will cause waviness in the work surface. In addition unbalance may cause the wheel to break with the probability of serious damage and injury. Balancing is usually done in the static position of wheel by shifting the position of weights on one of the mounting flanges of wheel. Poor balance may be detected by the vibrations set up in the machine, poor finish and difficulty in maintaining size.

5.17. Operating Speeds and Feeds

The surface speeds of grinding wheels are generally high. Table 5.6 shows some typical grinding operations and the average values of wheel surface speeds. The amount of feed for rough grinding varies from 0.025 to 0.1 mm and for finish grinding from 0.005 to 0.01 mm.

Table 5.6

Type of grinding	*Surface speed (metre per min)*
Surface grinding	1200—1800
Cylindrical grinding	1600—1950
Centreless grinding	1500—1800
Tool and cutter grinding	1300—2000
Snagging (Resinoid bonded wheel)	1800—2200

5.18. Theory of Grinding

During grinding the grinding wheel starts removing the material as soon as it comes in contact with the workpiece. As shown in Fig. 5.19 when an abrasive grain starts to enter the workpiece at K the depth of cut is zero and it increases gradually as the wheel and the work revolve. As usually wheel rotates at higher speed than the work the point of maximum cut depth is almost at the point where the wheel leaves the work. Area KMN is the chip with its maximum thickness of NL.

Let D_1 = Diameter of wheel.

D_2 = Diameter of workpiece.

V = Surface velocity of wheel.

v = Surface velocity of workpiece.

T = Time taken by a grain on grinding wheel to move from K to M.

f = Radial feed.

Arc $KM = V \times T$.

During this time a point on workpiece at A will be able to move only up to N.

Arc $KN = v \times T$

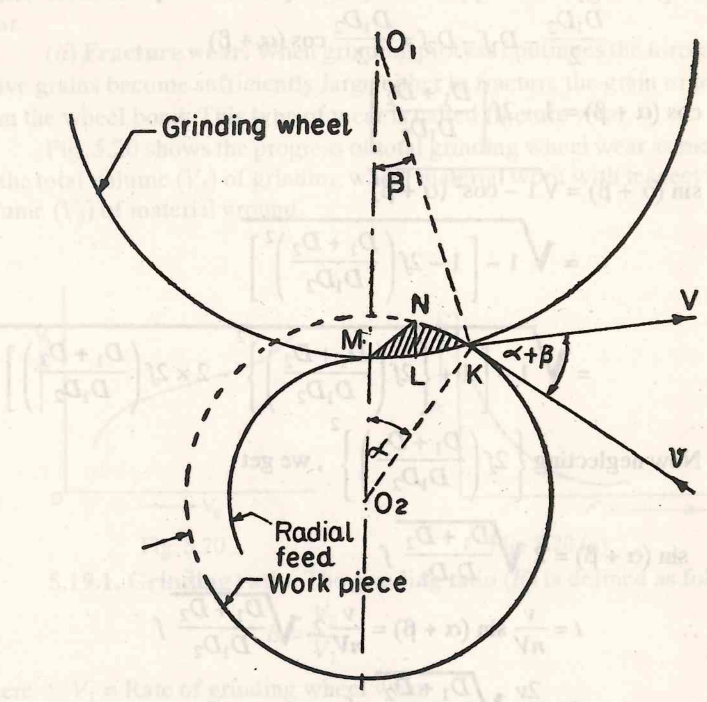


Fig. 5.19

By ignoring the very small amount of curvature which occur, KLN may be treated as a right angled triangle, the right angle at L.

$$NL = KN \sin(\alpha + \beta) = vT \sin(\alpha + \beta).$$

If n = number of grits per unit length of wheel circumference then the maximum chip thickness per grit or grain depth of cut (t) is given by

$$t = \frac{NL}{n(\text{Arc } KM)} = \frac{vT \sin(\alpha + \beta)}{n \,.\, V \,.\, T}$$

$$= \frac{v}{nV} \sin(\alpha + \beta)$$

Now from $\Delta\, O_1O_2K$

$$O_1O_2^2 = O_1K^2 + O_2K^2 - 2\, O_1K \times O_2K \cos \angle O_1KO_2$$

$$\left(\frac{D_1}{2} + \frac{D_2}{2} - f\right)^2 = \left(\frac{D_1}{2}\right)^2 + \left(\frac{D_2}{2}\right)^2 - 2\,\frac{D_1}{2} \cdot \frac{D_2}{2} \cos[180 - (\alpha + \beta)]$$

$$= \left(\frac{D_1}{2}\right)^2 + \left(\frac{D_2}{2}\right)^2 + \frac{D_1 D_2}{2} \cos(\alpha + \beta)$$

Neglecting f^2 as compared to D_1 and D_2 and on simplification, we get

$$\frac{D_1D_2}{2} - D_1f - D_2f = \frac{D_1D_2}{2}\cos(\alpha + \beta)$$

$$\cos(\alpha + \beta) = 1 - 2f\left[\frac{D_1 + D_2}{D_1D_2}\right]$$

$$\sin(\alpha + \beta) = \sqrt{1 - \cos^2(\alpha + \beta)}$$

$$= \sqrt{1 - \left[1 - 2f\left(\frac{D_1 + D_2}{D_1D_2}\right)\right]^2}$$

$$= \sqrt{1 - \left[1 + \left\{2f\left(\frac{D_1 + D_2}{D_1D_2}\right)\right\}^2 - 2 \times 2f\left(\frac{D_1 + D_2}{D_1D_2}\right)\right]}$$

Now neglecting $\left\{2f\left(\frac{D_1 + D_2}{D_1D_2}\right)\right\}^2$, we get

$$\sin(\alpha + \beta) = 2\sqrt{\frac{D_1 + D_2}{D_1D_2}f}$$

$$\therefore \quad t = \frac{v}{nV}\sin(\alpha + \beta) = \frac{v}{nV}2.\sqrt{\frac{D_1 + D_2}{D_1D_2}f}$$

$$t = \frac{2v}{nV}\sqrt{\frac{D_1 + D_2}{D_1D_2}.f}$$

Let F = Force on individual grits of grinding wheel.

The force F is proportional to the area of the chip formed which is proportional to the square of grain depth of cut

$$F \propto t^2$$

$$\propto \left(\frac{2v}{nV}\right)^2 \frac{D_1 + D_2}{D_1D_2}.f \propto \left(\frac{v}{V}\right)^2 \frac{D_1 + D_2}{D_1D_2}.f$$

$$\frac{2}{n} = \text{constant.}$$

The above expression shows that the grits will break from the wheel if the force exceeds bond strength and also increase in work speed will be more effective in breaking the grits than increasing the radial feed.

5.19. Grinding Wheel Wear

In the grinding process the grains of abrasive are suujected to wear and the grinding wheel losses its cutting capacity.

There are two types of grinding wheel wear.

(*i*) **Attritious wear.** During grinding when the active grains make repeated contact with the work piece, the sharp edges are worn away, producing flat areas or wear scars on the grains. This type of wear is called attritious wear.

(*ii*) **Fracture wear.** When grinding process continues the forces on the active grains become sufficiently large either to fracture the grain or to tear it from the wheel bond. This type of wear is called fracture wear.

Fig. 5.20 shows the progress of total grinding wheel wear as measured by the total volume (V_1) of grinding wheel material worn with respect to total volume (V_2) of material ground.

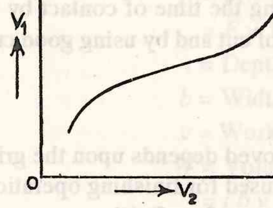


Fig. 5.20

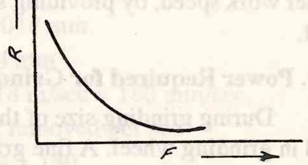


Fig. 5.20 (*a*)

5.19.1. Grinding ratio. The grinding ratio (R) is defined as follows.

$$R = \frac{V_2}{V_1}$$

where V_1 = Rate of grinding wheel wear

V_2 = Rate of metal removal.

A worn grinding wheel ceases to cut and its cutting capacity can be restored by dressing which may be described as sharpening operation. It is observed that it is sufficient to remove a layer of dulled grains 0.08 mm deep to restore the cutting capacity of a grinding wheel.

A high grinding ratio is desirable. Fig. 5.20 (*a*) shows the variation of grinding ratio (R) with thrust force (F) acting during grinding.

5.20. Grinding Temperature

In grinding there is rise in temperature due to the resistance to deformation during shearing of the chips as well as the frictional resistance encountered in the chip tool interface. The temperature changes arising from the grinding process may relate to

(*i*) The mean grit temperature (T).

(*ii*) The mean temperature at or just below the ground surface (T_s).

The grit temperature is found as follows

$$T = \text{A.E.}\sqrt{\frac{V.t}{K.P.C.}}$$

where A = a constant depending on wheel work pair

E = Total specific energy of grinding
V = Surface velocity of grinding wheel
t = Maximum grit depth of cut.
K = Thermal conductivity of material.
P = Density of job material.
C = Specific heat of job material.

The rate of wheel wear depends upon the total grit temperature (T). The surface temperature (T_s) is determined by calculating the shear zone temperature. The severe temperature gradients in the work surface during grinding tend to produce very high residual stresses. Surface damage and residual stresses can be minimised by reducing the time of contact by using higher work speed, by providing small depth of cut and by using good cutting fluid.

5.21. Power Required for Grinding

During grinding size of the chips removed depends upon the grit size used in grinding wheel. A fine grit should be used for finishing operations as it will remove finer chips and leave a smoother surface finish.

Fig. 5.21 shows a surface grinding operation. F and R art the component of forces acting on all the grits in contact with the workpiece.

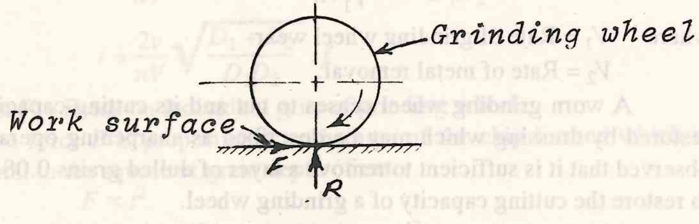


Fig. 5.21

P = Power required for grinding
$= F \times V$ Watts

where F = Tangential force upon wheel in Newtons.
V = Wheel speed in m/sec.
H = Power required per mm^3 of metal removed per second

$$= \frac{P}{W} \text{J/mm}^3$$

where W = Volume of metal removed per second
$= t.b \times v.$

where t = Depth of cut (mm)
b = Width of cut (mm)
v = Work speed (mm/sec).

Example 5.1. *Calculate the power required per mm^3 of metal removed per second for a surface grinding operation using the following data.*

Wheel speed = *20 m/s*
Work speed = *0.18 m/s*
Tangential force = *84 N*
Depth of cut = *0.018 mm.*
Width of cut = *14 mm.*

Solution. F = Tangential force = 84 N
V = Wheel speed.
P = Power required.
$= F \times V = 84 \times 20 = 1680$ Watts.
t = Depth of cut = 0.018 mm.
b = Width of cut 14 mm
v = Work speed = 0.18 m/sec = 180 mm/sec.
W = Volume of metal removed per sec
$= t.b\, v = 0.018 \times 14 \times 180$
$= 45.36$ mm^3.
H = Power required per mm^3

$$= \frac{P}{W} = \frac{1680}{45.36}$$

$= 37$ J/mm^3

Example 5.2. *(a) Define the following*
(i) Abrasive grain size.
(ii) Grade of a grinding wheel.
(b) During external cylindrical grinding the following observations were made.

Diameter of work piece = *40 mm.*
Diameter of grinding wheel = *240 mm.*
Wheel velocity = *16 m/sec.*
Work velocity = *14 m/min.*
Wheel depth of cut = *0.03 mm*
Grains are 0.5 mm apart
Calculate grain depth of cut.

Solution. (*a*) **Size of grain.** The size of abrasive grain used in a grinding wheel is designated by a number corresponding to number of openings per unit length in the screen used to size the grain. A since number however generally indicates only an average grain size since in sizing the grain a finite number of screen are used.

Grade. The grade of hardness of a grinding wheel indicates the relative strength of the bond which holds the abrasive grains in place. Wheel grade is indicated by letters A to Z, A being the softest wheel and Z the hardest. The effective grade of the wheel depends strongly on the speed of wheel and other grinding variables and whether a cutting fluid is used.

(*b*) D_1 = Diameter of grinding wheel

= 240 mm.

D_2 = Diameter of workpiece

= 40 mm.

v = Surface velocity of workpiece

= 14 m/min = 0.23 m/sec = 230 mm/sec.

V = Wheel velocity = 16 m/sec.

= 16000 mm/sec.

f = Radial feed.

= Wheel depth of cut.

= 0.03 mm.

n = Grit spacing or grains per mm.

$$= \frac{1}{0.5} = 2$$

t = Grit depth of cut

$$= \frac{2.v}{n.V.} \sqrt{\frac{D_1 + D_2}{D_1.D_2} \times f}$$

$$= \frac{2 \times 230}{2 \times 16000} \sqrt{\frac{240 + 40}{240 \times 40} \times 0.03}$$

= 0.00043 mm.

5.22. Polishing

It is surface finishing process by which scratches and tool marks are removed with a polishing wheel. The workpiece is brought in contact with the revolving wheel that has been charged with a very fine abrasive. Polishing wheels are made of canvas, leather felt or paper. Tolerances of 0.025 mm or less can be obtained in machine polishing.

5.23. Buffing

It is also a surface finishing process and is used to produce a lustrous surface of attractive appearance. In this very little amount of material is removed. In this process also the workpiece is brought in contact with the revolving wheel. Buffing wheels are made up of felt, or cotton. Powdered abrasives are applied to the surface of the wheel. The abrasive may consists of iron oxide, chromium oxide, emery etc.

5.24. Lapping

Lapping is the process of producing an extremely accurate highly finished surface. Lapping is carried out by means of lapping shoes called laps.

The laps are made up of soft cast iron, copper, lead and brass. The lap material is always softer than the material to be finished. Fine abrasive particles are charged (caused to become embedded) into the lap. Silicon carbide, aluminium oxide and diamond dust are the commonly used lapping powders. Oil and thin greases are used to spread the abrasive powders. As the charged lap is rubbed against workpiece surface the abrasive particles in the surface of the lap remove small amounts of material from the workpiece surface. Thus it is the abrasive that does the cutting and the soft lap is not worm away. The material removed by lapping is usually less than 0.025 mm.

Lapping can be done either by hand or by special machines. In hand lapping the lap is flat similar to a surface plate. The lap has a carefully turned surface with a series of grooves in it. Grooves are provided to collect the excess abrasive and chips. The surface of lap is charged with a fine abrasive. The work is moved across the surface of the lap using reciprocating rotary motion. Fig. 5.22 shows how one surface of a hardened steel part may be finished on a flat cast iron lap. Fig. 5.23 shows a squaring lap in which the edge of the steel part is lapped at right angles to the bottom surface.

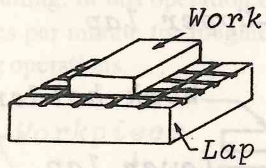


Fig. 5.22

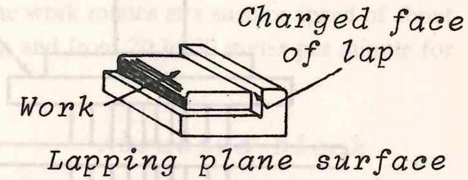


Fig. 5.23

Machine lapping consists of two flat abrasive laps. The two labs called upper and lower laps rotate in the opposite direction. (Fig. 5.24). Work holder can take a number of workpieces which are merely pushed around by the work holder and are not clamped in any way.

The nature of relative motion in lapping depends upon the shape and other features of the surface being lapped. Slightly differing motions are imparted to the workpiece and the lap so that the path of abrasive grains of lap is not repeated on the work. Laps are made from cast iron, soft steel copper, brass and hard wood. Lapping machines are of general purpose and single purpose types are available. The single purpose types include machines for lapping valve seats, crankshaft, crank pins and journals, cam shafts, gears etc. Cylindrical and flat surfaces are generally finished in general purpose machines.

In lapping the results depend upon the following factors :

(*i*) Type of lapping medium or abrasive material. For example aluminium oxide is used for improved surface finish whereas silicon carbine is used for rapid stock removal.

(*ii*) Type of lap material.

(*iii*) Speed and pressure of lapping motion. In lapping speeds between 1.5 to 4 m/sec are commonly used.

(*iv*) Material to be lapped. This factor affects the surface finish and non ferrous metals require finer grit size to produce proper surface finish.

5.25. Honing

Honing is an abrading process mostly used for finishing internal cylindrical surfaces such as drilled or bored holes. Removal of metal by honing involves the use of a number of bonded abrasive stones called hones. Honing stones are formed by bonding abrasives like aluminium oxide or silicon carbide in vitrified or resinoid bond. Material like sulphur, resin or wax can be added to the ponding agent to improve the cutting action.

Although honing can be done by hann as in finishing the faces of cutting tools it is more often done with special equipment. The honing stones are usually held in a honing head. Controlled light pressure is used to hold the stones against the work surface. The honing stones (hones) can be forded

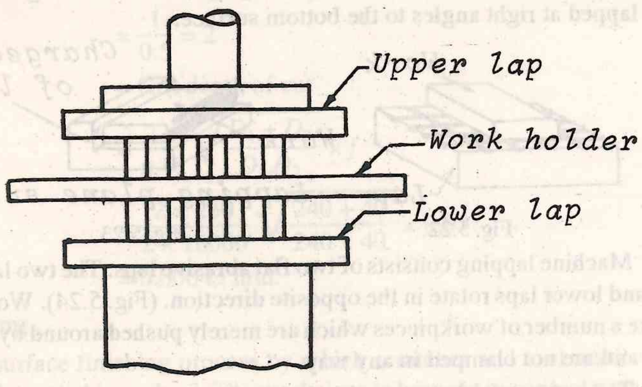


Fig. 5.24

radially outwards as desired. Single and multiple spindle honing machines are available in both vertical and horizontal spindle types. For honing single, internal cylindrical surfaces a procedure where in a machine rotates the hone is used quite often the workpiece being manually held and reciprocated over the hone.

Fig. 5.25

Honing is both a sizing and finishing operations. The primary function of honing is to remove scratches remaining from grinding and the amount of metal removed usually is less than 0.125 mm. Geometrical error in a cylindrical bore corrected by honing is shown in Fig. 5.25.

5.26. Super Finishing

It is an abrasive process for removing smear metal, scratches and ridges produced by machining and grinding operations and other surface irregularities from parts that are to have highly finished surface. It is used for producing an extremely high quality of surface finish and is used for removing very small amount of stock. The amount of metal removed is generally 0.005 to 0.0025 mm. Therefore, to achieve such a close dimensional accuracy grinding is generally employed prior to super finishing. In super finishing an abrasive stick is retained in a suitable holder and applied to the surface of the workpiece with a light pressure. As compared to honing super-finishing is done at much lower speed and super finishing is largely used for finishing outside surfaces whereas honing is mostly used for finishing inside surfaces.

Fig. 5.26 shows the principle of super finishing process. The abrasive block reciprocates across the work with a similar amount of over run at each end of stroke. At the same time the work rotates about its axis. These two motions produce a high degree of accuracy. The work is flooded with lubricant during cutting. In this operation the work rotates at a surface speed of about 10 metres per minute for roughing and from 20 to 30 meter per minute for finishing operations.

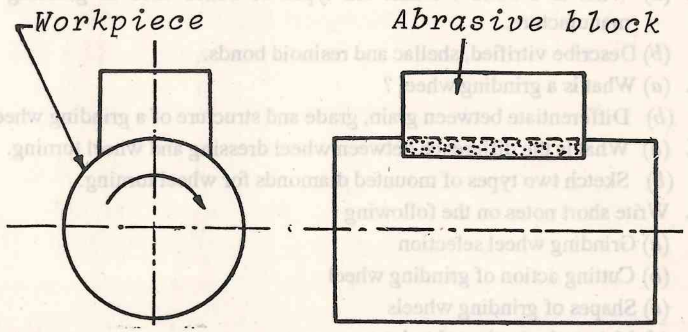


Fig. 5.26

Super-finishing is compared with honing as follows :

(*i*) Super-finishing uses very high controlled pressure.

(*ii*) Super-finishing uses rapid short strokes.

(*iii*) It uses controlled stroke paths so that a single grit never traverses the same path twice.

(*iv*) Copious amounts of low viscosity lubricant—coolant floods over the surface is used.

The abrasives used are aluminium oxide for materials of high tensile strength such as carbon, alloy and high speed steels and materials of considerable hardness. Silicon carbide abrasives are preferable for low tensile materials such as cast iron aluminium brass and materials such as brake linings. Bonded diamond dust is used for finishing cemented carbide tools.

5.27. Specific Energy for Grinding

The energy per unit volume of metal removed or specific energy for surface or internal or external grinding is given by the following relation

$$E = \frac{HV}{U.b.d}$$

where E = Specific energy

H = Tangential force between grinding wheel and work piece

V = Surface speed of grinding wheel

U = Table speed

b = Width of each cut

d = Wheel depth of cut.

PROBLEMS

5.1. Define the term grinding.

5.2. Describe the various types of abrasives in grinding wheels.

5.3. (*a*) What is a bond ? Name six types of bonds used in grinding wheel manufacture.
(*b*) Describe vitrified, shellac and resinoid bonds.

5.4. (*a*) What is a grinding wheel ?
(*b*) Differentiate between grain, grade and structure of a grinding wheel.

5.5. (*a*) What is the difference between wheel dressing and wheel turning.
(*b*) Sketch two types of mounted diamonds for wheel turning.

5.6. Write short notes on the following :
(*a*) Grinding wheel selection
(*b*) Cutting action of grinding wheel
(*c*) Shapes of grinding wheels
(*d*) Mounted wheels and points.

5.7. Differentiate rough grinder and precision grinder.

5.8. Make a neat sketch of centre type cylindrical grinder and explain its operation.

5.9. Make a neat sketch of chuck type internal cylindrical grinder and explain its operation.

5.10. (*a*) What is surface grinding ?
(*b*) Make a neat sketch of horizontal wheel spindle and reciprocating table surface grinder and explain its operation.

5.11. (*a*) What is centreless grinding ?
(*b*) Make a neat sketch of centreless grinder and explain its operation.
(*c*) State the advantages of centreless grinding.

5.12. Write short notes on the following :
(*a*) Mounting of grinding wheel
(*b*) Grinding wheel balancing
(*c*) Marking system of grinding wheel.

5.13. Write short notes on the following :
(*a*) Lapping (*b*) Honing
(*c*) Super finishing (*d*) Polishing and buffing
(*e*) Tool and cutter grinder.

5.14. Describe the following :
(*a*) Grinding wheel wear (*b*) Grinding temperature
(*c*) Power required for grinding.

5.15. Define the following :
(*i*) Grinding ratio
(*ii*) Specific energy for grinding.

6

Chatter and Surface Finish

6.1. Chatter and Vibrations in Machining

Sometime a machine tool can vibrate due to the cutting process itself. In such conditions the exciting force is not coming from an outside element, it is supplied by the cutting process itself. These types of vibrations are self induced vibrations and generally called as machine tool chatter. Chatter is the resonant vibration of the cutting tool, workpiece or the machine tool. It is often so severe that machining must be discontinued and the cutting conditions changed. Its severity is determined by the periodic vibration in the cutting forces and vibrational frequencies such as those of the work, tool and tool support etc. Chatter produces the following effects :

(*i*) It increases wear of the cutting tool and machine tool and dis-adjusts the joints in the fixture and machine tool.

(*ii*) Vibration of the machine-tool-workpiece system deteriorates the surface finish and accuracy.

(*iii*) It reduces tool life.

(*iv*) Heavy vibrations make it necessary to reduce the rate of metal removal and sometimes tool operation becomes very difficult.

Elimination of chatter is essential to preserve workpiece quality and to protect tool life. Presence of chatter necessitates a reduction in the cutting speeds of 10 to 15% when high speed steel tools are used. Chatter tends to occur when damping or dynamic stiffness is small.

Production of chatter depends upon the following factors :

(*i*) Design of machine tool.

Rigidity of the machine tool and the cutting system has a great deal to do with chatter proneness.

(*ii*) Type of workpiece material

(*iii*) Type of cutting operation

(*iv*) Type and design of fixturing

(*v*) Geometry of cutting tool

(*vi*) Feed, speed and depth of cut.

6.1.1. Vibrations in machine tool

Most machine tools vibrate because of mechanical defects. Such defects are always present. A well designed and well built machine tool operates smoothly because the defects are small but when defects are large, vibrations become excessive.

Different parts of machine tool structure are subjected to loading in different ways because of the following reasons :

(*i*) Changes in workpiece and cutter diameter.

(*ii*) Direction of feed.

(*iii*) Varying depth of cut.

Further the moving parts of machine tools do not always move at the same velocity because of wide range of feed and speed combinations.

This results in a vibratory system having a very complex dynamic behaviour. The vibrations produced affect the machine tool, cutting tool and workpiece.

Vibrations in a machine tool occur due to the following reasons.

(*i*) Un-balanced of rotating parts.

(*ii*) Misalignment of coupling and bearing.

(*iii*) Defective drive (belt, chain gear drive).

(*iv*) Interference in gears.

(*v*) Self induced vibrations because of cutting process (tool chatter) is generated and changes its magnitude.

(*iv*) Hydraulic forces.

(*vii*) Aero dynamic forces.

(*viii*) Mechanical looseness or insufficient rightness of fasteners.

Each cause of vibration generates a force which is changing in either its direction or its magnitude. It is the force which causes vibrations and resulting vibrations characteristics will be determined by the manner in which force is generated and changes its magnitude.

Mechanical vibrations of engines, machines, structures etc. produce side effects with high level of noise and ending with mechanical failure.

Vibration measurement and analysis leads to the early detection of component deterioration. The vibration level can be reduced by changing faulty machine components or repairing them by balancing, aligning etc. The level at machine vibrations as measured at specific points after certain fixed number of operating hours can be used as an indication of machine condition.

6.2. Types of Vibrations

In metal cutting two types of vibration may take place.

(*i*) Forced vibrations.

(*ii*) Self excited vibrations.

1. **Forced vibrations.** Forced vibrations are produced by the cyclic vibrations in the cutting forces such as

(*i*) Variable forces acting on the system as a result of interrupted cutting.

(*ii*) Centrifugal forces of inertia of unbalanced rotating masses.

(*iii*) The impact forces caused by manufacturing errors on the working surfaces of components of the mechanism for transmitting motion.

(*iv*) Rough spindle bearing.

The forced vibrations can result in an increasing amplitude of vibration and is called regenerative chatter (Fig. 6.1).

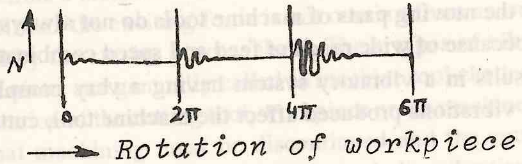


Fig. 6.1. Regenerative chatter in turning.

Forced vibrations which are produced under the action rhythmically varying force on the cutting tool such as RPM of unbalanced pulley spindle, workpiece have a frequency corresponding to the frequency of vibrating agent which may be quite different from natural frequency of vibrating members. Forced vibrations cause problems for finishing operations such as grinding, finish boring, finish turning etc.

2. **Self excited vibrations.** These vibrations take place due to the following reasons :

(*i*) Variability of the force of friction between the flowing chip and the tool and between the tool and work.

(*ii*) Non-uniform work hardening of the layer being cut across its thickness.

(*iii*) Instability of the built up edge which leads to changes in the cutting angle and the cross sectional area of the uncut chip in the cutting process.

Other factors which produce vibrations are as follows :

(*i*) Faulty bearings. (*ii*) Imperfect balancing.

(*iii*) Faulty meshing of gears. (*iv*) Weak structure of machine tool.

(*v*) Machine tool over loaded.

(*vi*) Machine tool mounted on a faulty foundation.

6.3. Factors Affecting Chatter

(*i*) **Rigidity of the system.** Higher the rigidity of the machine tool workpiece system and smaller the clearance between its members the less favourable the conditions for the origination of vibrations.

(*ii*) **Stiffness of work support.** The intensity of chatter increases with the distance from the point of support. The work support should be quite rigid. Moreover hang of tail stock spindle reduces the rigidity and gives rise to more vibrations.

(*iii*) **Stiffness of tool.** The cutting tool should be firmly clamped with a minimum of overhang beyond the point of support. The more the tool overhang from tool holder the greater the vibrations.

(*iv*) **Cutting speed.** Vibrations first increase and then decrease with and an increase in cutting speed.

(*v*) **Nose radius.** Vibrations increase with an increase in the nose radius of the tool.

(*vi*) **Workpiece material.** In machining steels especially of tough grades heavier vibrations are produced than in machining materials like cast iron.

(*vii*) Faulty bearings also cause vibrations.

(*viii*) Vibrations may be produced by weak structure of machine tool, overloading of machine tool and machine tool mounted on a faulty foundation.

(*ix*) Faulty meshing of gears also sometime produce vibrations.

6.4. Types of Vibratory Systems

Chatter during machining produces these types of systems.

(*i*) Statically stable system.

(*ii*) Statically stable but dynamically unstable.

(*iii*) Statically and dynamically stable system.

In machining self induced vibrations may be considered as free vibrations with negative damping. The negative damping increases the amplitude of vibrations (Fig. 6.2). A statically stable system in one in which displacement from the equilibrium position sets up a force tending to bring the system back to equilibrium position. A system with positive damping conditions are dynamically stable. (Fig. 6.3). A dynamically stable system is also statically stable under normal conditions. Machine tools are statically and dynamically stable. However they may become unstable through the effect of cutting

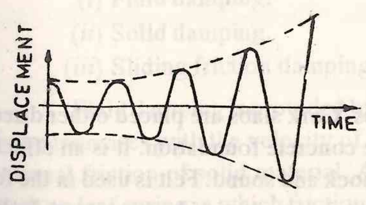


Fig. 6.2

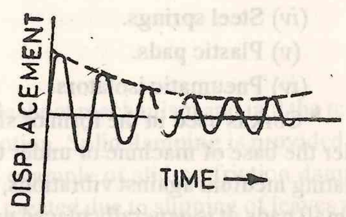


Fig. 6.3

process. The machine tool designer should know the magnitude and frequencies of the disturbing forces likely to occur during the operation of the machine tool so that he is able to design the machine such that the natural frequencies of the various parts of the structure do not approach the forcing frequencies.

6.5. Elimination of Chatter

It is desirable to reduce chatter in order to improve workpiece surface finish and to protect the machine tool. Self excited vibrations are more severe than the forced vibrations. Chatter can be reduced by the following methods.

(*i*) Chatter can be reduced by the use of special devices such as vibration dampers which impede the development of vibrations by increasing the forces of resistance in the machine fixture tool workpiece system.

(*ii*) Rigid installation of machine tool on its properly prepared foundation reduces the vibrations.

(*iii*) The use of cutting fluids sometimes helps to reduce vibrations.

(*iv*) The machine tool should be dynamically balanced to limit the unbalanced forces produced during its operation.

(*v*) The site where the machine tool is to be installed should be quite for away from the vibration causing machines such as presses, forging hammers, compressors etc.

6.6. Vibration Isolation

Vibrations produced during operation of a machine tool should be reduced to below the permissible level of vibrations to keep the machine tool in good condition, to increase the productivity and to achieve better precision (accuracy) on workpiece surface. Some of the methods used to reduce vibrations are as follows.

(*a*) Elastic vibration isolators are being widely used now-a-days in the installation of machine tools that have dynamic action on the surroundings. Machine tool can be easily installed on vibration isolators and a better quality of surface finish can be obtained from machine tool. Vibration isolators can be made up of the following materials :

(*i*) Cork.

(*ii*) Felt.

(*iii*) Rubber.

(*iv*) Steel springs.

(*v*) Plastic pads.

(*iv*) Pneumatic isolators.

Cork is used in the form of slabs. Cork slabs are placed either directly under the base of machine or under the concrete foundation. It is an effective isolating medium against vibrations, shock and sound. Felt is used in the form of small pads. It is generally placed under the machine to be supported. Rubber pads have the advantage of enduring compression as well as shear.

Steel springs are preferred over other materials as their properties are known more precisely than other materials.

For machines moving at a steady speed the degree of isolation is determined by the ratio (r) defined as follows :

$$r = \frac{\text{Operating frequency of machine}}{\text{Natural frequency of foundation}}$$

By choosing a suitable natural frequency it is possible to find degree of isolation which obviously depends upon the environmental conditions of the site.

(*b*) Vibrations can be reduced by perfectly balancing the rotating equipment of the machine tool. The machine tool should be so installed on the floor that there are no vibrations. Proper isolation of vibration helps to achieve the following objectives :

(*i*) Longer bearings life.

(*ii*) Longer machinery maintenance costs.

(*iii*) Improved working conditions for the workers.

(*iv*) There will not be any vibrations in the building structure.

(*v*) Improved plant layout.

Fig. 6.3 (*a*) shows a method of isolating the machine vibrations.

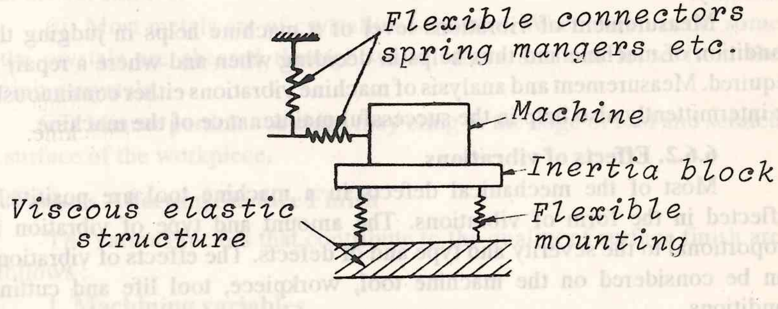


Fig. 6.3 (*a*)

(*a*) Vibration damping helps in reducing vibration by absorbing energy in the form of friction. In vibrations isolating system damping can be provided in the following ways :

(*i*) Fluid damping.

(*ii*) Solid damping.

(*iii*) Sliding friction damping.

Fluid damping is provided by dashpot mechanism and in it the resisting force increases with the velocity of motion. Solid damping is provided due to internal friction of solid material. An example of sliding friction damping is built up leaf spring in which friction is created due to slipping of leaves against each other when the spring oscillates.

(*iv*) Vibrations can be reduced by replacing or repairing defective parts of a machine. Unbalanced rotors, gears, pulleys etc. try to produce vibrations and should be repaired in time.

6.6.1. Vibration measurement in machine tools

Vibration measurement given valuable information about the condition of the machine tool which otherwise can only be obtained by stripping the machine down and carrying out a mechanical inspection. Some of the vibration instruments are as follows :

(*i*) Vibrometer,
(*ii*) Analyser,
(*iii*) Vibration recorder,
(*iv*) Vibration monitor.

Vibrometer gives the overall vibration values to assess the vibration severity of the machine vibration and it measures vibration as displacement in microns. Velocity in mm/s and acceleration in m/sec^2. Analyser is useful for segregation of overall vibration into components at various frequencies whereas vibration recorder is used to record the data obtained by analyser. It is coupled along with the vibration analyser. Vibration monitor is used to measure vibrations of bearings of selected strategically machinery continuously.

Measurement of vibrations level of a machine helps in judging the condition of machine and thus helps in deciding when and where a repair is required. Measurement and analysis of machine vibrations either continuously or intermittently also help in the successful maintenance of the machine.

6.6.2. Effects of vibrations

Most of the mechanical defects in a machine tool are positively reflected in the form of vibrations. The amount and type of vibration is proportional to the severity and type and of defects. The effects of vibrations can be considered on the machine tool, workpiece, tool life and cutting conditions.

(*i*) **Effects of vibrations on machine tool.** Due to vibrations the various parts of machine tool start vibrating and if frequency of vibrations approaches the natural frequency of vibrations of that part the amplitude of vibrations will be quite high and the part may even break.

(*ii*) **Effect of vibration on tool life.** Vibrations if present reduce the life of cutting tool by about 70 to 80%.

(*iii*) **Effect of vibration on work piece.** Due to vibrations the surface finish and dimensional accuracy are affected.

(*iv*) **Effects of vibrations on cutting conditions.** Due to vibrations the cutting speed does not remain constant. The chip thickness as removed by the cutting tool also does not remain constant and due to this the cutting forces also vary.

6.7. Surface finish

The quality of machined surface is characterised by the accuracy of its manufacture in respect to the dimensions specified by the designer. Every machining process leaves its evidence on the surface that has been machined. This evidence is in the form of finely spaced micro irregularities left by the cutting tool. (Fig. 6.4). Each kind of cutting tool leaves its own pattern that can be indentified. This pattern is called surface finish or surface roughness. Whenever two machined surfaces come in contact with each other the quality of the mating surfaces plays an important role in the performance and wear of the mating parts. A good surface finish is desirable. Some degrees of roughness which may be extremely small is always present on any surface because of the following reasons.

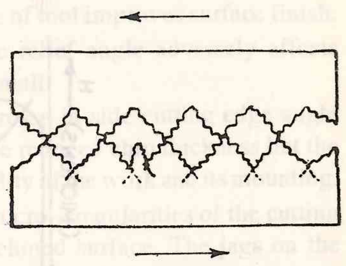


Fig. 6.4. Contact of micro-irregularities.

(*i*) Metals are not absolutely homogeneous. Some portions may be harder than others and may cause the cutting tool to deflect or spring away from the cut surface.

(*ii*) Most metals are of crystalline structure. When metal is cut some of the crystals are sheared through while others are torn loose from the adjoining crystals.

(*iii*) Minute particles or chips may cling to the edge of tool and scratch the surface of the workpiece.

6.8. Factors Affecting Surface Finish

The various factors that contribute to the quality of surface finish are as follows :

1. Machining variables

(*a*) Cutting speed.
(*b*) Feed.
(*c*) Depth of the cut.

(*a*) **Effect of cutting speed.** Increase in cutting speed improves the surface finish due to the continuous reduction in built up edge (Fig. 6.5). The curve *A* represents the machining of steels except high alloy grade steels. In the beginning the surface roughness increases when cutting speed changes from V_1 to V_2. This is due to the beginning of built up edge formation which reaches its maximum value at the cutting speed V_2. Then the formation of built up edge is reduced due to the rise in temperature and at cutting speed V_2 it almost disappears. This reduces the height (*H*) of micro irregularities. With further increase in cutting speed the surface roughness continues to decrease.

There is almost no hump on the curve *B* obtained in machining high alloy steels, non-ferrous metals and cast iron. This is due to the completed absence of built up edge formation.

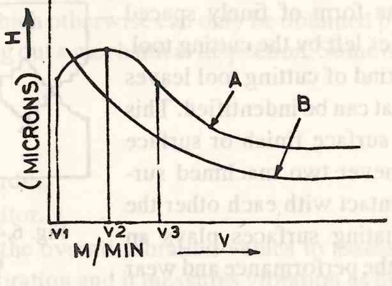


Fig. 6.5

(*b*) **Effect of feed.** Increase in feed rate deteriorates, surface finish. It is observed that a rate of feed (*f*) in the range from 0.12 to 0.15 mm per revolution has a negligible effect on the height (*H*) of irregularities but further increase in the feed rate increases surface roughness. Fig. 6.6 shows the variation of feed with height of micro-irregularities when different cutting fluids are used.

(*c*) **Effect of depth of cut.** Increase in depth of cut deteriorates surface finish.

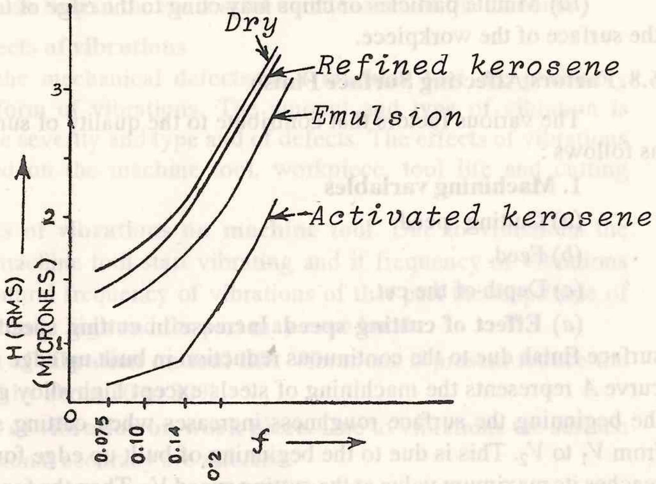


Fig. 6.6

2. **Tool geometry.** The effect of tool geometry on surface finish is as follows :

(*a*) **Nose radius.** Increase in nose radius improves surface finish. There is an appreciable improvement in surface finish upto 0.3 mm nose radius. Higher value of nose radius produces less improvement in surfaces finish and on the other hand it causes chatter during machining.

(*b*) **Rake angle.** Increase in rake angle of tool improves surface finish.

(*c*) **Relief angle.** An increase in the relief angle adversely affects surface finish but the effect is on the whole small.

(*d*) **Side cutting edge angle.** An increase in side cutting edge angle improves surface finish largely because of the reduced chip thickness but the degree of improvement depends upon the rigidity of the work and its mounting.

(*e*) **Cutting edge.** The height of the micro-irregularities of the cutting edge effects the micro geometry of the machined surface. The jags on the cutting edge are reproduced directly on the ridges of the machined surface, increasing their height. Therefore cutting edge of the tool should be carefully ground and lapped to reduced the micro-irregularities of the cutting edge.

3. Accuracy of bearings.
4. Method of chip removal.
5. Quality of machine tool.
6. Nature of work material.
7. Chatter or vibrations of machine tool.

An increase in cutting speed, an increase in rake angle and the application of a suitable lubricant would lead to an improvement in the quality of the machined surface.

6.9. Surface Finish Terminology

Surface texture includes roughness, waviness, lay, flow etc. as shown in Fig. 6.7.

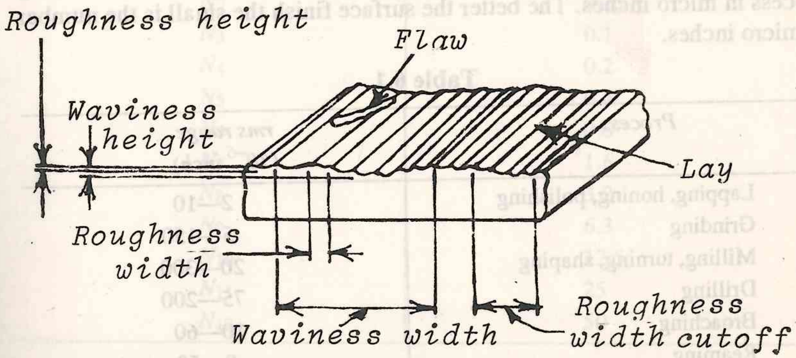


Fig. 6.7

(*a*) **Roughness.** Roughness consists of surface irregularities which result from the various manufacturing process. These irregularities combine to form surface texture.

(*b*) **Roughness height.** Roughness height is the height of irregularities with reference to an average line. It is measured in millimetres.

The value of roughness height is expressed in two ways.

(*i*) Arithmetical average value or centre line average value.

(*ii*) Root mean square (rms) value.

In most cases the arithmetical average value of roughness height is used. Occasionally the root mean square (rms) value is used.

The rms is obtained by taking the square root of the sum of the squares of *y* measurements divided by the number of *y* measurements. In terms of the measurements indicated in Fig. 6.8 the average and rms values are calculated as follows.

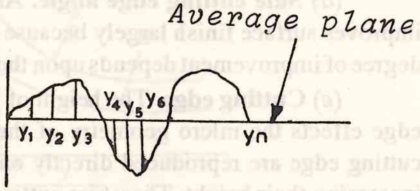


Fig. 6.8

$$\Sigma y_n = y_1 + y_2 + y_3 + \dots y_n$$

The centre line average (CLA) value or Arithmetical average (*AA*) height is given by

$$AA = \frac{\Sigma y_n}{n}$$

where *n* is the total number of vertical measurements.

The r.m.s. (root mean square) value is obtained as follows :

$$\text{r.m.s.} = \sqrt{\frac{y_1^2 + y_2^2 + y_3^2 \dots y_n^2}{n}}$$

Table 6.1 shows some of the rms ranges for the various machining process in micro inches. The better the surface finish the small is the number of micro inches.

Table 6.1

Process	*rms range* (10^{-6} *inch*)
Lapping, honing, polishing	2—10
Grinding	5—150
Milling, turning, shaping	20—300
Drilling	75—200
Broaching	10—60
Reaming	8—50
Sawing	250—1000
Blanking	30—100
Forging	100—400
Sand casting	500—1000

(*c*) **Roughness width.** Roughness width is the distance parallel to the normal surface between successive peaks or ridges which constitute the predominate pattern of the roughness. It is stated in millimetres.

(*d*) **Roughness width cut off.** It is the greatest spacing of repetitive surface irregularities so to be included in the measurement of average roughness height. It should always be greater than the roughness width in order to obtain the total roughness height rating. It is expressed in millimetres.

(*e*) **Lay.** It is the direction of predominant surface pattern produced and reflects the machining method.

(*f*) **Waviness.** This refers to the irregularities which are outside the roughness width cut off values. It may be result of work deflecting during machining, working and vibration.

(*g*) **Waviness width.** It is the maximum permitted variation in waviness height. It is measured in millimetres.

(*h*) **Waviness height.** It is the peak to valley distance. It is also expressed in millimetres.

(*i*) **Flaws.** Cracks, scratches and ridges are called flaws. They are not regularly recurring and are imperfections outside the regular pattern of surface texture.

The ISO recommended arithmetical mean roughness values and grade numbers for the specification of surface roughness are indicated in Table 6.2.

Table 6.2

Roughness grade number	*Roughness value* (μm)
N_1	0.005
N_2	0.25
N_3	0.1
N_4	0.2
N_5	0.4
N_6	0.8
N_7	1.6
N_8	3.2
N_9	6.3
N_{10}	12.5
N_{11}	25
N_{12}	50

6.10. Ideal Surface Roughness

The ideal surface roughness represents the best possible finish which may be obtained for a given tool shape and feed and can only be approached if built up edge, chatter, inaccuracies, in machine tool movement etc. are eliminated. Ideal surface finish for the turning operation where a sharp corner tool is used is shown in Fig. 6.9 and where a tool having nose radius is shown in Fig. 6.10.

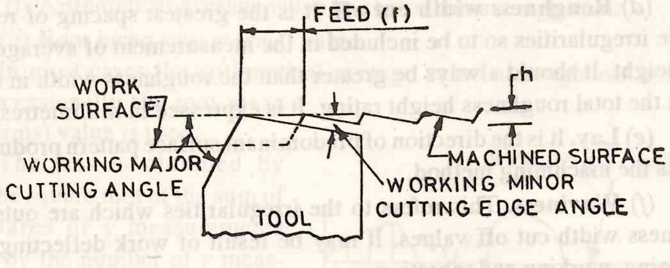


Fig. 6.9

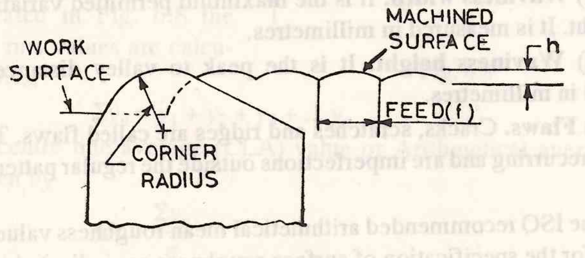


Fig. 6.10

For a sharp corner tool (Fig. 6.9) the roughness is extremely sensive to changes in minor cutting edge angle.

Let ψ = Minor cutting edge angle.

θ = Working major cutting edge angle.

f = feed in mm/revolution.

h = Ideal value of surface roughness.

$$= \frac{f}{\cot\theta + \cot\psi}$$

For a rounded corner tool (Fig. 6.10) the ideal value of surface roughness is given by

$$h = \frac{f^2}{8r}$$

where r = Nose radius in mm.

6.11. Measurement of Surface Roughness

Surface finish is measured by different method using different units of measurement. The commonly used methods are as follows :

(*i*) Comparison with roughness standards.
(*ii*) Interferometry method.
(*iii*) Profilometer.

(1) **Comparison with roughness standard.** In this method flat and cylindrical sample surfaces finish machined by the common workshop processes and then calibrated are used as a basin of comparison. The thumb or fingernail is moved along the surface of workpiece and a mental note taken of the amount of resistance and the depth of irregularities. The thumb or fingernail is then moved across a series of sample surfaces acting as standards. The standard surface which gives approximately the same roughness feeling as that of workpiece indicates the roughness of the workpiece. This method depends upon individual judgment and lacks precision on this account but it is relatively cheap to apply and is a convenient method for general purposes.

(2) **Interferometry method.** This method is useful for viewing very highly finished surface. In this method the finished surfaces are seen through a microscope which incorporates and interferometer.

(3) **Profilometer.** It is used to obtain an enlarged tracing of the surface irregularities. It has a sharp diamond stylus on the end of arm. The stylus is moved across the surface being measured and the stylus follows the contours of irregularities. As the stylus passes over the surface it rises and falls by amounts proportional to surface roughness.

The relative displacement is highly magnified electronically and results presented either as a surface finished graph or as a roughness value. The stylus is required to be slided with respect to a datum set up by the skid (Fig. 6.11).

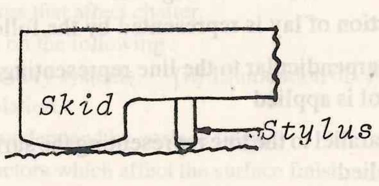


Fig. 6.11

6.12. Surface Finish Representation

Surface finish is either denoted as per IS : 3073—1967 by the symbol ∇ (mean height of the surface irregularities in microns both above and below a mean line) or by the symbol $^n\surd$ (root mean square height of the surface irregularities n indicating the value in micro inches). The two systems compare with each other as follows :

Type of finishing operation	*Representation as per IS : 3073—1967*		*Corresponding value in micro inches*
	Symbol	*Value in microns*	
Rough Machining	∇	8—25	250—1000
Fine Machining	∇∇	1.6—8	63—250
Grinding Finish	∇∇∇	0.025—1.6	2—63
Lapping	∇∇∇∇	< 0.025	< 2

According to Indian standards the surface roughness is expressed in terms of *CLA* value denoted by R_a.

Fig. 6.12 shows representation of surface roughness.

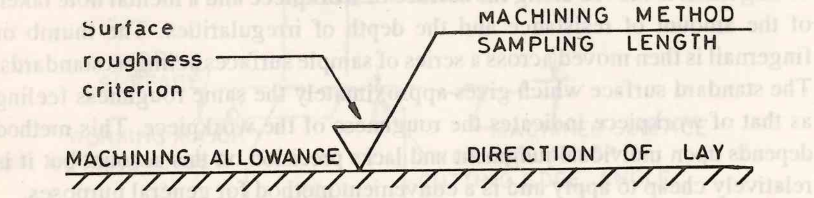


Fig. 6.12

Fig. 6.13 shows a typical value of R_a as 0.16 with a cut off length of 0.30 and direction of lay perpendicular and method of machining as lapping.

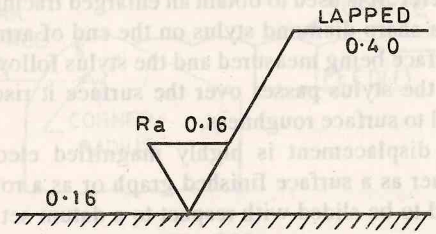


Fig. 6.13

The direction of lay is represented by the following symbols

⊥ Lay perpendicular to the line representing the surface to which the symbol is applied

= Lay parallel to the line representing the surface to which the symbol is applied

X Lay angular in both directions to the line representing the surface to which the symbol is applied

R Lay approximately radial relative to the centre of the surface to which the symbol is applied

M Lay multidirectional.

6.13. Units of Surface Roughness

The following units are generally used :

Micro inch (μ-in) = 10^{-6} inch

Micro (μ-m) meter = 10^{-6} metre = Micron

Nanometres (nm) = 10^{-9} metre (USA/France)

= 0.001 μ-m.

Surface roughness values in microns for different manufacturing processes are indicated in Table 6.3.

Table 6.3

Manufacturing Process	*Surface Roughness (Microns)*
Turning	0.32 to 25
Drilling	1.6 to 22
Milling	0.32 to 25
Shaping	1.6 to 25
Surface grinding and cylindrical grinding	0.063 to 5
Lapping	0.012 to 0.016
Honing	0.025 to 0.42
Broaching, reaming	0.4 to 3.2
Boring	0.4 to 6.4

PROBLEMS

6.1. (*a*) What is chatter in machine tools ?
(*b*) What are the effects of chatter ?

6.2. Describe the following types of vibrations :
(*a*) Forced vibrations. (*b*) Self-excited vibrations.

6.3. Describe the factors that affect chatter.

6.4. Write short notes on the following :
(*i*) Types of vibratory systems. (*ii*) Elimination of chatter.
(*iii*) Vibration isolation.

6.5. (*a*) What do you understand by surface finish ?
(*b*) Explain the factors which affect the surface finish.

6.6. Define the following :
(*a*) Roughness height.
(*b*) Arithmatical value of surface roughness.
(*c*) R.M.S. value of surface roughness
(*d*) Roughness width. (*e*) Waviness width.
(*f*) Waviness height. (*g*) Flaw.
(*h*) Lay.

6.7. Discuss the methods of measuring surface roughness.

6.8. Write short notes on the following :
(*a*) Surface finish representation. (*b*) Units of surface roughness.

6.9. Sketch and describe a method to isolate vibrations in a machine tool.

6.10. Write short notes on the following :
(*a*) Vibration measurement in rotating machine tool.
(*b*) Effects of vibrations in machine tool.
(*c*) Causes of vibrations in a machine tool.

7

Basic Features and Kinematic Requirements of Machine Tools

7.1. Machine Tool

A metal cutting machine tool is defined as a power driven machine capable of producing various shapes in metal by cutting away the surplus material. The principle used in all the machine tools is one of the generating the surface required by providing suitable relative motions between the cutting tool and the workpiece. The metal removed by the cutting tool is called chip and will vary in size, shape and form according to the type of material being cut, the cutting tool angle and the position of the tool relative to the workpiece. The surface produced by the cutting process is called machined surface. The accuracy of construction and operation of a machine tool is very necessary feature, because tools reproduce and multiply their own errors.

In a metal cutting machine tool the energy is expended in deformation of material for producing finished surfaces. The purposes of any machine are as follows :

(*i*) To produce surfaces.

(*ii*) To trace formed surfaces.

(*iii*) To provide a finish to a given surface.

The general design of the machine tool takes care of the maximum cutting forces like tangential, axial and radial forces, weight of structures etc., and bending moment and torque produced by them. Bed forms the vital part of the machine tool on which table and other relevant parts of the machine tool move. It is therefore evident that the bed should be sufficiently strong and rigid. Further it should be easier to remove the chips produced during machining. Keeping in view of the strength and rigidity and removal of chips, box type construction of the bed is normally used. Beds of the machine tools are generally made from cast iron or steel. Grey cast iron with some percentage of nickel and chromium is preferred. Beds may be produced by casting or fabricated from steel plates. However casting is a faster process.

Guide ways or slide ways on which work or tool with their relevent units move should be strong and should have long life. The surfaces of the

guide way should be perfectly machined so that it maintains good amount of accuracy and precision. Slide ways may be made from cast iron or steel. The slide ways should have a hardness of 50—55 HRC.

The shaft and spindles should be so designed that they can take axial, bending and twisting loads. The bearings should be so selected that they can resist static and dynamic loads.

A machine tool requires variety of speeds and feeds. This is provided by a suitably designed gear box.

While choosing the drive motor for the machine tool the maximum cutting speed, feed and circulation of the lubricating oil are to be taken into account.

The machine tool should have high productivity and precision. This can be achieved by making the machine tool strong rigid and by making it free from vibrations.

Careful maintenance increases the life and efficiency of the machine tool. A thorough weekly cleaning is essential for any machine tool in continuous use. A general survey of the lubricating system may be restricted to the observation of oil level marks, refilling the oil periodically, and to daily lubricating of all openly moving mechanisms and links and guide ways. The oil filter and pumps should be cleaned once in a year. The ball bearings of the motor require cleaning and refilling with grease once every year. The machine tool before being sent for sales should be tested properly.

Fig. 7.1 (*a*) shows schematically the power input to machine tool and output from the machine tool in the form of finished workpiece.

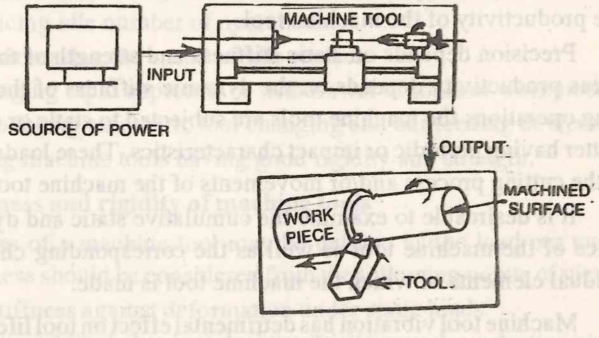


Fig. 7.1 (*a*)

7.1.1. Characteristics of machine tool

A machine tool intended for cutting metals at high speed should possess the following characteristics :

(*i*) It should be powerful.

(*ii*) It should be capable of operating at high speeds.

(*iii*) It should be rigid (vibration proof).

(*iv*) It should be durable.

(*v*) It should be safe in operation.

(*vi*) The machine tool should provide facilities for reducing not only the machining time but the handling time as well.

(*vii*) It should have good lubrication facilities.

(*viii*) There should be reliable and rapid clamping of the workpiece and tool.

(*ix*) It should have well balanced rotating parts.

(*x*) It should be simple in design and should have good appearance.

(*xi*) Its cost of manufacturing and operation should be low.

(*xii*) There should be safety and convenience of controls such as

(*a*) Rotating and moving parts should be shielded with hoods.

(*b*) The worker should be protected from chips, abrasives dust and coolant by means of screens, shields etc.

(*c*) The machine tool control system should be automated to as large as possible.

7.1.2. Objectives of machine tool

The basic objectives of a machine tool are as follows :

(*i*) Precision

(*ii*) Productivity.

Precision means the accuracy with which a job can be manufactured on a machine tool. Productivity means the volume of materials removed per minute from the workpiece. More the volume of material removed more will be the productivity of the machine tool.

Precision depends on static stiffness and strength of the machine tool whereas productivity depends on the dynamic stiffness of the machine tool. During operations the machine tools are subjected to static or dynamic loads, the latter having periodic or impact characteristics. These loads are associated with the cutting process and/or movements of the machine tool members.

It is desireable to examine the cumulative static and dynamic characteristics of the machine tool as well as the corresponding characteristics of individual elements of which the machine tool is made.

Machine tool vibration has detrimental effect on tool life which, in turn, lowers down the productivity and increases the cost of production. It is therefore desireable that a machine tool should be free from vibrations. For example when it is found that vibration is being transmitted from the foundation the machine tool can be isolated from the ground so that no appreciable vibration is transmitted. This is done by supporting the machine tool on springs and dampers as shown in Fig. 7.1 (*b*).

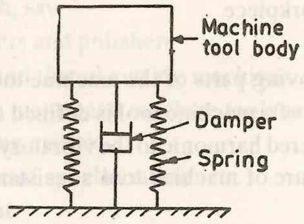


Fig. 7.1 (*b*)

While analysing the dynamic behaviour of machine tools, rigidity and stability are two important characteristics to be considered. Dynamic rigidity (stiffness) is defined as the ratio of amplitude of vibratory force considered harmonic to the vibratory displacement at a given frequency. It is the measure of machine tool's resistance to vibration. Dynamic stability indicates that the masses of a distributed system oscillate with decreasing amplitudes towards the original state of equilibrium.

7.1.3. Production capacity

The production capacity (Productivity) of a machine tool can be increased as follows.

(*i*) By decreasing machining time. This is achieved by :

(*a*) Increasing cutting speed or feed.

(*b*) machining several workpieces simultaneously.

(*c*) concentrating a number of cutting tools in each station.

(*ii*) By decreasing handling time. This is achieved by :

(*a*) reducing idle number of operations.

(*b*) By increasing the speed of idle strokes.

(*c*) arranging rapid approach or withdrawal of tools or workpieces.

(*iii*) By introducing automatic tool changing and bar feeding devices.

(*iv*) By using machine tools having good rigidity and strength.

7.1.4. Stiffness and rigidity of machine tools

The stiffness of a machine tool may be defined as the load per unit deformation. Stiffness should be considered from the following points of view

(*i*) Static stiffness against deformation under static loads.

(*ii*) Dynamic rigidity behaviour during vibrations under pulsating and inertia forces.

Amongst the static deformation the more important are which are caused by bending and torsional loads because these produce misalignments and displacements of the guiding elements which affect the working accuracy of machine tools. Following forces produce such loading and deformation conditions.

(*i*) Weight of workpiece
(*ii*) Cutting force
(*iii*) Weight of moving parts of the machine tool.

Dynamic rigidity of a machine tool is defined as the ratio of amplitude of vibratory force considered harmonic to the vibratory displacement at a given frequency. It is the measure of machine tool's resistance to vibrations.

7.1.5. Precision

A good surface finish of parts produced on a machine tool is desireable. The following factors affect the accuracy of finished components made on a machine tool :

(*i*) Cutting tool geometry.
(*ii*) Strength and stiffness of machine tool
(*iii*) Machining variables like :
  (*a*) cutting speed
  (*b*) feed
  (*c*) depth of cut.
(*iv*) Accuracy of bearings
(*v*) Vibrations in machine tool
(*vi*) Nature of workpiece material
(*vii*) Methods of chip removal.

7.1.6. Productive time

The various factors of productive time are as follows :

(*i*) *Set up time* : This includes :
  (*a*) preparatory time to get tools
  (*b*) time to arrange tools on machine.
(*ii*) *Handling time* : This includes :
  (*a*) time for loading and unloading of workpieces and tools.
  (*b*) time for measurements.
(*iii*) *Down time* : This includes
  (*a*) time lost in break downs
  (*b*) time lost in sudden minor accidents.
(*iv*) Machining time.

7.2. Classification of Machine Tools

The principle type of machine tools on which cutting tools are used in the modern workshop might be classified as follows :

(*i*) Planer, shaper
(*ii*) Lathe
(*iii*) Milling machine
(*iv*) Drilling, tapping and reaming machines

(*v*) Broach, saw
(*vi*) Grinders and polishers
(*vii*) Gear and thread cutting machines.

The above mentioned machine tools may further be classified according to the following criteria :

(*i*) Degree of specialisation
(*ii*) Weight
(*iii*) Degree of accuracy.

(*i*) **Degree of specialisation.** In respect of their degree of specialisation the machine tools can be referred to one of the following groups :

(*a*) **General purpose (Universal) machine tools.** They are designed for performing a great variety of machining operations on a wide range of workpieces. They are employed chiefly in piece and small lot production and for repair jobs.

(*b*) **Single purpose machine tools.** They are designed for performing a single definite machining operation. They may be readily set up for machining different sized parts of the same type. Machine tools used for machining crankpins of crankshafts, for turning the cam contours on camshafts are included in this type.

(*c*) **Specialised machine tools.** These machine tools are used to machine a certain definite workpiece by making the necessary changes in their construction. This group includes unit built machine tools.

(*d*) **Special machine tools.** These machine tools are meant for performing a certain definite operation in machining a certain definite workpiece. Specialised and special machine tools find application in large lot and mass production.

(*ii*) **Weight.** According to weight machine tool can be classified as follows :

(*a*) **Light weight machine tools.** They weigh up to one ton.
(*b*) **Medium weight machine tools.** Their weight varies from 1 to 10 tons.
(*c*) **Heavy weight machine tools.** They weigh over 10 tons.

(*iii*) **Degree of accuracy.** According to the degree of accuracy achieved the machine tools are classified as follows.

(*a*) Standard accuracy.
(*b*) Above standard accuracy.
(*c*) High accuracy.
(*d*) Precision machine tools.
(*e*) High precision or machine tools.

General purpose machine tools are standard accuracy machine tools. Above standard accuracy machine tools are similar to standard accuracy machine tools except that higher requirements are made to the accuracy with which the critical parts are manufactured as well as to the quality of assembly and adjustments. High accuracy machine tools have certain units that are specially designed with the aim of maintaining the high accuracy standards. In the manufacture of precision machine tools the accuracy requirements are still higher than for high accuracy machine tools. High precision machine tools are intended for making the parts which determine the accuracy of high accuracy machine tools and precision machine tools.

7.3. Control Systems of Machine Tools

Machine tools are fitted with various control systems meant to generate controlling movements which are essential for carrying out a machining process in accordance with the technical specifications of the part being machined. Two main functions of control systems are as follows :

(*i*) Changing speeds and feeds.

(*ii*) Providing the working and auxiliary motions in the desired sequence necessary for machining a particular part.

In addition, the machine tools are provided with safety controls to prevent damage to the machine tool and cutting tool during operation.

Machine tool controls may be of following types.

(*i*) Mechanical

(*ii*) Hydraulic

(*iii*) Electrical.

7.4. Safety and Convenience of Machine Tool Controls

Convenient controls protect the machine tool operator from excessive fatigue and thus contribute towards safety. Machine tool controls should be simplified and made convenient. The control system should be rationally selected and should be automated to as large extent as possible. Safety of machine tools is ensured by following control measures.

(*i*) Shielding the rotating and moving parts of machine tools with hoods.

(*ii*) Providing reliable clamping for workpiece and tools.

(*iii*) Protecting the machine tool operator from chips, abrasive dust and coolant by means of screens, shields etc.

(*iv*) Providing devices for safe handling of large and heavy workpieces.

(*v*) Providing reliable earthing of the machine tool.

7.5. Cutting Motion in Machine Tool

In order to obtain the required shape on the workpiece it is necessary that the cutting edge of the cutting tool should move in a particular manner with respect to the workpiece. There are two types of motions in a machine tool.

(*i*) Working motion (*ii*) Auxiliary motion.

Working motion. In machine tools the working motions are powered by an external source of energy such as electrical or hydraulic.

The process of chip removal is effected by the working motions of machine tool (formative motions) which are transmitted either to the cutting tool, or to the work or to both simultaneously. Working motions of a machine tool are of the following types.

(*a*) Primary cutting motion or Drive motion.

(*b*) Feed motion.

Both primary cutting motion and feed motion is specified by speed or feed rate.

Primary cutting motion. It provides for cutting the chip from the blank at the cutting speed equal to the velocity with which the chip leaves the work. The most commonly used types of primary cutting motions are of two types :

(*i*) Rotary primary cutting motion.

(*ii*) Reciprocating primary cutting motion.

Rotary primary cutting motion. Rotary motion may be transmitted either to the work as in lathe group of machine tool or to the tool as in grinding machine, drilling machine of milling machine. Fig. 7.1 shows the machine tools with rotary primary motion.

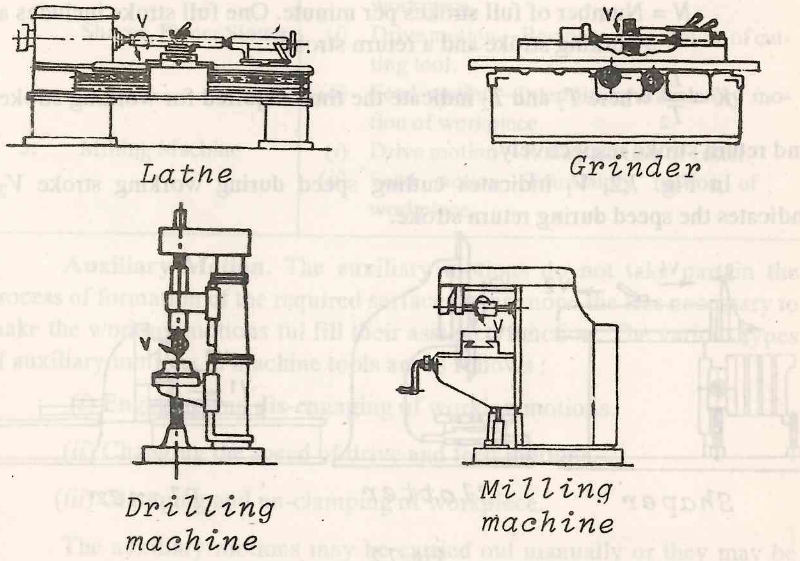


Fig. 7.1

The cutting speed (V) of a rotary cutting motion is given by

$$V = \frac{\pi D N}{100} \text{ m/min.}$$

where D = Diameter of surface being machined or of the rotating tool. (mm)

N = R.P.M. of workpiece of tool.

Reciprocating primary cutting motion. This type of motion is used in shapers, planers, slotters, power hacksaws, broaching machines. This motion can be transmitted to the tool as in shaper and slotter or to the work as in planer.

Fig. 7.2 shows machine tools with a reciprocating primary cutting motion. In machine tools using reciprocating primary cutting motion be cutting takes place periodically.

In such machine tools the cutting cycle consists of a working stroke during which the tool cuts the chips and the idle or returns stroke during which the tool or work returns to its initial position. The speed of return stroke should be kept higher than that of working stroke in order to reduce the non-productive time in machining. The average value of cutting speed (V) is determined as follows :

$$V = \frac{L(K+1)N}{1000\,K} \text{ metre per min.}$$

where L = Length of working stroke in millimetre.

N = Number of full strokes per minute. One full stroke includes a working stroke and a return stroke.

$K = \frac{T_1}{T_2}$ where T_1 and T_2 indicate the time required for working stroke and return stroke respectively.

In Fig. 7.2, V_1 indicates cutting speed during working stroke V_2 indicates the speed during return stroke.

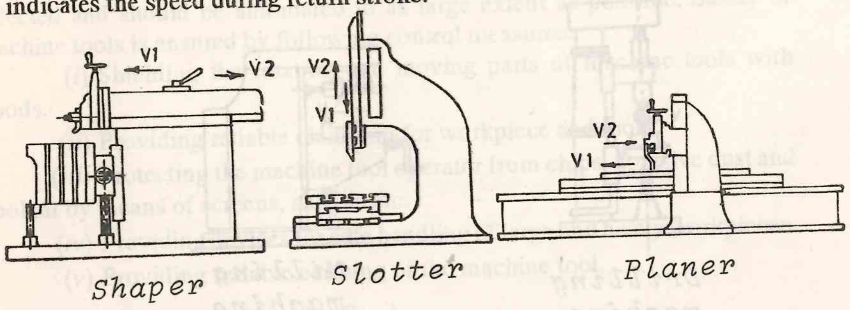


Fig. 7.2

The primary cutting motion of certain machine tools may be of a more complex nature. It can also be a combination of rotary and reciprocating motions.

Feed motion. The rate of feed or speed of the feed motion is substantially less than the cutting speed. The feed motion enables the cutting process to be extended to the whole surface to be machined on the work. Other conditions being equal, the rate of feed determines the cross sectional area of the chip. The accuracy of the primary cutting motion depends mainly on the design of the main spindle while the accuracy of feed motion depends upon the design of the bed.

Table 7.1 indicates working motions for some of the machine tools.

Table 7.1

S. No.	*Machine Tool*	*Working motions*
1.	Lathes and Boring Machines	(*i*) Drive motion—rotary motion of workpiece. (*ii*) Feed motion—translatory motion of cutting tool in axial or radial direction.
2.	Drilling Machine	(*i*) Drive motion—Rotary motion of drill. (*ii*) Feed motion—Trasnlatory motion of drill.
3.	Grinding machine	(*i*) Drive motion—Rotary motion of grinding wheel. (*ii*) Feed motion—Rotary, Translatory of workpiece.
4.	Shaper, Planer Slotter	(*i*) Drive motion—Reciprocating motion of cutting tool. (*ii*) Feed motion—Intermittent translatory motion of workpiece.
5.	Milling Machine	(*i*) Drive motion—Rotary motion of cutter. (*ii*) Feed motion—Translatory motion of workpiece.

Auxiliary Motion. The auxiliary motions do not take part in the process of formation of the required surface but are none the less necessary to make the working motions ful fill their assigned function. The various types of auxiliary motions in machine tools are as follows :

(*i*) Engaging and dis-engaging of working motions.

(*ii*) Changing the speed of drive and feed motions.

(*iii*) Clamping and un-clamping of workpiece.

The auxiliary motions may be carried out manually or they may be automated in automatic machine tools.

7.6. Forces in Machine Tool

The various forces which tend to deform the machine tool parts or workpiece are as follows :

(*i*) Static loads such as weight of machine tool and its various parts.

(*ii*) Dynamic loads such as the forces caused due to rotating or reciprocating masses.

(*iii*) Cutting forces.

(*iv*) **Friction forces.** The forces are usually taken proportional in machine tool design to the normal load of the friction surfaces lubrication conditions and sliding velocity.

7.7. Process Capability of a Machine Tool

The process capability of a machine tool depends upon its rigidity which is defined as its capability to resist deformation produced due to the introduction of cutting forces generated during machining. A machine tool must possess static as well as dynamic rigidity so that it is able to produce jobs with in high degree of accuracy consistently over a long period of time.

A machine tool is a group of links (elements) connected in sequence by joints which constitute a closed dimensional circuit. The inherent quality of the element system controls the accuracy and is known as process capability of the machine tool. Process capability can be improved by using following techniques.

(*i*) By changing rigidity of links.

(*ii*) By reducing range of cutting force.

(*iii*) By reducing number of links.

7.7.1. Compliance of machine tool

Compliance of a machine tool is the reciprocal of rigidity. Static compliance is defined as ratio of displacement of force. The compliance of a centre lathe is calculated as follows :

Fig. 7.2 (*a*) shows a shaft being turned on a centre lathe.

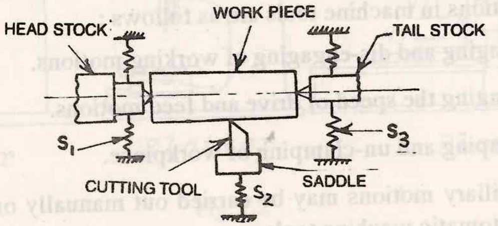


Fig. 7.2 (*a*)

S_1 = Rigidity of head stock

S_2 = Rigidity of saddle

S_3 = Rigidity of tail stock

Y_1 = Deflection at head stock

Y_2 = Deflection at cutting point

Y_3 = Deflection at tail stock

Y_4 = Deflection of the saddle.

The deflection curve under cutting load (F_y) is shown in Fig. 7.2 (*b*)

$$Y_2 = Y_1 + (Y_3 - Y_1) \times \frac{x}{L} \quad ...(1)$$

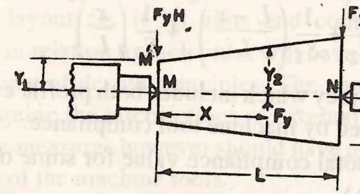


Fig. 7.2 (*b*)

L = Length of workpiece.

x = Distance of the cutting tool tip from the head stock end.

Now $$y_1 = \frac{F_{yH}}{S_1}$$

$$y_3 = \frac{F_{yT}}{S_3}$$

$$F_{yH} = F_y \times \frac{L - x}{L}$$

$$F_{yT} = F_y \times \frac{x}{L}$$

From equation (1)

$$y_2 = \frac{F_{yH}}{S_1} + \left(\frac{F_{yT}}{S_3} - \frac{F_{yH}}{S_1}\right) \times \frac{x}{L}$$

$$= \frac{F_y}{S_1} \times \frac{L - x}{L} + \frac{x}{L}\left[\frac{F_y}{S_3} \times \frac{x}{L} - \frac{F_y}{S_1} \times \frac{L - x}{L}\right]$$

$$= \frac{F_y}{S_1}\left[\frac{L - x}{L}\right]^2 + \frac{F_y}{S_2}\left(\frac{x}{L}\right)^2$$

Let Y = Deflection of machine tool at cutting point.

$$= Y_4 + Y_2$$

$$= \frac{F_y}{S_2} + \frac{F_y}{S_1}\left(\frac{L - x}{L}\right)^2 + \frac{F_y}{S_3}\left(\frac{x}{L}\right)^2$$

$$= F_y\left[\frac{1}{S_2} + \frac{1}{S_2}\left(\frac{L - x}{L}\right)^2 + \frac{1}{S_3}\left(\frac{x}{L}\right)^2\right]$$

S = Rigidity of machine tool

$$= \frac{F_y}{Y} = \frac{1}{\frac{1}{S_2}+\frac{1}{S_1}\left(\frac{L-x}{L}\right)^2+\frac{1}{S}\left(\frac{x}{L}\right)^2}$$

$$C = \text{Compliance of machine tool} = \frac{1}{S}$$

$$= \frac{1}{S_2}+\frac{1}{S_1}\left(\frac{L-x}{L}\right)^2+\frac{1}{S_3}\left(\frac{x}{L}\right)^2$$

The machining accuracy which includes both profile as well as dimensional accuracy is determined by machine tool compliance.

The representative total compliance value for some of machine tools is indicated in Table 7.1. (A).

Table 7.1 (A)

Machine Tool	*Description*	*Compliance (Micron/kgf)*
Centreless grinding machine	—	1
Lathe (workpiece clamped in chuck)	(*i*) H = 200 mm (*ii*) H = 300 mm (*iii*) H = 400 mm	1.5 1.2 0.57
Lathe (workpiece clamped between centres)	(*i*) H = 200 mm (*ii*) H = 300 mm (*iii*) H = 400 mm	0.75 0.52 0.38
Automatic bar lathe	Screw type	0.2—0.3
Vertical milling machine		0.4
Vertical turning and boring mill	—	0.35

7.8. Essential Requirements of a Machine Tool

A machine tool should possess the following requirements :

(*i*) **Low cost.** The initial cost of the machine tool as well as the cost of production should be low.

(*ii*) **High accuracy.** The machine tool should be capable of producing high quality products at highest possible speed.

(*iii*) **High useful life.** The machine tool should render a trouble free service while retaining its accuracy for longer period.

(*iv*) **Low maintenance cost.** The maintenance of machine tool should be easy and maintenance cost should be low.

(*v*) **Reliability.** The machine tool should retain accuracy over period of its life.

(*vi*) **Ease of operation.** It should be easy to operate the machine tool.

(*vii*) **High production capacity.** It is defined as the ability of machine tool to machine a definite number of workpieces in unit time.

(*viii*) **Appearance.** The appearance of machine tool is receiving much attention in recent years. If the machine tool being developed has an advantageous design layout *i.e.* if its units and component assemblies are properly positioned in relation to each order will have a sufficient good shape from the point of view of design principles. The appearance can be further improved by redesigning the intersections of external sources, the surface of the covers etc. These measures however should have no adverse effects on the operational features of the machine tools.

(*ix*) **Safety.** Reliable protection for the operator not only against accident but against excessive fatigue as well is a must in modern machine tool.

(*x*) **Ease of manufacture.** It should be easier to manufacture and assemble various parts of machine tool.

7.9. Selection of Machine Tool

Each machine tool is used to perform particular type of machining operation or operations such as turning, drilling, boring, facing, shaping milling broaching, grinding etc. The selection of a machine tool depends upon the following factors.

(*i*) The type of product required.

(*ii*) Degree of accuracy desired. The machine tool should be selected based on the accuracy desired on the job. It is not desirable to select the most accuracy machine tool available in the market for a less accurate job as this will increase the cost of production.

(*iii*) Amount of metal to be removed.

(*iv*) Size of workpiece.

(*v*) Quantity of products required.

7.10. General Requirements of Machine Tool Design

The requirements of a machine tool design are as follows :

(*i*) High productivity.

(*ii*) High accuracy of components manufactured.

(*iii*) Safety and convenience of controls.

(*iv*) Simplicity of design. (*v*) Low cost of manufacturing.

(*vi*) Low cost of operation. (*vii*) Good appearance.

7.11. Basic Features of a Machine Tool

A machine tool is fundamentally an assembly of following basic elements. (Fig. 7.3).

(*i*) Bed, structure of frame.
(*ii*) Slides and slide ways.
(*iii*) Spindles and spindle bearing.
(*iv*) Power units.
(*v*) Transmission linkage.
(*vi*) Work holding and tool holding elements.

7.12. Bed, Structure or Frame

Machine tools parts such as beds, bases, columns, carriages, tables etc. are known as machine tool structures. Following are the essential requirements of structures for their satisfactory performance.

(*i*) The machine tool structures should be made of proper materials.

(*ii*) They should have high static and dynamic stiffness.

(*iii*) All important mating surfaces of the structures should be machined with a high degree of accuracy to provide the desired geometrical accuracy.

Depending upon the function structures are divided into following groups :

(*i*) Beds and bases on which the various sub-assemblies are mounted.

(*ii*) Box type housings in which individual units are assembled such as spindle head, speed box housing.

(*iii*) Parts used to support the cutting tool and work piece such as table, carriage, tail stock, and knee.

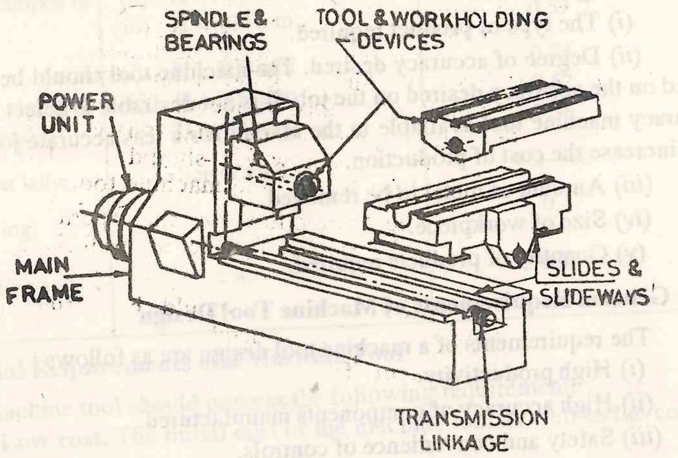


Fig. 7.3

Bed is the main element which acts as a base for the rest of the units. Bed is usually made from cast iron has more compressive strength, is a cheap material and can absorb the vibrations set up during machining. The bed has one or more slide ways cast as an integral part of it and for this cast iron has

an advantage that it can be easily machined, has ideal wearing properties and if required a hard surface can be produced by the induction hardening process. Cast iron possesses vibration proof characteristics.

Modern welding developments have made it possible to produce fabricated steel structures as an alternative to cast iron and in many cases with advantage in regard to cost, lightness and time saving. Fig. 7.4 shows a section of a fabricated lathe bed.

The different types of sections having same cross sectional area and outer parameter which are commonly used for beds are shown in Fig. 7.5.

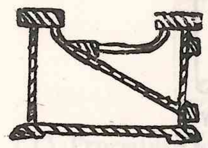


Fig. 7.4

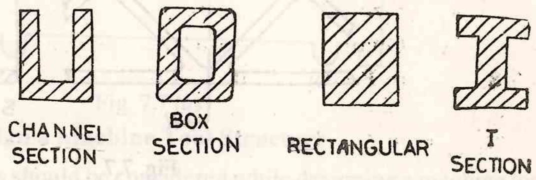


Fig. 7.5

It is observed that box section is more suitable as it is strong in bending and torsion and can be easily produced. To avoid massive sections in castings carefully designed systems of ribbing are used to offer the maximum resistance to bending and torsional stresses.

Beds, bases, columns and frames of machine tools are generally made from cast iron because of the following advantages possessed by cast iron.

(*i*) It has high compressive strength.

(*ii*) It can be easily cast into intricate shapes.

(*iii*) It has better capacity to absorb vibrations.

(*iv*) It possesses good lubricating properties due to the presence of free graphite in it.

(*v*) It can be machined to a fairly high degree of accuracy and provided a fine surface finish.

(*vi*) It can be easily alloyed with elements like nickel, chromium, molybdenum etc. to increase its hardness.

(*vii*) The cost is fairly low.

However, cast iron can not be easily welded. Therefore, the fabricated structures are made from mild steed which can be easily welded.

Two basic types of ribbing are as follows :

(*a*) Box ribbing.

(*b*) Diagonal ribbing.

The box formation is convenient to produce, apertures in the walls permitting the positioning and extraction of cores. Diagonal ribbing provides greater torsional stiffness and permits swarf to fall between the sections. It is quite commonly used for lathe beds. Fig. 7.6 shows box ribbing and Fig. 7.7

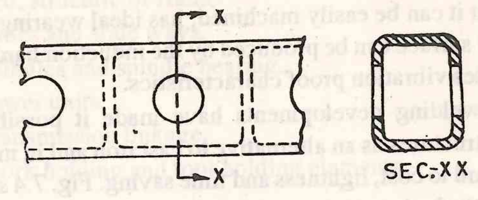


Fig. 7.6

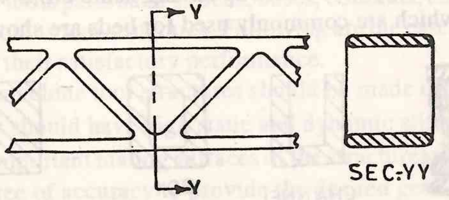


Fig. 7.7

shows diagonal ribbing. Diagonal ribbing is quite commonly used in medium and large size machine tools.

Box type, section has the highest torsional stiffness and is best suited in terms of strength and stiffness. The stiffness of machine tool structures like beds, frames, columns etc. can be improved by using ribs and stiffners. The effect of ribs and stiffners depends, to a large extent, upon how they are arranged. Stiffners may be arranged in following two ways.

(*i*) Diagonal stiffners.
(*ii*) Vertical stiffners.

To obtain high surface finish the machine tool should be free from vibrations. Besides other factors the design of the bed influences the vibration characteristics of the machine tool. By controlling the following factors with regard to the design of the machine tool structure the vibrations can be reduced.

(*i*) By arranging machine tool structure to have natural frequencies which do not coincide with those of the cutting action.

(*ii*) The natural frequency is given by

$$w_n = \sqrt{\frac{k}{m}} \text{ radians/sec.}$$

where w_n = Natural frequency

k = Static stiffness of the structure = $\frac{P}{y}$

P = Straining force.

y = Deformation in the direction of force.

m = Mass.

Since natural frequency is proportional to the square root of the static stiffness, therefore the static stiffness of the structure should be as high as possible. Further to obtain high frequencies an attempt should be made to reduce the mass to the minimum.

(*iii*) The material of the structure should be capable of absorbing vibrations.

Fig. 7.7 (*a*) shows typical cross-section of the table of a machine tool.

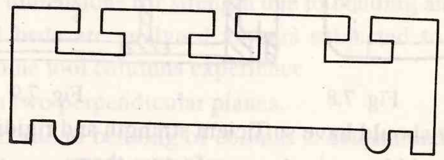


Fig. 7.7 (*a*)

7.13. Procedure to Design a Machine Tool Structure

Following factors should be considered while designing a machine tool structure.

(*i*) Decide materials for structure.
(*ii*) Decide manufacturing process such as
(*a*) Cast (*b*) Fabricated.
(*iii*) Type of structure
(*a*) Close (*b*) Open.
(*iv*) Forces acting on structure which can cause bending and twisting.
(*v*) Take into account weight of structure, weight of workpiece etc.
(*vi*) Nature of vibrations to be generated during working.
(*vii*) The structure should have sufficient stiffness and strength.

7.13.1. Use of reinforcing ribs or stiffness in lathe beds

The strength and rigidity of lathe beds with parallel and diagonal ribs depends upon the following factors :

(*i*) Number of ribs. (*ii*) Arrangements of ribs.
(*iii*) Thickness of main number of bed beam.
(*iv*) Ratio of depth and length of the bed.
(*v*) Ratio of width and length of the bed.

Fig. 7.8 shows a typical section of lathe bed. Fig. 7.9 shows a cross-section of a cast iron bed for a heavy lathe.

The main requirement made to the bed, base or column of a machine tool is that it maintains the proper relative positions of the units and parts mounted on it over a long period of service under all specified working conditions. The beds, bases or column should satisfy the following requirements.

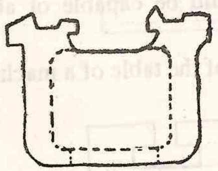


Fig. 7.8

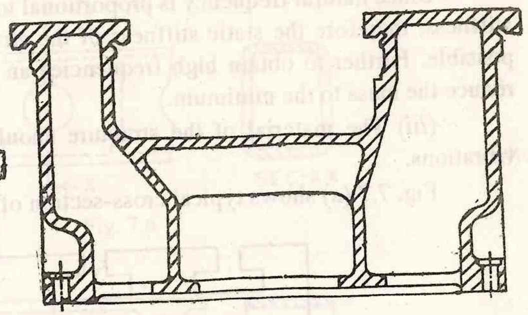


Fig. 7.9

(*i*) They should have sufficient strength and rigidity.

(*ii*) It should be easier to manufacture them.

(*iii*) Their cost should be low.

(*iv*) Minimum amount of metal should be used during their manufacture.

The configuration of bed (base and column etc.) is determined by the following factors.

(*i*) By the arrangement of ways on bed for various units of machine tool.

(*ii*) By weight, dimensions and length of stroke of main units and parts.

(*iii*) By the necessity of housing various mechanisms inside the bed.

(*iv*) By the various openings, apertures etc. to be provided in the bed walls.

7.13.2. Forces to be considered for machine tool structures design

While designing a machine tool structure the following forces should be taken into account.

(*i*) *Cutting force.* This force depends on the following :

(*a*) Work-piece material.

(*b*) Machining parameters like feed, depth of cut, cutting speed etc.

(*c*) Wear of cutting tool.

(*ii*) *Friction force.* This is considered proportional to the normal force on the contacting surface. Coefficient of friction may be taken as follows :

μ = Coefficient of friction
= 0.001 for steel, for rolling friction
= 0.002 for C.I. for rolling friction
= 0.002 – 0.05 under conditions of liquid friction
= 0.03 – 0.2 under conditions of semi-liquid conditions
= 0.2 – 0.35 under dry friction.

(*iii*) Forces of reaction.

(*iv*) Inertial forces due to vibrations and transient processes during speeding up and braking.

(*v*) Forces due to mass of structure, workpiece, fixtures and clamping devices.

The machine tool should be designed based on following :

(*i*) Designing for bending stiffness.

(*ii*) Designing for torsion stiffness.

(*iii*) Checking dimensions for strength due to bending and torsion.

Machine tool beds are analysed as bars subjected to bending and torsion whereas machine tool columns experience.

(*a*) bending in two perpendicular planes.

The deflection due to bending of column is determined by analysing the column as a centilever fixed at the base.

(*b*) Shearing in two perpendicular planes.

(*c*) torsion.

The effect of holes and apertures on the torsional stiffness of column should be taken into account. Machine tool bases are designed as plates on an elastic foundation. The dimensions are determined from the consideration that the maximum deflection due to load acting on plate should not exceed the specified limits. The machine tool rectangular tables are treated as rectangular plates of constant thickness. Cross rails, arms, arms should be designed for torsion and bending.

7.14. Slides and Slide Ways (Guide Ways)

A slide is a moving element providing a straight line movements to a workpiece or a tool holder at a controlled feed rate. A slide way gives accurate guiding constrains to the slide and may contain some form of adjustment to eliminate play between the two members as wear takes place. The following points should be considered while designing slide ways.

(*i*) Provision should be made for effective lubrication. Slide ways may be lubricated intermittently through grease or oil nipples, a method suitable where movements are frequent and speeds low or the slide ways may be lubricated continuously *e.g.* by pumping through a metering valve and pipe work to the point of application, the film of oil introduced between the surface must be extremely thin to avoid the floating of slide.

(*ii*) Protection. The slide ways should be maintained in good order. This is achieved as follows.

(*a*) By providing protective guards to prevent accidental damage.

(*b*) Possibility of chips getting entrapped should be minimum. It is desirable to have a form of slide ways which does not retain chips such as the inverted vee type.

(*iii*) **Accuracy.** The slide ways should be accurately manufactured so as to provide the accurate alignment under working load and to provide the required motion to slide smoothly. The required accuracy and finish of slide ways are obtained by suitable machining technique. The general tolerance for straightness of machine tool slide ways is 0—0.02 mm for 1000 mm.

(*iv*) **Deformation.** Deformation due to cutting forces should be minimum.

Grey cast iron is most commonly used materials for slide ways. It is employed when the slide ways are made integral part with the bed and correspondingly with the travelling units. The wear resistance of cast iron slide ways can be increased by surface hardening performed with flame or induction hardening. Steel slides are also used. They in the form of strips are either welded to a steel bed or they are secured by screws to a cast iron bed. Fig. 7.10 shows a lathe bed with hardened steel slides secured to the bed.

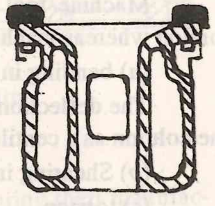


Fig. 7.10

The actual shape of the slide way depends upon the following factors :

(*a*) Load to be carried.
(*b*) Degree of accuracy required.
(*c*) Direction of cutting forces.
(*d*) Position of the element which is used for transmission.
(*e*) Type of machine.

The common types of slide ways are as follows :

(*a*) Flat slide way. (*b*) Vee and flat slide way.
(c) Dovetail slide way. (*d*) Roller slide way.

(*i*) **Flat slide ways.** Fig. 7.11 shows flat slide ways. They possess a larger load carrying capacity suitable for the larger type of machine. They provide a large areas of contact thus wear is kept to a minimum. It is easier to manufacture such slide ways and the geometric feature of these slide ways can be easily checked. On the other hand they have to following disadvantages :

(*a*) They require devices for adjusting the clearances.
(*b*) They have tendency to accumulate dirt.
(*c*) They retain the lubricant comparatively poor.

(*ii*) **Vee and flat slide ways.** Vee ways are more difficult to manufacture than flat ways but are capable of self adjustment *i.e.* clearances are automatically eliminated under the action of load. It has no tendency to accumulate dirt. The drawback of the inverted vee type slide way is the lack of bearing surface which results in rapid wear.

For lathe bends both flat and inverted vee slide ways are commonly used. Fig. 7.12 shows a combination of vee and flat slide ways. It is simple to manufacture and is easily rescraped when wear has taken place.

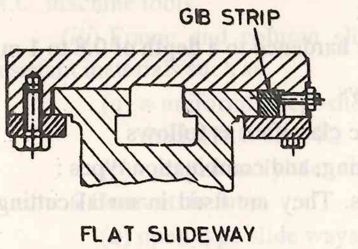


Fig. 7.11

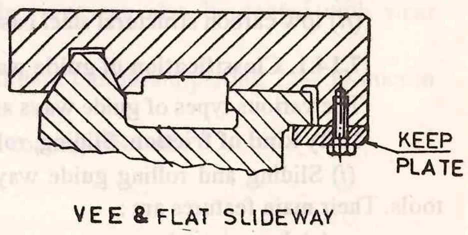


Fig. 7.12

(*iii*) **Dovetail slide ways.** They occupy small space. They are commonly used where the cutting forces tend to produce upward movement of slide thus causing vibrations. The gib strip can be adjusted so that the two elements of the slide are a good sliding fit. This type of slide ways are used in centre lathe cross slide and compound slide. (Fig. 7.13)

(*iv*) **Roller and ball slide ways.** In this system (Fig. 7.14) rollers retained in a brass cage interposed between the sliding members. This arrangement reduces the friction between the two members of the slide because rolling friction is substituted for sliding friction. Roller slide ways can be used to move heavy loads positively and accurately.

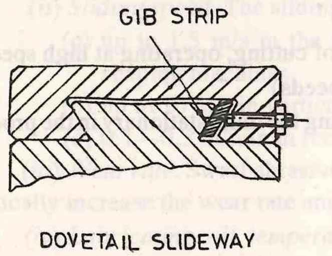


Fig. 7.13

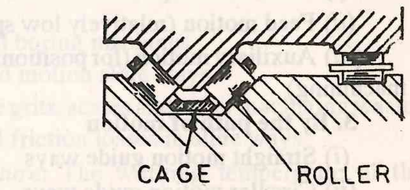


Fig. 7.14

Fig. 7.14 (*a*) shows ball slide ways in which steel balls are inserted between sliding surfaces.

They have the following positive features

(*i*) Low friction (*ii*) High stiffness
(*iii*) Uniformity of motion (*iv*) High velocity of motion.

In these guide ways the contact of rolling elements with guide way surfaces occurs over a point or a line. It is therefore necessary that the guide way material has high contact strength to be able to transmit large loads through small contact area.

Both roller and ball slide ways are also called anti-friction slide ways (guide ways). Materials that are commonly used for making antifriction guide ways are as follows :

(*i*) spindle steel with HRC 60—62

(*ii*) low carbon structural steel case hardened to a depth of 0.8 to 1 mm.

7.14.1. Classification of guide ways

The various types of guide ways are classified as follows :

1. By kind of friction. Sliding, rolling, and combination types :

(*i*) Sliding and rolling guide ways. They are used in metal cutting tools. Their main features are :

(*a*) Long travels

(*b*) Wide speed ranges [from fine feed rates to considerable main motion]

(*c*) High accuracy

(*ii*) Sliding guides :

(*a*) Sliding guides are used in metal forming machines and are subjected to great axial loads.

(*b*) Sliding guides are used for cross heads (slides) in piston-type engines with typically high speeds, elevated temperature and loads acting in a single plane.

(*iii*) Sliding and rolling guides used in instruments where loads are insignificant and accuracy requirements are quite essential.

2. By kind of motion

(*i*) Main motion (in the direction of cutting, operating at high speeds)

(*ii*) Feed motion (relatively low speeds)

(*iii*) Auxiliary motion (for positioning the units stationary in the process of machining)

3. By the path of motion

(*i*) Straight motion guide ways

(*ii*) Circular motion guide ways

(*iii*) Curvilinear motion guide ways

4. Location of path of motion in space

According to the location of path of motion in space guide ways are of following types

(*i*) Horizontal

(*ii*) Vertical

(*iii*) Inclined.

5. Position features

(*i*) Guide ways made integral with machine frames, housings, or other components

(*ii*) Attached guide ways which may be fastened or abrasive bonded in the form of plates, strips etc. Attached guide ways of bronze, zinc alloys and plastics are used for work tables, slides and other shorter ways in heavy and N.C. machine tools.

(*iii*) Frame and column slide ways can also be coated with wear resistant materials such as

(*a*) a uniformly deposited hard chromium plating 25—50 micron thick HRC 68—72

(*b*) sprayed molybdenum coating HRC 65.

6 Geometric form

(*a*) open type slide ways

(*b*) closed type slide ways

7.14.2. Slide ways working conditions

Slide ways should be subjected to proper pressure, sliding velocities, and lubrication.

(*i*) *Permissible pressure.* The maximum permissible pressure on feed motion ways with the most commonly used cast iron on cast iron sliding pair is as follows :

(*a*) 25 to 30 kg/cm^2 in medium size general purpose machine tools

(*b*) 10 to 15 kg/cm^2 in heavy machine tools

(*c*) 100 to 130 kg/cm^2 in the slides of heavy machines with a bronze on cast iron sliding pair.

(*ii*) *Sliding speed.* The sliding speed commonly used is as follows :

(*a*) up to 1.5 m/s in the main-motion slide ways of planing and shaping machines

(*b*) up to 10 m/s in vertical boring machines

(*c*) 0.1—0.3 m/min in feed motion slide ways.

(*iii*) *Wear rate.* Swarf abrasive grits, scales and other machining wastes drastically increase the wear rate and friction losses in slide ways.

(*iv*) *Lubricating oil temperature.* The working temperature of the lubricating oil is normally close to the room temperature.

7.14.3. Oil for slide ways

To reduce friction force in slide ways use should be made of slide way oils. The grade and viscosity are selected depending on the operating conditions such as

(*i*) Sliding speed

(*ii*) Pressure

(*iii*) Slide way protection against dirt

(*iv*) Motion uniformity

(*v*) Positioning accuracy requirements

(*vi*) Spatial arrangement of the slide ways

For slide ways substantially free from dirt and with scant lubrication, industrial oils of higher viscosity should be used. Greater loads and lower sliding speeds also call for oils of higher viscosity.

Where exposure of dirt is considerable and lubrication is meagre the lower viscosity industrial oils should be used.

7.14.4. Friction in slide ways

In slide ways following three types of friction may take place

(*i*) Boundary friction

(*ii*) Fluid friction

(*iii*) Mixed (simultaneously boundary and fluid) friction.

The influence of various factors on friction in slide ways is as follows :

(*i*) *Pressure.* Pressure at very low speeds (less than 30 mm per minute) has little effect on coefficient of sliding friction. However at higher speeds coefficient of sliding friction rises with pressure since increased pressure impedes the development of the hydrodynamic pressure.

(*ii*) The viscosity of oil at every low speeds hardly affects coefficient of sliding friction. At higher speeds the increase in viscosity results in significantly reduced coefficient of sliding friction.

(*iii*) The frictional characteristics are substantially improved with the use of hydraulic relief method where by oil pressure takes up part of the external load.

The coefficient of static and sliding friction in uniformly loaded hydraulically relieved slide ways at speed less than 50 mm per minute is approximately determined as follows

$$f_h = f\left(1 - \frac{P_h}{P}\right)$$

where f_h = Coeff. of friction for hydraulically relieved slide ways

f = Coefficient of friction under same conditions without hydraulic relief.

P_h = Hydraulic relief force

P = External load.

7.14.5. Accurate positioning of slide ways

Following means are used for improving the uniformity of motion and the accuracy of positioning of slide ways (guide-ways)

(*i*) Change over to fluid-friction (hydro static) ways

(*ii*) Using proper lubricating oils

(*iii*) Use of rolling guides.

(*iv*) Application of slide ways relieved of pressure (hydraulically, mechanically and pneumatically).

(*v*) Raising of the stiffness of the drives and gear trains.

(*vi*) Use of special high stiffness drive systems.

(*vii*) Use of damping devices in feed drives.

(*viii*) Improvement in quality of manufacture of slide ways and using proper materials for slide ways

(*ix*) Proper installation of machine tools.

7.14.6. Classification of rolling guides

Rolling guides are classified as follows :

(*i*) *By geometrical form.* The rolling guides are of two types :

(*a*) prismatic (*b*) cylindrical

(*ii*) *By the method of rolling.* Rolling guides may be

(*a*) without preloading

(*b*) partly preloading
(preload adjusted in a horizontal direction)

(*c*) fully pre loaded.

Rolling guides without pre-loading are much simpler and cheaper in manufacture. Preloaded rolling guides are hardened and are designed for high stiffness and high tilting moments.

(*iii*) *Rolling guides with balls.* The ways are flat, prismatic or cylindrical in cross-section. They are suitable for smaller loads. They are made of hardened steels.

(*iv*) *Rolling guides with rollers.* They can take up high load. Their load carrying capacity is 20 to 30 times greater than that of ball type rolling guides of the same dimensions. The stiffness of these guides is about 2.5 to 3.5 times the stiffness of rolling guides with balls. In these guides made of hardened steel ways the length and diameter are related as follows

$$r = \frac{L}{D}$$

$$= 1.5 \text{ to } 2$$

where L = Length of roller

D = Diameter of roller.

The force of friction becomes smaller with greater diameter of rolling elements and lower working load.

7.15. Requirements of Guide Ways

Requirements of a slide way are as follows :

(*i*) It should be strong

(*ii*) It should possess sufficient stiffness

(*iii*) There should be less wear

(*iv*) The pressure distribution should be uniform (*v*) It should provide good guidance

(*vi*) There should be less friction.

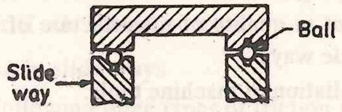


Fig. 7.14 (*a*)

7.15.1. Design criteria for slide ways

Slide ways are designed based on the following :

(*i*) *Wear resistance.* It is governed mainly by the maximum pressure acting on the mating surfaces. This condition may be expressed as

$$f_m \le f_p$$

where f_m = Maximum pressure acting on mating surfaces

f_p = Permissible value of maximum pressure.

(*ii*) *Stiffness.* In this case the deflections of the cutting edge in directions that significantly influence the machining accuracy should not exceed the permissible deflection.

$$\delta_m \le \delta_p$$

where δ_m = Maximum deflection at the cutting edge

δ_p = Permissible deflection at the cutting edge.

Slide ways should be oiled from time to time to ensure their proper functioning.

The coefficient of friction between the sliding surfaces at a particular instant of time depends on the time period elapsed since the last oiling Fig.7.14 (*b*) shows the variation of coefficient of friction (μ) with times (*t*).

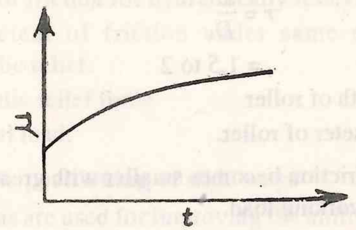


Fig. 7.14 (*b*)

7.15.2. Machine tool columns

Columns support spindle head and knee-table unit. The principal design requirements of columns are same as those of beds *i.e.* high static and dynamic stiffness. The columns are made with thin-walled circular or box sections. The number and size of holes and openings is kept as small as possible

and the section is strengthened by means of stiffners. Generally the area of columns section gradually increases as we move from the top towards the base.

In general machine tool columns are subjected to following type of loads :

(*i*) Torsion

(*ii*) Bending in two perpendicular planes.

(*iii*) Shearing in two perpendicular planes.

The dimensions of the column cross-section should be such that the total deflection due to various loads is within permissible limits. The deflection due to bending of column is determined by analysing the column as a cantilever fixed at the base.

The deflection (δ) due to shearing of column is calculated as follows :

$$\delta = \frac{K.P.L.}{C.A.}$$

where P = Shearing force

L = Distance from base of the section where deformation is to be found

C = Shear modulus for material of column

A = Area of cross-section

K = Coefficient distribution of shearing displacement.

7.16. Materials of Beds and Guides

The materials used for beds frames and guides should possess the following properties.

(*a*) Easy fabrication (*b*) Strength

(*c*) Damping capacity (*d*) Wear resistance.

The materials commonly used for machine tool structures (beds, frames etc.) are east iron and steel.

Whether the structures should be made from cast iron or steel depends on the following factors :

(*i*) Material properties

(*a*) Strength—Steel has higher strength than cast iron.

(*b*) The unit rigidity of steel under tensile, torsional and bending loads is higher.

(*c*) Cast iron has higher inherent damping properties.

(*ii*) Manufacturing of structures :

(*a*) Welded structures made of steel can have much thinner walls as compared to cast structures.

(*b*) A welded structure can be easily repaired and improved whereas any corrections in a cast structure are much more difficult.

(*iii*) Economy—The cost of structure should be low. In welded structures cost of material, welding, machining, welding fixture etc. has to be considered and in cast structures, the cost of material, casting, machining, pattern etc. has to be considered.

(*a*) It is observed that cast iron should be preferred for making complex and heavy structures and steel should be preferred for smaller sized structures.

(*b*) Combined welded and cast structures are becoming popular.

Slide ways are made from cast iron and low carbon of low alloyed steels. Grey cast iron is cheap but does not have good wear resistance. The wear resistance of grey cast iron slide ways (guide ways) can be considerably improved by proper heat treatment. The wear resistance of cast iron slide ways can be further improved by applying hard coatings such as chrome plating of slide way with a 25-50 micron layer provides a hardness of HRC 70 and this increases the life of slide ways considerably. Steel slide ways are manufactured separately and then attached to the bed.

Semisteel with nickel and chromium is a suitable slide way material. The bed is flame hardened by heating the top surface above the critical temperature and then quenching in a moderate rate.

Sometimes plastic slides are also used backed by cast iron or steel pieces. The various advantages of plastic guides are as follows :

(*i*) Low friction (*ii*) Less wear
(*iii*) Uniform pressure (*iv*) Easy fabrication.

However plastic guides have less strength and hardness and can be used for low speed-range.

Table 7.2 indicates the allowable maximum pressure (*p*) in sliding guides.

Table 7.2

Material	*Type of duty*	*(kg/cm²)*
Steel Cast Iron	Low velocity lathes High velocity traverses Special purpose machines Planers Low velocity lathes and milling machines	30—40 2—4 5—7 10 26—30

7.17. Wear Resistance of Guides

Following factors are responsible for causing high rate of wear of slide ways :

(*i*) Uncovered slide ways : such slide ways will get worn out because of swarf, dirt etc.

(*ii*) Poor lubrication

(*iii*) Frequent stops and reversal of work tables or tool slides.

(*iv*) Non-uniform use of slide ways along the length.

The period over which a machine tool can maintain its original accuracy depends on the wear resistance of guides. The wear resistance of guides depends on the following factors :

(*i*) Material and its hardness (*ii*) Pressure on guides
(*iii*) Sliding velocity (*iv*) Surface finish
(*v*) Friction (*vi*) Lubrication.

Cast iron with a pearlitic structure is wear resistant besides having good mechanical properties. Inserted steel guides having hardness of about HRC 63 are being used widely. Plastic guides have also been introduced. Guides having accurate surface finish have more war resistance. To reduce wear of guides the pressure over them should be uniformly distributed and the pressure should be within permissible limits. Friction should be minimum.

Friction and hence wear can be reduced by

(*i*) Lubrication of sliding surfaces

(*ii*) By using ball and roller guides

(*iii*) By protecting the guides from dust etc.

7.18. Life of Guide Ways

Life of guide ways should be more. Following methods help in increasing life of guide ways :

(*i*) By using proper material

(*ii*) By providing proper heat treatment

(*iii*) By using proper lubrication

(*iv*) By using proper configuration

(*v*) By providing proper clearance between guide ways and the parts sliding on it.

7.18. (*a*) Working Life of rolling guides

Rolling guides are finding ever increasing application in modern machinery and equipment. Rolling guides offer significant advantages such as

(*i*) Low friction force

(*ii*) Good positioning repeat ability on reversals

(*iii*) Accuracy maintained over time

(*iv*) Moderate lubrication requirements.

Rolling guides provide a very high uniformity of motion of machine components stick slip occurs only if pre load is excessive or the quality of rolling guides is poor. The accuracy of positioning of machine components in rolling guides defined by the deviation from the specified position amounts to 0.1—0.2 microns provided the drive is rigid enough.

Rolling guides are mainly because of the following reasons.

(*i*) *By mechanical impurities.* Metal chips getting into the guides disrupt contact between the mating parts and cause

(*a*) slip and jamming of the rollers.

(*b*) scores and brinelling of cast iron ways

Abrasives produce wear of ways and inadequate supply of coolant brings about considerable fretting wear.

(*ii*) *Slip of rolling bodies.* The slip of rolling elements results from the defects of the cage and from the use of small diameter rollers (needle rollers). Guides with rolling bodies in cages assume more uniform motion.

Rolling guides have long service life at small loads and at low speeds. For high speed and high load applications rolling guides should be back calculated for surface layer fatigue strength. Surface roughness has considerable effect on rolling guide performance. Better surface finish reduces friction and improves stiffness and wear resistance.

7.18. (*b*) Friction in Rolling guides

In rolling guides the force of friction is made up of two components as follows :

(*i*) Frictional force under no load

(*ii*) Frictional force proportional to load.

The frictional force under no load conditions results from the friction of rolling elements against the cage and from viscous friction associated with the lubricant.

The frictional force proportional to load is determined mainly by rolling friction as such and friction due to the difference in velocities at the contact.

F = Friction force

$$= S + \frac{\mu}{r} \times N$$

where S = Initial friction force on one surface of guide (Kgf)

μ = Co-efficient of friction

= .001 for hardened steel ways

= .0025 for cast iron ways.

r = Radius of rolling element (cm)

N = Normal force on guide way surface (Kgf)

The friction force becomes smaller with greater diameter of rolling elements and lower working load (or preload).

Fig. 7.14(*c*) shows variation of friction force (F) and normal force (S).

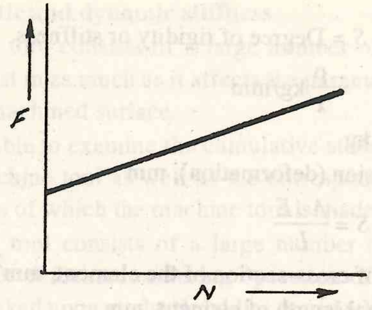


Fig. 7.14 (*c*)

The variation of friction force (F) and speed of motion (V) is indicated in Fig. 7.14 (*d*).

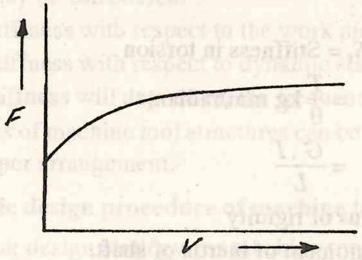


Fig. 7.14 (*d*)

7.18. (*c*) Methods of improving functioning of Slide ways

The service properties of slide ways can be improved by the following methods :

(*i*) To provide favourable frictional conditions :

This can be achieved as follows :

(*a*) Using hydrostatic ways with a high rigidity oil film.

(*b*) Using automatically controlled hydrostatic ways that ensure an extremely high rigidity of the film in the specified load range.

(*c*) Using lubricating system utilising both hydrostatic and hydrodynamic lift.

(*d*) Using combined sliding and rolling guides.

(*e*) Using proper lubricant.

(*f*) Using proper materials for slide ways.

(*ii*) To provide adequate protection to guide ways.

(*iii*) To use optimal cross-section of slide-ways.

(*iv*) To use optimal surface finishes.

7.18.1. Basic principles of design for rigidity

The operating properties of a machine tool depends on degree of rigidity of its individual units and parts. The rigidity of a mechanical element is defined as follows :

S = Degree of rigidity or stiffness

$= \frac{\rho}{x}$ kg/mm

where ρ = Load, kg

x = Extension (deformation), mm

$$S = \frac{A \cdot E}{L}$$

where A = Area of cross-section of the element, mm^2

L = Original length of element, mm

E = Modulus of elasticity, kg/mm^2.

Similarly, stiffness in torsion for a shaft subjected to twisting moment (T) is found as follows :

S_t = Stiffness in torsion

$= \frac{T}{\theta}$ kg mm/radian

$= \frac{G \cdot I}{L}$

where G = Modulus of rigiaity

I = Polar moment of inertia of shaft.

θ = Angle of twist in shaft in radian.

Analysis for rigidity is particularly important for ensuring the adequate accuracy of components produced on the machine tools.

7.18.2. Basic principles of design for strength

While designing a machine tool elements for strength the induced stresses in the machine tool elements should be compared with allowable stresses. The strength conditions is therefore as follows :

$$\sigma_1 \leq \sigma \quad \text{or} \quad \tau_1 \leq \tau$$

where σ_1 and τ_1 are induced tensile or compressive and induced shear stress respectively.

σ and τ are allowable tensile or compressive stress and shear stress respectively

$$\sigma = \frac{\sigma_y}{n}$$

$$\tau = \frac{\tau_y}{n}$$

where σ_y = Yield stress in tension or compression

τ_y = Yield stress in shear

n = Factor of safety.

7.18.3. Static and dynamic stiffness

A machine tool consists of a large number of elements and its behaviour is of interest in as much as it affects the parameters of machining and the quality of the machined surface.

It is desireable to examine the cumulative static and dynamic characteristics of the machine tool as well as the corresponding characteristics of individual elements of which the machine tool is made.

A machine tool consists of a large number of elements and these elements experience deformation during operation of the machine tool and therefore can be looked upon as elastic bodies (springs) with a certain stiffness (spring constant).

To analyse the behaviour of structures under static loading two types of static stiffness may be considered.

(*i*) Static stiffness with respect to the work piece accuracy.

(*ii*) Static stiffness with respect to dynamic stability.

Dynamic stiffness will depend on the frequency of the applied force.

The stiffness of machine tool structures can be improved by using ribs and stiffners in proper arrangement.

7.18.4. Basic design procedure of machine tool structures

The common design strategy for machine tool structures is based on the following :

(*i*) Design for bending stiffness

(*ii*) Design for torsional stiffness

(*iii*) Strength due to bending and torsion.

While designing the following forces should be taken into account :

(*i*) Cutting force (*ii*) Friction force

(*iii*) Force of reaction

(*iv*) Forces due to mass of structures, workpiece fixtures and clamping devices

(*v*) Inertial forces due to vibrations.

7.19. Spindles and Bearings

Spindles. Machining accuracy depends to a considerable extent in many types of machine tools upon the rotational accuracy of the spindle which transmits motion to the cutting tool or to the work. Generally machine tool spindles are made up of alloy low carbon steel heat treated to give a case hardened surface. Such a spindle possesses resistance to wear combined with a tough core for strength in torsion. Where high precision spindles with maximum stability are required such as spindles for external grinding machines Nitralloy is used. Spindles of heavy machine tools are made of manganese steel with subsequent normalisation or hardening followed by high tempering. Spindles are made hollow with a tapered hole at the front end for receiving the centring element (spindle nose). In case of lathe spindle the external screw threads are cut at nose end to receive the chuck or face plate on it. Fig. 7.15 shows a spindle of lathe machine.

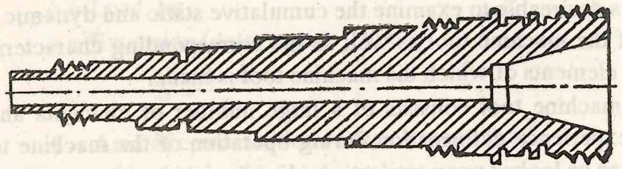


Fig. 7.15

Spindle Bearings. The development of precision bearings for machine tools is a pre-requisite for the development of precision machine tools. The geometrical accuracy and surface finish of a machined component depend largely on the quality of spindle bearings used in the machine tool. The necessity of maintaining an accurate and suitable location of the axis of the rotating spindle at any given speed and load has long been appreciated. Sustained efforts to realize this requirement in practice have resulted in the development of a number of different types of bearings.

The purpose of spindles is not merely that of transmitting power but in doing so without introducing vibrations which may affect the accuracy of the work. Whatever type of bearings are used the spindles mounting must be rigid so that short stiff spindles should be the aim. If this is not attainable then an extra bearing may be the solution. It is preferable that a spindle should be relieved of bending stresses and that the drive should be one of pure torque. For precision work, the machine tool spindle bearings must fulfil the following requirements :

(*i*) They should provide minimum deflection under varying loads.

(*ii*) They should provide maximum truth of running under loads of different magnitude and direction.

(*iii*) They should provide maximum temperature variation throughout the speed range.

(*iv*) They should possess adjustability to obtain minimum radial and axial slackness.

(*v*) They should provide simple and convenient assembly.

(*vi*) They should have sufficiently long service.

The spindle unit of a machine tool performs the following functions.

(*i*) To clamp the cutting tool or workpiece.

(*ii*) To centre the workpiece or cutting tool.

(*iii*) To impart rotary or rotary cum translatory motion to the cutting tool or workpiece.

Spindle unit should fulfil the following requirements :

(*i*) The spindle unit (spindle and spindle bearings) must have high static stiffness. Machining accuracy is influenced by bending, axial as well as torsional stiffness.

(*ii*) The spindle unit should have high dynamic stiffness.

(*iii*) The spindle should rotate with a high degree of accuracy.

(*iv*) The spindle unit should have a fixture which provides quick and reliable centring and clamping of cutting tool or workpiece.

(*v*) The spindle and spindle bearings should have sufficient wear resistance.

7.20. Materials of Spindles

In machine tool spindle design the critical design parameter is not strength but stiffness. Stiffness is primarily determined by the modulus of elasticity. Although strength of alloy steels is more than plain carbon steels but modulus of elasticity is more or less equal. Therefore costly alloy steels may not be used for making spindles. Following steels are recommended for making spindles :

(*i*) For normal accuracy spindles C 1045 steels, hardened and tempered to HRC 30.

(*ii*) For above normal accuracy spindles steel 5140 (AiSi).
HRC 50—55, induction hardened.

(*iii*) For spindles of precision machine tools.
Low alloyed steel 5120 (AiSi)
HRC 55—60 case hardened.

7.21. Lubrication of Bearings

Machine tool bearings are lubricated with mineral oils having a viscosity selected to suit conditions of operation such as :

(*i*) A light oil (low viscosity oil) for high speed bearings with a fine clearance fit between shaft and bearing.

(*ii*) A heavy oil (high viscosity oil) for heavily loaded low speed bearings.

The spindle oil should possess the following properties :

(*a*) It should be non corrosive.

(*b*) It should not readily oxidise.

(*c*) It should have high cooling effect.

Depending on the conditions of operation a bearing may be run.

(*i*) Dry. (*ii*) Partially lubricated.

(*iii*) Fully lubricated.

When the bearing runs dry a metal to metal contact exists and wear rate is quite high. The coefficient of friction lies between 0.15 to 0.4 according to the materials in contact. In partial lubrication the bearing elements are not completely separated by an oil film but some oil or grease is present. The coefficient of friction is generally between 0.02 to 0.1. In fully lubricating bearings the bearing surfaces are completely separated by an oil film. In such bearings friction is minimum and wear is almost eliminated.

7.22. Selection of Bearings

The various considerations in the selection of bearings are as follows :

(*i*) *Direction of load relative to bearing axis.* The various loads which a bearing may be required to meet are :

(*a*) Axial thrust. (*b*) Radial load.

(*c*) Combination of axial thrust and radial load.

(*ii*) *Intensity of loads.* Ball bearings can sustain considerable loads, Roller bearings with their line contact are preferred for severe conditions and shock loads.

(*iii*) Speed of rotation.

(*iv*) Thermal stability

(*v*) *Shaft stiffness.* Rigid bearings are used for stiff well aligned shafts and self aligning bearings are used for shafts subjected to flexure or misalignment.

(*vi*) Class of accuracy of the machine.

7.23. Types of Bearings

Both sliding and rolling friction bearings are used in spindle supports. The various types of bearings used are as follows :

1. Rolling bearings.
   (*i*) Ball bearings.
   (*ii*) Roller bearings.
2. Plain bearings.

7.24. Rolling Bearings

Fig. 7.16 shows a ball bearing whereas a cylindrical roller bearing is shown in Fig. 7.17 and a taper roller bearing is shown in Fig. 7.18. Taper roller bearings have a wide field of usefulness especially in connection with machine tool spindles, gear shafts etc. where high axial and radial forces are combined. One of the method of increasing the accuracy of ball or roller bearings in the spindle is preloading *i.e.* they are fitted with very slight interference fits which take up all radial play between the bearing and spindle leaving the only deflections to be those due to elastic stressing.

This eliminates the clearance between the bearing rings and the balls or rollers and in addition sets up elastic deformation that improves the total

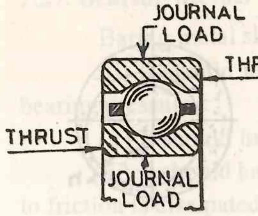


Fig. 7.16

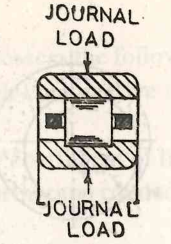


Fig. 7.17

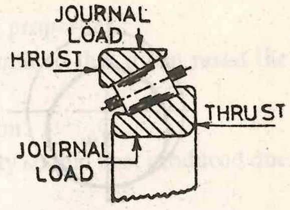


Fig. 7.18

rigidity of the spindle unit. Angular contact ball bearings or tapered roller bearings installed in pairs are preloaded by adjustments made during assembly without the need of special devices.

The distinguishing features of anti friction bearings (ball bearings and roller bearings) as compared to sliding bearings are as follows.

(*i*) Low starting resistance.

(*ii*) Low frictional moments and heat generation.

(*iii*) High load capacity per unit width of bearing.

(*iv*) Less consumption of lubricants.

(*v*) Easy maintenance.

Ball bearings are less prove to heating and permit larger speeds. They are less sensitive to small alignment errors. However ball bearings have higher load capacity. While choosing the type of antifriction bearings following factors should be considered.

(*i*) Radial and axial run out of spindle.

(*ii*) Radial and axial stiffness of spindle unit.

(*iii*) Heat generation.

(*iv*) Thermal deformation of spindle.

(*v*) Maximum permissible speed.

7.25. Plain Bearings

A plain bearing is formed when a shaft rotates in a bush, lines or the bore of a housing. The plain bearings are of the following types :

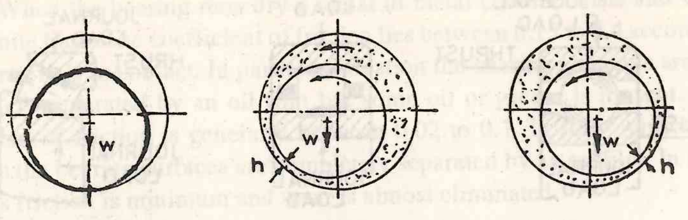
(*a*) Journal bearing.

(*b*) Thrust bearing.

(*c*) Combination of journal and thrust bearing.

Journal bearing is capable of carrying radial loads whereas the thrust bearing is capable of carrying axial load.

Fig. 7.19 shows the behaviour of a shaft (journal) in a plain bearing with the clearance. Space filled with oil and the load acting as shown, when the journal is at rest position the oil will drain from the bearing leaving the shaft in metal to metal contact with the bearing as shown at Fig. 7.19 (*a*). As shaft starts to rotate it rolls upto the left and a thin film of oil substitutes the



(a) (b) (c)

Fig. 7.19

metal to metal contact [Fig. 7.19 (b)]. As the speed increases the oil drawn under pressure through friction caused by shaft rotation forces the journal to the right and balances the external load Fig. 7.19 (c).

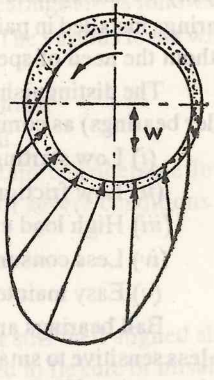


Fig. 7.20

The value of minimum film thickness (*h*) depends on load *W*. Higher is the load *W* small will be the value of *h*, Fig. 7.20 shows relative magnitude of pressures normal to the surface of a plain bearing spindle.

7.25.1. Comparison of plain and rolling bearings

1. The frictional loss is greater in plain bearings than in rolling bearings.
2. Plain bearings are used where simplicity and cheapness is required, or where a high standard of precision is not essential.
3. Rolling bearings need reduced torque for starting from rest.
4. Rolling bearings are more reliable.
5. The rolling bearings can be easily lubricated.
6. Maintenance cost of rolling bearings is low.
7. Rolling bearing can be easily replaced.

7.26. Hydrostatic (externally pressurised) Bearings

These bearings have provisions for supplying oil from an external source at considerable pressure to several pockets in the bearings. (Fig. 7.21). The oil flows out through the clearances between a shoulder of the spindle and the end of the bearing. Hydro-static bearings can operate under fluid friction conditions even at the slowest speed of rotation such bearings are particularly suitable for applications involving heavy loads and low speeds.

Fig. 7.21

7.27. Bearing Metals

Baring metal should possess the following properties :

(*i*) It should have high compressive strength so that it can resist the bearing pressure.

(*ii*) It should have low coefficient of friction.

(*iii*) It should have high thermal conductivity so that heat produced due to friction is dissipated easily.

(*iv*) It should be able to resist the temperature without loosing strength.

(*v*) It should be *wear resistant.*

(*vi*) It should maintain a continuous oil film.

(*vii*) It should be able to embed in itself any dirt or grit present in lubricating oil.

(*viii*) It should be shock resistant.

The various bearing metals are classified as follows :

(*i*) Copper base bearing metals.
(*ii*) Tin base bearing metals.
(*iii*) Lead base bearing metals.
(*iv*) Cadmium base bearing metals.

Copper Base Bearing Metals. Copper base bearings metals contain copper 85% and tin 10% and the remaining is zinc and lead. These alloys are stronger and harder and are used for heavy loads.

Tin Base Bearing Metals. The most commonly used alloy is babbit metal which contains 85% tin, antimony 10% and copper 5%. It has low coefficient of friction and is used where bearings are subjected to higher pressure and load.

Lead Base Bearing Metal. It contains lead, tin, antimony and copper. Lead may be 10 to 30% and antimony 10 to 15%. Bearings of this metal are used for light loads.

Cadmium Base Bearing Metal. It contains cadmium 95%, very small amount of irridium. It has more compressive strength and has more favourable properties at higher temperature.

7.28. Power Units

The electric motor is universally adopted power unit for machine tool. There may be only one motor from which other movement are transmitted or there may be a main motor with separate drive motor for individual element such as a coolant pump motor or a feed movement motor. The basic, lathe is shown in Fig. 7.3.

7.29. Transmission Element

They are used to transmit and control the essential movement from the motor. They include the drives to the spindle and the feed drives. They are of the following types :

(*a*) Mechanical

(*i*) Pulleys (*ii*) Belts

(*iii*) Screws and nuts (*iv*) Gears

(*b*) Hydraulic

(*c*) Pneumatic.

Slide movement is usually controlled by a lead screw and nut arrangement which may be hand driven or power driven.

7.30. Work Holding and Tool Holding Elements

Different machine tools use different types of work holding devices such as three or four jaw chucks are used on a lathe and vices in drilling and shaping machines. Tool holders are designed to suit a particular type of tool.

If the material of different parts of the machine tool has been correctly chosen with due regard for the operating conditions, and design calculations have been done with sufficient accuracy, such factors as *wear resistance* of the elements that primarily affect performance (ways, spindle journals in sleeve bearings, sleeve and antifriction spindle bearings, lead screws and nuts, etc.) will be less and a suitably long *service life* will be ensured.

7.31. Kinematics in Machine Tools

Kinematics is the branch of science related to position and movement. The kinematic functions to be performed by any machine tool are as follows :

(*i*) To transfer motion and power from the input shaft to the output spindle.

(*ii*) To transfer motion from rotation to translation or reciprocation or *vice versa*.

Such transformation of motions are obtained by a chain of higher pairs or lower pairs comprising the drive of machine tools.

Alignments are closely related to the kinematics of a machine both as regards straight line and accuracy of rotation about a fixed axes. The machine tool must be capable of maintaining it, alignment under conditions of (*i*) static loading and (*ii*) dynamic loading. A machine tool is fundamentally a mechanism which produces linear motion by slides and angular motion by spindles all accurately aligned relatively to each other.

7.32. Geometric Forms of Engineering Components

The components produced by machine tools are essentially combination of mainly the following geometric forms :

(*i*) Cylinder (*ii*) Cone

(*iii*) Sphere (*iv*) Flat surface

(*v*) Helical surface.

In order to produce these geometric forms on a machine tool surplus material must be cut away as chips or swarf. This requires that the machine tool be capable of reproducing controlled movements of workpiece or tool or both in such a way that the required geometrical spaces are obtained.

7.33. Methods of Production of Surfaces

The required machined surface is produced by forming or by generating or by a combination of these two fundamental methods.

The various methods of producing geometrical surfaces are as follows :

(*i*) Forming (*ii*) Generating

(*iii*) Copying (tracing) (*iv*) Tangent tracing.

A geometrical surface is usually defined as the trace obtained in the motion of one geometrical generating line called the generatrix along other geometrical generating line called the directrix. A cone is an example of ruled surface where the generatrix rotates along a directrix with one of its end fixed at a point called vertex (Fig. 7.22).

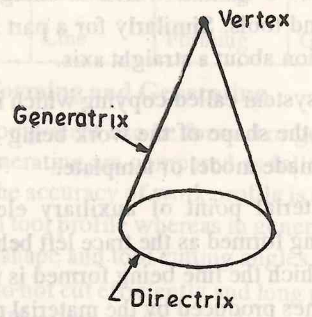


Fig. 7.22

The relative motion of the geometrical lines in producing surfaces are called formative motions. Real surfaces can be shaped on metals or other materials with the help of auxiliary bodies having auxiliary real surfaces lines and points called auxiliary material elements.

In forming the shape of work produced is direct replica of the cutting tool. Milling of the teeth of a straight spur gear by an involute shaped cutter. Fig. 7.23 is an example of forming. In generating the surface produced is the locus or envelope of a large number of successive relative positions between the tool and the work. An example of this is the production of cylindrical shape on a lathe where the work is rotated and the tool movement is controlled so that the tool travels in a path parallel to the axis of the work producing a cylindrical shape (Fig. 7.24).

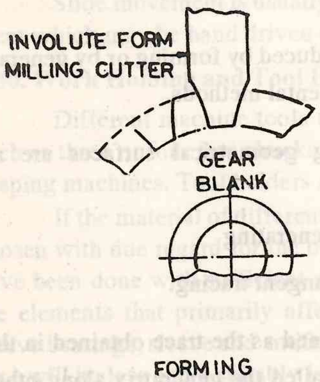


Fig. 7.23

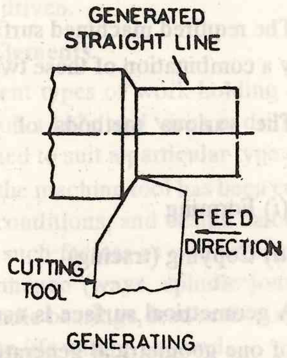


Fig. 7.24

The forming and generating principles are of importance in the kinematic design of machine. In a machine part requiring a linear motion the machine tool must produce a motion which is straight and in a definite relationship to the work and tools. Similarly for a part requiring an angular motion there must be rotation about a straight axis.

There is one more system called copying which is used for producing more complicated shapes, the shape of the work being a replica of a master component, or accurately made model or template.

In tracing the material point of auxiliary element (cutting tool) produces a line or path being formed as the trace left behind. (Fig. 7.25). The tangent tracing is one in which the line being formed is tangent to a series of supplementary auxiliary lines produced by the material point (Fig. 7.26).

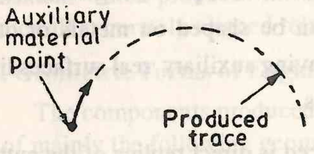


Fig. 7.25

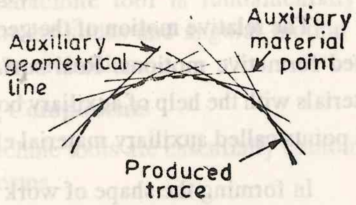


Fig. 7.26

Table 7.3 indicates the inter-relation between processing methods and methods of geometrically shaping the surfaces.

Table 7.3

Processing method	*Formative tool*	*Type of auxiliary element*	*Method of obtaining geometrical generating lines*		*Number of formative motions*
			Generatrix	*Directrix*	
Metal cutting (machining)	Cutting edge	Line or point	Tangent	Generating tangent or tracing	1 to 3
Casting	Foundry moulds	Surface	Forming	Forming	0
Gear hobbing	Hob	Line or point	Generation	Tracing	2
Blanking	Dies	Line	Forming	Tracing	1
Grinding	Grinding wheel	Line of point	Tangent	Generating tracing or tangent	2 or 3
Wire drawing	Die	Line	Forming	Tracing	1
Die forging	Dies	Surface	Forming	Forming	0
Rolling	Rolls	Line	Forming	Generating	1

7.34. Comparison of Forming and Generating

A profile on a component can be formed or generated.

Forming and generating are compared as follows :

(*i*) In forming the accuracy of work profile is entirely dependent upon the accuracy of the form tool profile whereas in generating the work profile is independent of the tool shape and tool cutting angles.

(*ii*) Form tools do not cut efficiently and long profile can cause chatter and poor surface finish. But long profiles can be easily generated with better surface finish.

(*iii*) It is easier to generate internal profile than to form it.

(*iv*) It is difficult to produce complex form tools and secondly they are expensive. Equipment used in generating is usually expensive in the first instance but proves to be economical on production work because of lower variable cost and higher quality of work.

(*v*) Tool should be set correctly both in forming and generating.

7.35. Degrees of Freedom

A body in space (Fig. 7.27) has six degrees of pure movement as follows :

(*i*) Linear movement along any one of the three conventional axes *XX*, *YY* or *ZZ*. Thus the body has three degrees of freedom by means of axial translation.

(*ii*) Rotational movement about any one of the axes, *XX*, *YY* or *ZZ* thus providing further three degrees of freedom.

All movements on a machine tool are made up from one or more or these six degrees of freedom. *ZZ* axis of motion on a machine tool is usually parallel to the axis of the main spindle. The *XX* axis is, if possible, arranged horizontally and parallel to the work holding surface. The *YY* axis obviously has to be mutually perpendicular to the other two axes.

A body will be constrained from movement by six locations suitability applied and which take into consideration kinematic principles. The removal of one location will then permit one degree of freedom, the removal of two locations will permit two degrees of freedom and so on.

7.36. Trends in the Development of Modern Machine Tools

A machine tool should have highest possible productive capacity under the condition that the necessary and adequate machining accuracy is ensured. To achieve this number of most essential special trends used in modern machine tools are as follows :

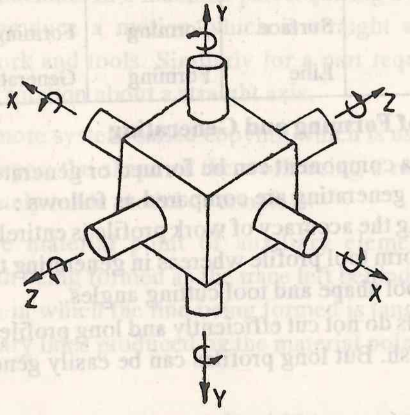


Fig. 7.27

(*i*) The power of main drive is increased to increase the speeds of the cutting and feed motions in order to reduce machining time and to operate simultaneously a number of cutting tools.

(*ii*) More extensive systems of infinitely variable (stepless) speeds and feed are being applied enabling the optimum cutting conditions to be set up and changes as required without stopping the machine. This also reduces the machining time.

(*iii*) Machine tools are being equipped with a great variety of auxiliary devices whose aim is to reduce the part of the handling time. Some of such devices are as follows :

(*a*) Devices for facilitating blank loading and removal of the finished workpiece.

(*b*) Devices for quickly changing cutting tools.

(*c*) Machanized fixtures for rapidly changing the position of the work.

(*iv*) The static and dynamic rigidity of machine tools and their vibration proof properties are being increased.

(*v*) The working cycle is being automated to set up a positive working pace constant for the given set up for the purpose of reducing the handling time and to ensure required machining accuracy irrespective of the skill of the operator.

(*vi*) Multi-tool machine tools such as multi-tool lathes, multi-spindle drilling, milling and boring machines are being used.

(*vii*) Machine tool controls are being simplified mainly by automation of the working cycle.

(*viii*) There is a wide ever-increasing application of electrotechnic, electronics hydraulics and pneumatics for performing various functions.

7.36.1. General requirements of Machine Tool Design

A machine tool should fullfil the following requirements.

(1) *High productivity*. It is achieved by following methods

(*i*) By cutting down machining time

(*ii*) By cutting down non-productive time

(*iii*) Using automatic machines.

(2) *Accuracy*. Accuracy of producing components can be obtained by following methods

(*i*) By using accurate guiding elements

(*ii*) By using short kinematic trains

(*iii*) By increasing static and dynamic stiffness of machine tool structure

(*iv*) By reducing thermal deformations during machining.

(3) Simplicity in design

(4) Safety and convenience of controls.

Safety of controls is achieved by taking following measures

(*i*) Shielding the rotating and moving parts of machine tools.

(*ii*) Providing reliable clamping devices for workpiece and tool

(*iii*) Providing devices for safe handling of heavy workpieces

(*iv*) Using reliable earthing of machine tool

(5) Good appearance
(6) low cost of
(*a*) manufacturing
(*b*) operation
(7) Easier installation.

7.37. Maintenance of Machine Tool

Proper maintenance of machine tool helps to extract trouble free service from it. Planned and timely maintenance helps to reduce the break-down time of the machine tool thereby increasing its availability which ultimately results in better efficiency and higher productivity with the same capital investment and manpower. Time and money spent on planned maintenance will always pay high dividends. Hence the maintenance if carried out at right time in the right quantum at the right cost by the right personnel will go a long way in reducing the cost of production and increasing productivity.

7.38. Machine Tool Efficiency

The efficiency of the machine tool depends on the energy lost due to friction. The horse power of machine tool should be higher than horse power required at the cutter.

Table 7.4 shows efficiency of the some types of machine tools.

Table 7.4

Type	*Efficiency (%)*
Direct drive spindle	90
One belt drive	85
Two belt drive	70
Geared head	70

Example 7.1. *Calculate breadth and length of guide way for a total load of 450 kg. The viscosity of lubricant is 0.015 kg sec/m² and slide is moving with a transverse rate of 3.5 m/min. The minimum film thickness is 0.01 mm. The permissible pressure is 1.8 kg/cm².*

Solution. The maximum possible load (P) that can be sustained by a guide is given by the relation,

$$P = \frac{0.133\, ZVB^3}{h^2}$$

where P = Maximum possible load in kg

Z = Absolute viscosity = 0.015 kg sec/m²

V = Velocity of sliding = 3.5 m/min.

$= \frac{35}{60}$ m/sec.

B = Breadth

h = Minimum film thickness = 0.01 mm

$= 0.01 \times 10^{-3}$ metre

$$450 = \frac{0.133 \times 0.015 \times 3.5 \times B^3}{(0.01 \times 10^{-3})^2}$$

$$B = 0.07 \text{ m} = 7 \text{ m}$$

$$A = \text{Area} = L \times B$$

$$L \times B = \frac{P}{p}$$

where p = Permissible pressure

$= 1.8$ kg/cm³

$$L \times B = \frac{450}{1.8}$$

Length, $$L = \frac{450}{1.8 \times B} = \frac{450}{1.8 \times 7}$$

$= 35.7$ cm.

Example 7.2. *Discuss the factors which help in achieving high productivity and high accuracy from machine tools.*

Solution. Following factors help in achieving high productivity.

(*i*) Cutting down machining time.
(*ii*) Cutting down non-productive time.
(*iii*) Machining with more than one tool simultaneously.
(*iv*) Using automatic machines, transfer lines and N.C. machine tools.

Machining time can be reduced by using high cutting speeds and feed rates. The application of stepless, mechanical, hydraulic and electrical drives also help in reducing machining time. Nonproductive time can be reduced by using jigs and fixtures which help in reducing clamping and unclamping time.

Higher accuracy of components manufactured on machine tools can be achieved by following measures.

(*i*) Improving geometrical accuracy of machine tools. This is achieved by using accurate guide ways, power screws etc.

(*ii*) Improving the kinematic accuracy of machine tools.

(*iii*) Increasing static and dynamic stiffness of machine tool structures. Higher the static stiffness of machine tool structures the smaller will be its deformation due to the cutting forces and hence higher will be the accuracy of machining. A high dynamic stiffness reduces the vibrations during machining and this helps in obtaining better accuracy.

(*iv*) Minimising the thermal deformation between the tool and workpiece during machining.

PROBLEMS

7.1. Define a machine tool. Classify the machine tools.

7.2. Explain the following for a machine tool :

(a) Primary cutting motion

(b) Feed motion.

7.3. What are the essential requirements of a machine tool ?

7.4. Name the basic features of a machine tool. Briefly explain any three.

7.5. Write short notes on the following :

(a) Selection of machine tools.

(b) Forces in a machine tool.

7.6. (a) What is a slide way ?

(b) What are the points to be considered while designing slide ways ?

(c) Name the materials commonly used for slide ways.

(d) Make neat sketches of three different forms of slide and slide ways. Briefly explain them.

7.7. Give three reasons way cast iron is the material mainly used for the production of machine beds.

7.8. Illustrate how a dovetail slide way system eliminates all degrees of freedom except one linear movement required for slide movement.

7.9. Describe the following types of bearings used in machine tool spindles :

(i) Ball and roller bearings.

(ii) Plain bearings.

(iii) Hydrostatic bearings.

7.10. Write short notes on the following :

(a) Lubrication of bearings.

(b) Selection of bearings.

(c) Bearing materials.

(d) Maintenance of machine tools.

(e) Stiffness and rigidity of machine tool.

(f) Wear resistance of guides.

7.11. What are the advantages and disadvantages of plain and rolling bearings ?

7.12. What are kinematics of a machine tool ?

7.13. Write short notes on the following :

(a) Generating, forming and copying.

(b) Degree of freedom.

7.14. Write a note on "The Trends in the Development of Modern Machine Tools".

7.15. Why box section is more suitable for beds of machine tools.

7.16. Prove that compliance (c) of a centre lathe is given by

$$C = \frac{1}{S_2} + \frac{1}{S_1}\left(\frac{L-x}{L}\right)^2 + \frac{1}{S_3}\left(\frac{x}{L}\right)^2$$

where S_2 = Rigidity of saddle

S_1 = Rigidity of head stock

S_3 = Rigidity of tail stock

L = Length of workpiece

x = Distance of cutting tool tip from head stock end.

7.17. Write short notes on the following :

(a) Process capability of a machine tool.

(b) Compliance of a machine tool.

(c) Types of forces in a machine tool.

(d) Spindle unit functions and requirements.

7.18. Discuss the basic objectives of a machine tool.

7.19. Write short notes on the following :

(a) Productivity of a machine tool

(b) Precision

(c) Productive time

(d) General requirements of machine tool design.

7.20. Discuss the design criteria for slide ways.

7.21. Describe the design procedure for machine tool structures.

7.22. Describe the following for a machine tool :

(i) Column of a machine tools

(ii) Spindle of machine tool.

7.23. Write short note on :

(i) Control systems of machine tool

(ii) Safety and convenience of controls.

(iii) Static and dynamic stiffness of machine tools

(iv) Design criteria of machine tool structures.

7.24. Discuss general requirements of machine tool design.

7.25. Write short notes on the following :

(a) Working life of rolling guides

(b) Friction in rolling guides.

(c) Methods of improving the functioning of slide ways.

8

Kinematic Drives of Machine Tools

8.1. Drive

Machine tool drives are used to transmit motion from power source to the operative element of the machine tool. The general requirement for the machine tool drives is that they should have provision for regulating the speed of travel of the operative elements. The regulation may be in discrete steps or it may be stepless *i.e.* continuous. The former are called stepped drives and latter are called stepless drives.

The transmission systems for cutting and feed motions constitute drive and are obtained by a chain of higher pairs. Machine tool drives can be classified according to :

(*i*) Source of power.

(*ii*) Transmission system.

(*iii*) Nature of motion produced.

The machine tools are universally driven by electric motors and further transmission is obtained by any of the following methods :

(*a*) Mechanical drives using belts, gear trains, chains, lead screw and nut etc.

(*b*) Hydraulic drive.

(*c*) Electrical drive.

In mechanical drives the transmission of motion from external source to the operative element can take place through mechanical elements such as gears, belts, chains etc. Mechanical drives may be of stepless type or stepped type but hydraulic drives and electrical drives are invariably stepless in nature.

Mechanical transmission is used for transmitting rotary as well as translatory motion to the operative element. Hydraulic transmission is used in machine tools for providing rotary as well as translatory motion, although the latter application is more common. Hydraulic transmission, as a rule, provides stepless regulation of speed and feed rate.

Machine tool drive basically consists of the following :

(*i*) an electric motor.

(*ii*) a transmission arrangement.

Selection of drives depends upon the following factors :

(*i*) Surface finish and accuracy desired.

(*ii*) Production time.

(*iii*) Simplicity of design with respect to maintenance, repair and control.

(*iv*) Power to weight ratio.

(*v*) Optimum efficiency.

8.1.1. Individual drive and group drive

Each machine tool may be driven individually by its own motor called Individual drive or may be driven by a belt from a line shaft called Group drive which supplies power to other machine tools also. Further transmission is either mechanical (belts, gears, etc.) electrical or hydraulics.

Group drive is more economical in fixed charges, power consumption and maintenance. The main draw back of group drive is that in case of break down all machine tools in the group become idle. Further in group drive layout of machine tools is controlled by the position of line shaft. Individual drive has the following advantages :

(*i*) Layout is simple and better utilisation of floor space is achieved.

(*ii*) Cleanliness and lighting of shop are improved.

(*iii*) Machine tools requiring wide variations in speed can be run efficiently.

Modern practice favours the use of individual drive. Machine tool drives may be classified as follows :

(*i*) *Main drive.* It is responsible for carrying out major machining operation like cutting, forming etc. Adjustable speed is the desirable feature f this drive.

(*ii*) *Feed drive.* It is used to feed the tool into work piece and *vice versa*.

(*iii*) *Transverse drive.* It is used for positioning the tool with respect to work.

Choice between group drive and individual drive depends on the following factors.

(*i*) Initial cost.

(*ii*) Operating cost.

(*iii*) Machine tool requirement.

8.1.2. Electric motors for machine tool drives

The majority of the machine tool drives are made suitable for operation on standard 3 phase 50 cycle 400/440 volts, A.C. supply. Selection of electric motors depends on the following factors :

(*i*) The capacity of motor.

(*ii*) The power supply such as A.C. or D.C.

(*iii*) The electrical characteristics of motors such as starting characteristics, running characteristics and speed control.

(*iv*) Mechanical features like mounting enclosures transformation of drive, noise level, type of cooling.

(*v*) Cost.

(*vi*) The motor should be capable of delivering load, torque requirements and temperature rise of the motor should be within safe value.

(*vii*) Over load capacity.

Squirrel cage induction motors are the most popular choice due to their simplicity robustness and low cost. They can be made available with a wide variety of operating characteristics. In general speed regulation is good. A.C. commutator motors have infinitely variable speed over a wide range but their cost is high. D.C. machines are used where wide range of speed variation is required. D.C. shunt motors with field and/or armature control are very commonly used on main drives of machine tools. For traverse drives D.C. series or compound wound motors are preferred.

Following types (Table 8.1) of electric motors are recommended for machine tools of different types.

Table 8.1

Machine Tool	*Type of Motor*
1. Lathe	
(*a*) Main drive and feed drive	(*i*) Multispeed squirrel cage
	(*ii*) Adjustable speed D.C. motor
(*b*) Traverse drive	(*i*) D.C. series
	(*ii*) High slip squirrel cage motor
2. Shapers, slotters	(*i*) Constant speed squirrel cage motor
3. Planers	(*i*) Multispeed squirrel cage
	(*ii*) D.C. adjustable voltage
4. Drilling machines	(*i*) Constant speed squirrel cage motor
	(*ii*) D.C. shunt motor
5. Milling machine	(*i*) Squirrel cage
	(*ii*) D.C. shunt
6. Presses, forging machines	(*i*) High slip squirrel cage
	(*ii*) D.C. compound wound
7. Power saw	Constant speed squirrel cage.
8. Grinder	
(*a*) Wheel	(*i*) Constant speed squirrel cage
	(*ii*) Adjustable speed D.C.
(*b*) Traverse	(*i*) Constant speed squirrel cage

The power rating of the electric motor for a general purpose machine tool is calculated as follows :

$$P_m = \frac{P_C}{\eta} \text{ kW}$$

where P_m = Power rating of electric motor in kW

P_C = Total power required for removing metal, kW

η = Coefficient of efficiency of the drive.

The value of P_C is found as follows :

$$P_C = \frac{F_Z \cdot V}{6120} \text{ kW}$$

where F_Z = Cutting force in kg

V = Cutting speed in m/min.

The value of η is found as follows :

$$\eta = \eta_1, \eta_2, \eta_3, \ldots, \eta_r$$

where $\eta_1, \eta_2, \eta_3, \ldots, \eta_r$ are the coefficient of efficiency of the individual transmissions involved in transmitting motion from the motor to the operative element.

Table 8.2 indicates the values of coefficient of efficiency for various transmission systems.

Table 8.2

Transmission System	*Coefficient of efficiency*
Ball or roller bearing	0.99
Spur gear drive	0.98
Helical gear drive	0.97
Bevel gear drive	0.96
Belt drive with flat belt	0.98
Belt drive with V belt	0.96

8.2. Strength and Power of Machine Tools

The power capacity of a machine tool depends on strength and rigidity of machine tool. A heavy machine tool uses a high power motor whereas a light machine tool is equipped with a small motor. The electric motor power should be more than that required at the cutting zone. There should be minimum loss of power.

The specific power is the value of required for per cubic centimetre per minute of stock removal. It depends on the following factors :

(*i*) work piece material

(*ii*) type of operation

(*iii*) rake angle of cutting tool

(*iv*) size of cut and speed.

Table 8.3 indicates specific power or average values of kW per cubic centimeter per minute of stock removal for some of the materials for different machining operations.

Table 8.3

Workpiece material	Machining Operations			
	Turning	*Shaping*	*Drilling*	*Milling*
Steel (medium)	0.07	0.07	0.08	0.09
Cast iron (soft)	0.015	0.02	0.03	0.04
Aluminium	0.01	0.15	0.025	0.03
Brass	0.01	0.01	0.025	0.035

8.3. Machine Tool Spindle Speeds

To machine work of any diameter D, at a cutting speed V the spindle speed is given by

$$N = \frac{1000\,V}{\pi D}\ \text{R.P.M.}$$

where D is in mm and V is in metre per minute. Since the cutting speed is taken constant for a particular work tool pair, the spindle speed must vary as the work diameter changes. The spindle speeds can be obtained by two types of drives.

(*i*) Stepped drive.

(*ii*) Stepless drive.

In stepped drive the output spindle speeds are obtained in a fixed number through single or multiple stages. Whereas in stepless drives infinitely variations of output speeds over a certain range can be obtained in single or multiple stages.

Fig. 8.1 shows the stepped drive with three steps output in single stage whereas Fig. 8.2 shows stepless output in single stage with infinite steps.

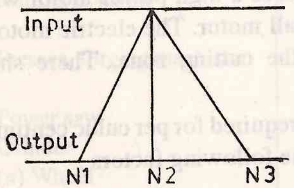


Fig. 8.1

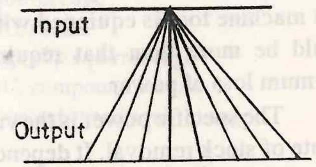


Fig. 8.2

In a stepped drive the following factors should be decided first.

(*i*) Maximum spindle speed (N_{max}).

(*ii*) Minimum spindle speed (N_{min}).

(*iii*) Number of spindle speed steps (n).

(*iv*) The number of stages in which the steps are to be obtained.

The extreme values of spindle speeds can be determined for machine tools if the extreme diameters to be cut are known and also maximum and minimum cutting speeds have been established for the given diameter

D_{max} = Maximum diameter of workpiece

D_{min} = Minimum diameter of workpiece

V_{max} = Maximum cutting speed.

V_{min} = Minimum cutting speed.

R_n = Range ratio of spindle speeds = N_{max}/N_{min}

Now, $$N_{max} = \frac{1000\,V_{max}}{\pi D_{min}}$$

$$N_{min} = \frac{1000\,V_{min}}{\pi D_{max}}.$$

Therefore the minimum spindle speed is dependent upon the maximum diameter of work that can be accommodated and on the minimum cutting speed.

$$R_n = \frac{N_{max}}{N_{min}} = \frac{1000\,V_{max}}{\pi D_{min}} \times \frac{\pi D_{max}}{1000\,V_{min}}$$

$$= \frac{V_{max}\,D_{max}}{V_{min}\,D_{min}} = R_v\,R_d$$

where $R_v = \dfrac{V_{max}}{V_{min}}$ and $R_d = \dfrac{D_{max}}{D_{min}}$

R_v is called ratio of cutting speeds and R_d is called ratio of workpiece diameters. The recommended values of range ratio (R_n) for some of the machine tools are indicated in Table 8.4.

Table 8.4

Machine Tool	R_n
Grinding machines	1—10
Shaper, planer, slotter	10
Automatic lathes	8—10
Drilling machines	20—30
Milling machines	30—50
Centre lathe	40—60

Spindle speeds generally form a series which may be any one of the following types :

(*i*) Arithmetical progression (A.P.)

(*ii*) Geometrical progression (G.P.)

(*iii*) Logarithmic progression (L.P.)

If spindle speeds were in arithmetic progression the steps between on spindle speed and the next would be too far apart at low speeds and too close together at high speeds where as spindle speeds in geometric progression provide a more even range of cutting speeds at each step as illustrated below.

Let the range of n spindle speeds be $N_1, N_2, N_3 \dots N_n$ where N_1 is the minimum spindle speed and N_n is the maximum spindle speed. For any given spindle speed a change in work diameter will produce a proportionate change in cutting velocity. Let the cutting velocity limits be V_{max} and V_{min}.

At N_1, Max. diameter of work $= \dfrac{1000\,V_{max}}{\pi N_1}$

Min. diameter of work $= \dfrac{1000\,V_{min}}{\pi N_1}$

At N_2, Max. diameter of work $= \dfrac{1000\,V_{max}}{\pi N_2}$

Min. diameter of work $= \dfrac{1000\,V_{min}}{\pi N_2}$

At N_3, Max. diameter of work $= \dfrac{1000\,V_{max}}{\pi N_3}$

Min. diameter of work $= \dfrac{1000\,V_{min}}{\pi N_3}$

Now for constant cutting velocity, minimum diameter at N_1 R.P.M. will be same as the max. diameter as N_2 R.P.M.

$$\frac{1000\,V_{min}}{\pi N_1} = \frac{1000\,V_{max}}{\pi N_2} \text{ and so as}$$

$$\frac{V_{max}}{V_{min}} = \frac{N_2}{N_1} = \text{constant ratio} = \frac{N_3}{N_2} = \frac{N_4}{N_3} \dots \frac{N_n}{N_{n-1}}$$

This is a series in geometric progression. Therefore, the spindle speeds are arranged in geometrical progression.

Let ϕ = constant ratio or common ratio

$$\phi^{n-1} = \frac{N_2}{N_1} \times \frac{N_3}{N_2} \times \frac{N_4}{N_3} \dots \frac{N^n}{N^{n-1}} \qquad \dots(1)$$

$$\phi = \sqrt[n-1]{\frac{N_n}{N_1}} = \sqrt[n-1]{R_n}$$

where R_n is the range ratio of spindle speed variation.

For a G.P. the useful value of ϕ lies between 1 and 2, *i.e.* $1 < \phi \le 2$. In the great majority of general purpose machine tools with stepped speed variation the commonly used values of ϕ are 1.12, 1.26, 1.41, 1.58, 1.78, or 2.

These numbers belong to Renard Series and are known as Preferred Numbers.

8.4. Ray Diagram

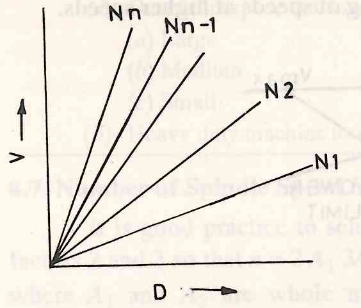


Fig. 8.3. Ray diagram.

For constant speed N the relation between cutting speed V and work diameter D is a straight line. Graphically the relation between V, D and N is represented by Ray Diagram shown in Fig. 8.3.

8.5. Speed Spectrum

The maximum and minimum values of cutting speed (V) in a machine tool is decided by the following two factors :

(*i*) Minimum life of cutting tool for maximum velocity (V_{max}).

(*ii*) Lowest economically justifiable velocity (V_{min}).

$$V = \frac{\pi DN}{1000} \text{ m/min.}$$

where D = work dia. in mm

N = R.P.M.

For a constant value N

$$V \propto D.$$

This gives a straight line graph. As shown in Fig. 8.4, the maximum diameter that can be machined at N_1 revolution per minute should not be more than D_1 and should not be less than D_2. If diameter becomes less than D_2 than the maximum and economical velocity is N_2, where $N_2 > N_1$ and so on. This is shown in speed spectrum for geometric progression in Fig. 8.4. The speed spectrum shows that speed loss is constant at all diameters and there is less crowding at higher speeds. N_5 is greater than N_4, N_4 is greater than N_3 and so on.

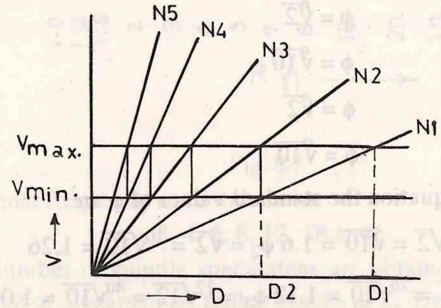


Fig. 8.4. Speed spectrum in geometric progression.

If the spindle speeds were arranged in arithmetic progression the speed spectrum will be as shown in Fig. 8.5. In this case it is observed that speed loss becomes a function of diameter and is larger at lower speeds. It is further observed that there is considerable crowding of speeds at higher speeds.

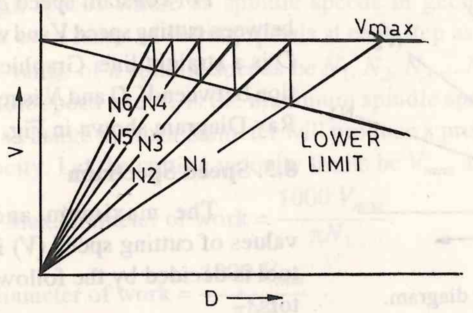


Fig. 8.5. Speed spectrum in Arithmetic progression.

8.6. Standard Values of Common Ratio

The adoption of standardised spindle speeds is of considerable help in production engineering. Standard value of ϕ have been established for standard series of spindle speeds. Generally a series is chosen such that after p number of terms each figure is doubled and after y number of terms another figure becomes 10 times as shown in Fig. 8.6.

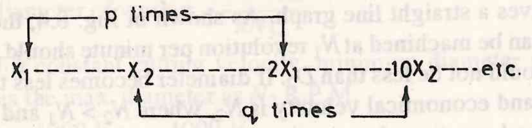


Fig. 8.6

$$\therefore \quad 2x_1 = x_1.\phi^p$$

$$10x_2 = x_2.\phi^q$$

From (1) $\quad \phi = \sqrt[p]{2}$

From (2) $\quad \phi = \sqrt[q]{10}$

or $\quad \phi = \sqrt[p]{2}$

$$\phi = \sqrt[q]{10}$$

Solving this equation the standard values of ϕ are

$$\phi_1 = \sqrt[1.5]{2} = \sqrt[5]{10} = 1.6 \; \phi_2 = \sqrt[3]{2} = \sqrt[10]{10} = 1.26$$

$$\phi_3 = \sqrt[6]{2} = \sqrt[20]{10} = 1.12 \; \phi_4 = \sqrt[12]{12} = \sqrt[40]{10} = 1.06.$$

Table 8.5 indicates the typical values of common ratio (ϕ) for some of the machine tools.

Table 8.5

Machine Tool	ϕ
(*i*) General purpose machine tools	
(*a*) Large	1.26
(*b*) Medium	1.41
(*c*) Small.	1.58
(*ii*) Heavy duty machine tools and automats	1.12

8.7. Number of Spindle Speed Steps

It is good practice to select a number of speed steps (n) having the factors 2 and 3 so that $n = 2A_1\, 3A_2$ where A_1 and A_2 are whole numbers. This requirement is met by the values n = 2, 3, 4, 6, 8, 9, 12, 16, 18; 24. 27, 32, 36.

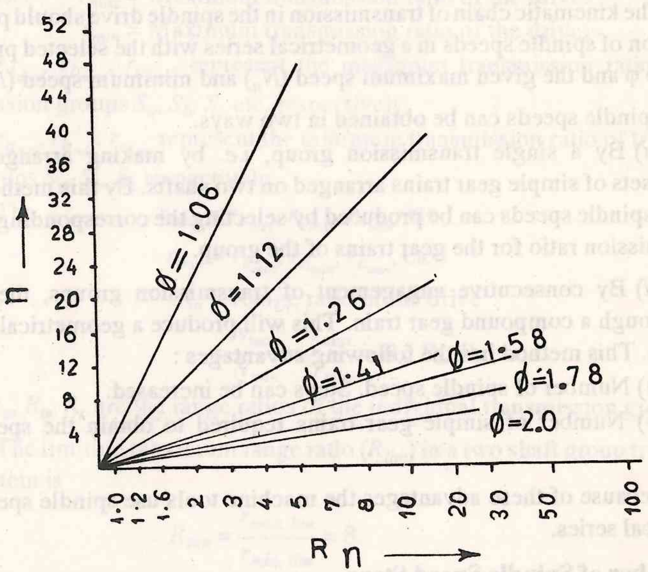


Fig. 8.7

The most frequently used values are

$$n = 3, 4, 6, 8, 12, 18 \text{ and}$$

The number of spindle speed steps are obtained by cluster of gears comprising 1, 2 or 3 gears or by pulley blocks of 2, 3 or 4 pulleys.

The number of spindle speed steps (n) is related to the range ratio R_n and common ratio ϕ by the following expression :

$$n = 1 + \frac{\log R_n}{\log \phi} = \frac{\log (R^n \phi)}{\log \phi}$$

The value of n calculated from the above formula is rounded off to a whole number after which the range ratio variation R_n is correspondingly changed.

Fig. 8.7 shows the relationship between speed range ratio (R_n) number of speed steps (n) and common ratio (ϕ) of the speed series.

The value of R_n and n depends upon the following factors :

(*i*) Purpose of the machines tools.

(*ii*) Nature of the manufacturing process.

(*iii*) Type of cutting tools to be used.

(*iv*) Required degree of versatility of the machine tool.

(*v*) Properties of work piece material.

8.8. Principle Kinematic Relationship in the Spindle Drive

The kinematic chain of transmission in the spindle drive should provide a gradation of spindle speeds in a geometrical series with the selected progression ratio ϕ and the given maximum speed (N_n) and minimum speed (N_1).

Spindle speeds can be obtained in two ways.

(*i*) By a single transmission group, *i.e.* by making arrangements between sets of simple gear trains arranged on two shafts. By this method any series of spindle speeds can be produced by selecting the corresponding series of transmission ratio for the gear trains of the group.

(*ii*) By consecutive engagement of transmission groups, the drive being through a compound gear train. This will produce a geometrical series of speeds. This method has the following advantages :

(*a*) Number of spindle speed. Steps can be increased.

(*b*) Number of simple gear trains required to obtain the speeds is reduced.

Because of these advantages the machine tools use spindle speeds in geometrical series.

8.9. Number of Spindle Speed Steps

Number of spindle speeds (n) is obtained by consecutive engagements of transmission groups. The number of spindle speeds is calculated as follows :

$$n = S_a . S_b . S_c \ldots\ldots S_z$$

where S_a, S_b, S_c etc. represent the number of simple gear trains in each consecutive group. For example for the drive shown in Fig. 8.8.

$$n = S_a . S_b . S_c = 3 \times 3 \times 2 = 18.$$

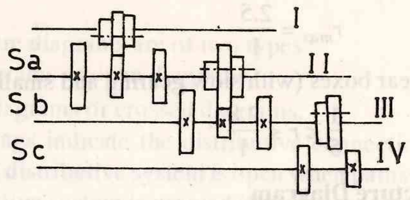


Fig. 8.8

8.10. Range Ratio of Speed Variation in a Drive

Any regularity in the series of spindle speeds is the result of a similar regularity in the series of transmission ratio (r) in the drive. When consecutive gear trains of transmission are engaged the total transmission ratio of the drive is equal to the product of the transmission ratio of the simple trains that make up the drive.

Let r_{max} = Maximum transmission ratio of the drive.

r_{min} = Maximum transmission ratio of the drive.

$r_{a_{max}}$, $r_{b_{max}}$, $r_{c_{max}}$, represent the maximum transmission ratio of the transmission groups S_a, S_b, S_c etc. respectively.

$r_{a_{min}}$, $r_{b_{min}}$, $r_{c_{min}}$ represent the minimum transmission ratio of transmission groups S_a, S_b, S_c respectively.

The $\quad r_{max} = r_{a_{max}}, r_{b_{max}}, r_{c_{max}}$, etc.

$\quad r_{min} = r_{a_{min}}, r_{b_{min}}, r_{c_{min}}$, etc.

$\therefore \quad R_n$ = Range ratio of the drive

$$= \frac{N_{max}}{N_{min}} = \frac{r_{max}}{r_{min}} = R_a \, R_b \, R_c \text{ etc.}$$

where R_a, R_b, R_c are the range ratios of the individual transmission groups.

The limiting maximum range ratio (R_{lim}) in a two shaft group transmission system is

$$R_{lim} = \frac{r_{max,\ lim}}{r_{min,\ lim}} = 8.$$

8.11. Limiting Transmission Ratios

It is a common practice to limit the transmission ratio of gears in a gear box in order to avoid excessively large diameters of the driven gears and a consequent increase in the radial overall dimensions of the drive. The commonly used values of transmission ratio are as follows :

For spur gear $\quad r_{min} = \frac{1}{4}$; $r_{max} = 2/1$

For helical gears $\quad r_{min} = \frac{1}{4}$

$$r_{max} = \frac{2.5}{1}$$

For feed gear boxes (with slow gearing and small diameter gears).

$$\frac{1}{5} \le r \le \frac{2.8}{1}.$$

8.12. Speed Structure Diagram

This diagram is developed from the kinetic arrangement of the drive to represent speeds at output as well as intermediate shafts, of a gear box. In this diagram shafts are shown by vertical equidistant and parallel lines. The speeds are plotted vertical on a logarithmic scale with log ϕ as a unit. Transmission engaged at definite speeds of the driving and driven shafts are shown on the diagram by rays connecting the points on the shaft lines representing these speeds. The transmission ratio is expressed in the form of ϕ_m, when m is the number of intervals between the horizontal lines spanned by the corresponding ray. If the speeds are written from the bottom to the top in the increasing order of magnitude then for transmission ratio, $r > 1$ the ray is inclined upward and for $r < 1$ that is for reduction transmission the ray is inclined downward and for $r =$ the ray is horizontal. Fig. 8.9 shows a ray diagram for driving shaft I and driven shaft II which has maximum speed N_8 and minimum System N_1.

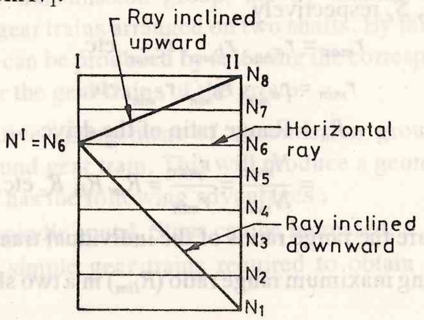


Fig. 8.9

For transmission engaged at $N_I = N_6$ and $N_{II} = N_3$ the ray is inclined upward ($N_I = N_6$ means the speed of shaft I is N_6 and $N_{II} = N_8$ indicates that the speed of shaft II is N_8) N_8 being greater than N_6. In this case the transmission ratio (r) is ϕ^2 as there are two intervals between N_6 and N_8. For transmission engaged at $N_I = N_6$ and $N_{II} = N_6$ the ray is horizontal and in this case $r = \frac{1}{\phi_0}$. For transmission engaged at $N_I = N_6$ and $N_{II} = N_1$ the ray is inclined downwards and the transmission ratio is less than one and is given by $r = \frac{1}{\psi^m} = \frac{1}{\psi^5}$, as there are five intervals between N_1 and N_6.

Speed structure diagrams are of two types :

(*a*) Wide diagrams or open diagrams.

(*b*) Narrow diagrams or crossed diagrams.

These groupings indicate the distributive connection between input and output point. The distributive system is open when paths do not cross each other and the distributive system is crossed if the paths cross each other.

Fig. 8.10 shows the possible open diagrams for a spindle to have six speeds for a three shaft gear box. I is driver shift, II is intermediate shaft and III is driven shaft. Fig. 8.11 shows crossed speed structure diagrams for a spindle having six speeds.

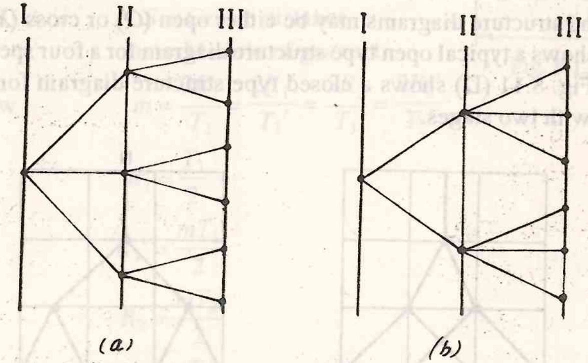


Fig. 8.10

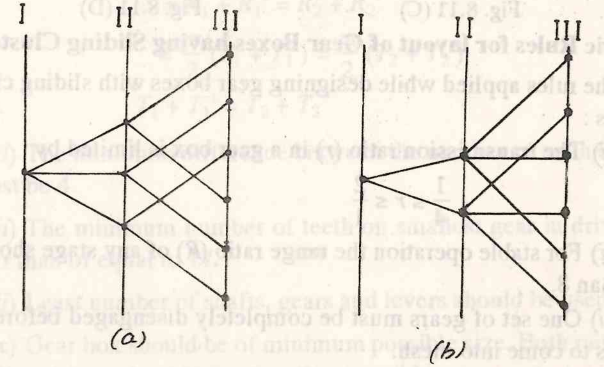


Fig. 8.11

Speed diagrams may also be classified as follows :

(*i*) Unilateral speed diagrams.

(*ii*) Bilateral speed diagrams.

In unilateral speed diagrams the speed changes in one direction only as shown in Fig. 8.11 (A) whereas in bilateral speed diagrams the speed changes take place in both direction as shown in Fig. 8.11 (B).

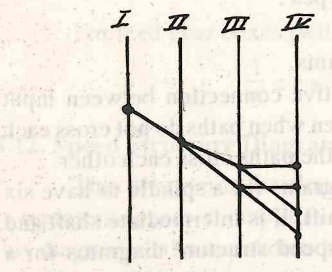


Fig. 8.11 (A)

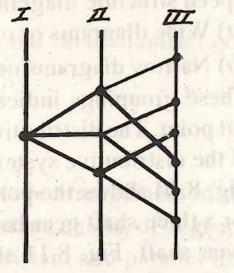


Fig. 8.11 (B)

The structure diagrams may be either open (*O*) or cross (*X*) type. Fig. 8.11 (C) shows a typical open type structure diagram for a four speed gear box whereas Fig. 8.11 (D) shows a closed type structure diagram for four speed gear box with two stages.

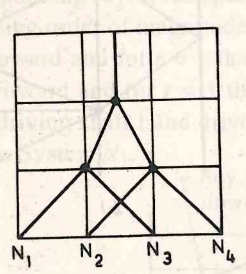


Fig. 8.11 (C)

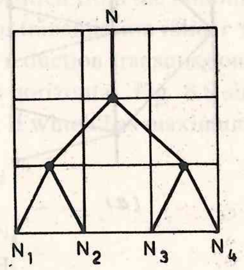


Fig. 8.11 (D)

8.13. Basic Rules for layout of Gear Boxes having Sliding Clusters

The rules applied while designing gear boxes with sliding clusters are as follows :

(*i*) The transmission ratio (*r*) in a gear box is limited by

$$\frac{1}{4} \le r \le \frac{2}{1}$$

(*ii*) For stable operation the range ratio (*R*) of any stage should not be greater than 8.

(*iii*) One set of gears must be completely disengaged before the other set begins to come into mesh.

(*iv*) The axial gap between two adjacent gear must be equal to at least two gear width. Fig. 8.12 shows a 2-step stage. The distance space requirement along the axis is 4*C*, where *C* indicates the width of one gear.

(*v*) The sum of teeth of mating gears in a given stage must be the same for same module in a clustered set.

Consider the two step stage of gears shown in Fig. 8.12.

Let T_1 = Number of teeth on gear 1 (driven)

T_1' = Number of teeth on gear 1′ (driver)

T_2 = Number of teeth on gear 2 (driver)

T_2' = Number of teeth on gear 2′ (driven)

R_1 = Pitch circle radius of gear 1

R_1' = Pitch circle radius of gear 1′

R_2 and R_2' be the pitch circle radius of gear 2 and 2′ respectively.

S = Centre distance

m = Module of gear set.

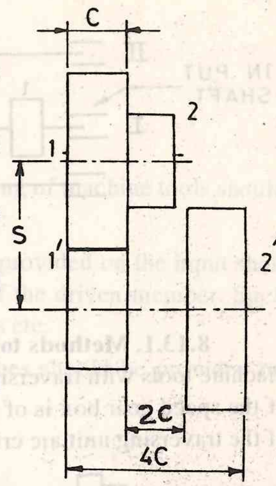


Fig. 8.12

Now $$m = \frac{2R_1}{T_1} = \frac{2R_1'}{T_1'} = \frac{2R_2}{T_1} = \frac{2R_2'}{T_2'}$$

$$R_1 = \frac{T_1}{2}$$

$$R_1' = \frac{mT_1}{2}$$

$$R_2 = \frac{mT_2'}{2}$$

$$R_2' = \frac{mT_2'}{2}$$

$$S = R_1 + R_1' = R_2 + R_2'$$

$$= \frac{m}{2}(T_1 + T_1') = \frac{m}{2}(T_2 + T_2')$$

$$\therefore \quad T_1 + T_1' = T_2 + T_2'$$

(*vi*) The minimum difference between the number of teeth of adjacent gears must be 4.

(*vii*) The minimum number of teeth on smallest gear in drives should be greater than or equal to 17.

(*viii*) Least number of shafts, gears and levers should be used.

(*ix*) Gear box should be of minimum possible size. Both radial as well as axial dimensions should be as small as possible.

Fig. 8.12 (*a*) shows a typical method of reducing radial dimensions of speed gear boxes. In this the axes of shafts I and III have been adjusted along the same straight line.

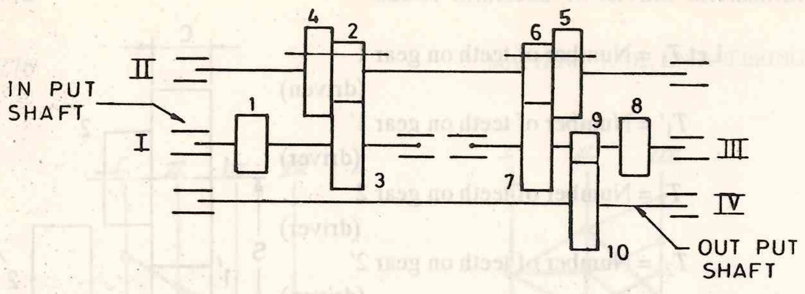


Fig. 8.12 (*a*)

8.13.1. Methods to reduce axial dimensions in speed gear box. In machine tools with traversing spindle head the reduction of axial dimensions of the speed gear box is of great importance because small axial dimensions of the traversing unit are critical from the point of view of stability.

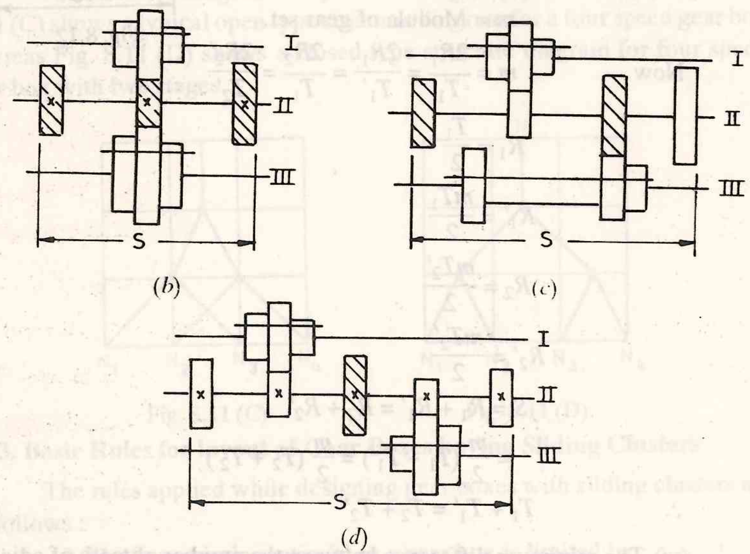


Fig. 8.12

The commonly used methods to reduce axial dimensions of speed boxes are as follows :

(*i*) Using three link gears

(*ii*) Using two link gears

(*iii*) Using one link gear.

Fig. 8.12 (*b*) shows three link gears method

$$S = 7C$$

Fig. 8.12 (*c*) shows use of two link gears

$$S = 10C$$

Fig. 8.12 (*d*) shows one link gear method

$$S = 13C$$

where C = Width of one gear

X = Link gear.

Following features related to the functioning of machine tools should be taken into account while designing gear boxes :

(*i*) A friction clutch and brake should be provided on the input shaft in case of machine tools having a large inertia of the driven member. Such machine tools include vertical turret lathes planers etc.

(*ii*) Reversing devices with friction clutches should be provided on machine tools like

(*a*) turret lathes

(*b*) thread cutting lathes

(*c*) radial drilling machines etc.

so that cutting tool can be brought to its initial position. The reversal speed should be nearly 1.5 times more than the cutting speed.

(*iii*) Gear transmissions which do not slide during speed changing should be made helical in order to provide smooth running of the spindle.

(*iv*) In case the spindle head traverses during the working operation then the electric motor should be mounted on the speed box and the transmission from motor shaft to the input shaft of the speed box should be obtained using a clutch or gear pair.

8.14. Shaft Size Calculation

The shafts in a gear box transmit torque from input gear to output gear. Shaft diameter (d) is calculated as follows :

$$\text{H.P.} = \frac{2\pi NT}{4500}$$

where H.P. = Horse power transmitted

T = Torque in kg-m

N = R.P.M.

$$T = \frac{\pi}{16} \cdot f_s \cdot d^3 \approx 0.2 f_s d^3$$

where f_s = Permissible shear stress (Torsional) in kg/cm^2.

Taking into account bending and to provide sufficient rigidity, the value of f_s is assumed 120 kg/cm^2 for mild steel shaft.

$$T = 0.2 \times 120 \times d^3 = 24\, d^3$$

$$\therefore \quad d = \sqrt[3]{\frac{T}{24}}$$

8.15. To Determine Module for Gears

The module (m) for a gear is calculated as follows :

Let T = Torque transmitted in kg-mm

D = Pitch circle diameter

R = Pitch circle radius

T_1 = Number of teeth

m = Module in mm

F = Tangential force acting at the pitch points transmitted by the gear.

$$F = \frac{T}{R}\ ; m = \frac{D}{T_1}$$

$$D = mT_1$$

$$R = \frac{mT_1}{2}$$

$$F = \frac{T}{R} = \frac{2T}{mT_1}.$$

Also the value of F for tooth strength is given by

$$F = B.m.C \text{ (kg)}$$

where B = Width of gear in mm

C = Material constant

= 2 for Mild steel = 1 for Cast iron.

Now $\frac{B}{m} = Y\ ; B = m.Y$

where Y is constant.

The value of Y varies from 8 to 15 and the commonly used value for machine tools is 10.

$$\therefore \quad F = BmC$$

$$F = mY.mC$$

$$= m^2.Y.C$$

$$m = \sqrt{\frac{F}{YC}}$$

The following modules in mm have been recommended by I.S.I.

1, (1.115), 1.25, (1.375), 1.5, (1.75), 2, 2.25, 2.5, (2.75), 3, [3.25], 3.5, [3.75], 4, 4.5, 5, 5.5, 6, [6.5], (7), 8, (9), 10, (11), (12), (14) 16, (18), 20.

Modules given in round brackets should be given second choice and those given in square brackets should be given third choice.

The rest of the values are preferred modules which should be normally used.

8.16. Kinematic Functions of Machine Tools

Every machine tool is required to perform one or more of the following kinematic functions :

(*i*) To transfer motion from input to output spindle

(*ii*) To transform motion from rotation to translation or reciprocation or *vice-versa*.

8.16.1. To determine number of teeth on gears

The number of teeth of gears depends on transmission ratio. They are determined after plotting the speed chart of gear box.

It is recommended that $T_{\min} \geq 20$ in speed boxes

≥ 16 in feed boxes.

However minimum number of teeth (T_{min}) can be calculated using the following formula.

$$T_{\min} = 2A \times \frac{1 + \sqrt{1 \pm G(2 \pm G)\sin^2\alpha}}{(2 \pm G)\sin^2\alpha}$$

where A = Tooth addendum coefficient

G = Transmission ratio

α = Pressure angle

Table 8.5 (A) indicates minimum number of teeth for different values of G, A and angle α.

Table 8.5 (A)

G	$\alpha = 20°$, $A = 0.8$	$\alpha = 20°$, $A = 1$
1 : 1	10	13
1 : 2	12	15
1 : 3	12	15
1 : 4	13	16
1 : 5	13	16
1 : 10	14	17

Example 8.1. *A machine spindle is to operate on ferrous metals at 30 m/min and is required to have 5 speeds. The spindle can accommodate H.S.S. Cutters ranging from 10 to 60 mm diameters. Determine the following :*

(a) Spindle speeds.

(b) Plot a graph between cutting velocity and cutter diameter for each spindle speed and calculate the range of cutting velocity for : (i) 12 mm dia. cutter (ii) 36 mm diameter cutter.

Solution. Let N_1 = Minimum speed of spindle

N_n = Maximum speed of spindle

V = Cutting speed = 30 m/min.

D_{max} = Max. diameter of cutter in mm

D_{min} = Min. diameter of cutter in mm

$$N_1 = \frac{1000 \times V}{\pi . D_{max}} = \frac{1000 \times 30}{\pi \times 60}$$

$= 159.2$ say 160 R.P.M.

$$N_n = \frac{1000 \times V}{\pi . D_{min}} = \frac{1000 \times 30}{\pi \times 10}$$

$= 955.4$ say 956 R.P.M.

n = Number of spindle speed = 6

ϕ = Common ratio

$$= \sqrt[n-1]{\frac{N_n}{N_1}} = \sqrt[5]{\frac{956}{160}} = 1.43.$$

The various speeds are shown in Table 8.6.

Table 8.6

Speed ratio	N_1	N_2	N_3	N_4	N_5	N_6
Spindle speed	160	229	328	469	671	956
Cutter diameter (V = 30 m/min)	59.71	41.72	29.2	20.38	14.24	9.98

From Fig. 8.13.

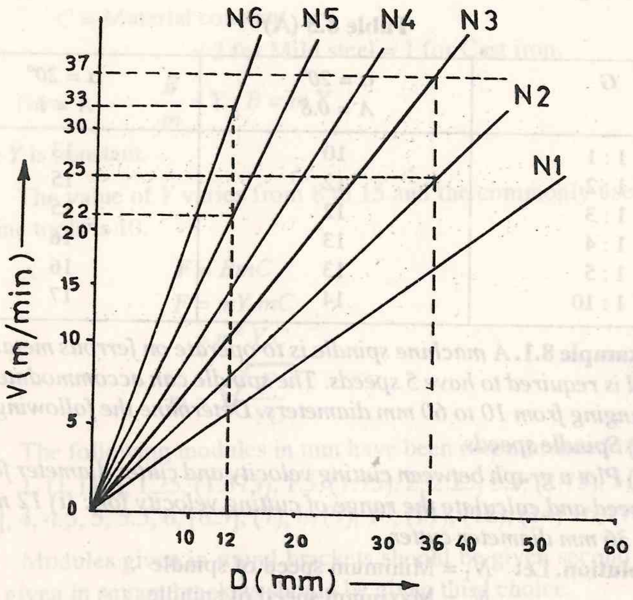


Fig. 8.13

For 12 mm diameter

V_{max} = 33 m/min.

V_{min} = 22 m/min.

Range = 33 – 22 = 11 m/min.

For 36 mm diameter

V_{max} = 37 m/min.

V_{min} = 25 m/min.

Range = 37 – 25 = 12 m/min.

Example 8.2. *A machine tool spindle is to have six speeds and is to run at a maximum speed of 768 R.P.M. and a minimum speed of 24 R.P.M. Calculate the spindle speeds.*

Solution. N_1 = Min. speed = 24 R.P.M.

N_n = Maximum speed

= 768 = R.P.M.

n = Number of spindle speeds = 6

ϕ = Common ratio

$$= \sqrt[n-1]{\frac{N_n}{N_1}} = \sqrt[5]{\frac{867}{24}} = 2$$

∴ Spindle speeds are as follows :

24, 48, 96, 192, 384, 768.

Example 8.3. *A solid steel gear having 24 teeth is to transmit a maximum torque of 17 kg-m. Determine the module and width of gear.*

Solution. F = Tangential force

$$= \frac{T}{m(T_1/2)}$$

where m = Module in mm

T = Torque in k-mm = 1700 kg-mm

T_1 = Number of teeth = 24

$$F = \frac{17{,}000 \times 2}{m \times 24} = \frac{34{,}000}{m \times 24} \quad ...(1)$$

Also $F = m^2.Y.C$

$$m^2Y.C. = \frac{34{,}000}{m \times 24}$$

Now $Y = 10$

$C = 2$ for mild steel

$$F = m^2 \times 10 \times 2 = 20\ m^2 \quad ...(2)$$

From (1) and (2)

$$\frac{34{,}000}{24\ m} = 24\ m^2$$