavy for making stress very low.

Ultimate Tensile Strength, Yield Strength and Proof Stress

The maximum stress reached in a tension test is defined as **ultimate tensile strength**. As shown in Figure 1.3 the highest stress is at point *e* and ultimate tensile stress (UTS) is represented by σ_u. Some authors represent it by S_u. The point *c* marks the beginning while *d* marks the end of yielding. *c* is called upper yield point while *d* is called the lower yield point. The stress corresponding to lower yield point is defined as the **yield strength**. For the purposes of machines, the part has practically failed if stress reaches yield strength, (σ_Y), for this marks the beginning of the plastic deformation. Plastic deformation in machine parts is not permissible. Hence one may be inclined to treat σ_Y as failure criterion. We will further discuss this later in the unit.

It is unfortunate to note that many practical materials show σ – ε diagrams which do not have such well defined yielding as in Figures 1.2 and 1.3. Instead they show a continuous transition from elastic to plastic deformation. In such cases yield strength (σ_Y) becomes difficult to determine. For this reason an alternative, called **proof stress**, is defined which is a stress corresponding to certain predefined strain. The proof stress is denoted by σ_p. A σ – ε diagram for a material, which shows no distinct yield is shown in Figure 1.5. The proof stress is determined corresponding to proof strain ε_p which is often called offset. By laying ε_p on strain axis to obtain a point *q* on ε axis and drawing a line parallel to elastic line to cut the σ – ε curve at *p* the proof stress σ_p is defined. Then σ_p is measured on stress axis. The values of proof strain or offset have been standardized for different materials by American Society for Testing and Materials (*ASTM*). For example, offset for aluminum alloys is 0.2%, same is for steels while it is 0.05% for cast iron (CI) and 0.35% for brass and bronze.

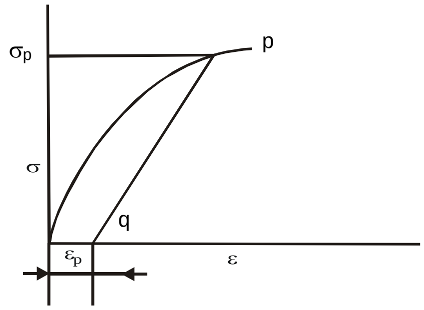


Figure 1.5 : Proof Stress (σ_p) Corresponding to Offset ε_p

Toughness and Resilience

Since the force, which pulls the tension test specimen, causes movement of its point of application, the work is done. This work is stored in the specimen and can be measured as energy stored in the specimen. It can be measured as area under the curve between load (P) and elongation (Δl). In case of $\sigma - \varepsilon$ curve area under the curve represents energy per unit volume.

Toughness is regarded as ability of a material to absorb strain energy during elastic and plastic deformation. The resilience is same capacity within elastic range. The maximum toughness will apparently be at fracture, which is the area under entire $\sigma - \varepsilon$ diagram. This energy is called **modulus of toughness**. Likewise the maximum energy absorbed in the specimen within elastic limit is called **modulus of resilience**. This is the energy absorbed in the tension specimen when the deformation has reached point *a* in Figure 1.2. But since in most materials the proportional limit, elastic limit (points *a* and *b* in Figures 1.2 and 1.3) seem to coincide with yield stress as shows in Figure 1.3, the modules of resilience is the area of triangle as shown in Figure 1.6.

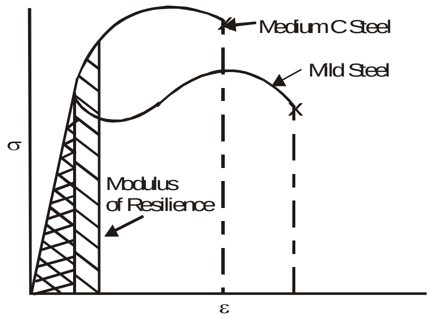


Figure 1.6 : Resilience and Toughness for Two Materials

It can be seen that modulus of resilience is greater for medium carbon steel than for mild steel, whereas modulus of toughness of two materials may be closely same. Medium carbon steel apparently has higher UTS and YS but smaller percent elongation with respect to mild steel. High modulus of resilience is preferred for such machine parts, which are required to store energy. Springs are good example. Hence, springs are made in high yield strength materials.

SAQ 1

(a) Discuss the procedure of Design.

(b) What characteristics a designer must possess?

(c) Sketch a stress-stain diagram. What properties you can define with the help of this diagram?

(d) Distinguish between a brittle and ductile material. Why is a brittle material not favoured for use as machine element?

(e) Define modulus of resilience and modulus of toughness.

1.6 STRESS STRAIN DIAGRAM FOR MILD STEEL

Mild steel as steel classification is no more a popular term. It was in earlier days that group of steel used for structural purposes was called mild steel. Its carbon content is low and a larger group of steel, named low carbon steel, is now used for the same purposes. We will read about steel classification later. Mild steel was perhaps developed first out of all steels and it was manufactured from Bessemer process by blowing out carbon from iron in a Bessemer converter. It was made from pig iron. The interesting point to note is that this steel was first studied through $\sigma - \varepsilon$ diagram and most properties were studied with respect to this material. The term **yield strength** (YS) is frequently used whereas yield behaviour is not detectable in most steel varieties used today. It is mild steel, which very clearly shows a yield behaviour and upper and lower, yield points. Figure 1.7 shows a typical $\sigma - \varepsilon$ diagram for mild steel.

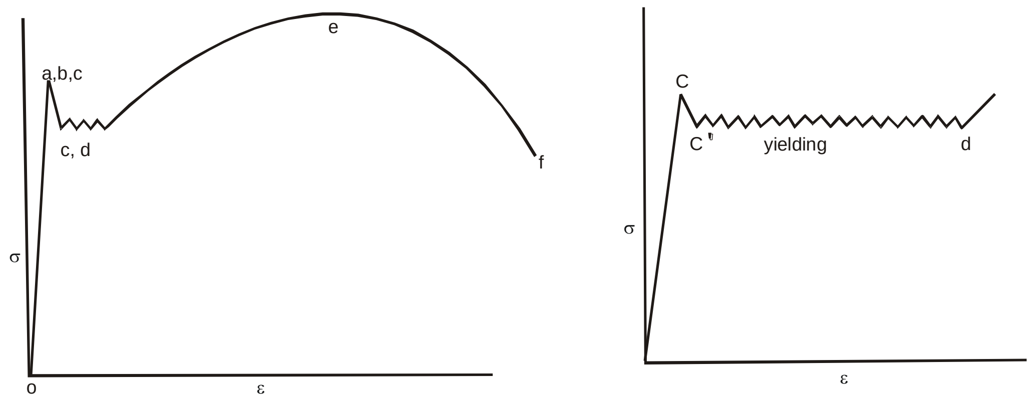


Figure 1.7 : $\sigma - \varepsilon$ Diagram for Mild Steel

The proportional limit, elastic limit and upper yield point almost coincide. *d* is lower yield point and deformation from *c*′ to *d* is at almost constant stress level. There is perceptible drop in stress from *c* to *c*′. The deformation from *c*′ to *d* is almost 10 times the deformation upto *c*. It can be seen effectively if strain is plotted on larger scale, as shown on right hand side in Figure 1.7, in which the ε scale has been doubled.

The mechanism of yielding is well understood and it is attributed to line defects, dislocations.

The UTS normally increases with increasing strain rate and decreases with increasing temperature. Similar trend is shown by yield strength, particularly in low carbon steel.

1.7 COMPRESSION STRENGTH

Compression test is often performed upon materials. The compression test on ductile material reveals little as no failure is obtained. Brittle material in compression shows specific fracture failure, failing along a plane making an angel greater than 45^o with horizontal plane on which compressive load is applied. The load at which fracture occurs divided by area of *X*-section is called compressive strength. For brittle material the stress-strain curves are similar in tension and compression and for such brittle materials as CI and concrete modulus of elasticity in compression is slightly higher than that in tension.

1.8 TORSIONAL SHEAR STRENGTH

Another important test performed on steel and CI is *torsion test*. In this test one end of specimen is rigidly held while twisting moment or torque is applied at the other end. The result of test is plotted as a curve between torque (T) and angle of twist or angular displacement θ. The test terminates at fracture. The $T - \theta$ curves of a ductile material is very much similar to load extension or $\sigma - \varepsilon$ curve of tensile test except that the torque does not reduce after attaining a maximum value but fracture occurs at maximum torque. It is because of the fact that there is no reduction in the sectional area of the specimen during the plastic deformation. The elastic limit in this case can be found as the point where straight line terminates and strain hardening begins, marked as point *b* in Figure 1.8. Mild steel will show a marked yielding while other ductile materials show a smooth transition from elastic to plastic deformation. The plastic deformation zone in torsion is much larger than in torsion because the plastic deformation beginning from outer surface and spreads inside while in tension the stress being uniform over the *X*-section the plastic deformation spreads over entire section at the same time.

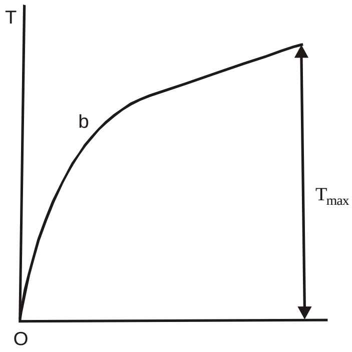


Figure 1.8 : Torque-twist Diagram in Torsion

The *modulus of rapture or ultimate torsional shear strength* is calculated form

$$\tau_u = \frac{3}{4} \frac{T_{max}}{J} \frac{d}{2}$$

where T_{max} is maximum torque, *j* is polar moment of inertia of the specimen section of diameter *d*. From the $T - \theta$ diagram the slope of linear region can be found as proportional to modulus of rigidity, which is ratio of shearing stress to shearing strain.

1.9 ELASTIC CONSTANTS

Within elastic limit the stress is directly proportional to strain. This is the statement of Hooke's law and is true for direct (tensile or compressive) stress and strain as well as for shearing (including torsional shearing) stress and strain. The ratio of direct stress to direct strain is defined as *modulus of elasticity* (*E*) and the ratio of shearing stress and shearing strain is defined as *modulus of rigidity* (*G*). Both the moduli are called elastic constants. For isotropic material *E* and *G* are related with Poisson's ratio

$$G = \frac{E}{2\,(1 + v)}$$

Poisson's ratio which is the ratio of transverse to longitudinal strains (only magnitude) in tensile test specimen is yet another elastic constant. If stress σ acts in three directions at a point it is called volumetric stress and produces volumetric strain. The ratio of volumetric stress to volumetric strain according to Hooke's law is a constant, called *bulk modulus* and denoted by *K*. It is important to remember that out of four elastic constants, for an isotropic material only two are independent and other two are dependent. Thus *K* can also be expressed as function of any two constants.

$$K = \frac{E}{3\,(1 - 2v)}$$

It may be understood that elastic constants *E* and *G* are not determined from tension or torsion test because the machines for these tests undergo adjustment of clearance and also some deformation, which is reflected in diagram ordinarily. The constants are determined from such devices, which show large deformation for comparatively smaller load. For example, *E* is determined by measuring deflection of a beam under a central load and *G* is determined by measuring deflection of a close-coiled helical spring under an axial load. Poisson's ratio is normally not measured directly but is calculated from above equation. The *elastic constants* remain fairly constant for a class of material and are independent of specimens.

1.10 HARDNESS

Hardness of a material is its ability to resist indentation or scratching. This property is the measure of resistance to wear and abrasion. Both scratch and indention methods are used for determining this property. For engineering purposes indentation method is used. The load that is used to cause indentation on a flat surface by an indenter is divided by surface area of indentation to obtain a number that is called hardness number. A ball of 10 mm diameter made in hardened steel is used as an indenter under a load of 30000 N and kept applied for 30 sec. The area of indentation is

$$\left(\frac{\pi D}{2}\right)(D - \sqrt{D^2 - d^2})$$

with D as diameter of the ball and d as the diameter of impression on flat surface. Different loads are used for different materials. Brinell hardness number is the ratio of load P and area of indented surface as given above. Instead of using the area of surface of indentation to divide the load P to obtain harness number one can use the area of circular impression on the surface or the projected area or the depth of indentation directly can be used as an indicator of hardness. The indenting load divided by projected area of indentation is defined as **Meyer hardness number**. The depth of the indentation mode by a conical indenter is called **Rockwell hardness number**. Rockwell hardness uses different loads and indentors for having different Rockwell scales. Rockwell C is commonly used for steels. Rockwell method is generally preferred over Brinell because it does not require a finished surface, it can be determined on a finished part without spoiling the surface and it gives the reading of hardness directly. Rockwell method measures the depth of the indentation and hardness, called Rockwell hardness number is inversely proportional to the depth of indentation.

It is no wonder that a relationship exists between hardness of a material and its strength because both are related to bonding forces at atomic level. Because of nature of stress in a hardness test being complex (triaxial) and effect of friction creeping in due to contact between the indentor and the specimen such relationship is difficult to establish. However, empirically the ultimate tensile strength and Rockwell c hardness are related as

$$\sigma_u = 33\ R_c$$

It is also interesting to note that techniques, which increase the ultimate tensile strength of material also increase the hardness. Increase in strength and hardness is associated with decrease in ductility (%age elongation), increase in yield or proof strength and consequent increase in modulus of resilience. For this reason hardness is often used in lieu of elaborate tension test for characterizing a material or checking effectiveness of any treatment. Hardness is also used for calculating UTS (σ_u) in design.

It may also be mentioned here that while the treatments given to material may alter yield strength, ultimate tensile strength, hardness and %age elongation, the modulus of elasticity will remain unchanged. That's why the constants of material are to be differentiated from mechanical properties.

1.11 FATIGUE

Fatigue is not the property but the behaviour of material under stress which changes with time. Most interesting thing about fatigue is that a stress level which is below yield or elastic limit is safe if applied once, but if same level is applied repeatedly upon a specimen then it will fail. Such a failure under repeated stressing is called fatigue failure and has discernible characteristics.

The most important characteristic of fatigue failure is that it is without perceptible plastic deformation in the region of fracture. Even if the specimen is loaded under axial tensile stress which reverses and whose magnitude is below yield strength, the fatigue failure will occur and there will be no necking or elongation in the specimen. The fracture surface has a characteristic appearance with rings (under magnification) and rough surface (Figure 1.9).

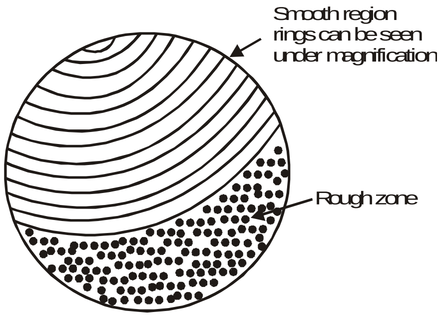


Figure 1.9 : Characteristic Fatigue Fracture

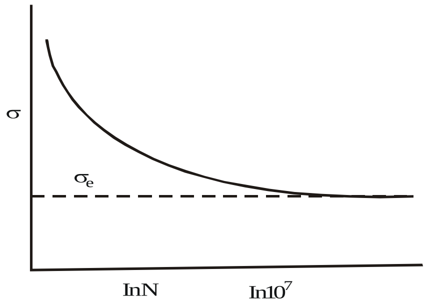


Figure 1.10 : A Typical Fatigue Curve

The number of cycles after which the specimen fails is called the fatigue life at the applied stress. If stress level is plotted against *ln* of number of cycles at failure the characteristic fatigue curve is obtained (Figure 1.10). The curve indicates that at lower stress level the specimen tends to have longer life or even may not fail. All fatigue tests are stopped at 10^7 cycles and a specimen surviving 10 million cycles is regarded survival or non-failure. The stress level at which specimen survives 10 million cycles is called *fatigue strength* or *endurance limit* (former denoted by σ_e is preferably used). Fatigue life at given stress level and fatigue strength are two fatigue properties and they are influenced by several factors such as specimen size, surface finish, stress concentration, temperature, frequency, etc. A smooth polished specimen at frequency less than 1000 cycles/min. and room temperature will have

$$\sigma_e = 0.5\ \sigma_u \text{ (steels)}$$

$$\sigma_e = 0.4\ \sigma_u \text{ (non-ferrous)}$$

The fatigue strength is affected by several variables :

(a) Fine finished surfaces result in high fatigue strength.

(b) Stress concentration reduces fatigue strength but not as much as stress concentration factor.

(c) All treatments that improve static strength also improves fatigue strength.

(d) **Under-stressing** is process of stress cycling below fatigue strength. It improves fatigue strength. Gradually increasing cyclic stress up to fatigue strength is **coaxing**.

(e) Small size specimen (6 to 12 mm dia) have higher fatigue strength than larger size specimen (> 6, mm dia), but after 100 mm dia, this effect levels off.

(f) Corrosive atmosphere, high temperature cause reduction in fatigue strength.

1.12 CREEP

Yet another important behaviour of material arises when the material is subjected to a constant load over a long time. It is found that a body of material subjected to a load which causes stress less than yield strength, over a long period of time, undergoes a deformation which increases as time passess. The strain so created may ultimately cause the failure. The behaviour of material is termed *creep* and the strain is known as *creep strain*. The rate at which strain increases will decide after what time the material will fail. At higher stress the strain rate will be higher and vice-versa. It may be noted from the definition given here that the temperature is not a requirement for creep deformation to occur. Creep occurs at all temperatures. However, the creep rate is accelerated with increasing temperature and at temperature which is close to half of melting point temperature on absolute scale, creep becomes an important consideration in design. Thus theoretically though higher temperature is not an essential condition for creep yet at higher temperature it is a real problem. The creep rate at constant temperature increases with increase in stress and at constant stress it increases with increase in temperature. The characteristic creep curve is plotted between creep strain and time and is characterised by three stages as shown in Figure 1.11. A designer would prefer to load a machine part in such a way that only *secondary creep* having a constant creep rate sets in. *Tertiary creep* is characterized by increasing creep rate and fast ends in fracture. Creep becomes an important consideration in gas turbine blading design because temperature is high. The higher limit of temperature in gas turbine is limited because of creep of blading material.

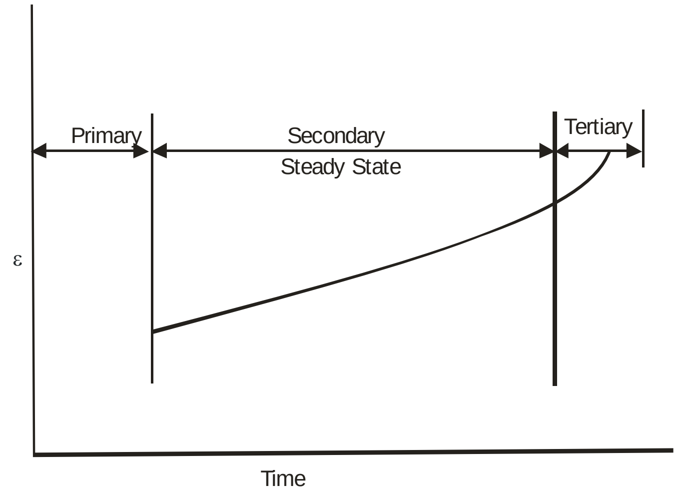


Figure 1.11 : Creep Curve : Three Stages of Creep are Depicted

Sometime a quantity like *creep strength* is defined as a stress at a given temperature which will produce minimum creep rate of a certain amount usually 0.0001 %/hour. *Creep rupture* strength is a stress at given temperature, which will cause rupture after a predefined life in number of hours say 1000 or 10,000 hours. Rupture is theoretically a fracture occurring with *X*-sec. reduced to zero. Both creep strength and creep rupture strength are arbitrary and not used in design but for comparing two materials.

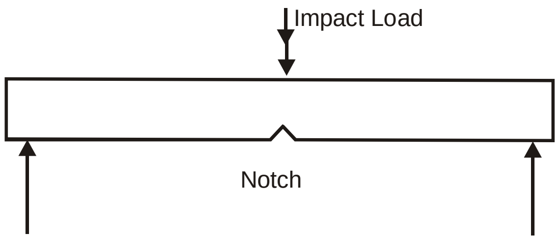
A consequence of creep is a phenomenon called *stress relaxation*, which refers to decrease of stress at constant strain. Problem of stress relaxation is common in bolts used to clamp two parts at higher temperature. For example, bolts used to clamp cover on a pressure vessel, at high temperature may lose stress after some time and thus clamping force gets reduced.

Addition of 1.25% Cr and 0.5% Mo in 0.1% C steel improves creep resistance. Addition of Cr in varying proportion along with Mo in steel help improve creep resistance in general. Nickel base alloys like Inconel (C-0.04, Fe- 7.0, Cr-15.5, Ni-76) have high creep resistance. Cobalt base super alloys are also used for various purposes against creep.

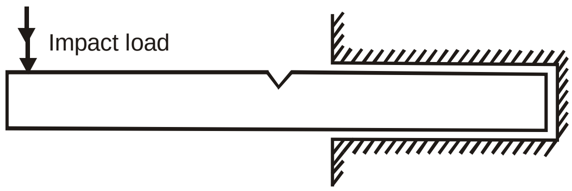
1.13 IMPACT STRENGTH

Impart is a rapidly applied load. A notched specimen is broken under impact loading in an impact test. The state of stress at notch is complex, in fact triaxial and impact load causes a high strain rate. The combination of rapidly applied load and notch makes the material to behave in a brittle manner and raises the yield strength. Thus the fracture occurs before yielding. It is often difficult to calculate the stress at notch and hence the energy absorbed in fracturing the specimen is measured as the material property and is given a name as **impact strength**. Such a value cannot be used for designing but it is an indicator of the fact as to how much tendency the material has to behave as brittle material. The machine for such a test consists of a swinging hammer, which through a free fall is allowed to strike a notched specimen in a way to stress notch in tension. The potential energy of hammer before striking (i.e. in its raised position) can be calculated and also the potential energy of the hammer after striking and causing the fracture of the specimen can be calculated from the height reached by hammer at the end of its swing. The difference of two potential energies minus loss of energy in moving through air is the energy absorbed by the specimen in fracturing. This energy is the impact strength of material of specimen.

Two configuration of notched specimen are in common use and they are shown in Figure 1.12. **Charpy test** uses the specimen as simply supported beam while **Izod test** uses the specimen as cantilever. In both the cases the load is so applied that notch is in tension. A 10 mm × 10 mm cross-section bar supported over a span of 40 mm and carrying a *V*-notch of depth equal to 1/3 of the depth of section is a common Charpy test specimen. To compare results from different sources standardization of specimens is necessary. An Izod specimen may be rectangular or circular in section.



(a) Chary test



(b) Izod test

Figure 1.12 : Impact Test Configuration

Apart from two worst condition, viz. of impact and notch, which render specimen brittle a third condition to be explored is temperature. The material tends to become brittle at low temperature and hence performing impact tests on notched specimens at different temperature is imperative. The results of such a test are depicted in Figure 1.13 wherein the impact strengths are plotted as function of temperature. The results apparently centre on a temperature T_r showing that for $T > T_r$ the impact strength increase fast but for $T < T_r$ it reduces fast. Such a temperature is called *transition temperature* as it represents the transition from ductile to brittle nature as temperature reduces. The operation of a machine part or structural component near transition temperature on higher side carries the risk that if temperature reduces slightly the material may start behaving in a brittle manner. Impact tests are often useful in establishing transition temperature. The purpose could be to avoid such a temperature or to select a material whose transition temperature is higher than the operating temperature. The material most susceptible to this transition is mild steel and this material is largely used for structures. The non-ferrous material like alloys of Cu and A1 do not show such transition from ductile to brittle. For evaluating performance of welded mild steel such tests are often performed because the mild steel welded structures are often used in ship building. The ships have to operate in warm and cool climates.

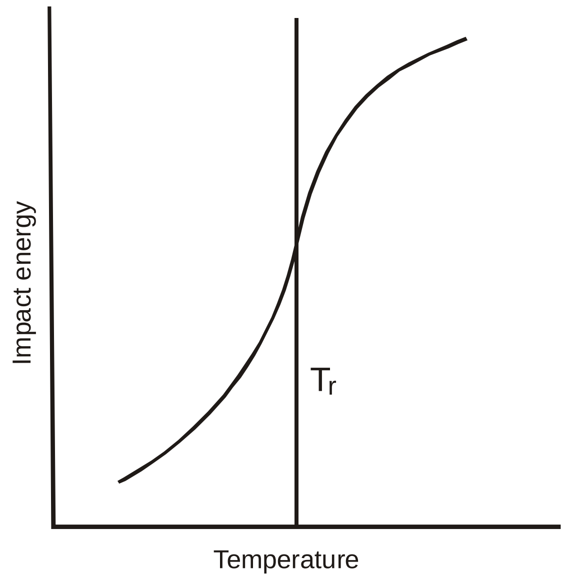


Figure 1.13 : Influence of Temperature on Notched Bar Impact Energy

1.14 ENGINEERING MATERIALS

The *materials* used for *structures*, *tools*, *machines* and other *durable goods* are generally regarded as *engineering materials*. These materials are variously classified. *Organic* and *inorganic* materials are close to scientific division. Materials of both types are used for engineering purposes. Organic substances are mostly derived from living organisms and necessarily contain carbon as one constituent. Animal hides (leather), wood, oil (petroleum), several chemicals, paints, man made polymers and natural resins are examples of organic materials. All elements including metals and their alloys, acids not having carbon as its constituent, ceramic, non living natural materials like sand and rock are regarded as inorganic materials. Both types are found in gaseous, liquid and solid states.

Composites are combination of materials in which neither solution nor chemical reaction occurs but properties improve for engineering purposes purely because of mechanical interaction between the constituents. All constituents may be organic or inorganic or both. Reinforced concrete is a common example while reinforced plastics, cemented carbide tools are also composites. Reduction in weight, coupled with high strength and stiffness have opened possibilities of development of newer composites.

Because of *ductility*, *malleability*, *electrical conductivity* and *strength* the metals have become very common and dependable engineering martial. Though most metals are elements (like Fe, A1, Cu, Zn) very few are used in practice. Their properties improve by alloying. The most commonly used alloy is steel which has Fe as most important constituent and C and Si as alloying elements in very small proportion. Alloys like steel have become very dependable materials because their properties can be altered by heat treatment.

High temperature application requires the materials to remain sufficiently strong over a wide range of temperature. The oxides, borides, nitrides and carbides of several metallic elements have high wear resistance, high strength at elevated temperatures but have marked brittleness. Such materials are described as ceramics.

Polymers or *plastic* have acquired a great deal of popularity for making parts of complicated shapes but not subjected to high loads. These are organic compounds made by chemical processes and are used in form of fibres, sheets and in various other shapes. Most composites are made using plastics. The composites and plastics have good resistance against corrosion.

Perhaps the most common engineering materials after *bricks* and *concrete* are *alloys*. *Steel* is the foremost example. The elemental metals are mixed in liquid state or heated to liquid state where they may have total or partial solubility and on cooling the solids may have total or partial solubility. Combination of two or more metals produce alloys in solid state in most cases they possess properties better than the constituents. Equilibrium diagrams drawn between temperature (ordinate) and % age composition of one of the two constituents give great deal of information about alloys. Number of phases at any temperature and their chemical composition can be found from phase or equilibrium diagrams.

Pure iron may contain 99.99% iron, which could be produced by very costly electrolytic process. Though not good for much strength, pure iron is used for research transformer cores. Commercial iron may 99% pure. While being expensive it is used for special purposes for high corrosion resistance and electrical conductivity. Wrought iron contains about 3% slag particles distributed uniformly in iron matrix. The presence of slag is helpful in increasing resistance against fatigue and corrosion. This material is used for steam, oil and water pipelines. The alloys of iron containing upto 2% carbon along with small amounts of S, Si, P and Mn are classified as steel. Cast iron is yet another alloy of iron containing more than 2% of carbon.

1.15 STEEL

By far the commonest engineering material, after brick and concrete, is steel. Steel is known for its several favourable properties. It has strength and ductility, good electrical and thermal conductivity, it is amenable to machining and other manufacturing processes and it is comparatively easily produced.

A Steel containing *C* in the range of 0.04 to 1.2% along with Mn (0.3 to 1.04%), Si (upto 0.3%), S (max 0.04%), P (max 0.05%) is classified as plain carbon steel. Another group is called alloy steel. C steel is further divided into three groups. They are described here.

Low C Steel

Carbon less than 0.27%. It is marked by high ductility, low strength, good machinability and formability. They are weldable but do not respond to heat treatment.

Medium C Steel

Carbon varies between 0.27 and 0.57%. This steel is heat treatable and good strength is achievable after treatment. This steel is stronger and tougher than low carbon steel and machines well.

High C Steel

They contain more than 0.57% C. The high C steel responds readily to heat treatment. In heat-treated state they develop very high strength and hardness and thus become less machinable. They also lose ductility and in the high carbon range may become very brittle. The higher C content makes these steel difficult to weld.

Following table describes applications, the properties required for applications and the steel which can provide such properties.

Table 1.1 : Application of Plain C Steel

Sl. No.	Application	Properties	Steel
1.	Nails, rivets, stampings	High ductility, low strength	Low C (AISI 1010), 0.08/0.13,0.1 Max, 0.3/0.60
2.	Beams, rolled sections	High ductility, low strength, toughness	Low C (1020), 0.17/0.20,0.10/0.20, 0.3/0.60
3.	Shafts and gears	Heat treatable for good strength and ductility	Med C (1030), 0.27/0.35, 0.20/0.35, 0.5/0.80
4.	Crank shaft, bolts, connecting rod, machine component	Heat treatable for good strength and ductility	Med C (1040), 0.36/0.45, 0.20/0.35, 0.60/0.90
5.	Lock washers, valve springs	Toughness	High C (1060) 0.54/0.66, 0.20/0.35, 0.60/0.90
6.	Wrenches, dies, anvils	High toughness and hardness	High C (1070), 0.64/0.76, 0.20/0.35, 0.60/0.90
7.	Chissels, hammers, shears	Retains sharp edges	High C (1080)
8.	Cutters, tools, taps, hacksaw blades, springs	Hardness, toughness, heat treatable	High C (1090), tool steel

* Composition in % of C, Si, Mn (in this order) with Max P-0.04% and Max S-0.05.

1.16 ALLOY STEEL

Plain C steels contain C in the range of 0.04 to 1.2. Additionally they contain Mn (0.3 to 1.04%), Si (up to 0.3%), S (0.04% Max) P (0.05% Max). Other than C no element has significant effect on mechanical properties except that Mn may provide some hardenability. S and P are undesirable elements.

Several advantages in terms of improved mechanical properties and corrosion resistance are obtained by adding one or several alloying elements like Si, Mn, Ni, Cr, Mo, W, V, Cu, B, A1, etc. The various advantages of alloy steel are :

(a) Higher hardness, strength and toughness, hardness on surface and over bigger cross-section.

(b) Better hardenability and retention of hardness at higher temperatures (good for creep and cutting tools).

(c) Higher resistance against corrosion and oxidation.

The alloying elements affect the properties of steel in 4 ways :

(a) By strengthening ferrite while forming a solid solution. The strengthening effects of various alloying elements are in this order : Cr, W, V, Mo, Ni, Mn and Si.

(b) By forming carbides which are harder and stronger. Carbides of Cr and V are hardest and strongest against wear particularly after tempering. High alloy tool steel use this effect.

(c) Ni and Mn lower the austenite formation temperature while other alloying elements raise this temperature. Most elements shift eutectoid composition to lower C % age.

(d) Most elements shift the *isothermal transformation curve- (TTT) to lower temperature, thus lowering the critical cooling rate. Mn, Ni, Cr and Mo are prominently effective in this respect*.

Effects of individual alloying elements on properties of steel :

Sulfur

S is not a desirable element in steel because it interferes with hot rolling and forging resulting in *hot-shortness* or *hot embitterment*. *S*, however, is helpful in developing free cutting nature. *S* up to 0.33% is added in *free cutting steel*. If steel is not free cutting *S* is restricted to 0.05% in open hearth or converter steel and to 0.025% in electric furnace steel.

Phosphorous

P produces cold shortness, which reduces impact strength at low temperature. So its %age is generally restricted to level of S. It is helpful in free cutting steels and is added up to 0.12%. It also improves resistance to corrosion.

Silicon

S_i is present in all steels but is added up to 5% in steels used as laminates in transformers, motors and generators. For providing toughness it is an important constituent in steel used for spring, chisels and punches. It has a good effect in steel that it combines with free O_2 forming S_iO_2 increasing strength and soundness of steel castings (up to 0.5%).

Manganese

12 to 14% of Mn produces extremely tough, wear resistant and non-magnetic steel called *Hatfield Steel*. It is important ingredient of free cutting steel upto 1.6%. Mn combines with S, forming MnS. For this purpose Mn must be 3 to 8 times the S. Mn is effective in increasing hardness and hardenability.

Nickel

Ni is good in increasing hardness, strength and toughness while maintaining ductility. 0.5% of Ni is good for parts subjected to impact loads at room and very low temperature. Higher amounts of Ni help improve the corrosion resistance in presence of Cr as in stainless steel. Nickel in steel results in good mechanical properties after annealing and normalising and hence large forgings, castings and structural parts are made in Ni-steel.

Chromium

Cr is common alloying element in tool steels, stainless steels, corrosion resistant steels (4% Cr). It forms carbide and generally improves hardness, wear and oxidation resistance at elevated temperature. It improves hardenability of thicker sections.

Molybdenum

Mo is commonly present in high-speed tool steel, carburising steel and heat resisting steel. It forms carbide having high wear resistance and retaining strength at high temperatures. Mo generally increases hardenability and helps improve the effects of other alloying elements like Mn, Ni and Cr.

Tungsten

W is important ingredient of tool steel and heat resisting steel and generally has same effects as Mo but 2 to 3% W has same effect as 1% of Mo.

Vanadium

Like Mo, V has inhibiting influence on grain growth at high temperature. V carbide possesses highest hardness and wear resistance. It improves fatigue resistance. It is important constituent of tool steel and may be added to carburising steel. Hardenability is markedly increased due to V.

Titanium

Addition of Ti in stainless steel does not permit precipitation of Cr carbide since Ti is stronger carbide former and fixes the C.

Cobalt

It imparts magnetic property to high C steel. In the presence of Cr, Co does not permit scale formation at high temperature by increasing corrosion resistance.

Copper

Atmospheric corrosion resistance of steel is increased by addition of 0.1 to 0.6% Cu.

Boron

Very small %age (like 0.001 to 0.005) of B is effective in increasing hardness particularly in surface hardening *boriding* treatment.

Lead

Less than 0.35% Pb improves machinability.

Aluminum

Al in %age of 1 to 3 in nitriding steels is added to improve hardness by way of forming A1 nitride. 0.01 to 0.06% A1 added during solidification produces fine-grained steel castings.

We may also correlate certain desired properties with alloying elements. They are mentioned below.

(a) **Hardenability** is improved by addition any or more than one of the following. Si, Mn, Ni, Cr, Mo, W, B.

(b) **Toughness, that is the capacity to absorb energy before fracture increases with addition of Si and Ni.**

(c) The presence, of Cr, Mo and W helps steel to retain **strength at high temperatures.**

(d) Cr, Mo and W also help improve resistance against corrosion.

(e) **Wear resistance** of steel increases when alloyed with Cr, Mo, W and V.

(f) The **impact strength at low temperature** improves due to Ni.

(g) Cu helps steel achieve better resistance against atmospheric corrosion.

(h) **Surface hardenability** is improved by addition of Al.

(i) V helps increase **fatigue strength** of steel.

(j) Steels with S, P and P_b have better **machinability.**

Table 1.2 describes application, desired properties and composition of several alloy steels.

Table 1.2 : Applications of Alloy Steels

Sl. No.	Application	Desired Properties	Composition
1.	Rail Steel	Strength, ductility, impact and fatigue strength	C-04% to 0.6% Mn and Cr- upto 1%
2.	Spring steel (tension, compression, torsion)	Good elongation, high elastic limit (20 to 30%, 1200-1400 MPa)	(a) C-0.6, Mn-0.9 Si-2.0 (b) C-0.5, Mn-0.8, Cr-1.0, V-0.15 (c) C-0.5, Mn-0.9 Cr-0.5, Ni-0.6 Mo-0.2
3.	Structural steel (bridges building, cars, gears, clutches, shafts)	High strength, toughness, high temperature strength, corrosion resistance	Wide range of alloy steels containing several alloying elements
4.	Weldable steel for welded structures	Weldability, high resistance to atmospheric corrosion, resistance to brittle fracture	C-0.15 to 0.3% with some Cu and V
5.	Concrete reinforcing steel	Bend 90^o-180^o, torsteel with ribs for grater surface area. Elong = 16% UTS =500-650 MPa Y.S. = 35 MPa	C-0.3 to 0.4%, Min 0.5 to 0.8% C-0.45 to 0.6%, Mn-0.7 to 1.1%
6.	High speed steel for cutting tools	Resist temperature upto 550-600^{o}C Cutting tools requiring high hardness at working temperature 18 : 4 : 1 steel and 6 : 5: 4: 2 steel	C-8%, W-18% Cr-4%, V-1% C-8%, W-6%, Mo-5%, Cr-4%, V-2%
7.	Creep resisting steel	Application in pipeline upto 400-550^{o}C Other parts upto 500^{o}C	Mo-0.4% to 0.6% V-0.25% to 1.0% Cr-upto 6.0% C-low carbon
8.	Ball bearing steel	Rolling element, inner and outer races. High hardness 61-65 R_c high fatigue strength	C-0.9 to 1.1% Cr-0.6 to 1.6%, Mn-0.2 to 0.4%
9.	Hadfield Mn steel excavating and crushing machine, railroad crossing, oil well, cement, mining industries. Used as casting and hot rolled	Resistance to abrasion ad shock, high toughness, strength ad ductility	C-1 to 1.4% Si-0.3 to 1.0% Mn-10 to 14% with Fe
10.	High strength low alloy steel (HSLA) for automotive parts	High strength/weight ratio. Balanced properties such as toughness, fatigue strength, weldability and formability	C-0.07 to 1.3%, TI, V, A1 Co less than 0.5%

1.17 STAINLESS STEEL

Stainless steel is an alloy steel but has become a class on its own because of widespread applications. It also has several unique properties. Being steel all types of stainless steel essentially contains C but they also contain chromium. Many of stainless steels also contain nickel. The important properties of stainless steels are mentioned below :

(a) They have wide range of strength and hardness accompanied by ductility.

(b) Stainless steels resist corrosion because very thin hydrous oxide layer forms on surface, which obstructs further penetration of oxygen.

(c) They exhibit good creep resistance and resist oxidation at elevated temperatures.

(d) They have good thermal conductivity.

(e) Stainless steels are weldable and machinable.

(f) They can be worked hot and cold.

(g) Since the surface is not corroded, they maintain good surface appearance and *finish*.

(h) It does not show a very steep transition (ductility to brittleness) under impact.

Combination of these properties render stainless steels as the best possible material against corrosion, chemical attacks, high temp, low temperature and for critical parts that are required to be small in size. They are also capable to bear high stress concentration as ductility help plastic deformation under increased stress at stress concentration. Gears, shafts and springs are made in stainless steel to take advantage of high strength, ductility and corrosion resistance if sizes have to be keeping smaller. Blades for compressors and turbine, chemical containers, surgical instruments are made in stainless steel to take advantage of anti corrosive properties.

There are three major types of stainless steels :

Ferritic Stainless Steel

This is the most abundantly used stainless steel and has ferritic structure because of which it cannot be heat-treated. It has high resistance against corrosion and oxidation. It is used in furnace as container of acids and trims of automobiles.

Carbon content of ferritic steel varies from 0.08 to 0.2%, Cr from 12 to 20, Mn from 1 to 1.5%, and Si is 1.0%.

Martensitic Stainless Steel

This steel has martensitic structure and hence hardness. It can be hardened by quenching. It is used for table wear, surgical instruments, springs, blades of turbines and tools like cutting blades. The composition is C-0.01 to 1.2%, Cr-12 to 18%, Mn-1 to 1.2%, Si-0.05 to 1.0, Ni-1.0 to 2.0%. For surgical instruments 0.75% Mo is added. Free machining quality achieved big additional of 0.75% S.

Austenitic Stainless Steels

This steel has austenitic structure. C is less than 0.2 whereas Cr varies between 16 and 24% while Ni from 8 to 22%. Ni helps stabilizing austenite. Mn and Si, respectively vary between 2 to 10% and 1 to 3%. Addition of 0.15% makes this steel free cutting. The most widely used variety is 18.8 stainless steel which contains 18% Cr and 8% Ni. This steel can be easily cold worked and does not strain harden. It is used for chemical plants, mainly with joints. It is, however, susceptible to intergranular corrosion.

1.18 CAST IRON

Cast iron plays very important role in engineering practice, as it is one of the commonest materials for manufacturing of machines and their parts. It is being used since fourteenth century while steel came in use during 19th century. Casting is a process in which molten metal is poured in a mould and on solidifying the casting of the shape of mould is obtained. General properties of cast iron are :

(a) Cheap material.

(b) Lower melting point (1200^{o}C) as compared to steel (1380-1500^{o}C).

(c) Good casting properties, e.g. high fluidity, low shrinkage, sound casting, ease of production in large number.

(d) Good in compression but CI with ductility are also available.

(e) CI is machinable in most cases.

(f) Abrasion resistance is remarkably high.

(g) Very important property of CI is its damping characteristic which isolates vibration and makes it good material for foundation and housing.

(h) Alloy CI may be good against corrosion.

CI is prepared from melting pig iron in electric furnace or in cupola furnace. Electric furnace gives better quality.

CI contains different elements in addition to Fe. The carbon content of CI is more than 2%. Si Varies between 0.5 to 3.0%. It is very important because it controls the form of C in CI. S content in CI varies between 0.06 to 0.12% and is largely present as FeS, which tends to melt at comparatively low temperature causing hot shortness. Mn inhibits formation of FeS.

Though P increases fluidity of CI – a property helpful for pouring – it has to be restricted to 0.1 to 0.3% because it reduces toughness. P is present in the form of FeP.

Mn in CI varies from 0.1 to 1.0% though such a small Mn does not affect properties of CI. It certainly helps improve upon hot shortness by taking care of S.

Several other alloying elements like Ni, Cr, Mo, Mg, Cu and V may be added to CI to obtain several desirable properties.

CI containing C in form of cementite is called *white cast iron*. Microstructure of such CI consists of pearlite, cementite and ledeburite. If C content is less than 4.3% it is hypoeutectic CI and if C is greater than 4.3% it is hypereutectic CI. White cast iron has high hardness and wear resistance and is very difficult to machine, it can be ground, though. Hardness of white CI varies between 350-500 BHN and UTS between 140-180 MPa. White CI is normally sand cast to produce such parts as pump liners, mill liners, grinding balls, etc.

CI containing carbon in form of graphite flakes dispersed in matrix of ferrite or pearlite is classified as *grey cast iron*. The name is derived from the fact that a fracture surface appears gray. Gray CI differs in %age of Si from white cast iron while C %age is almost same. The liquid alloy of suitable composition is cooled slowly in sand mould to decompose Fe_3C into Fe and C out of which C is precipitated as graphite flakes. Addition of Si, A1 or Ni accelerates graphatisation. The graphite flakes vary in length from 0.01 to 1.0 mm. Larger flakes reduce strength and ductility. The best properties of gray CI are obtained with flakes distributed and oriented randomly. Inoculant agents such as metallic A1, Ca, Ti, Zr and SiC and CaSi when added in small amount cause formation of smaller graphite flakes and random distribution and orientation.

Grey CI is basically brittle with hardness varying between 149 to 320 BHN and UTS of 150 to 400 MPa. Different properties are obtained by varying cooling rate and quantity of inoculant agents. It has excellent fluidity, high damping capacity and machinability. If grey CI is repeatedly heated in service to about 400^{o}C, it suffers from permanent expansion called growth. Associated with dimensional change are loss of ductility and strength as a result of growth. When locally heated to about 550^{o}C several times this material develops what are called fire cracks resulting into failure.

Grey CI is used for *clutch plates*, *brake drums*, *beds of machine tools* and *equipments*, *counter weights in elevator* and *furnace*, *gear reducer casing*, *motor housing*, *pump housing*, *turbine housing*, *engine frames*, *cylinders* and *pistons*.

Iron castings are sometimes cooled rapidly on the surface to obtain white CI structure while inside is allowed to cool slowly to obtain gray CI structure. Such a combination is called *chilled* or *mottled* CI. Metal or graphite chillers are used to chill the casting on outer surface. High hardness and wear resistance on the surface and low hardness and strength at the core are obtained in chilled CI. *Railroad freight car wheels*, *grain mill rolls*, *rolls for crushing ores*, *hammers* etc. are made in chilled CI.

High strength grey CI is obtained by addition of strong inoculating agent like CaSi to liquid alloy before casting process. UTS in the range of 250 to 400 MPa is obtained. This CI is called *meehanite iron* and can be toughened by oil quenching treatment to a UTS of 520 MPa.

If graphite in CI is present in form of nodules or spherods in the matrix of pearlite or ferrite the material is called **nodular cast iron**. The CI has a marked ductility giving product the advantage of steel and process advantage of CI. It is basically a grey CI in which C varies between 3.2 to 4.1%, Si between 1.0 to 2.8% while S and P are restricted to 0.03 and 0.1%, respectively. Ni and Mg are added as alloying elements. *Crank shafts*, *metal working rolls*, *punch* and *sheet metal dies* and *gears* are made out of nodular CI. The defects like growth and fire cracks are not found in this class of iron. This makes it suitable for *furnace doors*, *sand casting* and *steam plants*. It also possesses good corrosion resistance making it useful in *chemical plants*, *petroleum industry* and *marine applications*.

White CI containing 2.0 to 3.0% C, 0.9 to 1.65% Si, < 0.18% S and P, some Mn and < 0.01% Bi and B can be heat treated for 50 hours to several days to produce temper carbon in the matrix of ferrite or pearlite imparting malleability to CI. This class is known as *malleable cast iron* and can have as high as 100 MPs of UTS and 14% elongation. Duet to such properties as strength, ductility, machinability and wear resistance and convenience of casting in various shapes, malleable CI is largely used for automotive parts such a *crank* and *cam shafts*, *steering brackets*, *shaft brackets*, *brake carriers* and also in *electrical industry* as *switch gear parts*, *fittings for high and low voltage transmissions* and *distribution system* for railway electrification.

Addition of alloying elements such as Ni and Cr provide shock and impact resistance along with corrosion and heat resistance to CI. These are called alloyed CI : 3 to 5% Ni and 1 to 3% Cr produces Ni-hard CI with hardness upto 650 BHN and *modified Ni-hard* CI with impact and fatigue resistance is produced by adding 4-8% Ni and 4-15% Cr. *Ni-resist CI* with 14 to 36% Ni and 1 to 5% Cr is alloy CI having good corrosion and heat resistance.

1.19 NON-FERROUS MATERIALS

A typical jet turbine is made up of several metallic materials. It consists of 38% Ti, 12% Cr, 37% Ni, 6% Co, 5% A1, 1% Nb and 0.02% Ta, and others. All of them are non-ferrous and example only goes to show that in engineering practice, the non-ferrous materials are finding increasing applications. They represent, in certain cases, the advantages of high strength and low weight while in some other cases they surpass the mechanical strength of ferrous materials. In certain cases metals like copper and aluminum have no alternative from the wide range of steel and cast iron. Electric conductor and aircraft bodies are the examples. The aluminium alloys are exclusively used for cooking utensils, as building materials and for aircraft bodies. Copper alleys are used as conductor in electric machine, as transmission cables and tubing in heat exchangers. The non-ferrous alloys also show creep resistance and resistance to oxidation at high temperatures. However, steel may continue to dominate the scene for its strength, heat treatability and cost. The cost ratios on per weight basis between other materials and steel are: Ti alloys-62, Cu alloys-8, Mg alloys-13, Al alloys-80, low alloy steel-2.4, stainless steel-5.51, gray castiron-1.22.

A large variety of alloys of A1, Cu, Mg, Ni are used for making several parts of machine. They offer varied advantages of lightweight, favourable weight to strength ratio, machinability, castability and formability. Al alloys are used for their high electrical conductivity, corrosion resistance, good strength, etc. in such applications as electrical conductors, storage tanks, marine parts and air craft parts, etc. Cu and Ti alloys are similarly used in automotive radiators, heat exchanger, electrical machines, condenser, builder's hardware. There are innumerable uses of non-ferrous materials which may include man made plastic materials along with metallic alloys and readers are advised to find uses and corresponding composition of a particular alloy form numerous sources. We take up material requirement of a particular machine element, called bearing. We will take up design of bearings in one of units as we move ahead in our studies but description of materials for one type of two bearings, viz. – sliding contact bearing is taken up in next section.

1.20 BEARING MATERIALS

Bearing is a very important part of machines and materials used for bearings assume great importance. In general it can be said that a good bearing material should possess following characteristics :

(a) It should be strong enough to sustain bearing load,

(b) It should not heat rapidly,

(c) It should show a small coefficient of friction,

(d) It should wear less, having long service life, and

(e) It should work in foundry.

Generally it is expected that the journal and bearing would be made of dissimilar materials although there are examples where same materials for journals and bearings have been used. When the two parts are made in the same material the friction and hence the wear are high.

Cast iron has been used as bearing material with steel shafts in several situations. However, the various non-ferrous bearing alloys are now being used largely as bearing materials because they satisfy the conditions outlined above more satisfactorily.

Bronzes, babbitts and copper-lead alloys are the important bearing materials that are widely used in service. Certain copper zinc alloys, that is brasses, have been used as bearing materials, but only to limited extent. Since brass in general is cheaper, it has replaced bronze in several light duty bearings.

Table 1.3 describes some bearing bronzes.

Table 1.3 : Bearing Bronzes

Bronze and SAE Number	Composition %	Mechanical Properties			Applications
		UTS MPa	YS MPa	% Elong.	
Leaded gun metal, 63	Cu, 86-89; Sn: 9-11; Pb, 1-2.5; P, 0.25 max, impurities, 0.5 max	200	80	10	Bushing
Phosphor bronze, 64	Cu, 78.5-81.5; Sn, 9-11, Pb, 9-11; P, 0.05-0.25; Zn, 0.75 max impurities, 0.25 max	167	80	8	Heavy loads
Bronze backing for lined bearings, 66	Cu, 83-86; Sn, 4.5-6.0; Pb, 8-10; Zn, 2.0; imp, 0.25 max.	167	80	8	Bronze backed bearings
Semi-plastic bronze, 67	Cu, 76.5-79.5; Sn, 5-7; Pb, 14.5-17.5; Zn, 4.0 max; Sb, 0.4 max; Fe, 0.4 max, imp 1.0 max	133	–	10	Soft and good antifriction properties

Bearing bronzes are the cooper-tin alloys with small additions of other constituents. Under conditions of heavy load and severe service conditions, bronzes are especially of great advantages. They possess a high resistance to impact loading and, therefore, are particularly used in locomotives and rolling mills bearings. However, they get heated up fast as compared to other bearing materials, such as babbits. Bronze lined bearings are easily removed and finished bushings are generally available in stocks.

The alloys of tin, copper, lead and antimony are called *babbitts*. The tin provides the hardness and compressive strength to babbitts, copper makes them tough, antimony prevents shrinkage while lead contributes to ductility. Bearing liners are extensively made in babbitts for their better antifriction properties than bronzes.

When babbitt is backed up by a solid metal of high compressive strength it gives good service under high speeds, heavy pressure, impact loads and vibrations. The backing material could be bronze or steel. A thin layer of high-tin babbitt thoroughly fused to a tinned bronze or steel has exceptional load carrying capacity and impact strength. In case of cast iron bearings the babbitt is anchored in place by dovetail slots or drilled holes because babbitt does not fuse with cast iron. Babbitt bearing linings of dependable strength and life are made by pouring molten material into bearing, allowing to solidify and fuse thoroughly and then machining to finished sizes. While the melting point of babbitt varies between 180 and 245^{o}C, depending upon composition, the pouring should be done when metal is in fully fluid state. For example, SAE 10 babbitt has a melting point of 223^{o}C, it should not be poured below 440^{o}C. Some Babbitt materials are described in Table 1.4.

Table 1.4 : Babbitts (White-bearing Metals)

SAE No.	Composition %	Application
10.	Sn, 90; Cu, 4-5; Sb, 4-5; Pb, 0.35 max.; Fe, 0.08 max; As, 0.1, Max; Bi, 0.08 max.	Thin liner on bronze backing
11.	Sn, 86, Cu, 5-6.5; Sb, 6-7.5; Pb, 0.35 Max; Fe, 0.08 max; As, 0.1 max; Bi, 0.08 max	Hard babbitt good for heavy pressures
12.	Sn, 59.5; Cu, 2.25-3.75; Sb, 9.5-11.5; Pb, 26.0 max; Fe, 0.08 max, Bi, 0.08 max.	Cheap babbitt, good for large bearings under moderate loads
13.	Sn, 4.5-5.5; Cu, 0.5 max; Sb, 9.25-10.75; Pb, 86.0, max; As, 0.2 max	Cheap babbitt for large bearing under light load.

Copper-lead alloys, containing a larger percentage of lead have found a considerable use as bearing material lately. Straight copper-lead alloys of this type have only half the strength of regular bearing bronzes. They are particularly advantageous over babbitt at high temperature as they can retain their tensile strength at such temperatures. Most babbitt have low melting point and lose practically all tensile strength at about 200^{o}C. Typical copper-lead alloys contain about 75% copper and 25% lead and melt at 980^{o}C. The room temperature tensile strength of copper-lead alloy is about 73 MPa and reduces to about 33 MPa at about 200^{o}C.

Other Bearing Materials

An extensively hard wood of great density, known as *lignum vitae*, has been used for bearing applications. With water as lubricant and cooling medium its antifriction properties and wear are comparable with those of bearing metals. Lignum vitae has been used with satisfactory results particularly in cases of step brings of vertical water turbine, paper mill machinery, marine service and even roll neck bearing of rolling mills.

More recently, in such cases where use of water as lubricant is necessary, especially if sand and grit are present soft vulcanized rubber bearings have been used. A soft, tough, resilient rubber acts as a yielding support, permitting grit to pass through the bearing without scoring the shaft or the rubber.

Graphite, which is a form of carbon, has been used as lubricant in bronze bearing but bearing made entirely of carbon are being used. At low speeds carbon bearings can carry pressure as high as 6.8 MPa.

Synthetic and natural composite materials, plastic and reinforced plastic are being used as bearing material. However, their characteristics are not well established as yet. Powder metallurgy bushing permits oil to penetrate into the material because of its porosity.

1.21 PLASTIC

Plastic have gained immense popularity as engineering materials. These organic materials, also know as polymers lack strength of metals and can not stand temperature higher than 150^{o}C yet they offer the advantages of convenient manufacturing into several shapes and sizes right from molten state. They can be machined but cannot be formed from solid state as metals can be done. The plastics have good surface finish; they are not corroded and are not biodegradable. Due to the last property the plastics are difficult to dispose off. These materials do not conduct electricity hence are used for making electrical fittings. They are also bad conductors of heat, hence are used as insulators in and housing for instruments and equipment, which produce heat inside. The low density is a strong property of plastic. Heaviest plastic has specific gravity of 2.3 against 7.8 of steel and 2.7 of aluminum. The plastic content of automobile has gradually increased from 12 kgf in 1960 to 100 kgf in 1980 and to 150 kgf in nineties. The plastic replaces several times its weight in metals and automobiles thus become lighter. The plastics offer advantages like low cost, elimination of finishing processes, simplified assembly, reduction of noise and vibration.

Polymers are classified into three broad divisions, viz. plastics, fibres and elastomers. *Thermoplastic resins* are usually referred to as plastics and have the property of increasing plasticity, i.e. ability to deform plastically with increasing temperature. They have long chain structure. *Thermosetting* resins on the other hand have three-dimensional network of primary bonds. They do not soften on heating, they become harder due to completion of any left over polymerization reaction on heating.

Thermoplastics in common use are low density and high density polyethylene, rigid chlorinated polyvinyl chloride (PVC), polyproylene, ABS, Acrylic and polytetrafluoroethylene (PTFE). Most of them have maximum use temperature of about 100^{o}C. Only PTFE can be used at higher temperature upto 250^{o}C. This material is used for bearing. Polyethylene is used in automobile interiors. ABS is acronym for a family of thermoplastics made of *acrylonitrile*, *butadiene* and *styrene*. ABS is used for making body of business machine, telephone housing and pipe and fitting in drain waste.

Thermosetting plastics in large number are made and used in industry. They can resist little higher temperature than thermoplastics have higher insulation against heat and electricity and have better dimensional stability. Malamine is very popular in consumer items – particularly dinner sets. Most of these plastics like phenolic, epoxy and malamine are used as bonding agents in plywood and particle boards. Epoxy is also favoured coating surfaces for prevention of corrosion, improving surfaces and as primer on automobile body.

Elastomers are the materials, which deform from double the length to ten times original length. Rubber is an elastomer, which is obtained in liquid form trees but converted into solid by process of vulcanisation. The use of rubber as shock absorber or vibration dampner is well known. Styrenebutadiene is an artificial rubber.

1.22 MANUFACTURING CONSIDERATIONS

The subject concerns with the designer’s intimate understanding of methods of manufacturing. Any designed object can be given required shape by different methods of manufacturing and therefore the designer will have to specify the methods wherever he prefers a particular method. The selected material will have to be given a renewed consideration for manufacturing. For example, from stress consideration a gear wheel made in stainless steel may be better and smaller but its machining and teeth cutting will cost more as compared to medium carbon steel. The change of tools during machining operation may cost. Even in modern computer numerically controlled machines bringing required tool in position will not be cost free besides adding cost at programming stage. It is therefore, to be considered by the designer if the radit of fillets and shoulders may be kept same or they must be different. If the keyways can be cut in one setting in more than one location the cost may be reduced for shaft manufacturing. The pulleys can be cast or fabricated. The process needs to be examined on the basis of weight and cost. Sometimes an increased cost may be tolerated if weight is reduced. Similarly a welded structure from mild steel for the housing of a gear reducer may have to be compared with the cast structure either in cast iron or steel.

Casting in sand mould or permanent may be a question before designer in many cases. Although a permanent mould may appear to be a better choice for large number yet the use of pressure and conditions of melting from batch to batch and high initial cost may be prohibitive. Casting in general may pose several problems concerning rate of cooling, change of thickness, intricate nature of product and any subsequent machining need to be considered. The designer must consider that in casting metal at every location (i.e. a flat wall and a corner) do not cool at the same rate. If material in adjacent location cools differentially residual stresses are produced. They may even cause cracking. Such consideration may require basing thicknesses and radii not only on strength but also upon rate of cooling. The residual stress may not only cause reduction of strength but may result into undesirable deformation during subsequent machining. Large thicknesses or diameter in casting solidify over a much longer period and hence are prone to have coarse structure and lesser strength. The designer may have to assign a proper heat treatment to refine internal grain structure.

The designer ought to take note of the fact that in forging the deformation is concentrated more on the surface and inner material is not worked. In hot forging process therefore the structure of material is more liable to be refined on the surface creating non-uniformity of structure in the entire body. The refinement is often advantageous with improved strength, though defects are also some times created in severely worked material. On the other hand process like rolling, extruding and pressing are not confined to only surface in their effects. They result in uniform structure in the end. Cold processes are performed on softer alloys but stronger materials like steel are often worked hot. Cooling will eventually follow which if not controlled and slow can result in residual stresses. Anticipating the cooling stresses the designer may recommend the rate of cooling.

Plastic parts are often cast in moulds made individually or in pressure die cast. The design must keep minimum thickness within limit, not below 4.5 mm. The pressure die cast plastic may not require finishing by machining but cast parts need machining and hence proper thicknesses are to be provided. Very few parts of plastic are made by machining but designer must take care of temperature rise during cutting process. Slight rise in temperature may cause material to join by the side of machine surface. Internal threading has to be performed much more carefully. They can be better made during casting, 13 threads per cm can be cast easily. The colour of casting is difficult to maintain which creats problem in assembling parts. To avoid mismatch the surfaces may be spotted or streaked.

SAQ 3

(a) Classify steel and state application of stainless steel.

(b) Why is medium carbon steel preferred for making machine parts?

(c) What heat treatments are given to medium carbon steel? What are the benefits from such treatments?

(d) Differentiate between steel and CI. Contrast properties of plain C steel and CI and state use of CI.

(e) How could you make CI ductile?

(f) Classify CI and mention uses of each type.

(g) Mention non-ferrous materials, which are used in machines and structures. What are bearing materials?

(h) Mention compositions of phospher bronze, semi-plastic bronze and a babbit metal, which are used on bronze backing.

(i) Describe non-metallic materials that are used as bearing materials.

(j) Distinguish between two classes of plastic. Mention advantages of plastics as engineering material and describe at least five uses.

(k) What manufacturing consideration a designer has to make? Give examples of cutting, casting and forging processes in respect of metals. Which of these processes will be applicable to parts made in plastics?

1.23 HEAT TREATMENT

Heat treatment is the process through controlled heating and cooling of metal to induce desired properties. The process causes changes in the structural arrangements in the structure of the metal. The structure of an alloy is made up of different phases, which precipitate from molten mixture depending upon the rate of cooling. The reader may like to improve familiarity with phases by revising parts of Material Science and we will ignore such details in this text. The medium carbon steel, high carbon steel and alloy steel are especially sensitive to heat treatment. Several handbooks describe heat treatments of several classes of steel. It will suffice here to give brief description.

Annealing

The steel is heated slightly above the critical temperature cooled slowly, often keeping material in the furnace and shutting off heat. The annealing will result in uniform grain structure, reduced strength and hardness and increased ductility. Internal stresses which might have resulted from previous treatment (mechanical or thermal) are removed by annealing.

Normalising

The heating is same as in annealing but the metal is cooled faster by placing it out of the furnace. This treatment removes effect of any previous heat treatment and prepares the metal for further treatment.

Quenching

Quenching is rapid cooling at different rates. It is achieved by immersing the heated metal from above critical temperature into cold water or any other cooling medium. The quenching results in high hardness. Steels develop high hardness by retaining iron carbide which forms at critical temperature and does not find time to decompose as the cooling occurs very fast. Cooling media such as ice water, cool water, oil, hot oil, molten salts and molten lead are used depending upon desired cooling rate. The result of quenching is increased hardness and strength and decreased ductility while improper quenching may result in surface cracks.

Tempering

Some of the lost ductility due to quenching is restored through tempering. In this process the quenched metal is heated to some pre-decided temperature and metal is soaked for some time. The range of temperature used for steel is generally from 200^oC to 600^oC and cooling is done in the furnace. The tempering treatment also helps remove internal stresses, which are created due to hardening treatment. UTS, YS and hardness reduce while % elongation, impact strength increase due to tempering at temperatures of 300^oC and above. There is little effect on these properties below 300^oC.

Casehardening

Casehardening is a surface hardening process, often applied on low carbon steels which do not responded to heat treatment. The process consists in packing the steel piece in charcoal powder and covered from outside. The charcoal powder cuts of air. When heated in a furnace the carbon from charcoal penetrates the surface and on quenching the carburized surface retains hardness. The process is also known as carburizing and steels containing 0.1 to 0.25% C are easily carburized. The mechanism of hardening is two fold. Firstly the carbon of iron is very hard and due to quenching it is retained in the surface. Secondly due to increase in C in the surface layer, the residual compressive stress is produced. Surface hardening is advantageous in case of gear teeth since the inner bulk material still remains softer and tougher and thus combined advantage of harder surface and tougher core mereases the life.

It may be pointed out here that surface is the weakest region of the material in any form. Fatigue cracks initiate late in hard surface and the wear resistance in also better.

Besides carburizing by packing there are other methods of surface hardening of steels. In gas carburizing the metal is heated in gas atmosphere in controlled manner to avoid oxidation and permit absorption of the gas in the surface. The gasses used for the purpose are natural gas, coke oven gas, butane or propane. In the process called cyaniding the steel part is heated covered with the mixture of potassium ferrocyanide and potassium bichromate. In some cases the mixture is replaced by powdered potassium cyanide. A very hard case is produced by cyaniding. A thin hardened layer is produced by immersion of part in the heated cyanide solution. Natriding is yet another method of case hardening. It consists in heating the part in the presence of dissociated ammonia in the range of 570^oC to 610^oC.

The surface hardness of 60 Rockwell C associated with core hardness of 33 to 38 RC is produced by carburizing. Nitriding can produce surface hardness upto 70 RC and core hardness of 27 to 47 RC. Natrided parts can be tempered. All steels can be nitrided but those containing aluminum develop very high hardness. Nitralloy 135 and 135 modified is a highly preferred material for gears. It contains C-0.35/0.41, Mn-0.55, Si-0.3, Cr-1.20/1.60, Al-1.00, Mo-0.20/0.35. This material develops surface hardness of 65-70 and core hardness of 30-36 RC. AISI 4340 (C-0.40, Mn-0.70, Si-0.30, Cr-0.80, Mo-0.25, Ni-1.00) and AISI 4140 (C-0.40, Mn-0.90, Si-0.30, Cr-0.95, Mo-0.20) are two other steels, which are nitrided and used to make gears.

The high frequency current when passed through body of a part results in surface heating. Once heated this way, the part is quenched in water. This treatment resulting into hardened surface is called *induction* hardening for which steels containing 0.4 to 0.5% C is good.

SAQ 2

(a) Sketch $\sigma - \varepsilon$ diagram for mild steel and compare with $\sigma - \varepsilon$ diagram of other ductile material.

(b) Define elastic constants for isotropic material and give their correlation.

(c) Define hardness and state how is the hardness of metal measured. How is UTS related to hardness?

(d) What do you understand by fatigue strength and enumerate factors that affect fatigue strength?

(e) Describe three stages of creep.

(f) What is the use of *information* obtained from impact test?

1.24 SUMMARY

Design is a decision making process in which a designer formulates the problem in clear terms, finalies several alternatives, selects the best solution, analyzes the best solution, selects material and determines dimensions. The process allows for modification to achieve improvement at each step. The results are presented in form of a report which will necessarily contain drawings, instructions for heat treatment, special processes, etc. The designer of machine is required to have comprehensive knowledge of mechanical engineering so that he understands clearly the various forces that act upon several parts of machines and circumstances in which the machine and its parts have to perform. The designer must be conversant with methods of analyzing stress through theoretical, experimental and numerical methods. He may depend upon one or two of them so that he can analyze a part completely. The designer should be sensitive to human needs, capabilities and sensibilities so that his design fulfills the objective, can be operated and maintained by common person and pleases him to possess.

The engineering materials are used to make machine parts and there exist several of them. They are all used to serve specific purpose based upon properties. The properties that designer of machine will use will be related to strength and material behaviour under load. The properties normally needed by machine part are yield strength, ultimate tensile strength, percent elongation, toughness and resilience. They are determined from tension test on universal testing machine. The hardness and impact strength, though not used in direct calculation are used for selecting materials for specific purposes. Fatigue and creep are behaviours and conditions of varying load and constant load acting over a long period respectively. While latter is a condition to be considered only in case of higher temperatures, fatigue is the type of loading to which all machines, machine parts and structure are subjected. Fatigue strength, which is defined as the stress at which material will never fail, no matter how many times that stress varies, then appears to be the only important property on the basis of which machine parts must be designed. However, while on one hand its determination is difficult, on the other hand it has a definite relationship with ultimate tensile strength (UTS). Hence UTS can be used as design basis after fully understanding several factors that influence fatigue strength.

Out of several metallic materials steel is the most common choice because of such reasons as easy availability, good strength, workability, ductility and heat treatability. Cast iron is another good ferrous material preferred to produce casting for its availability, hardness, compressive strength and damping properties. Plain carbon steel, containing Mn, Si, S and P in addition to carbon with large proportion of iron is divided into three types, viz. low carbon (0.08 to 0.27% C), medium carbon (0.28-0.57% C) and high carbon (0.58 to 1.2% C) steels. Additionally Cr, Mo, Ni, V, Co, Al, Cu, etc. may be added to obtain series of alloy steels which have better mechanical properties with increased cost. Three types of stainless steels (ferritic, austenitic, martensitic) are in common use for their corrosion and oxidation resistances. Each alloying element imparts particular characteristic to steel. Steel of all types are heat treatable except low carbon steel. They, however, can be case hardened like medium carbon and some alloy steels. Plastics are being used for making parts of machines because they are light in weight. However, they cannot compete with metals in strength. Non-ferrous metals which are mainly alloys of aluminum, copper, zinc, magnesium, nickel, etc. are used for specific reasons of weight and properties. They are invariably used in sliding bearings.

The designer has to consider the available manufacturing processes and effects of such processes on final product.

1.25 KEY WORDS

Mechanical Properties : Mechanical properties of the metals are those which are associated with the ability of the material to resist mechanical forces and load.

Strength : It is the ability of a material to resist the externally applied forces without breaking or yielding.

Stiffness : It is the ability of a material to resist deformation under stress.

Elasticity : It is the property of a material to regain its original shape after deformation when external forces are removed.

1.26 ANSWERS TO SAQs

Refer the preceding text for all the Answers to SAQs.