# 1

# GENERAL INTRODUCTION

## 1.1 MANUFACTURING PROCESS

Manufacturing is the production of work pieces having defined geometric shapes. It is one of the most important production technologies. Other technologies are process technology (production of chemicals etc.) and energy technology (production of electricity etc.).

## 1.2 CLASSIFICATION OF MANUFACTURING PROCESSES

Manufacturing processes can be classified in six groups. They are :

### 1. PRIMARY SHAPING OR FORMING PROCESSES

Primary shaping or forming is manufacturing of a solid body from a molten or gaseous state or form an amorphous material. Amorphous materials are gases, liquids, powders, fibres, chips, melts and like. A primary shaping or forming tool contains a hollow space, which, with the allowance for contraction usually corresponds to the form of the product. Here, cohesion is normally created among particles. Some of the important primary shaping processes are;

1. Casting. 2. Powder metallurgy. 3. Plastic technology.

### 2. DEFORMING PROCESSES

Deforming processes make use of suitable stresses like compression, tension, shear or combined stresses to cause plastic deformation of the materials to produce required shapes without changing its mass or material composition. In forming, no material is removed; they are deformed and displaced. Some of the forming processes are;

1. Forging.
2. Extrusion.
3. Rolling.
4. Sheet metal working.
5. Rotary swaging.
6. Thread rolling.
7. Explosive forming.
8. Electromagnetic forming.

## 3. MACHINING / REMOVING PROCESSES

The principle used in all machining processes is to generate the surface required by providing suitable relative motions between the workpiece and the tool. In these processes material is removed from the unwanted regions of the input material. In this, the work material is subjected to a lower stress as compared to forming processes. Some of the machining processes are ;

1. Turning.
2. Drilling.
3. Milling.
4. Grinding.
5. EDM.
6. ECM.
7. Shaping and planing.
8. Ultrasonic machining.

## 4. JOINING PROCESSES

In this process two or more pieces of metal parts are united together to make sub-assembly or final product. The joining process can be carried out by fusing, pressing, rubbing, riveting or any other means of assembling. Some of the important joining processes are ;

1. Pressure welding.
2. Diffusion welding.
3. Brazing.
4. Resistance welding.
5. Explosive welding.
6. Soldering.

## 5. SURFACE FINISHING PROCESSES

These processes are utilized to provide intended surface finish on the metal surface of a job. By imparting a surface finishing process, dimension of the part is not changed functionally ; either a very negligible amount of metal is removed from or certain material is added to the surface of the job. Surface cleaning process is also accepted as a surface finishing process. Some of the surface finishing processes are :

1. Plastic coating.
2. Metallic coating.
3. Organic finishes.
4. Inorganic finishes.
5. Anodizing.
6. Buffing.
7. Honing.
8. Tumbling.
9. Electro-plating.
10. Lapping.
11. Sanding.

## 6. MATERIAL PROPERTIES MODIFICATION PROCESSES

In this type of process, material properties of a workpiece is changed in order to achieve desirable characteristics without changing the shape. Some of the processes are:

1. Heat and surface treatment. 2. Annealing. 3. Stress relieving.

## 1.3 TYPES OF PRODUCTION SYSTEMS

It is worthwhile to mention here the types of production since the choice of production type dictates the machine requirements, organizational system and to a large extent, layout, planning and inventory subsystems.

There are three main types of production, namely *job, batch* and *flow* or *process* production. The simplest way is to classify production processes by lot size, namely single-unit production, small lot production, medium lot production, large lot production, and continuous production.

The second method of classification is to determine whether the production process is continuous or intermittent. This is apparently a simpler method compared with the first one, but completely ignores lot size or the scope of production.

The third classification comprises three categories, namely small-scale production of a large variety of products, medium-scale production of a limited range of products, and a large-scale production of a small variety of products. Obviously, this method is related to the number of product types and production lot sizes, and is an effective means of analyzing modern production management.

The fourth classification is related to the size of the production system expressed through the number of employees or the amount of fixed assets involved, namely small production unit employing less than 20 workers, medium-small having 21 to 300 workers, medium with 301 to 1,000 workers and large with 1001 to 10,000 people, and a giant corporation employing more than 10,000 people.

## 1.4 PLANT LAYOUT

Plant layout is the arrangement of the physical elements of facilities (or machines / equipment) which make the product or service. Thus facilities layout is the overall arrangement of machines, men, materials handling, service facilities, and passage required to facilitate efficient operation of production system.

## 1.5 OBJECTIVES OF PLANT LAYOUT

The primary *goal* of plant layout is to maximize profits by the arrangement of all plant facilities to the best advantage of the total "manufacturing equation" – men, materials, machines, and money in fulfilling this goal. Objectives of plant layout are :

1. Minimize materials handling.
2. Reduce the manufacturing cost.
3. Afford economically output quantity and quality.
4. Maintain flexibility of arrangement and of cooperation to meet changing needs.
5. Maintain high turnover of work-in-process.
6. Reduce investment in equipment.
7. Make effective and economical use of floor space.
8. Utilize equipment and facilities in the best possible way.
9. Reduce work delays and stoppages.
10. Promote effective utilisation of manpower.
11. Avoid back-tracking.

## 1.6 TYPES OF LAYOUT

The pattern by which departments and facilities within departments are arranged may be viewed either in terms of work flow or the function of the productive system. According to *work flow pattern,* four basic types illustrated in Figures 1.1 and 1.2 are used in manufacturing operations. These are :

1. Fixed-position layout.
2. Product or line layout.
3. Process or functional layout.
4. Group layout.

Group layout is based on group technology philosophy is accepted as the fourth type of layout. In this type of layout an existing functional layout is converted to group layout to derive all benefits of product layout.

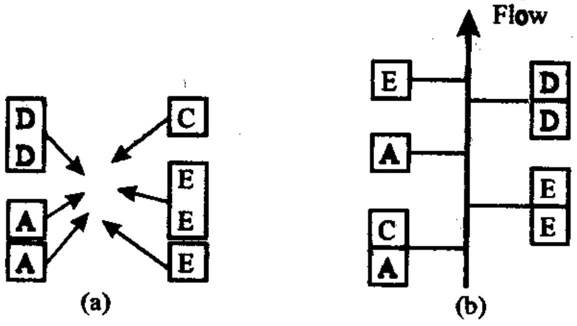

**Figure 1.1 Basic types of layouts**
(a) Fixed layout, (b) Product layout

## 1. FIXED POSITION LAYOUT

In fixed position layout, the product [Fig. 1.1(a)] by virtue of its bulk or weight remains at one location. The equipment, personnel required for the product manufacture are moved to the product, rather vice versa. This layout is observed to be used under following conditions :

1. When material forming or treating operation requires only tools or simple machines.
2. When only one or a few pieces of an item are to be manufactured.
3. When the cost of moving the major piece of material is high.
4. When the skill of workmanship lies in the abilities of workers or when it is designed to fix the responsibility of product quality on one workman or group of workers.

Examples of this type of layout are : sound stages on a movie lot, aircraft, locomotive, ship assembly shops, shipyards, etc.

*Advantages* of fixed-position layout are :

1. Handling of major assembly is reduced.
2. Highly skilled operators are allowed to complete their work at one point and responsibility for quality is fixed on one person or assembly crew.
3. Frequent changes in product design and in sequence of operations are possible.
4. The arrangement is adopted to variety of products and intermittent demand.
5. It is more flexible almost in all respects.

## 2. PRODUCT LAYOUT

In product layout, the equipment or assembly work stations are arranged according to the progressive steps of sequence or operations by which the product is made. Product layout is used advantageously in the continuous-production system where :

1. The number of end products is small.
2. The parts are highly standardized and interchangeable.
3. The volume of production for any item is high or large.
4. The demand of the product is fairly steady.
5. The continuity of material flow can be maintained.

This type of layout is exemplified in automobile assembly, food processing, and furniture manufacture.

*Advantages* of this type of layout generally include :

1. Reduced handling of material by transfer machines or conveyors.
2. Reduced amount of material in process, allowing reduced production time, and lower investment in materials.
3. More effective use of labour through :
    - (i) Greater job specialization.
    - (ii) Ease of training.
    - (iii) Wider labour supply.
4. Easier control.
5. Less inspection, less work-in-process, less floor area, and smaller aisles.

*Disadvantages* of product layout include :

1. Higher initial equipment investment.
2. Greater vulnerability to work stoppage.
3. Greater inflexibility due to changes in design, making it more costly.
4. Greater boredom due to highly repetitive nature of work.

## 3. PROCESS LAYOUT

In process layout, all operations of the same type are grouped according to the general function they perform, without regard to any particular product. Conceptually, same type of operations are performed in the same area. For example, all drilling machines may be grouped together in one area, all milling equipment will be in another work center, and work involving spot welding is still another, etc. Refer Fig 1.2.

The process layout is used advantageously where :

1. Volume is low.
2. Variety of products is many.
3. The demand for the product is small or intermittent.
4. General-purpose, low-cost machines are desirable.
5. Machines or processing producing unwanted noise, vibration fumes, or heat can be located in isolated areas.

This type of layout is exemplified in custom jobshop, department stores, hospitals, etc.

*Advantages* of this type of layout are :

1. Better machine utilisation allows lower machine investment.
2. Adaptable to a variety of products and to frequent changes in sequence of operations.
3. Readily adaptable to intermittent demands.
4. Makes easier the continuity of product in the event of :
   (i) Machine break-down.
   (ii) Storage of materials.
   (iii) Absent of workers.
5. Permits easier maintenance.
6. Allows incentives pay system to individual workers to raise the level of their performance.

*Disadvantages* of process layout are :

1. Operations cost per unit may be higher–often much higher because of the slow operation of the general purpose machines used.
2. Work routing, scheduling, and cost of accounting are costly due to separate costing of every new order.
3. Materials handling and transportation costs are high since products follow different routes every time and use of conveyors becomes uneconomical.
4. Inventories of materials in process are high and large storage space is required because of slow movement of materials.
5. Difficult to keep a good balance between labour and equipment needs.

### 4. GROUP LAYOUT

In group layout, the existing job shop/batch manufacturing shop is partitioned in a few groups of machines where each group produces its associated families of components. Group technology (GT) philosophy uses similarity of components from the processing point of view to create component families. By using the philosophy, a job-shop is transformed into a group technology environment which facilitates optimization of production scheduling.

The essence of GT makes use on similarities in recurring tasks in three ways.[1]

1. By performing similar activities together thereby avoiding wasteful time in changing from one unrelated activity to the next.
2. By standardizing closely related activities thereby focusing only on distinct differences and avoiding unnecessary duplication of effort.
3. By efficiently storing and retrieving information related to recurring problems thereby reducing the search time for the information and eliminating the need to solve the problem again.

Fig. 1.2 shows how a job shop can be partitioned to GT shops. It can be noted that the four components are the representative components of the component families.

*Advantages* of the group layout are :

1. Reduction in machine set-up time and cost.
2. Reduction in material handling cost.
3. Elimination of excess work-in-process inventory which subsequently allows the reduction in lot size.
4. Reduction in through-put time.
5. Simplification of production planning functions, etc.

*Disadvantages* of the group layout are :

1. Change of the existing layout to GT layout is time consuming and costly.
2. Inclusion of new components in the existing component families requires thorough analysis.
3. Change of input component-mix may likely to change cell structure.
4. Change in batch-sizes may change number of machines for any machine type.

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[1] Hyer N.L. and Wemmerlöv V., Group Technology and Productivity. Harvard Business Review. July-August, 1984, p140-149.

5. Existence of a large number of exceptional components leads to complexity in machine loading. Exceptional components are those which are processed by more than one machine groups.

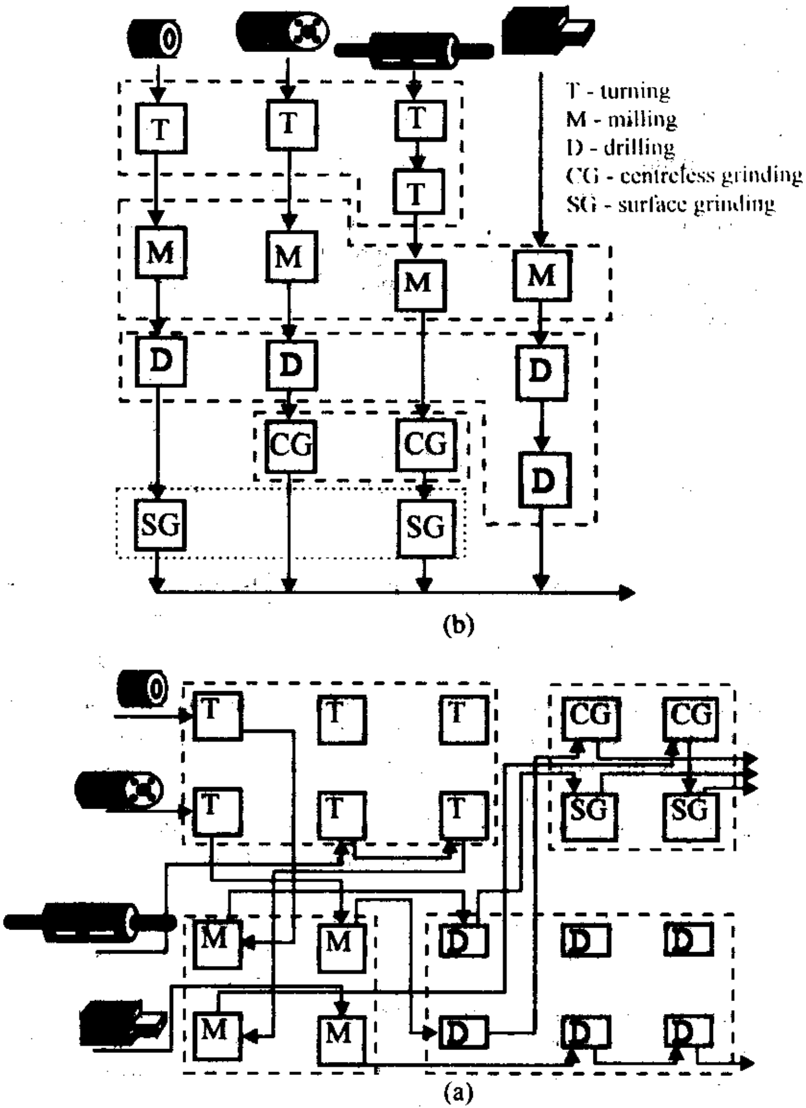


**Figure 1.2 Types of layout**

(a) Basic type : process layout. (b) Group layout

## 1.7 MANUFACTURING AND BASIC DEFINITIONS

***Manufacturing*** is a collection of interrelated activities that includes product design, documentation, material selection, planning, production, quality assurance, management and marketing of goods. The aim of manufacturing activities is to convert raw materials into finished goods on a profitable basis.

***Productivity:*** The dictionary meaning of the *productivity* is "the quality or state of being productive". This has originated from the understanding of the meaning of *productive efficiency* that is responsible for the growth of the economic condition of any industry or industries as a whole resulting in the prosperity of the society for improving the standard of living of its people. Productivity is the output-input ratio within a time period with due consideration for quality. In short,

$$\text{Productivity} = \frac{\text{output}}{\text{input}} \quad \text{or} \quad P = \frac{O}{I}$$

This concept of productivity implies effectiveness and efficiency of individual and organisational performance.

Different techniques of productivity improvement may be classified into five basic types.. These are :

1. Employee-based techniques
2. Task-based techniques
3. Technology-based techniques
4. Material-based techniques
5. Product-based techniques

***Interchangeability:*** Interchangeability refers that any part from a lot will fit to its counter parts. This is accomplished by establishing tolerances for part dimensions that take into account the manufacturing tolerance of mating parts. The result of design for interchangeable parts is interchangeable assembly. Assembly costs then become much lower than they would be if workers had to select combinations of mating parts that fit.

***Just-in-time (JIT) Management :*** Just-in-time management, also known as *synchronous manufacturing, lean production* and *stockless manufacturing* is a Japanese management philosophy which draws the attention of every modern manufacturing planners. The JIT philosophy evolves from three principles: reduction of production cost, elimination of waste and the recognizing workers abilities. The JIT strives to reduce *work in process* (WIP) by producing only the minimum number of required parts. It has been described as the *demand pull* rather than a *schedule push*. This description is based on the pulling action of KANBAN (a kind of *visible record* or *card*), the production control system used to ensure that the right amount of parts is made at the right time. In a JIT system, parts or components are not produced until these are needed by the downstream work-centres. The subassembly and parts requirements are actually determined on the final assembly line and passed upstream to supply work centres. This pull system works because of the commitment to many other elements that make up the JIT philosophy.

## 1.8 AUTOMATION, MECHANIZATION, CAD, CAM AND CIM

***Automation and Mechanization :*** *Automation* refers to the situation where a machine (or group of machines) replaces a human function or attribute. *Mechanization* refers to the preliminary automacity, which includes semiautomatic machines.

Automation in manufacturing can be classified as :

1. Fixed position automation, and
2. Soft automation.

In *fixed* (position) *automation*, the sequence of processing operations is fixed by the equipment configuration. This type of automation is achieved by cams, gears, wiring and other hardware. This configuration cannot be easily changed over quickly from one product types to other.

High production rates and high initial investment is the prerequisites of this type of system. Transfer line / machines, automatic screw machines, automatic assembly lines are the few examples.

*Soft automation* can further be divided in two types : ***programmable*** and *flexible*. In programmable automation, the production system is capable of manufacturing a variety of product types through numerical programming. However, changeover time, from manufacturing one type to the other type of component, cannot be eliminated. A numerical control machine is the example of this type. Generally a batch of components is produced at a time till the changeover takes place. Production rates in programmable automation are generally lower than that of fixed automations.

In flexible automation, the changeover of the equipment for manufacturing different component is very quick and automatic. The programming of the machine / facility is done off-line. In this type a mixture of different products can be produced one after another without any delay in between. Flexible machining system / centre is one such example of flexible automation.

Advantages of automation :

1. Increased productivity due to high throughput.
2. Lowering the labour costs.
3. Safety in processing.
4. Efficient utilisation of materials.
5. Reduction of in-process inventory.

***Computer-Aided Design (CAD)*** is the application of computer hardware and graphics software to aid or enhance the product design from conceptualization to documentation. In utilizing CAD, the computer draws pictures on the video screen or computer controlled cathode ray tube (CRT) of what the engineer has designed. The sophisticated CAD software is able to draw lines between points, creating a three-dimensional drawing that can be rotated to show all sides of the design. As such, CAD can speed up the normally slow and laborious work of drafting.

***Computer-aided Manufacturing (CAM)*** is the implementation of a wide range of automation technologies. It is the effective use of computer hardware and software in planning, management and control of production of an enterprise.

***Computer Integrated Manufacturing (CIM)*** is the integration of all aspects of manufacturing enterprise through the use of integrated systems and data communications coupled with new managerial philosophies that improve organisational and personal efficiencies. In a CIM, flexible automation of all manufacturing activities is realised. It represents the direction of the development of modern manufacturing.

Potential benefits of CIM are :

1. Improved customer service.
2. Improved quality.
3. Reduce inventory level.
4. Lower total costs.
5. Increase productivity.
6. Lower in WIP inventory.
7. High through-put.

## 1.9 INDUSTRIAL SAFETY

Accidents occur unexpectedly causing injury or loss to men and machines in industry. Not only the losses are direct (examples; compensation to the worker, medical expenditures etc.) but can be indirect also (loss of time of the co-workers, demoralization to the group, training of new worker if the injured worker is to be replaced etc.).

## CAUSES OF ACCIDENT

A large number of accidents can be avoided if proper safety rules are followed. Some of the causes of accidents are listed below :

1. Violation of safety rules and not using safety devices.
2. Improper use of gadgets and machine controls.
3. Ignorance of the system operation.
4. Unsafe working conditions.
5. Monotony and work-relating stresses.
6. Wear and tear of the functional components.
7. Organic diseases etc.

Two emotional factors that have been found to be related to accidents in many of the work situations are general emotional maturity and emotional conditions of the workers at the time of accidents. Mental ability is an important personal factor that has been co-related to accident frequency. For some jobs a certain minimum mental ability level is required if the operator is to escape dangers that is generated from the operation.

Another factor that is co-related to the accident-proneness of an individual is his lower perceptual and higher muscular speed.

## PREVENTIVE MEASURES

The following safety measures are only a few of the otherwise long list.

1. Use of the proper safety guards for reciprocating machine components (e.g. drop hammers, paper cutters etc.)
2. Fencing of dangerous and rotating parts like revolving shafts.
3. Incorporating safety devices (safety valves / facilities.)
4. Rigid construction of heavy items like hoists, cranes etc.
5. Proper insulation of electric wire and earthing of electric appliances.
6. Wearing appropriate safety shoe and other necessary items for body protection.
7. Maintenance cleanliness of shop floor.
8. Removal of metal chips with proper protection.
9. Avoiding fire hazard.

## ELECTRICAL SAFETY

Based on experience, a number of rules and regulations have been framed for handling of electrical appliances. If a person receives electric shock, mild or serious, directly or indirectly, the same must be reported as an electrical accident. In industry, an inquiry is normally ordered for every electrical accident. The following table shows the effect of electric current on human system.

**TABLE 1.1** EFFECT OF ELECTRIC CURRENT ON HUMAN SYSTEM

| *Electric current* | *Effect* |
|---|---|
| 1 to 8 ma | Perceptible but not painful |
| 8 to 15 ma | Painful shock ; muscular control is not lost |
| 15 to 20 ma | Painful shock ; muscular control is lost |
| 20 to 50 ma | Severe muscular contraction ; breathing difficult |
| 50 to 100 ma | Ventricular fibrillation ; a heart condition that results in instant death |
| 200 ma and above | Severe burns, clamp down the heart and stop it during the shock. This prevents the ventricular fibrillation. |

Source : Maintenance for Reliability, BVS Rao, Media Promoters, Bombay, 1980.

All items carrying electricity / having electric potential will have to be properly insulated. As the insulation have specific dielectric strength or voltage withstand capacity, the working voltage must, therefore, be kept substantially below the breakdown value. Ageing of insulation reduces the withstand capacity and should not be allowed to leak current. Switching contacts and point contacts should be checked periodically to avoid sparking and point heating. The following preventive measures must be followed.

1. All metallic parts, externally accessible must be earthed.
2. Defective and worn-out fittings must be replaced promptly.
3. Inflammable materials should not be kept near electric appliances, live wires or electric control panels.
4. Safety devices like fuse, circuit breakers over-tripping switches must be used when required.

5. Untrained persons should not be allowed to repair electrical faults.
6. Safety belts, helmet, rubber gloves, boots with rubber soles, and other safety items must be supplied to electric mechanics.
7. Standards of safety items must be maintained as per norms.
8. Avoid overloading any electric circuit.
9. Disconnect the electric appliances from main supply when not in use.
10. Avoid touching metal case of any electrical apparatus when it is in operation.

## FIRE SAFETY

Fire accidents cause enormous damage to properties, manpower and materials. Fire accidents can be classified in several ways. One such classification is shown in Table 1.2

It can be noted that the origin of fire is combustion. The three factors for combustions are ;

1. Presence of oxygen.
2. Availability of combustible materials.
3. Rise of temperature to the ignition point for the material.

The causes of fire accidents can be ;

1. Electric-short circuit.
2. Carelessness and ignorance.
3. Spontaneous combustion.
4. Riots, arsons, rivalry etc.

Prevention of the fire can be in the following direction.

1. Preventing spreading of fire by covering it with incombustible material.
2. Rescuing the affected persons from the spot.
3. Cooling ignition point of combustible items.
4. Taking suitable precautions and educating the workers about the possible hazards out of the consumables that spread fires.
5. Color coding of pressure vessel containing combustible fluids.
6. Maintaining fire extinguisher and water points in shop floor for proper precautions in case of fire hazards.

## 1.10 FACTORIES ACT AND ACCIDENTS

Various acts relating to accidents are spelt out in Workmen's Compensation Act-1923. The factories Act-1948 and Fatal Accidents Act-1855.

TABLE 1.2 CLASSIFICATION OF FIRE ACCIDENTS

*Accidents*

| *Indoor* | *Outdoors* | *Basic causes* | *Organizational defects* |
|---|---|---|---|
| • Petrochemical & fertilizer plants<br>• Manufacture of explosives & pyrotechnics<br>• Factories and workshops<br>• Construction premises<br>• Hospitals and schools<br>• Hostel and clubs<br>• Offices and shops<br>• Warehouses and storage depots<br>• Homes and dwellings<br>• Wood structures, thatched huts<br>• Temporary pandals & shamianas | • Coal dumps<br>• Oil and gas storage tanks and pipe lines<br>• Outdoor machinery & equipment<br>• Road trucks and cars<br>• Ship and aircraft<br>• Railway coaches<br>• Coal mines<br>• Grasslands and forests<br>• Timber depots<br>• Ignition of hot gases<br>• Lighting | • Arson<br>• Careless throwing of cigarettes, matches<br>• Poor housekeeping & dumping of trash<br>• Spontaneous combustion<br>• Electric sparks, overheating, welding<br>• Ignorance and forgetfulness<br>• Gas & oil stoves in the kitchen<br>• Candles and oil lamps<br>• Playfulness of children and fire-crackers<br>• Wearing nylon sarees in kitchen | • Inadequate fire-fighting facility<br>• Poor communication and transport facilities<br>• Absence of fire-drills and poor training of staff<br>• Poor design of buildings ; lack off exits & fire-escapes<br>• Lack of fire detection equipment<br>• Improper and poor maintenance<br>• Delayed first aid & medical help |

Source : Maintenance for Reliability, BVS Rao, Media Promoters, Bombay, 1980

**Workmen's compensation Act–1923.** *Section 3* of Workmen's' Compensation Act provides employer's liability for compensation. Compensation is dependent on four conditions.

1. Injury must be personal.
2. Injury must be by an accident.
3. Accident must have arisen out of and during employment.
4. Injury must have resulted either in death or total or a partial disablement for a period exceeding three days.

*Section 4* lays down the amount of compensation payable to the workers for four categories ranging from temporary disablement to death. *Section 10* also specifies the employer's liability to report fatal accidents to an authority.

**Factories Act–1948.** This act defines various terms of factories like manufacturing process, machinery, worker, power, prime movers etc. *Section 21* lays down rules for fencing of machinery for safeguard and also the provision for work on or near machinery in motion. *Section 23* of the act provides clauses to ban employment of young persons on dangerous machines.

The following machines are accepted as dangerous machines :

1. Decorticator and expeller.
2. Milling machines used in metal trades.
3. Guillotine machines.
4. Power presses, other than hydraulic presses.
5. Planten printing machine.
6. Circular saw.

*Section 24* specifies provision for striking gear and devices for cutting off power for safety. Other measures and provisions are self acting machines (*Section 25*), Hoist and lifts (*Section 28* by Act 20 of 1987), Revolving machinery (*Section 30*), Pressure plant (*Section 31*), Precaution against dangerous fumes (*Section 36*), and Precaution in case of fire (*Section 38*). Section 88 places an obligation on the management to notify accidents.

**Fatal Accidents Act–1855.** This act provides two kinds of damages as described below :

1. Damages proportionate to the loss caused by the death to the beneficiaries and
2. Damages to any pecuniary loss to the estate of the deceased.

The above mentioned damages will have a number of legal implications as specified in the act.

## REVIEW QUESTIONS

1. Define manufacturing. Classify various types of manufacturing processes and cite examples.
2. Give a brief account of the primary shaping processes you know.
3. List various machining processes.
4. What are the different types of production ? Briefly describe each of them. How do you classify them.
5. Define plant layout. List the objectives of plant layout.
6. What are the different types of standard plant layouts ? Explain.
7. What are the advantages of product layout.
8. What is group layout ? What are the basis on which the group layout is developed.
9. Write the situations in which various types of layouts are applied.
10. Briefly describe the product design process.
11. Describe in brief (a) modular design and (b) CAD.
12. Define accidents. List various causes of accidents.
13. List various human factors contributing to industrial accidents.
14. What are the preventive measures for occurring accidents.
15. What do you understand by electrical safety ?
16. Describe in brief the effects of electric current on human system.
17. How do you classify fire accidents ? What are the causes ? What are the preventive measures ?
18. Write is brief the clauses of accidents with respect to
    (a) Workmen's Compensation Act.
    (b) Factories Act.
    (c) Fatal Accident Act.

## 2

# FUNDAMENTALS OF METALS AND ALLOYS

## 2.1 INTRODUCTION

Metals have a common set of properties that make them most useful among the engineering materials. A metal may be described as a material which is solid at room temperature, has relatively high density, high melting temperature, low specific heat, good electrical and thermal conductivity, strength, hardness, etc. Most metals are elastic to a limit; they deform in proportion to stress and return to the original state when the stress is released. At higher stresses they deform plastically. Some metal will accept a deal of plastic deformation before failure.

A metal can exist in the gaseous, liquid and solid states. The state depends on the pressure exerted on the metal and on its temperature. Some of the properties that an element must have to be considered as a metal are :

1. Ability to donate electrons and form a positive ion.
2. Crystalline structure.
3. High thermal and electrical conductivity.
4. Metallic lustre.
5. Ability to be deformed plastically.

## 2.2 ATOM

Atom is the smallest particle of an element that can enter into a chemical combination with another element. Thus it is an ultimate building block of matter. A *molecule* on the other hand is the smallest particle of an element (or compound) that can stay independently. A molecule that consists of one atom is called a *monoatomic* (examples ; rare gases). *Diatomic* molecules are those which are made of two atoms (example ; hydrogen, nitrogen, oxygen). *Polyatomic* molecules are those which contain more than two atoms ; phosphorus molecules contain four atoms.

A *nucleus* of an atom consists of *protons* and *neutrons*. A proton has positive charge (1+) and a neutron though having almost the same weight of a proton is neutral in charge. Much smaller particles known as *electrons* move around the nucleus. An electron is having the same magnitude of charge of a proton with opposite sign. Nucleus diameter is about $10^{-5}$ nanometer while atomic diameter is about $10^{-1}$ nanometer. The number of protons in a nucleus equals to its ***atomic number***. The ***mass number*** of an atom equals to the combined number of protons and neutrons of an atom. Each element is assigned a symbol derived from its name. For example O is the symbol of oxygen.

## 2.3 STRUCTURE OF SOLIDS

A solid is an ordered cluster of molecules. All solids are either ***amorphous*** or *crystalline*. Solids in which the atoms are arranged chaotically, without any vestige of order, are amorphous. Examples are: plastics, glass, etc. On the contrary, solids in which the atoms arrange themselves in a definite or orderly manner and form are called crystalline which include all metals. Solids are classified according to the type of bond which holds the constituent particles of the solid together. On this basis solids can be classified as (1) ionic, (2) molecular, (3) covalent, and (4) metallic.

### IONIC SOLIDS

An ionic crystal is held together by ionic bond. Ionic solids have generally high melting points. This is due to the reason that considerable thermal energy is needed to overcome the attraction between oppositely charged ions. Ionic substances also carry electric currents in the molten states as the free ions move in electric potential difference. Particles of unit cells are *anions* and *cations*.

### MOLECULAR SOLIDS

Molecular solids often known as *Van dell Wall's solids* have molecules as individual units while the bonds within the molecules are covalent, the forces of attraction between the molecules are quite weak. Because of the relatively weak intermolecular force of attraction, molecular solids are soft, have low melting and boiling points and high vapour pressure.

### COVALENT SOLID

In covalent solids, atoms are held to one another by covalent linkage forming a giant network. Diamond, SiC, $SiO_2$ are the examples because of their strongly bonded rigid structures, most covalent solids are very hard and melt at high temperatures.

## METALLIC SOLIDS

Metallic solids are those in which positive ions occupy the lattice sites. The atoms of a metal assume nearly fixed positions relative to each other. A solid metal usually is composed of a multitude of crystals. Within any one crystal, the atomic arrangement is repeated by adjacent atoms. An imaginary line can be drawn through a string of atoms arranged side by side. In fact, such lines can be drawn in three coordinate directions and form a lattice work. This definite and orderly manner and form of the atoms producing a small, repeating, three dimensional, geometrical pattern having the same symmetry as the crystal in the aggregate is called the *space lattice* or *crystal lattice*.

The space lattice of any solid is built up of innumerable conjugate cells inside of which the atoms are arranged in a definite order. Each of these cells is known as *unit cell*. The unit cells may be considered as the effective building blocks of which solid metal is built, much the same as bricks are the building blocks of which walls are built. Thus, the basic geometric body created upon changing from the liquid to the solid state is referred to as the unit cell, and the aggregate (innumerable repetition of unit cells) is known as the space lattice.

There are altogether fourteen different crystal lattices, known as *Bravais space lattices*. In metals, however, there are six lattices. These are: (1) body-centered cubic (*bcc*), (2) face-centered (*fcc*), (3) closed-packed hexagonal (*hcp*), (4) Cubic, (5) body-centred tetragonal and (6) rhombohedral. The three most common crystal lattices are illustrated in Fig.2.1

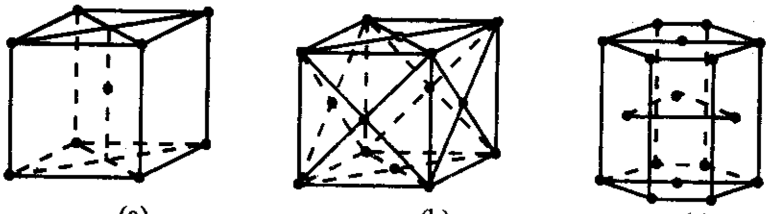

(a) (b) (c)

**Figure 2.1 Atomic arrangement in metal (space lattices)**
(a) body-centred, (b) face-centred, (c) close-packed hexagonal.

*Body-centered cubic crystal lattice* (*bcc*) is a centered cube with nine atoms of which eight are located at the corners of the cube and the ninth at the centre. This type of lattice is found, for example, in the following metals: barium, chromium, columbium, iron, molybdenum, tantalum, tungsten, vanadium, etc.

*Face-centered cubic crystal lattice* (*fcc*) has fourteen atoms of which eight are located at the corners of the cube and six at the centres of six faces. This lattice has a more compact packing of the atoms than the preceding one. This type is typical of the metals: aluminium, calcium, copper, gold, lead, nickel, platinum, silver, etc.

*Close-packed hexagonal crystal lattice* (*hcp*) is simply hexagonal and has a more compact arrangement of atoms. This is found in such metals as : beryllium, cadmium, cobalt, magnesium, titanium, zinc, zirconium, etc.

The atoms in the crystal lattices have been shown to be bound together by strong interatomic forces. The lines joining the atoms represent these forces which resist or tend to resist any attempt to tear the metal apart.

Atoms at the point of a space lattice continuously vibrate in what is called *thermal vibration*. The higher the temperature of the metal the larger the amplitude of their vibration. When the metal is heated to the melting point, the amplitude of this vibration reaches a certain *critical value* at which the crystal lattice is destroyed and the metal passes from the solid to the liquid state.

## COORDINATION NUMBER

An important concept in studying crystal structure is that of the *atomic packing factor*, the fraction of the space occupied by atoms, that is, the ratio of the volume of atoms to volume of unit cell. This is sometimes called *packing efficiency*. The packing of the crystal lattices is characterized by the *coordination number* (*CN*). This is the number of equally spaced nearest neighbours that each atom has in a given crystal structure. The higher the coordination number, the more closely packed the atoms are.

## CHANGES IN THE CRYSTAL STRUCTURE

Many materials such as iron, tin, zinc, nickel, cobalt, etc. are subject to crystalline transformation in the solid state upon changes in their temperature. They exist in one lattice form over a certain range of temperature, but at a somewhat higher or lower temperature the lattice form changes to another lattice form which is stable at that temperature range. Elements that occur in more than one crystallographic or lattice form is called *allotropy* or *polymorphy*, and the metal in which such changes occur is known as *allotropic*. The process in which the crystal lattice is changed in accordance with the temperature is called *allotropic* or *polymorphic transformations* of the metal.

The allotropic forms in which a metal exists are called its *modifications*. The different modifications of the same metal are designated by the Greek letter alpha, beta, gamma, delta, etc.

## ISOTROPY AND ANISOTROPY

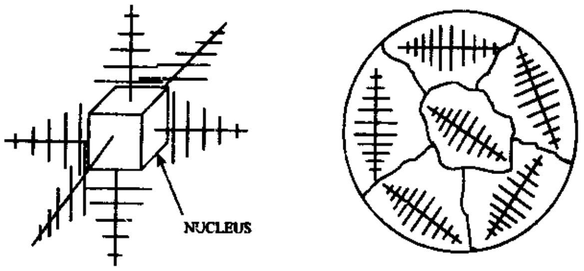
In strength of materials, a body is assumed to be continuous, homogeneous and isotropic. A body is continuous when it does not contain any void. It is homogeneous if it has identical properties at all the points in it. It is *isotropic* if the mechanical properties do not change with direction or orientation. Experience shows that mechanical properties of crystaline solids may differ greatly if measured to different direction on the specimen. This feature of solids is called *anisotropy*.

If the space lattice of a solid is cut by a plane in various directions, the number of atoms and the minimum distance between them vary for each plane. This has an effect on the bond between the atoms. As a result, mechanical properties of crystalline solids may vary, if measured in different directions.

In reality the crystal grains are so small that the material can be taken statistically homogeneous and isotropic. when a metal is highly deformed in a particular direction (for example in rolling, forging etc.), its mechanical properties may become anisotropic on a micro-scale. The mechanical properties of amorphous solids are always isotropic.

## 2.4 FORMATION OF GRAINS

All metals are crystalline and crystals are made up of several atoms. The individual crystals or grains are aggregated to form the visible mass of a solid metal.



(a) (b)

**Figure 2.2 Dendritic growth of crystal**
(a) dendritic growth, (b) dendrities in polycrystals and grain boundary

The formation of grains is shown schematically in Figure 2.2. Solidification or freezing is started when two or more atoms associate themselves to form a very small crystal, called *nuclei*. This may happen simultaneously at a number of locations throughout the liquid metal. This means that a number of nuclei forms within the solidifying metal as it continues to cool. The small crystal or the nucleus develops in the freezing of a liquid metal in the form of *dendrites* (*dendron* is a Greek word meaning a *tree*). A dendrite consisting of unit cells, which are exceedingly small, first form in a straight line. Straight line branches are then formed on the original straight line and so on as shown in Fig. 2.2 (a).

## GRAINS AND GRAIN BOUNDARY

Each crystal of proper geometrical form but having different orientation grows outward until it comes in contact with the adjacent crystal as depicted in Fig. 2.2 (b). The crystal growth is then gradually distorted due to interference of each crystal within its neighbours. Consequently, the crystals observed in the fracture of a metal of irregular shape are called *grains*. The final solid is said to be *polycrystalline* because of many crystals or grains of different orientations exist in it. Within each crystal the atoms may be "packed together" in geometrical pattern.

A boundary known as *grain boundary* is formed between two adjacent crystalline growth because of different orientations of the grains. If the orientations of the grains would not differ, they would unite, and there would not have any grain boundary. Grain boundaries interrupt the continuity of the lattice planes and increase the resistance of the metal to cold deformation.

## GRAIN SIZES

The number and size of grains that form depends jointly on two factors: (a) the rate at which the nuclei form, and (b) the rate of growth. For most metals the rate of grain growth is low enough so that the rate of nucleation has a great influence on the grain size. Since the amount of supercooling determines the minimum size of nuclei that are stable, *rapid cooling* usually produces *small grains*, while *slow cooling* produces fewer but *larger grains*. The size of grains produced also depends upon the number of nuclei formed.

The size and shape of the grains are changed in the production of ferrous and non ferrous metals by a widely used method known as *grain refining*. It involves the use of small amounts of what is known as a *modifier* into the molten alloy. Grain refining results in finer grains having a shape that differs from those in the untreated metal. It is, therefore, usual to distinguish between *fine grained* metals in which the rate of grain growth is slow, and *coarse grained* metals in which process proceeds rapidly. In general, a metal with fine grains will be somewhat harder and stronger than one with coarse grains. A fine grain metal, as a rule, has a greater yield strength, hardness, fatigue strength and resistance to impact. Thus, variation in coarsening tendency leads to variation in the characteristics of the metal.

## 2.5 IMPERFECTIONS IN CRYSTALS

The mathematically perfect crystal is an exceedingly useful concept. In actual crystals, however, *imperfections* or *defects* are always present, and their nature and effects are often very important in understanding the properties of crystals and the metal as a whole. Tiny imperfections cause some misalignment of the atoms, and this misalignment tends to weaken the crystalline structure. There are several kinds of crystalline imperfections. The place where an atom should be may be vacant, and that is called *vacancy*.

In another case there is *dislocation*. Two main kinds of dislocation are usually found to exist in the crystal. These are *edge* and *screw*. The edge dislocation depicted in Fig. 2.3 occurs at the end of an extra half plane of atoms, while the screw dislocation represented in Fig. 2.4 corresponds to a partial tearing of the planes, much as a stack of papers might be torn. In one sense, part of the planes of a lattice may be offset in screw dislocation. However, most dislocations are a combination of both types.

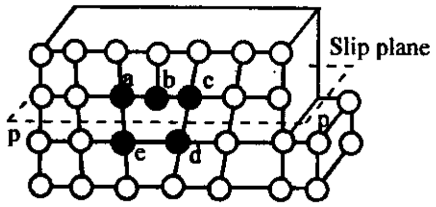


**Figure 2.3** **Edge dislocation**

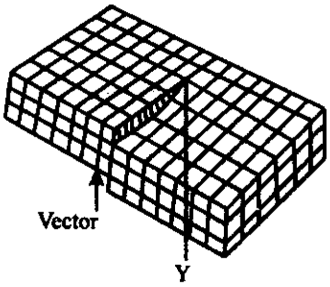


**Figure 2.4** **Screw dislocation**

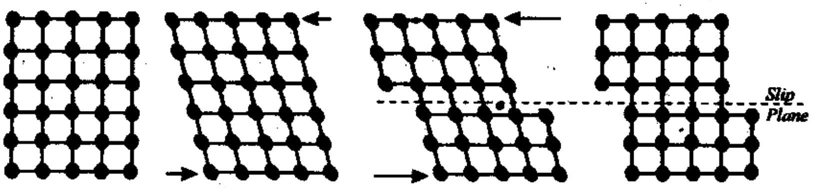
Also, space lattice mismatching occurs between crystals at grain boundaries. Large or small atoms distort the lattice. Quite small interstitial atoms may bulge the lattice. There are probably other kinds of imperfections not yet recognized. The number and distribution of the imperfections have a great effect on the properties of a metal.

## 2.6 DEFORMATIONS OF METALS

### DEFORMATION BY SLIP

If a stress is imposed on a crystal, some or all of the atoms are moved through their equilibrium positions, and the crystal is deformed. If the atoms are not moved out of regions of influence of their neighbours, they return to their original positions after the stress is removed. The deformation is said to be *elastic*. If enough stress is applied to deform the lattice permanently, the atoms do not return to their original positions and the deformation is said to be *plastic*. At stresses exceeding the elastic limit, plastic deformation is observed.

Plastic deformation takes place by one part of a crystal sliding on another. The crystal is divided into layers or slip blocks which are displaced in reference to each other and are separated by thin layers in which a considerable displacement of atoms has taken place. These intermediate layers with strongly distorted lattices are called *slip planes* as illustrated in Fig. 2.5.



(a) (b) (c) (d)

**Figure 2.5 Slip process in a single crystal**

Slip occurs most easily on planes with a high atomic density and large interplaner spacing. These slip planes are often the closest–packed planes for a given crystal structure. As a very crude approximation, the *slip* or the *glide* of a crystal can be considered analogous to the distortion produced in a pile of cards when it is pushed from one end as shown in Fig. 2.6. When observed under an optical microscope, deformation seems to take place by the slip of adjacent crystal zones. At high magnifications each *slip zone* appears composed of many small steps, called slip lines or *slip bands*, indicating displacement along preferred slip planes. In fact, slip takes place not by the movement of entire adjacent crystal zones, but by the movement of dislocations in the preferred slip planes. In the simplest view, a dislocation could be regarded as an extra line or plane of atoms inserted into the structure (Fig.2.3). Thus it is only necessary to move this extra line or plane of atoms along the slip plane instead of moving thousands of atoms at the same time over the entire slip surface. It is important to note that the *shear stress*, causing the slip, must reach a *critical value* on the slip planes before deformation can commence since the deformation characteristics of metals can be interpreted by considering the ease with which these dislocations can move and by considering obstacles that may impede or arrest their movement. The analogy of moving a large carpet helps in understanding the role of dislocation. If the carpet is in contact with the floor all over its area, a large effort is required to move it. If, however, a wrinkle is present and the wrinkle is moved from one end of the carpet to the other, the carpet is shifted a small distance. The energy required to shift the wrinkle *progressively* is considerably less than that required to drag the carpet as a whole across the floor. Similarly, enblock movement of the atoms is not needed in the process of slip. Fig. 2.7 shows how a dislocation travels across a lattice under stress, thus causing displacement of the lattice. It has been pointed out that one plane does not slip over another all at once but glides in a series of movement.

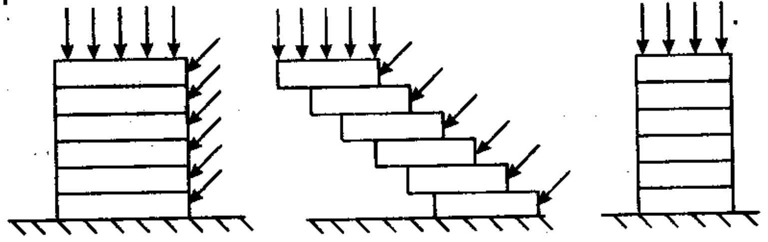


**Figure 2.6 Plastic deformation by slip**

Actually billions of dislocations ($10^8$ to $10^{10}$ per $mm^2$) are known to exist in a crystal and they cause large amount of slip which can be seen visibly. In addition, dislocations interact between themselves and generate new *sources*, i.e., *new dislocations* under excessive stress. So as the stress is continued or raised more and more dislocations are moved to cause more plastic deformation.

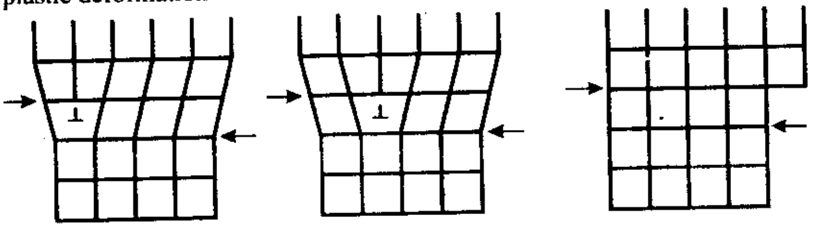


**Figure 2.7 Dislocation travels across a lattice under stress**

## DEFORMATION BY TWINNING

The second inportant mechanism by which metals deform is the process known as *twinning*. This results when a portion of the crystal takes up an orientation that is related to the orientation of the rest of untwinned lattice in a definite, symmetrical way. The twinned portion of the crystal is a mirror image of the parent crystal. The plane of symmetry between the two portions is called the twinning plane. Fig. 2.8 illustrates the classical atomic picture of twinning. The twinning plane is perpendicular to the paper. If a shear stress is applied, the crystal will twin about the twinning plane. The region to the left of the twinning plane is undeformed. To the right of this plane, the planes of atoms have sheared in such a way as to make the lattice a mirror image across the twin plane. The mechanism of twinning may thus be desired as the simple sliding of one plane of atoms over the next, the extent of the movement of each plane being proportional to its distance from the twinning plane.

It should be noted that twinning differs from slip in that every plane of atoms suffers some movement, and the crystallographic orientations of many unit cells are altered.

Twinning may be produced by mechanical deformation or as a result of annealing following plastic deformation. The first type is known as *mechanical twins,* while later is called *annealling twins.* Mechanical twins are produced in *bcc* or *hcp* metals under conditions of rapid rate of loading (shock loading) and decreased temperature.

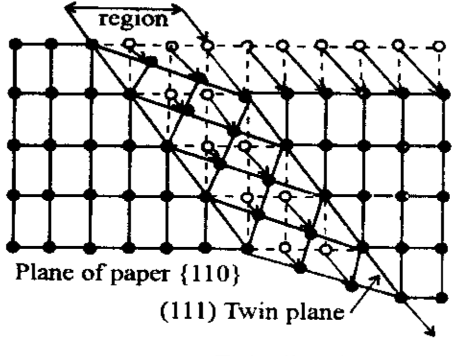


**Figure 2.8 Twinning in a fcc-crystal lattice**

The important role of twinning in plastic deformation comes not from the strain produced by the twinning process but from the fact that orientation changes resulting from twinning may place new slip system in a favourable orientation with respect to the stress axis so that the additional slip can take place. Thus, twinning is important in the overall deformation of metals with a low number of slip system, such as *hcp* metals. However, it should be understood that only a relative small fraction of the total volume of a crystal is reorientated by twinning.

## 2.7 PROPERTY CHANGES BY DEFORMATION

### WORK HARDENING

At some higher stress, plastic deformation begins. When the metal is deformed at a relatively low temperature, typically below one half of an absolute melting point, the movement of dislocations is limited mostly to their own slip plane. Obstacles such as grain boundaries, foreign atoms and other dislocations impede or arrest their movement, and the movement becomes more difficult. This causes *work-hardening* or *strain-hardening* because a higher stress is necessary to move the entangled and crowded dislocations. As dislocations are piled up under higher and higher stress, they are forced to combine into small cracks that ultimately grow to fracture in the metal. Work-hardening, considered as a strengthening mechanism, is utilized in processing many metals to provide strength and hardness greater than the metal possesses in the as-cast condition.

### SOLID SOLUTION HARDENING

As just indicated, anything that interferes with the flow of dislocations across a grain makes that grain harder. That may be a distortion of the space lattice or the presence of a foreign material. The first is the mechanism in what is called *solid solution hardening*, and the second is *dispersion hardening*.

### STRAIN AGEING

If a specimen, which has been overstrained beyond the yield point, is allowed to rest or age before retesting, the yield point return to a higher stress. This process, which is accompanied by hardening due to increased stress is known as *strain ageing* or more especially strain age hardening.

### PREFERRED ORIENTATION

It is presumed that the entanglement and pile up of dislocations causing strain-hardening becomes so great that they promote formation and growth of cracks rather than further slip. In addition, cold work destroys the randomness of grain orientations, thereby depriving the polycrystalline material of a statistical equality of properties in all directions--the so called quasi-isotropy. The grains now exhibit a *preferred orientation* or *texture*. A metal which has to undergo a severe amount of deformation as in rolling or wire drawing develops a preferred orientation. In that case certain crystallographic planes tend to orient themselves in preferred number with respect to the direction of the maximum strain.

### SEASON CRACKING

In addition to the changes in physical and chemical properties, internal stresses, often of a very high intensity, may be left in an object after cold deformation.

Metals such as brass with internal stresses appearing after working is susceptible to inter crystalline corrosion, if it is stored for a long period. This leads to disintegration or failure of the metal. This phenomenon is called *season cracking* or more correctly *stress corrosion cracking*.

## 2.8 RECOVERY, RECRYSTALLISATION AND GRAIN GROWTH

Plastic deformation, which distorts the crystal lattice and breaks up the blocks of initial equiaxed grains to produce fibrous structure or thin plates, increases the energy level of metal.

Deformed metal, in comparison with its undeformed state, is in a nonequilibrium, thermodynamically unstable state. Therefore, spontaneous processes occur in strain-hardened metal, even at room temperature, which bring it into a more stable condition. If the temperature is raised sufficiently, the metal attempts to approach equilibrium through three processes : (a) recovery, (b) recrystallisation, and (c) grain growth. A schematic drawing indicating recovery, recrystallisation and grain growth and the chief property changes in each region is shown in Fig. 2.9.

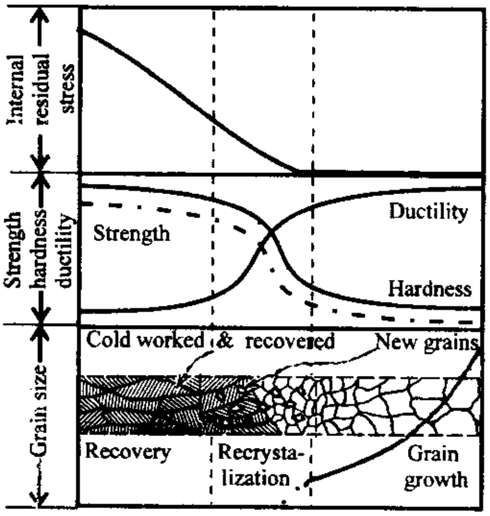


**Figure 2.9 Recovery, recrystallisation and grain growth**

### RECOVERY

If a strain-hardened metal is heated to a comparatively low temperature, the elastic distortions of the crystal lattice are reduced due to the increase in amplitude of thermal oscillation of the atoms. This heating will slightly lower the strength of the strain-hardened metal but the elastic limit and ductility will increase, though they will not reach the values possessed by the initial material (before strain-hardening). No changes in microstructure are observed in this period. This partial restoration of the original properties, produced by reducing the distortion of the crystal lattice without noticeable changes in microstructure, is called *recovery*.

At a given temperature the rate of the recovery is fastest initially and drops off at longer times. Thus the amount of recovery that occurs in a practical time increases with increasing temperature. In a given cold worked metal the individual properties recover at different rates and attain various degrees of completion.

## RECRYSTALLISATION

The formation of new equiaxed grain in the heating process, instead of the oriented fibrous structure of the deformed metal, is called *recrystallisation*. This is illustrated in Fig. 2.10. The first effect of heating is to form new minute grains as shown in white in (a), and these rapidly enlarge until further growth is restricted by grain meeting another as shown in (b) and (c). Ultimately, the original system of grains go out of the picture and the new crystallized structure is shown at (d), the original grains being

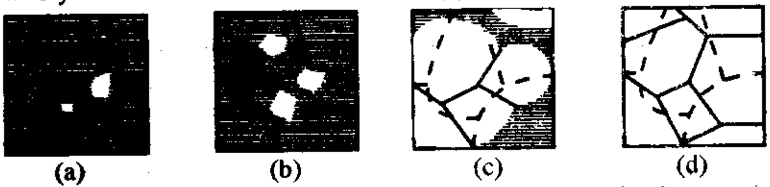
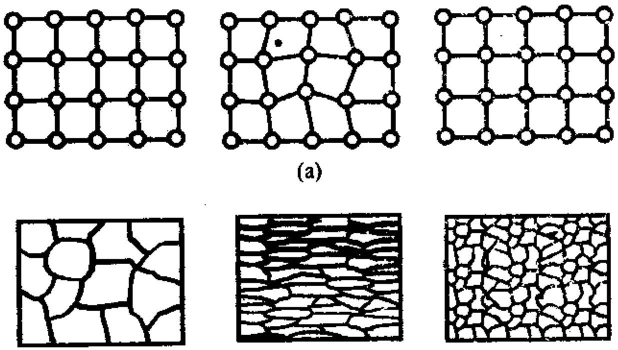

(a) (b) (c) (d)

**Figure 2.10 The birth of new grains – recrisallisation**


(a)

(b) (c) (d)

**Figure 2.11 Plastically deformed metal**

(a) Crystalline structure, (b) Structure before deformation, (c) structure resembling fibres, (d) structure after recrystallinsation indicated in the drawing by dotted lines. Recrystallisation, in fact, does not produce new structures but produces new grains or crystals of the same structure. Recrystallisation, in essence, consists in having the atoms of the deformed metal overcome the bonds of the distorted lattice, the formation of nuclei of equiaxed grains and subsequent growth of these grains due to transfer of atoms from deformed to undeformed crystallites. In fine, grains are refined and acquire a shape resembling fibres as shown in Fig.2.11.

The temperature at which crystallization takes place, that is, new grains are formed, is called *recrystallisation temperature*. This is defined as that temperature at which 50 per cent of the cold-worked material will recrystallise in one hour.

### GRAIN GROWTH

Just after a metal has recrystallised, the grains are small and somewhat regular in shape. The grain will grow if the temperature is high enough or if the temperature is allowed to exceed the minimum required for recrystallisation. This growth is the result of a tendency to return to more stable and larger state, and appears to depend primarily on the shape of the grain.

For any temperature above the recrystallization temperature, normally there is *practical maximum size* at which the grains will reach *equilibrium* and cease to grow appreciably, no matter how long they are held at the temperature. There are, however, certain kinds of abnormal grains growth that occur as a result of applied or residual gradients of strain due to nonuniform impurity distribution, and which permit growing very large single grains.

## 2.9 FRACTURE

*Fracture* is the separation of a body under stress into two or more parts and is usually characterized as either *brittle* or *ductile*. Brittle fracture occurs by the very rapid propagation of a crack after little or no plastic deformation. In crystalline materials brittle fracture usually proceeds along characteristic crystallographic planes called *cleavage* planes, and a brittle fractured surface in a polycrystalline material has a *granular* appearance because of changes in orientation of these cleavage planes from grain to grain. Brittle fracture can proceed along a grain boundary path instead of along cleavage planes. This is called *intergranular* fracture and may be attributed to embrittling films which have segregated in the grain boundaries. In either case, brittle fracture occurs normal to the maximum applied tensile stress.

Ductile fracture is fracture occurring after extensive plastic deformation and is characterized by slow crack propagation resulting from the formation and coalescence of voids. A ductile fractured surface has a characteristic dull, fibrous appearance.

The relation between ductile and brittle fracture is one of degree. Nodular cast iron fails in a ductile manner as compared to grey cast iron but is considered brittle compared with steel. Frequently, the two types exist in the same rupture because of progressive hardening as failure takes place. Many steels fail by ductile fracture at high temperatures and by cleavage at low temperatures.

## 2.10 METAL ALLOYS

In engineering, pure metals are rarely used because of their physical and mechanical properties. This has led to the development of alloys.

A substance that possesses metallic properties and is composed of two or more elements, of which at least one is metal, is called an *alloy*. The metal present in the alloy in largest proportion is called the *base metal*. All other elements present, in the form of metal or nonmetal, are called *alloying elements*. These alloying elements are added intentionally to get certain desirable properties which are not found in the base metal. Sometimes, they come in the process of alloying as impurities, which are present more or less accidentally.

Alloying elements, either in small quantities or in high quantities, may result in a marked change in the properties of the base metal. The structure resulting from addition of alloying elements to a base metal determines the properties of the alloy as a whole. The type and extent of change of properties depend on whether the alloying elements are insoluble in, dissolve in or from a new base with the base metal.

Each constituent of an alloy is called a *component*. A pure metal comprises a one-component. But alloys may be binary or two component, ternary or three-component, etc.

## 2.11 SOLIDIFICATION OF AN ALLOY

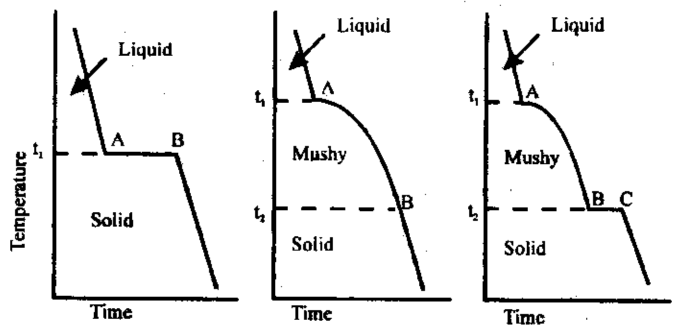
As stated earlier, a pure metal freezes at a *constant and definite temperature*. But an alloy does so over a *range of temperatures* as depicted in Fig. 2.12. The character of the cooling curves in the case of an alloy depends upon the solubility of its components in the solid state.

This is explained in the following way. The crystal structure of pure metals consists of one characteristic lattice arrangement for a given temperature range. The crystal structure in alloys is much more complicated by the presence of the alloying elements, which may exist together with the base metal in different ways.

## TYPES OF ALLOYS

After solidification the alloying elements may exist in the base metal atoms in three general ways.

1. Alloying atoms may be relatively *soluble* in the base metal atoms forming a *solid solution*.
2. Alloying atoms may form a *compound* with the base-metal atoms producing an *intermetallic compound*.
3. Alloying atoms may be relatively *insoluble* in the base-metal atoms forming a *mechanical mixture*.



(a) (b) (c)

**Figure 2.12 Cooling curves for pure metals and alloys**
(a) pure metal, (b) solid solution, (c) multi-phase alloy.

**Solid solutions.** When elements combine to form alloys by completely dissolving in each other they are said to be in solid solutions. In a solid solution, the different types of atoms of the components in the alloy form a common crystal lattice. The component, whose lattice is retained, is called the *solvent*.

Conditions under which metallic solid solutions are formed are: (a) the components have the same crystal lattice and (b) there is no large difference in the lattice form of the alloying components.

The two most typical kinds of solid solutions are substitutional and interstitial. These are illustrated in Fig. 2.13.

In *substitutional* solid solutions, a part of atoms at the points of the solvent crystal lattice has been replaced by solute atoms.

In *interstitial* solid solutions, the atoms of the solute metal occupy the vacant positions or interstices between the atoms of the solvent.

The nature of solid solutions has important effects on many alloy properties. For example, strength and hardness increase with the amount of solute present, but ductility usually decreases.

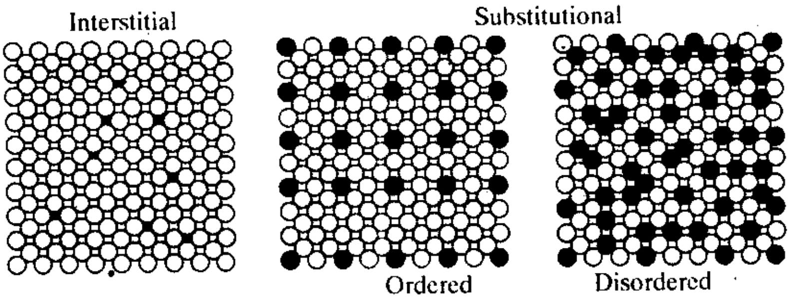


**Figure 2.13 Interstitial and substitutional solid solution**

**Intermetallic compounds**. Compounds are obtained upon chemical interaction of certain compounds of alloys. They are commonly formed between metal and nonmetals. Chemical compounds in an alloy not only have a definite chemical composition but also possess distinct physical and mechanical properties.

In an intermetallic compounds, the lattice form is characteristic of the compound. It differs from those of its components, and usually is more complex. The lower order of symmetry in the complex lattices results in low electrical conductivity, and greater resistance to slip. Consequently, such compounds are very hard and brittle. To be of real value, they must be well dispersed through the structure. The softer base metal will then strengthen the latter.

**Mechanical mixtures**. In some cases when a liquid solution is cooled, crystals of all components separate simultaneously from the melt and form a close mechanical mixture. This is also known as *eutectic mixture*. In mechanical mixtures, metals retain their same structural identity and properties.

## ALLOY PHASES

A *phase* is physically and chemically homogeneous portion of a matter. This is homogeneous in the sense that its smallest adjacent parts are indistinguishable from one another. Each phase has its own atomic arrangement, physical properties, and chemical properties. A phase change, accordingly, is accompanied by change in properties.

It is therefore evident that solid solution, intermetallic compound and mechanical mixture that a solid alloy may contain are considered as different phases.

All changes which take place in a system consisting of several phases, in accordance with thermal conditions such as temperature and pressure, conform to the so-called phase rule. The *phase rule* establishes the relationship between the number of degrees of freedom, the number of components and the number of phases. It is expressed mathematically as follows :

$$P = C + 2 - F$$

in which P is the number of phases, C is the number of components, F is the number of degrees of freedom in the system (the temperature, pressure and concentration).

The effects of pressure may be neglected in applying the phase rule.

## 2.12 EQUILIBRIUM DIAGRAMS

The solidification of metal alloys is clearly understood by means of equilibrium diagrams. These are graphic representations of changes in state due to variations in temperature and concentration. Since this diagram indicates the nature and constitution of alloys, and the amount and composition of phases in a given system, it is also known as *constitution diagram* or *phase diagram.*

Equilibrium implies that changes occurring in a system as a result of process proceeding in one direction are fully compensated by changes due to the reversal of the process in the system. So it is considered as a dynamic condition of balance between atomic movements where the resultant is zero. The rates of changes of temperature or of composition have been extremely slow during the experimental work, so that the alloy would "come to rest" before a variable such as temperature, were again changed. The condition, therefore, is one of rest rather than change.

Equilibrium diagram indicate the following :

1. Temperature at which the solid alloy will start melting and finish melting.
2. Possible phase changes which will occur as the result of altering the composition or temperature.

## 2.13 IRON-CARBON EQUILIBRIUM DIAGRAM

The binary iron-carbon equilibrium diagram is the basis of steel and cast iron. It concerns transformations that occur in alloys having compositions from pure iron to cementite (6.67 per cent carbon). There are two versions of iron-carbon equilibrium diagram :

1. Iron-cementite system.
2. Iron-graphite system.

These two systems depend on the rate of cooling. Rapid cooling produces cementite and the system is known as Iron-cementite system. In this system, the structures formed in the solidified phases do not reach sufficiently complete equilibrium. So Iron-cementite system is a *metastable* one. While slow cooling produces graphite and the system is known as Iron-graphite system. The structures that are formed in the solidified phase reach sufficiently complete equilibrium. So this is a *stable* one.

### IRON-CEMENTITE SYSTEM

If a series of time-temperature heating curves are made for steels of different carbon contents and the corresponding critical points plotted a diagram similar to Fig. 2.13 would be obtained. This diagram, which applies only under slow cooling conditions, is known as a partial Iron-carbon phase diagram. By referring to this diagram one may readily observe the proper quenching temperatures for any carbon steel. The critical points in Fig. 2.13 on the line *PSK* are denoted by $A_1$, those on line *GS* by $A_3$, and those of line *SE* by $A_{cm}$.

Let us take the example of a piece of 0.20 per cent carbon steel which has been heated to a temperature around 850°C. Above $Ar_3$, point (*GS* line) this steel is a solid solution (interstitial type) of carbon in gamma iron and is called *austenite*. It has a face-centred cubic lattice and is nonmagnetic. Plain austenite may contain up to about 2 per cent carbon at a temperature of 1130°C. Upon cooling this steel the iron atoms start to form body-centred cubic lattice below the point $Ar_3$ (*GS* line). This new structure that is being formed is called *ferrite* or *alpha iron* and is solid solution of carbon in alpha iron containing up to 0.008 per cent carbon at room temperature. As the steel is cooled to $Ar_1$, (*PSK* line), additional ferrite is formed. At the $Ar_1$ line the austenite that remains is transformed to a new structure called *pearlite*. The name pearlite is due to its pearly lusture. It consists of alternate plates of ferrite and cementite and contains about 87 per cent ferrite. Pearlite may be either fine-to-coarse lamellar or granular structure. This is a strong substance and may be cut reasonably well with cutting tools, i.e., the pearlite constituent in steel is machinable.

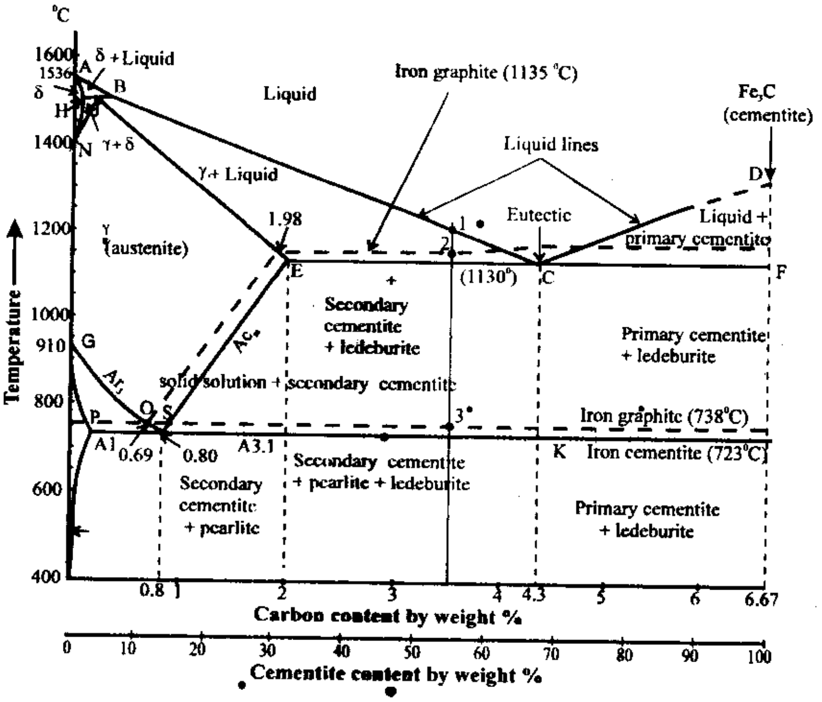


**Figure 2.13 Iron-carbon equilibrium diagram**
(Iron-cementite system, iron–graphite diagram in dotted line)

As the carbon content of the steel increases above 0.20 per cent, the temperature at which the ferrite is first rejected from the austenite drops until, at about 0.80 per cent carbon (point *S*), no free ferrite is rejected from the austenite. This steel is called *eutectoid* steel and is 100 per cent pearlite. The eutectoid point in any metal, as said earlier, is the lowest temperature at which changes occur in a solid solution. If the carbon content of the steel is greater than eutectoid (0.8 per cent carbon), a new line is observed in the iron carbon phase diagram denoted by $A_{cm}$ (*S* line). The line denotes the temperature at which iron carbide is first rejected from the austenite instead of ferrite. The iron carbide ($Fe_3C$) is known as *cementite*. It is extremely hard, brittle and appears as parallel plates (lamellar layers), as rounded particles (spheroids) or as envelopes around the pearlite grains. At point *C*, the eutectic mixture containing 4.3 per cent carbon is known as *ledeburite*. This is rarely seen in slowly cooled alloys since it breaks down, due to its unstable nature, to other phases during cooling after solidification.

Steels containing less than 0.80 per cent carbon are called *hypoeutectoid* and those which contain more than 0.8 per cent carbon are called *hypereutectoid* steels. This terminology applies only to plain and low alloys steels. With high alloy steels the eutectoid composition is altered and the structure may not even exist.

## IRON-GRAPHITE SYSTEM

It has already been said that iron carbide or cementite is a metastable, although under normal conditions, it tends to persist indefinitely. When cementite does decompose it does according to the reaction :

$$Fe_3C \leftrightarrow 3Fe + C$$

In the stable phase, *free carbon* or *graphite* occurs instead of the phase known as cementite. Upon small degree of supercooling, graphite is formed when cast iron solidifies from the liquid state. Slow cooling promotes graphitisation. Rapid cooling partly or completely suppresses graphitisation and leads to the formation of cementite.

An iron-graphite system (as dotted line) is shown in Fig. 2.13. The case of a carbon alloy containing 3.5 per cent carbon by weight is taken as an illustration.

At point 1 the alloy is in the liquid state. At point 2 on the cooling line the reaction that occurs can be expressed as :

$$\text{liquid alloy} \quad \underset{\text{heating}}{\overset{\text{cooling}}{\longleftrightarrow}} \quad \text{austenite } (\gamma) + \text{free graphite}$$

Between points 2 and 3, the excess carbon in the austenite is precipitated out as free graphite and not as cementite.

At point 3, the eutectoid reaction occurs. This is expressed as:

$$\text{austenite } (\gamma) \quad \underset{\text{heating}}{\overset{\text{cooling}}{\longleftrightarrow}} \quad \text{ferrite } (\alpha) + \text{free graphite}$$

The process of graphitisation is controlled by varying the rate of cooling and by proper alloying of the metallic matrix.

## REVIEW QUESTIONS

1. Define a metal and describe its structure.
2. What is the Crystal lattice of a solid metal and what part of the lattice is called a unit cell ?
3. What characteristic of atomic structure of metals accounts for their relatively high thermal and electrical conductivity ?
4. What occurs when a metal is solidified under (a) slow cooling and (b) super cooling condition ? Explain them with cooling curves.
5. Describe how separate grains are formed when a metal is solidified.
6. What two characteristics of the metal determine the number of grains that will form ?
7. Describe how grain boundary is formed.
8. Explain (a) dendritic and (b) grains growth.
9. Explain (a) allotropy, (b) anisotropy and (c) isotropy.
10. What do you understand by isotropy and anisotropy ? Illustrate with examples.
11. What is meant by crystal imperfections ? State the effect of their presence in materials.
12. What is meant by elastic and plastic deformation ?
13. What is slip ? Of what significance is it ? How does it operate ?
14. Explain with neat sketches the mechanism for dislocation in plastic deformation.
15. Distinguish between edge dislocation and screw dislocation.
16. What is strain – or work-hardening and season cracking ? What is the mechanism of strain-hardening? State the effects of strain-hardening.
17. Explain : (a) strain ageing, (b) preferred orientation, and (c) fracture.
18. What is fracture ? Name various types of fracture that occur in metals ?
19. Distinguish between the term " recovery" and "recrystallisation".
20. Define : Alloy and alloying elements.
21. What is a solid solution ? Explain the different types of solution.
22. What is a phase? What is the phase rule and what information does it provide ?
23. What is an equilibrium diagram ? Why is it called "equilibrium" ?
24. How many informations for equilibrium diagram be obtained ?
25. Describe an "iron-carbon equilibrium diagram" and state the micro-constituents that are obtained in the transformations in iron indicating their character.
26. What do you understand by hypo-eutectoid and hyper-eutectoid steels ? Explain with the help of iron-carbon diagram.

# 3

# PROPERTIES, TESTING AND INSPECTION OF METALS

## 3.1 INTRODUCTION

The practical application of engineering materials in manufacturing engineering depends upon a thorough knowledge of their particular properties under a wide range of conditions. The term *property* is often used loosely and in several different senses to characterize materials. In the solid state, characteristics of a material are best described by its application behaviour or service condition. However, the range of properties found in different classes of materials is very large. Some of the very useful properties are: mechanical, electrical, magnetic, chemical, thermal and physical.

The designer or engineer is usually more interested in the behaviour of materials under load which is mechanical in nature. A brief review of the major mechanical properties and their significance to design is therefore, given in this chapter along with the important aspects of each test to assess their behaviour.

## 3.2 STRESS AND STRAIN

Experience shows that any material subjected to a load may either deform, yield or break, depending upon the magnitude of the load, the nature of the material and its cross-sectional dimension.

The sum total of all the elementary interatomic forces or internal resistances which the material is called upon to exert to counteract the applied load is called *stress*, and the resultant deformation expressed as a fractional change in dimension is termed *strain*.

According to the nature of the applied load, there are three types of stresses such as *tensile*, which acts to pull materials apart; *compressive*, the force that tends to squeeze materials; and *shear*, the tendency to cause one part to slide by another part. As there are different types of stresses there are corresponding strains.

Stress is equal to the load or force applied, specified in terms of load per unit of cross-sectional area, while strain is the change per unit length.

## "TRUE STRESS" AND "TRUE STRAIN"

Stress and strain defined in the aforesaid manner are called *conventional*, *nominal* or *engineering* stress and strain. In reality they are simply a measure of the load and deformation on a standard specimen in elastic range.

It is found that the change or deformation is negligible in elastic range, but in plastic region this change is appreciable. In recent years, therefore, engineers have been turning more and more to the so-called "true stress" and "true strain" (also called *natural* stress-strain) as proper measures of the mechanical behaviour of materials in both elastic and plastic regions.

True stress is defined as the ratio of the load on the specimen to the instantaneous minimum cross-sectional area supporting the load while true strain is defined as the integral of the ratio of an incremental change in length to the instantaneous length of the sample.

## STRESS-STRAIN RELATIONSHIPS

The relation between stress and strain is commonly shown by means of a stress-strain diagram. This is a diagram plotted with values of stress (load) as ordinate and values of strain (elongation, compression, deflection, twist, etc.) as abscissa. An engineering stress-strain curve is illustrated in Fig. 3.1.

## HOOK'S LAW AND MODULUS OF MATERIAL

In the elastic region of the material, the relation between stress and strain is governed by Hook's law. This states that stress is proportional to strain and independent of time. This law generally applies to most elastic materials for very small strain.

It follows from the Hook's law that the ratio of stress and strain is a constant characteristic of a material, and this proportionality constant is called *modulus of the material*. This is measured in force per unit area.

## POISSON'S RATIO

An important elastic constant is Poisson's ratio. It expresses the relationship existing between lateral strain and axial strain. The value of Poisson's ratio varies with different materials. For most structural materials it is usually between 0.3 and 0.6.

## 3.3 MECHANICAL PROPERTIES

The mechanical properties of materials define the behaviour of materials under the action of external forces, called *loads*. They are a measure of the strength and lasting characteristic of a material in service, and are of great importance in the design of tools, machines and structures.

Mechanical properties are structure sensitive in the sense that they depend upon the crystal structure and its bonding forces, and especially upon the nature and behaviour of the imperfections which exist within the crystal itself or at the grain boundaries.

The most important and useful mechanical properties are briefly explained below to ensure that the readers will be able to choose the proper material for a given design quickly and wisely.

## STRENGTH

The strength of a material is its capacity to withstand destruction under the action of external loads. The stronger the material the greater the load it can withstand. It therefore determines the ability of a material to withstand stress without failure. Since strength varies according to the type of loading, it is possible to assess tensile, compressive, shearing or torsional strengths.

The maximum stress that any material will withstand before destruction is called its *ultimate strength*. The *tenacity* of a material is its ultimate strength in tension.

## ELASTICITY

Elasticity is that property of a material by virtue of which deformation caused by applied load disappears upon removal of the load. In other words, elasticity of a material is its power of coming back to its original position after deformation when the stress or load is removed. Elasticity is a tensile property of the material.

**Proportional limit.** It is the maximum stress under which a material will maintain a perfectly uniform rate of strain to stress. Even though this value is difficult to measure, it is used in important applications such as precision instruments, springs, etc.

**Elastic limit.** Most materials can be stressed slightly above the proportional limit without taking a permanent set., The greatest stress that a material can endure without taking up some permanent set is called *elastic limit*. Beyond elastic limit, therefore, the material does not regain its original form and permanent set occurs.

**Yield point.** At a certain stress, ductile materials particularly cease offering resistance to tensile forces, i.e., they flow and a relatively large permanent set takes place without a noticeable increase in load. This point is called yield point. Some materials exhibit a definite yield point, in which case the *yield stress* or *yield strength* is simply the stress at this point. Mild steel is an instance of this.

**Proof stress.** Most ductile materials exhibit progressive yield and another measure of yield stress, usually known as *proof stress*.

Proof stress is defined as the amount of stress a material can withstand without taking more than a small amount of set, common measures being 0.1 or 0.2 per cent of the original gauge length.

## STIFFNESS

The resistance of a material to elastic deformation or deflection is called *stiffness* or *rigidity*. A material which suffers slight deformation under load has a high degree of stiffness or rigidity. For instance suspended beams of steel and aluminium may both be strong enough to carry the required load but the aluminium beam will "sag" or deflect further. In other words, the steel beam is *stiffer* or *more rigid* than aluminium beam.

If the material follows Hook's law, i.e., has a linear stress-strain relation, its stiffness is measured by the Young's modulus $E$. The higher the value of the Young's modulus, the stiffer the material.

In tensile and compressive stress, it is called *modulus of stiffness* or "modulus of elasticity"; in shear, the *modulus of rigidity*, and this is usually 40 per cent of the value of Young's modulus for commonly used materials; in volumetric distortion, the *bulk modulus*.

The term *flexibility* is sometimes used as the opposite of stiffness. However, flexibility usually has to do with flexure or bending. Also it may imply ease of bending in the plastic range.

## PLASTICITY

The plasticity of a material is its ability to undergo some degree of permanent deformation without rupture or failure. Plastic deformation will take place only after the elastic range has been exceeded.

Plasticity is important in forming, shaping, extruding and many other hot or cold working processes. Materials such as clay, lead, etc. are plastic at room temperature and steel is plastic when at bright heat. In general, plasticity increases with increasing temperature.

## DUCTILITY AND MALLEABILITY

Ductility is that property of a material which enables it to draw out into thin wire. Mild steel is a ductile material. The per cent elongation and the reduction in area in tension is often used as empirical measures of ductility.

Malleability of a material is its ability to be flattened into thin sheets without cracking by hot or cold working. Aluminium, copper, tin, lead, steel, etc. are malleable metals.

It is important to note that some materials may be malleable and not ductile. Lead for example, can be readily rolled and hammered into thin sheets but can not be drawn into wire. Although ductility and malleability are frequently used interchangeably, ductility is thought of as a tensile quality, whereas the malleability is considered as a compressive quality.

Current usage of the words ductility and malleability makes it almost synonymous with *workability* or *formability* which is clearly related to plastic deformation.

## RESILIENCE

Resilience is the capacity of a material to absorb energy elastically. On removal of the load, the energy stored is given off exactly as in spring when the load is removed.

The maximum energy which can be stored in a body upto elastic limit is called the *proof resilience*, and the proof resilience per unit volume is called *modulus of resilience*. In other words, the modulus of resilience is defined as the amount of energy required to stress unit volume of a material to its proportional limit. The quantity gives capacity of the material to bear shocks and vibrations.

## TOUGHNESS

Toughness is a measure of the amount of energy a material can absorb before actual fracture or failure takes place. For example, if a load is suddenly applied to a piece of mild steel and then to a peice of glass, the mild steel will absorb much more energy before failure occurs. Thus a mild steel is said to be much tougher than a glass.

The toughness of a material is its ability to withstand both plastic and elastic deformations. It is, therefore, a highly desirable quality for structural and machine parts which have to withstand shock and vibration. Manganese steel, wrought iron, mild steel, etc. are tough materials.

The work or energy a material absorbs is sometimes called *modulus of toughness*. Toughness is related to *impact strength*, i.e., resistance to shock loading.

## HARDNESS, HARDENABILITY AND BRITTLENESS

*Hardness* is a fundamental property which is closely related to strength. Hardness is usually defined in terms of the ability of a material to resist to scratching, abrasion, cutting, indentation, or penetration. It is important to note that the hardness of a metal does not directly related to the hardenability of the metal.

Many methods are now in use for determining the hardness of a material. They are Brinell, Rockwell, and Vickers.

*Hardenability* indicates the degree of hardness that can be imparted to metal, particularly steel, by the process of hardening. It determines the depth and distribution of hardness induced by quenching. The hardenability of a metal is determined by a *Jominy test* to determine how well a metal hardens from the centre of the metal to the interface of the metal. The Jominy Test(ISO 642:1999) involves heating a test piece from the steel (25mm diameter and 100mm long) to an austenitising temperature and quenching from one end with a controlled and standardised jet of water. A metal that is capable of being hardened throughout its structure is said to have high hardenability.

The *brittleness* of a material is the property of breaking without much permanent distortion. There are many materials which break or fail before much deformation takes place. Such materials are brittle, e.g., glass, cast iron. Therefore, a non-ductile material is said to be brittle material. Usually the tensile strength of brittle materials is only a fraction of their compressive strength.

## MACHINABILITY

Machinability is not an intrinsic property of a material, but rather the result of complex interactions between the workpiece and various cutting devices operated at different rates under different lubricating conditions. As a result, machinability is measured empirically, with results applicable only under similar conditions.

However, simply stated, it is the ease with which a metal can be removed in various machining operations. Good machinability implies satisfactory results in machining.

The machinability of a metal is indicated by percentages what is termed *machinability index.* All machinable metals are compared to a basic standard. The standard metal used for the 100 per cent machinability rating is *free-cutting steel.* Machinabilty index of carbon steels generally range from 40 to 60 per cent, and that of cast iron from 50 to 80 per cent.

## CREEP

The slow and progressive deformation of a material with time at constant stress is called *creep*. The simplest type of creep deformation is *viscous flow*. Depending on temperature, stresses even *below* the *elastic limit* can cause some permanent deformation. It is most generally defined as time-dependent strain occurring under stress. Metals generally exhibit creep at high temperatures, whereas plastics, rubber, and similar amorphous materials are very temperature-sensitive to creep.

There are three stages of creep. In the first one, the material elongates rapidly but at a decreasing rate. In the second stage, the rate of elongation is constant. In third stage, the rate of elongation increases rapidly until the material fails. The stress for a specified rate of strain at a constant temperature is called *creep strength*.

### FATIGUE

This phenomenon leads to fracture under repeated or fluctuating stress. Fatigue fractures are progressive beginning as minute cracks and grow under the action of fluctuating stress. The fatigue properties of a material determine its behaviour when subjected to thousands or even millions of cyclic load applications in which the maximum stress developed in each cycle is well within the elastic range of the material. Under these conditions failure may occur after a certain number of load applications, or the material may continue to give service indefinitely. In many instances a component is designed to give a certain length of service under a specified loading cycle; many components of high speed aero and turbine engines are of this type.

## 3.4 TESTING OF METALS

Testing is for the purpose of providing an engineer with the necessary data for his design calculations and determining whether a material, either in the raw or fabricated form, meets specifications. It is necessary that metals shall be tested so that their mechanical properties and especially their strength properties can be assessed and compared. Testing for mechanical properties will not always reveal the inherent unsoundness of a material. This is particularly true when a large latitude is provided for in the specimen. This necessitates both *destructive* and *non-destructive* testings.

Destructive testing uses various types of mechanical tests such as tensile, compressive, hardness, impact, fatigue and creep testing. Non-destructive testing, on the other hand, includes visual examination, radiographic, ultrasonic, liquid penetrant and magnetic particle testing.

## DESTRUCTIVE TESTING

## 3.5 TENSILE TESTING

A test almost universally employed to express mechanical properties and to supply the most useful fundamental information regarding the behaviour of materials is the tensile test. Probably the type of testing machine most commonly used is called the *universal testing machine*. The name "universal" is given in the sense that the machine may be adapted to carry out tension, compression, direct shearing and bending test.

In the tensile test, the test piece is first prepared by turning the same piece to the standard shapes specified. This may be either round or flat.

Before commencing the test two gauge marks are made on the specimen longitudinally usually 50 mm to 200 mm apart according to the size of the test piece. The ends of the test piece are then gripped in the tensile testing machine and gradually increasing load is applied until failure is approached. The amount of elongation in the test piece caused by the load is measured accurately by a mechanical, electrical, or optical device called *extensometer*. As the loading of the test piece progresses, load and deformation readings are recorded simultaneously. The stress is calculated from the loads and the original dimension of the piece and this stress is plotted graphically as abscissa with respect to its corresponding strain as ordinate to show the behaviour of metal at different states. The resulting graph is *stress-strain curve* shown in Fig. 3.1.

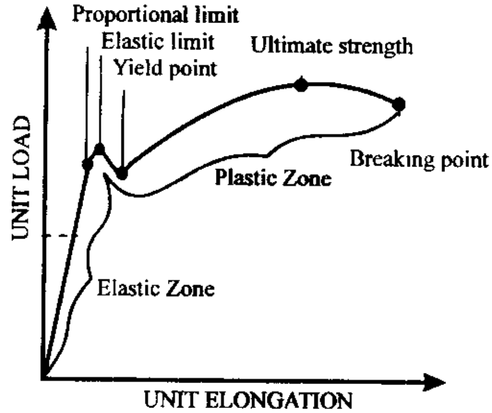


**Figure 3.1 A typical stress–strain curve**

The parameters which are used to describe the stress-strain curve of a material are the elastic limit, proportional limit, yield strength or yield point, tensile or ultimate strength, per cent elongation or reduction of area. The first two indicate elasticity, the second and third are strength parameters, and the last two indicate ductility. In addition to these, resilience and toughness can also be computed from the curve.

As the load is applied the test piece tends to change or changes its dimensions, depending upon the magnitude of the load. When the load is removed it can be seen that the deformation disappears. This occurred upto a certain value of the strain called *elastic limit*. This is depicted by the straight line relationship and a small deviation thereafter, in the stress-strain curve.

Within the elastic range, the limiting value of the stress upto which the stress and strain are proportional, is called the limit of proportionality. In the actual plotting of the curve, the *proportionality limit* is obtained at a slightly lower value of the load than the elastic limit. This may be attributed to the time lag on the regaining of the original dimensions of the test piece. This effect is frequently noticed in some nonferrous metals. Actually, the elastic limit is distinguishable from the proportionality limit more clearly depending upon the sensitivity of the measuring instrument.

When the load is increased beyond the elastic limit, plastic deformation starts. Simultaneously the specimen gets work hardened. A point is reached when the deformation starts to occur more rapidly than the increasing load. This point is called the *yield point*. The metal which was resisting the load till then, starts to deform somewhat rapidly, i.e., yield.

The highest value of stress after which a sudden extension occurs is known as the *upper yield point*, whereas the *lower yield point* is the stress which produces a considerable extension or elongation. In routine testing, it is the lower yield point which is measured.

Some materials exhibit a definite yield point, in which the yield stress is simply the stress at this point.

However, most ductile materials do not have a clear-cut yield (sharp-kneed stress-strain diagram) point. In this case, the curve passes smoothly from the elastic action to the section corresponding to plastic deformation. For such materials a "proof-stress" at a specified strain is calculated. This is usually determined upon completion of the test by an "offset method". Although 0.2 per cent is often employed for steels, and as much as 0.5 per cent for cast iron. However, from the point representing a strain of 0.2 per cent on the zero stress axis a line is drawn parallel to the elastic portion of the stress axis a line is drawn parallel to the elastic portion of the stress-strain curve. This line will intercept the stress-strain curve at the point at which the material being tested departs from elastic behaviour by 0.2 per cent. The stress at this point is the *yield strength*.

As said before, the gauge length is marked on the standard specimen. After the specimen is broken, the two pieces are kept together as if the specimen is not broken at all, with the two fractured surfaces matching each other. The distance between two gauge lengths is again measured. The elongation and the *per cent elongation* are computed.

*Percentage reduction in area* is the decrease in the cross-sectional area of the specimen upto failure, expressed as a percentage of the original cross-sectional area. Both percentage reduction in area and elongation indicate ductility of a material.

The *modulus of resilience* is represented graphically by the area under the stress-strain curve upto the proportional limit., It may be calculated otherwise from datas taken from the curve.

The *modulus of toughness* is assessed by the *total area* under the stress-strain curve. The total area under a stress-strain curve is greater for low and medium carbon steel and, therefore, they are tougher materials.

The *tensile* or *ultimate strength* is the stress corresponding to the maximum load reached before rupturing the specimen.

Hot tensile test is carried out to determine mechanical material properties at high temperature. Hot elastic limit and hot tensile strength depends on the test time as well as temperature.

## 3.6 COMPRESSION TEST

The compression test may be regarded as opposite to the tensile test in so far as the uniaxial load applied is compressive rather than tensile. The compression is rarely used as an acceptance test for structural materials. Since brittle materials are unsuitable for tension test these are usually used in compression to evaluate the strength properties of such materials. Brittle materials such as cast iron, concrete, mortar, brick, ceramics are commonly tested in compression.

Specimens are usually plain right cylinders or prisms whose ends are made as nearly flat and parallel as possible to avoid eccentric loading. Occasionally specimens have enlarged ends to add to their lateral stability.

A *universal testing machine*, fitted with compression plates, is usually used to apply the load, and the specimen should be measured in accordance with standard procedure before it is placed in the machine. After the specimen is properly placed and aligned, a small initial load is usually applied to hold it firmly while the strainometer is being attached. A strainometer especially made for use in compression is often referred to as a *compressometer*. From this point on, the conduct of the compression test is almost identical with that of the tension test.

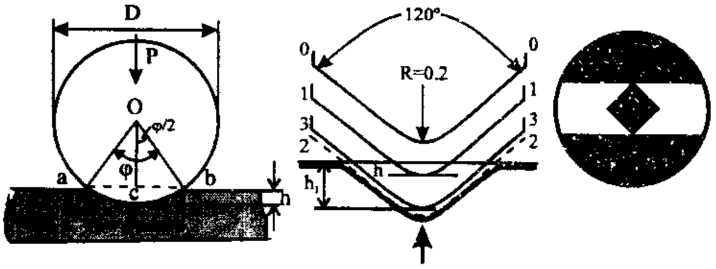
In commercial tests, the only property ordinarily determined is the *compressive strength*. For brittle materials with which fracture occurs, the ultimate strength is definitely and easily determined. For materials where there is no unique phenomenon to mark ultimate strength, arbitrary limits of deformation are taken as the criteria of strength.

In tests to determine modulus of elasticity, possion's ratio, proportional limit stress, and modulus of resilience, exactly the same procedure is followed as in tension.

## 3.7 HARDNESS TESTS

Hardness measurements for determining the properties of a machine component have found extensive application in the quality control of metals and metal products in all branches of industry due to the rapidity and simplicity of the tests and their nondestructive character.

The three most important forms of hardness test are (1) Brinell, (2) Rockwell, (3) diamond pyramid. A fourth type, the shore scleroscope has advantages in certain cases.



(a) (b) (c)

**Figure 3.2 Determining hardness of a metal**
(a) Brinell principle, (b) Rockwell principle, (c) Vickers principle

**Brinell hardness test.** The Brinell hardness test is the most commonly adopted test for hardness of iron and steel. In this test (Fig. 3.2), a hardened steel ball of 10 mm diameter is impressed on a flat polished surface of the sample under a load, usually 500 or 3,000 kg. A load of 750 kg with a 5 mm ball is also used. The load is maintained for 10 to 15 seconds and the diameter of the impression made on the test piece is subsequently measured by means of a microscope the order of accuracy being ± 0.01 mm. The Brinell hardness number is obtained from the equation :

$$\text{BHN} = \frac{\text{load on ball}}{\text{area of indentation}}$$

$$= \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})} \qquad 3.1$$

where BHN = Brinell hardness number
P = Load applied in kg
D = diameter of ball in mm
d = diameter of ball impression in mm

The harder the metal, the higher its Brinell number will be. In practice, hardness number corresponding to a particular indentation diameter is read off from a table in which load, indenter size, indentation sizes, and hardness numbers are correlated.

The Brinell test, irrespective of some limitations, does give a linear scale of hardness and is particularly useful for design work.

**Rockwell hardness test**. The Rockwell hardness test is based on the indentation of a hard tip, or indenter, into the test piece under the action of two consecutively applied loads—minor (initial) and major (final). In order to eliminate zero error and possible surface effects due to roughness or scale, the initial or minor load is first applied and produces an initial indentation .

A conical shaped diamond (called a brale ) with 120° apex angle and 0.2 mm radius is used as the indenter or penetrator in the Rockwell test for hard materials. For softer materials, a hardened steel ball 1.5 mm in diameter is generally used

A number of different scales are used, each scale being suitable for certain classes of materials. It should be understood that each scale is entirely arbitrary, the hardness number obtained having relevance to that particular scale only. Table 3.1 shows some of the commonly used scales.

**TABLE 3.1** ROCKWELL HARDNESS SCALE

| *Scale* | *Indenter* | *Major load (kg)* | *Dial number* | *Typical materials* |
|---|---|---|---|---|
| *A* | Diamond cone | 60 | Black | Cemented carbides, thin steel, case hardnened surfaces. |
| *B* | 1.5 mm ball | 100 | Red | Copper, aluminium, brass, malleable iron, grey cast iron. |
| *C* | Diamond cone | 150 | Black | Hard cast iron, hardened steel. |
| *D* | Diamond cone | 100 | Black | Thin steel specimens. |
| *E* | 3 mm ball | 100 | Red | Soft aluminium and alloys, magnisium alloys, bearing metals. |
| *F* | 1.5 mm ball | 60 | Red | Annealed copper and alloys, bearing alloys. |

After loading, the major load is removed. The Rockwell hardness number is the difference in depths of the indentations made by applying the major and 10 kg minor load, measured after removing the major load. Fig. 3.2 also shows the hardness determination with a diamond cone (brale) in a Rockwell test. The number 1—1 indicates the penetration of the cone under the minor load , 2—2 indicates the penetration of the cone under the major (final) load, and 3—3 indicates the penetration of the cone after major load is reduced again to the value of the minor load.

The load is applied and maintained for upto 15 seconds and then released, the *hardness number* then being read off the scale graduated in hardness units to the nearest whole number.

Rockwell tests are widely applied in industry due to the rapidity and simplicity with which they may be performed, high accuracy achieved and due to the small size of the impressions produced. The Rockwell hardness number may be converted into Brinell number using special tables or charts.

**Vickers hardness test**. The test is similar to that of the Brinell in that the hardness number is derived from the relationship between the applied load and the surface area of the indentation. The test consists in forcing a square-based diamond pyramid (with an angle of 136° between opposite faces) into the ground or even polished surface to be tested. The applied load is 5, 10, 30, 50, 100 or 120 kg. The impression produced by the test is of the form shown in Fig. 3.2. The load is selected according to the thickness and hardness of the specimen.

The Vickers hardness number or diamond pyramid hardness (*DPH*), determined in such tests is the load per unit area of the impression and is found from the formula :

$$DPH = 1.8544 \frac{P}{d^2} \qquad 3.2$$

where $P$ = load applied to the pyramid in kg
$d$ = diagonal of the impression in mm

As a rule, the Vickers hardness number is determined from special tables in accordance with the measured value of $d$ (length of the diagonal). Vickers and Brinell hardness numbers are expressed in the same units and coincide for hardness up to about 400. At higher hardness, the Vickers number is larger than the Brinell number.

Vickers hardness test is used for very hard materials and parts of small cross-section.

**Shore or rebound hardness test**. The shore scleroscope consists of a small diamond pointed hammer of very small weight (about 2.4 g) which is allowed to fall freely from a height of 250 mm down a glass tube graduated into 140 equal parts. The height of the rebound is taken as the index of hardness. This test is used for testing rolls and other machine components, and the instrument can be carried about in workshop. Shore value multiplied by 6 gives roughly the *BHN* on steels.

The scleroscope is very useful for testing the hardness of case-hardened surface which provides a very small hardness of the skin of the surface of the material.

**Microhardness measurement**. At the present time microhardness tests are widely used to determine the hardness of exceedingly thin layers, very small specimens and even separate structural components of alloys.

Two types of tests, indentation and scratch, are made to determine microhardness. The *indentation test* is based on combining a hardness tester, using a diamond pyramid indenter at low loads, with a metallurgical microscope. Loads from 1 to 200 g are applied. The microhardness number is determined from the formula,

$$H = 1.8544\frac{P}{d^2} \qquad 3.3$$

in which $P$ is the load in g, and $d$ is the length of the diagonal in microns.

Microhardness determination based on *scratch test* involves scratching the surface being tested by diamond under the action of a definite load. The width of the scratch is measured with a special microscope. The hardness value is defined either as the width of the scratch obtained at a certain constant load or as the load at which a scratch of definite width is obtained.

## 3.8 IMPACT TESTING

Metals sometimes fail when subjected to suddenly applied load or stress and in order to assess their capacity to stand sudden impacts, the impact test is employed. The impact test measures the energy necessary to fracture a standard notched bar by an *impulse* load and as such is an indication of the *notch toughness* of the material under shock loading.

Two major tests for determining impact toughness are *Izod* test and the *Charpy* test. Both of these methods use the same type of machine and both yield a quantitative value of the energy required to fracture.

The two most common kinds of impact test use notched specimens loaded as beams. The beams may be *simply loaded* (Charpy test) or *loaded as cantilevers* (Izod test). The notch is usually a V-notch cut to specifications with a special milling cutter. The function of the notch is to ensure that the specimen will break as a result of the impact load to which it is subjected. Without the notch, many alloys would simply bend without breaking, and it would therefore be impossible to determine their ability to absorb energy. It is important to note that the blow in Charpy test is delivered at a point directly behind the notch and in the Izod test the blow is struck on the same side of the notch towards the end of the cantilever. Fig. 3.3 shows the clamping arrangement in izod test.

The specimen is held in a rigid vice or support and is struck a blow by a traveling pendulum that fractures or severely deforms the notched specimen. The energy input is a function of the height of fall and the weight of the pendulum. The energy remaining after fracture is determined from the height of rise of the pendulum due to inertia and its weight. The difference between the energy input and the energy remaining represents the energy absorbed by the specimen. Modern machines are equipped with scales and pendulum-actuated pointers, which yield direct readings of energy absorption.

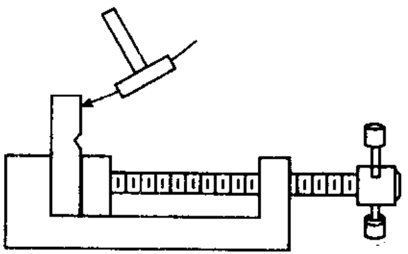


**Figure 3.3 Izod impact testing**

## 3.9 FATIGUE TESTING

Although yield strength is a suitable criterion for designing components which are to be subjected to static loads, for cyclic loading the behaviour of a material must be evaluated under dynamic conditions. The ***fatigue strength*** or ***endurance limit*** of a material is therefore used in the design of parts subjected to repeated alternating stresses over an extended period of time.

The fatigue test determines the stresses which a sample of a material of standard dimensions can safely endure for a given number of cycles. This is accomplished using a specimen having a round cross-section, loaded at two points as a rotating simple beam, and supported at its ends. The top surface of such a specimen is always in compression and the bottom surface is always in tension. The maximum stress always occurs at the surface, halfway along the length of the specimen, where the cross-section is minimum. For each complete rotation of the specimen, a point in the surface originally at the top centre goes alternately from a maximum in compression to a maximum in tension and then back to the same maximum in compression.

Specimens are tested to failure using different loads, and the number of cycles before failure is noted for each load. The results of such tests are plotted as graphs of applied stress against the logarithm of the number of cycles to failure. The curve is known as *S-N* curve. The usual procedure is to make a number of specimens of the same material and test other one under different stress conditions.

Two different types of $S$-$N$ curves occur, one showing a definite levelling off the curve, which indicates that the material has a definite *fatigue limit*. Commonly, ferrous metals shows distinct fatigue limit, while nonferrous metals do not. This is illustrated in Fig. 3.4. The fatigue limit is about 40 to 60 per cent of the tensile strength.

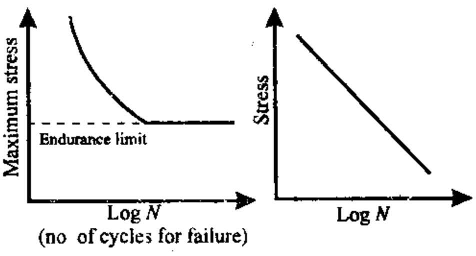


**Figure 3.4 Shape of fatigue curves**

## 3.10 CREEP AND STRESS RUPTURE TESTING

As metals are exposed to temperatures within 40 per cent of their absolute melting point, they begin to elongate continuously at low load; but at a temperature higher than this it becomes increasingly important. It is for this reason that the creep test is thought of a high-temperature test. A creep curve is a plot of the elongation of tensile specimen versus time, at a given temperature, under either a constant load or under a constant *true stress*. Tests may run for a period of days to many years. Fig. 3.5, a typical creep curve, shows four stages of elongation: (1) *instantaneous elongation* following the application of the load, (2) *transient* or *primary creep*, (3) *secondary creep*, and (4) *tertiary creep*. During the primary creep the rate of work hardening decreases because the recovery processes are slow, but during secondary creep both rates are equal. In the FOURTH stage of creep, grain boundary cracks or necking may occur which reduces the cross-sectional area of the test specimen.

### STRESS-RUPTURE TESTING

This is an extension of the creep test. In this test a sample is held under an applied load at a definite temperature until it fractures. The elongation of the sample, the time until fracture, the applied load and the testing temperature are all recorded. Then a series of curves are plotted which can be helpful to the designer when he must consider high-temperature applications such as gas and steam turbines, high-pressure steam lines, rocket engines, pressurized nuclear power sources and chemical-processing equipment which operate at high temperatures and pressures.

## 3.11 NONDESTRUCTIVE TESTING

The mechanical tests carried out on metals as described before involve cutting or destroying of the metal. But when a structure or metal part is not to be spoiled while testing, certain tests called *"nondestructive tests"* are carried out to detect flaw and crack in the metal. A brief description of these methods is given below.

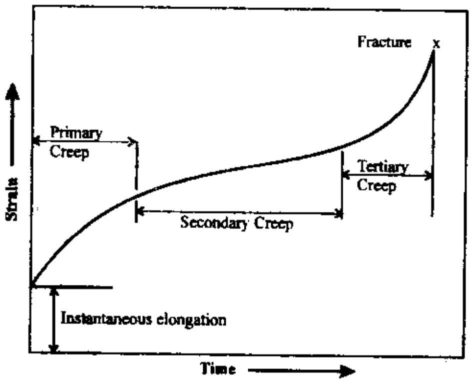


**Figure 3.5 Typical creep curve for a long-time, and high temperature creep curve test**

### VISUAL EXAMINATION

This is always the first step in the inspection of a component and may be done with the unaided eye or by using hand lens or a microscope. Although a seemingly elementary procedure, it should be carried out carefully and systematically on every component.

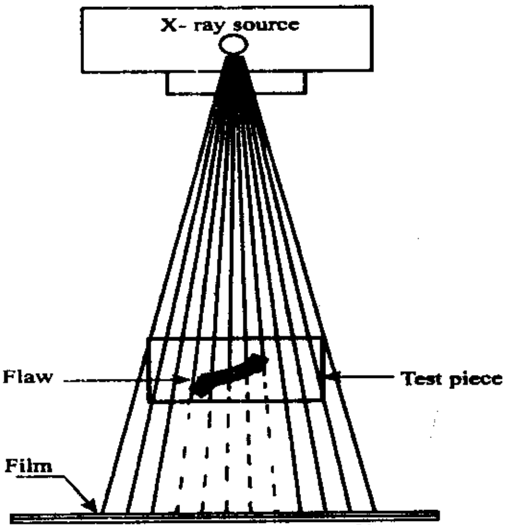
### RADIOGRAPHIC TESTS

These tests are based on the absorption and dispersion of X-rays or $\gamma$-rays passing through the material. By means of a luminescent screen or photographic plate, points of varying radiaion intensity that occur at faults can be detected.

As radiation sources, X-rays produced by Betatron devices (electron centrifuge) or $\gamma$-rays produces by radio-active decay processes are used. In these methods the radiation is passed through the metal being examined and is then allowed to impinge upon sensitive film. Thus, if an object has an internal defect, more radiation will be passed through the defective area than through the sound region and the deffect will show up as a dark area on the film. Unfortunately, scattering tends to obscure the defect, so that small defects may not be detected. In general, X-rays are preferred for laboratory testing since they offer greater control over intensity and they produce sharper pictures.

X-ray equipment is generally large and bulky, whereas gamma radiography depends upon the use of small, mobile sources of radioactivity, such as radioactive cobalt, iridium, samorium and other radioactive elements. In addition gamma rays, though of the same nature as X-ray, have a generally shorter wave length and therefore, more effective in the study of thick sections. Fig. 3.6 shows the basic principle of X-ray inspection.

In radio graphic tests, the inclusions appear darker, while blow-holes, cavities and porosity appear lighter, than the surrounding metal.



Darker area on film because of less absorption of X rays in void of flaw

**Figure 3.6 Radiography testing**

## ULTRASONIC TESTING

It relies upon transmission and reflection of ultrasonic beams or waves of frequencies between 100 kHz and 25 MHz. The ultrasonic waves are usually produced by the piezoelectric effect within the crystal probe which is placed on the surface of the specimen. Discontinuities below the surface cause reflection of the ultrasonic waves which appear as peaks upon the cathode-ray oscilloscope receiver. The size of the peak seen on the receiving tube is some indication of the size of the defect. The crystal probe thus becomes the receiver as well as the transmitter. Ultrasonic techniques are useful for detecting cracks, voids and defects far below the surface as well as near the surface. The basic principle of ultrasonic inspection is shown in Fig 3.7.

While radiation and ultrasonic tests are very sophisticated and yields excellent results under almost all circumstances, the older *hammer test* is still employed for the detection of internal defects. If a "sound" object, that is one free from large internal flaws, is struck sharply with a suitable hammer it emits a clear ringing note. whereas a defective object emits a flat, unusual note. This test gives valuable information to a skilled operator about the quality of the object.

## LIQUID PENETRANT TESTS

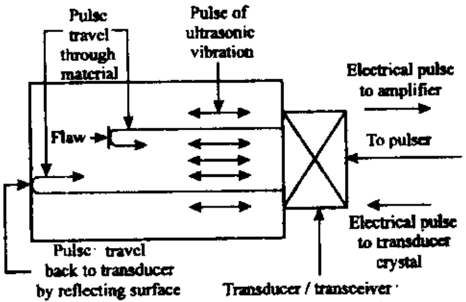


**Figure 3.7 Ultrasonic testing**

These tests reveal discontinuities that are open to the surface and may use dyes or fluorescent materials. They are specially useful for non-ferrous metals and nonmetallic substances. The simple test involves dipping the component into kerosene, wiping it dry, and then coating it thinly with whiting. Cracks will be revealed by a discoloured "line" appearing in the whiting, this being produced when kerosene trapped in the cracks seeps out slowly. Dyes may be used instead of kerosene, but fluorescent materials are probably the most widely used.

In the fluorescent test, the sample is immersed for some time in a hot bath of a strongly fluoresecent compound such as anthracence, used as a penetrating agent. The solution enters the cracks, if any, and remains there. The metal is then dried and examined under a quartz tube mercury vapour lamp. Any penetrated solution will be detected by the flourescence caused by the ultraviolet radiation of the light.

## MAGNETIC PARTICLE TESTS

Magnetic crack-detection apparatus is designed to detect normally invisible cracks on or extending near to the surfaces of articles made of magnetic materials.

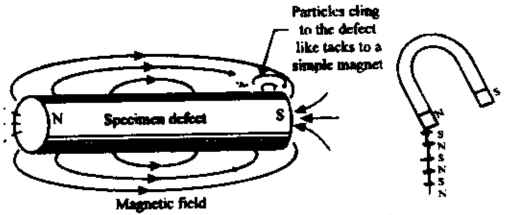


**Figure 3.8 Magnetic particle test**

The design of magnetic crack-detectors is based on the principle that, if a crack or flaw is present in a magnetic material through which a magnetic field is passing, the lines of force will be distorted near the fault owing to the local change of permeability associated with it. In the case of a piece without any flaw, lines of force will be uniform and straight.

Cracks and flaws can also be detected by magnetizing a ferrous metallic part, then sprinkling very fine iron dust over it. The magnetic poles formed at the crack gather a line of dust and outline the crack. The special equipment for this magnetic testing for cracks is known as *magnaflux*. The basic principle is shown in Fig. 3.8.

## REVIEW QUESTIONS

1. What is meant by mechanical properties of a materials ? State their importance in the design of a machine or structural elements.
2. What is engineering stress and strain? What is meant by "true stress" and "true strain" ? State where each of them is particularly used and suitable.
3. What are "modulus of elasticity" and "Poisson's ratio" ? What they indicate in material properties ?
4. Explain the difference between : (a) elastic limit and proportional limit, (b) yield point and yield strength, (c) toughness and resilience, (d) hardness and brittleness, (e) endurance limit and fatigue strength, (f) strength and stiffness, (g) ductility and malleability, (h) elasticity and plasticity.
5. Name five important mechanical tests which give valuable information about metal and alloys. What are the relative merits and draw-backs of each? What kind of results can be expected from these tests ?
6. Draw a stress-strain diagram for a low carbon steel specimen indicating the proportional limit, elastic limit, yield point, the point of maximum loading and rupture. Explain the above important data.
7. Explain how would you measure the following :
   - (a) reduction of area,
   - (b) percentage elongation,
   - (c) modulus of toughness,
   - (d) endurance limit,
   - (e) modulus of resilience
   - (f) creep limit,
   - (g) energy to fracture.
8. What does impact test signify ? Explain the procedure to be adopted in the impact test, conducted on a pendulum type impact testing machine.
9. What are different hardness tests of interest to the testing engineer under various situations ?
10. Draw a typical "creep test" curve, showing different stages of elongation for a long time high temperature creep test. State how the information is helpful to the design-engineer.
11. State the mechanism of : (a) fatigue failure, (b) creep failure.
12. Why are the non-destructive testing methods given importance ? List different types of non-destructive tests.
13. State and explain the principle of mangaflux method in finding flows in metal.
14. Describe briefly (a) liquid penetrant method (b) visual inspection method.