

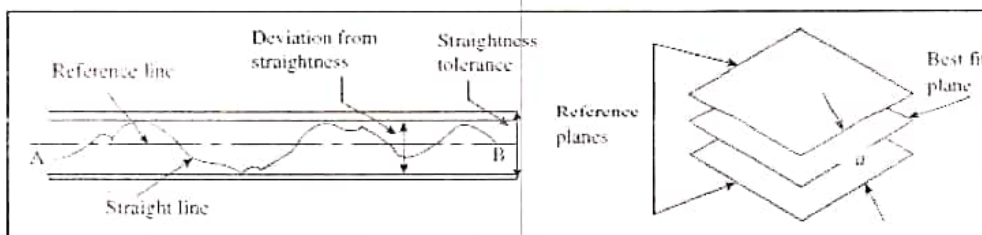
UNIT – VI

FLATNESS MEASUREMENT

Measurement of flatness of surface:

Machine tool tables, which hold work pieces during machining, should have a high degree of flatness. Many metrological devices like the sine bar invariably need a perfectly flat surface plate. Flatness error may be defined as the minimum separation of a pair of parallel planes that will just contain all the points on the surface. Figure 10.7 illustrates the measure of flatness error a . It is possible, by using simple geometrical approaches, to fit a best-fit plane for the macro surface topography.

Flatness is the deviation of the surface from the best-fit plane. According to IS: 2063-1962, a surface is deemed to be flat within a range of measurement when the variation of the perpendicular distance of its points from a geometrical plane (this plane should be exterior to the surface to be tested) parallel to the general trajectory of the plane to be tested remains below a given value.



Straightness of a line

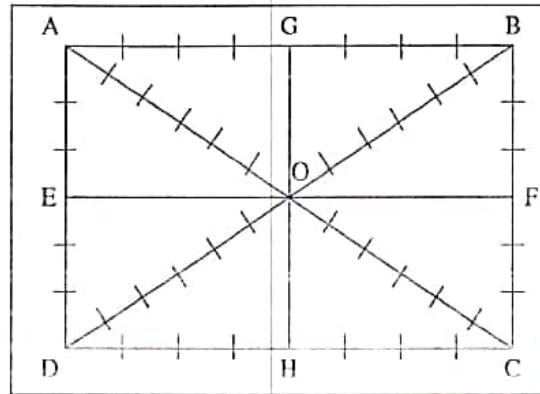
measurement of flatness error

The geometrical plane may be represented either by means of a surface plane or by a family of straight lines obtained by the displacement of a straight edge, a spirit level, or a light beam. While there are quite a few methods for measuring flatness, such as the beam comparator method, interferometry technique, and laser beam measurement, the following paragraphs explain the simplest and most popular method of measuring flatness using a spirit level or a clinometer.

Measurement of flatness error

Assuming that a clinometer is used for measuring angular deviations, a grid of straight lines, as shown in Figure is formulated. Care is taken to ensure that the maximum area of the flat table or surface plate being tested is covered by the grid. Lines AB, DC, AD, and BC are

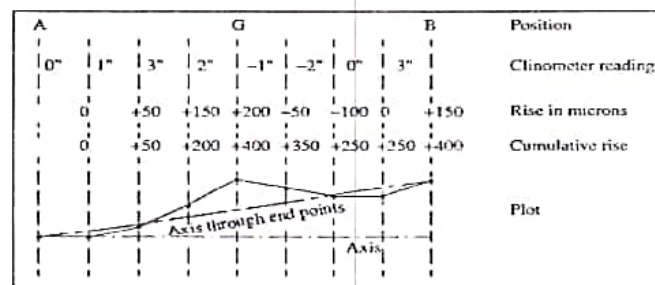
drawn parallel to the edges of the flat surface; the two diagonal lines DB and AC intersect at the centre point O. Markings are made on each line at distances corresponding to the base length of the clinometer.



Grid lines for flatness test

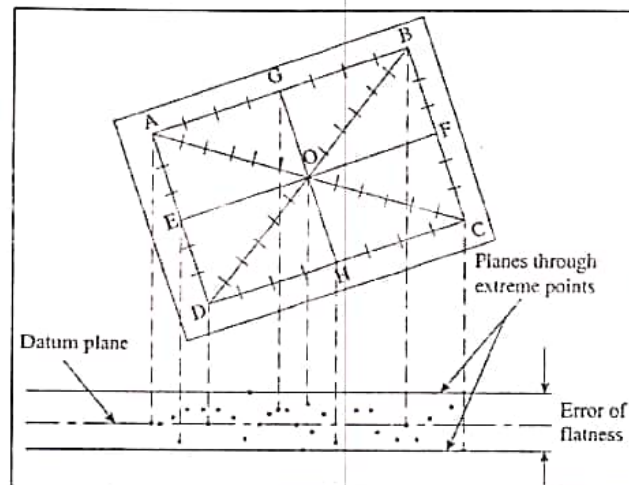
The following is a step-by-step procedure to measure flatness error:

1. Carry out the straightness test on all the lines and tabulate the readings up to the cumulative error column. Figure gives an example of line AB.
2. We know that a plane is defined as a 2D entity passing through a minimum of three points not lying on the same straight line. Accordingly, a plane passing through the points A, B, and D is assumed to be an arbitrary plane, relative to which the heights of all other points are determined. Therefore, the ends of lines AB, AD, and BD are corrected to zero and the heights of points A, B, and D are forced to zero.
3. The height of the centre 'O' is determined relative to the arbitrary plane ABD. Since O is also the mid-point of line AC, all the points on AC can be fixed relative to the arbitrary plane ABD. Assume A = 0 and reassign the value of O on AC to the value of O on BD. This will readjust all the values on AC in relation to the arbitrary plane ABD.
4. Next, point C is fixed relative to the plane ABD; points B and D are set to zero. All intermediate points on BC and DC are also adjusted accordingly.



Straightness plot for line AB

5. The same procedure applies to lines EF and GH. The midpoints of these lines should also coincide with the known midpoint value of O.
6. Now, the heights of all the points, above and below the reference plane ABD, are plotted as shown in Figure. Two lines are drawn parallel to and on either side of the datum plane, such that they enclose the
7. Outer most points. The distance between these two outer lines is the flatness error.



Plot of heights of all points with reference to the datum plane ABD

Some authors argue that the reference plane ABD that is chosen in this case may not be the best datum plane. They recommend further correction to determine the minimum separation between a pair of parallels that just contains all the points on the surface. However, for all practical purposes, this method provides a reliable value of flatness error, up to an accuracy of $10\text{ }\mu\text{m}$.

Instruments used for flatness measurement:

1. Straight edge
2. Surface plate
3. Auto collimator...Etc.

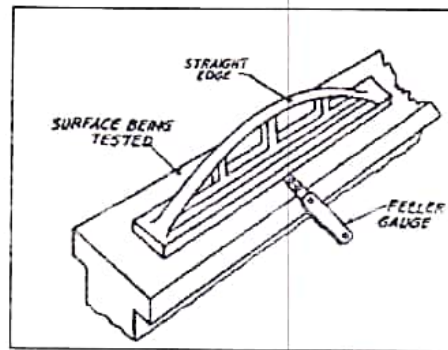
1. Straight edge:

A **straightedge** is a tool with an edge free from curves, or straight, used for transcribing straight lines, or checking the straightness of lines. If it has equally spaced markings along its length, it is usually called a ruler.

Straightedges are used in the automotive service and machining industry to check the flatness of machined mating surfaces.

True straightness can in some cases be checked by using a laser line level as an optical straightedge: it can illuminate an accurately straight line on a flat surface such as the edge of a plank or shelf.

A pair of straightedges called winding sticks are used in woodworking to amplify twist (wind) in pieces of wood.



Straight edge

An idealized straightedge is used in compass-and-straightedge constructions in plane geometry. It may be used:

- Given two points, to draw the line connecting them.
- Given a point and a circle, to draw either tangent.
- Given two circles, to draw any of their common tangents.

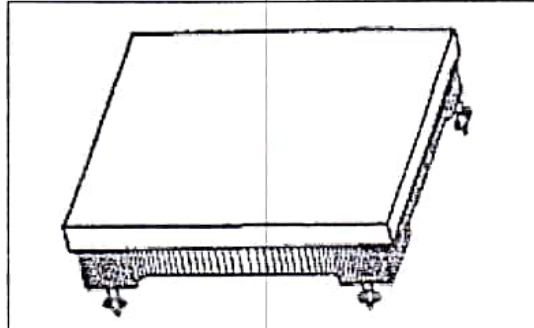
It may not be marked or used together with the compass so as to transfer the length of one segment to another.

It is possible to do all compass and straightedge constructions without the straightedge. That is, it is possible, using only a compass, to find the intersection of two lines given two points on each, and to find the tangent points to circles. It is not, however, possible to do all constructions using only a straightedge. It is possible to do them with straightedge alone given one circle and its center.

2. Surface plate:

A **surface plate** is a solid, flat plate used as the main horizontal reference plane for precision inspection, marking out (layout), and tooling setup. The surface plate is often used as the baseline for all measurements to the work piece, therefore one primary surface is finished extremely flat with accuracy up to 0.00001 in or 250 nm for a grade AA or AAA plate. Surface plates are a very common tool in the manufacturing industry and are often permanently

attached to robotic type inspection devices such as a coordinate-measuring machine. Plates are typically square or rectangular. One current British Standard includes specifications for plates from 160 mm x 100 mm to 2500 mm x 1600 mm.



Surface plate

3. Autocollimator

It is a special form of telescope that is used to measure small angles with a high degree of resolution. It is used for various applications such as precision alignment, verification of angle standards, and detection of angular movement, among others. It projects a beam of collimated light onto a reflector, which is deflected by a small angle about the vertical plane. The light reflected is magnified and focused on to an eyepiece or a photo detector. The deflection between the beam and the reflected beam is a measure of the angular tilt of the reflector. Figure illustrates the working principle of an autocollimator.

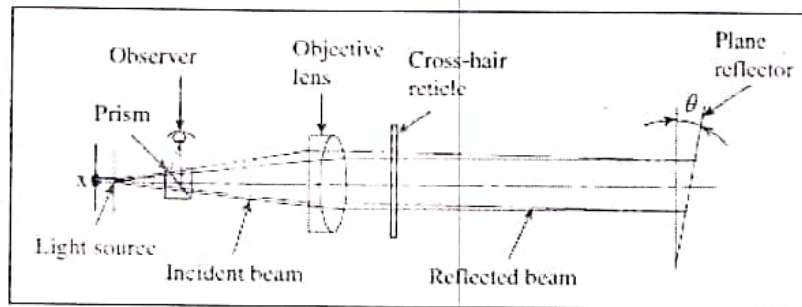
The reticle is an illuminated target with a cross-hair pattern, which is positioned in the focal plane of an objective lens. A plane mirror perpendicular to the optical axis serves the purpose of reflecting an image of the pattern back on to the observation point. A viewing system is required to observe the relative position of the image of the cross-wires. This is done in most of the autocollimators by means of a simple eyepiece. If rotation of the plane reflector by an angle q results in the displacement of the image by an amount d , then, $d = 2fq$, where f is the focal length of the objective lens.

It is clear from this relationship that the sensitivity of an autocollimator depends on the focal length of the objective lens. The longer the focal length, the larger the linear displacement for a given tilt of the plane reflector. However, the maximum reflector tilt that can be accommodated is consequently reduced. Therefore, there is a trade-off between sensitivity and measuring range. The instrument is so sensitive that air currents between the optical path and the target mirror can cause fluctuations in the readings obtained. This effect is more severe when the distance between the two increases. Therefore, an autocollimator is housed inside a

sheet-metal or a PVC plastic casing to ensure that air currents do not hamper measurement accuracy.

Autocollimators may be classified into three types:

1. Visual or conventional autocollimator
2. Digital autocollimator
3. Laser autocollimator



Principle of autocollimator

Visual Autocollimator

In this type of autocollimator, the displacement of the reflected image is determined visually. A pinhole light source is used, whose reflected image is observed by the operator through an eyepiece. Visual collimators are typically focused at infinity, making them useful for both short and long-distance measurements. The plane reflector is one of the vital parts of an autocollimator, because a mirror that is not flat will defocus the return image, resulting in poor definition of the image. High-quality mirrors with a flatness tolerance of $1\text{ }\mu\text{m}$ per 100 mm are used. Most visual collimators have a resolution of 3–5" over a distance of 1.5 m.

The following are some of the typical applications of visual autocollimators:

1. Determination of angular measurements up to 3"
2. Determination of straightness of machine guide ways
3. Determination of parallelism of slide movements with respect to guide ways
4. Flatness estimation of machine tables, surface plates, etc.
5. Verification of right angle prisms for angular errors
6. Angle comparisons of reflecting surfaces

Digital Autocollimator

A digital autocollimator uses an electronic photo detector to detect the reflected light beam. A major advantage of this type of collimator is that it uses digital signal processing technology to detect and process the reflected beam. This enables the filtering out of stray scattered light,

which sharpens the quality of the image. The illuminated target reticle slit is imaged back in its own plane through the objective lens and reflecting mirror. It is then re-imaged onto a vibrating slit by means of a relay lens. A photocell positioned behind the vibrating slit generates an output, which captures both the magnitude and the direction of rotation of the mirror from a central null position. These instruments have a resolution of up to 0.01 arc-second and a linearity of 0.1%. Since the output is digital in nature, it can be transferred to a data acquisition system, thereby facilitating storage and further processing of data. Another major advantage is that it can also measure angles of dynamic systems to a high degree of resolution, thanks to high sampling rates of digital electronic systems.

The following are some of the applications of a digital autocollimator:

1. Angular measurement of static as well as dynamic systems
2. Alignment and monitoring of robotic axes
3. Verification of angular errors of rotary tables, indexing heads, and platforms of machine parts
4. Remote monitoring of alignment of large mechanical systems

Laser Autocollimator

Laser autocollimators represent the future of precision angle measurement in the industry. Superior intensity of the laser beam makes it ideal for the measurement of angles of very small Objects (1 mm in diameter) as well as for long measuring ranges that extend to 15 m or more. Another marked advantage is that a laser autocollimator can be used for the measurement of Non-mirror-quality surfaces. In addition, the high intensity of the laser beam creates ultra-low noise measurements, thereby increasing the accuracy of measurement. TL40 and TL160 lasers are popular in autocollimators.

MACHINE TOOL ALIGNMENT TESTS

The basic objective of conducting acceptance tests is to ensure that all relative movements of the machine tool conform well within the accepted limits of deviations from designed values. This is important since the dimensions of the work part depend, to a large extent, on the accuracy of the mating parts of the machine tool. The phrase *acceptance test* is coined to signify the fact that the machine buyer will inspect the alignment of various parts of the machine tool in detail and will 'accept' the machine tool from the vendor's factory only after it conforms to accepted norms.

We can broadly classify the various tests under the following groups:

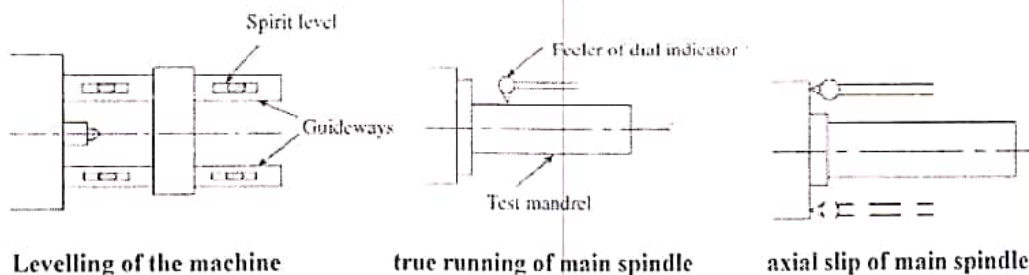
1. Tests for ensuring levelling of the machine tool in both horizontal and vertical planes
2. Tests for flatness of machine bed and straightness as well as parallelism of bed ways and bearing surfaces
3. Tests for Perpendicularity of guide ways with respect to other guide ways or bearing surfaces
4. Tests for true running of the machine spindle and its axial movements
5. Tests for assessing parallelism of spindle axis to guide ways or bearing surfaces
6. Tests for line of movements for slides, cross-slides, and carriages
7. Practical tests for assessing dimensional and geometric accuracy in machining

The following are the important tests carried out on a lathe:

Levelling of machine First and foremost, the machine should be checked for accuracy of levelling. The machine should be installed such that the lathe bed is truly horizontal. A sensitive spirit level or a clinometer can be used to verify the levelling of the machine. The spirit level is moved over the designated distance specified in the test chart, and the deviation is noted down. The test is carried out in both longitudinal and transverse directions.

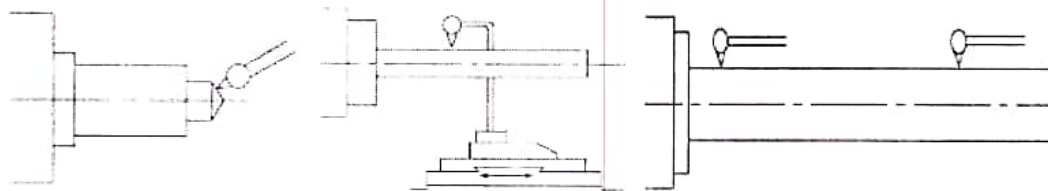
True running of main spindle The main spindle, while running, should not have any play or radial deviations from its axis. This is tested using a test mandrel of acceptable quality. The mandrel is fitted to the spindle bore and the dial indicator feeler is made to contact the mandrel surface as shown in Figure. The spindle is gently rotated by hand, and the deviations of the dial indicator are noted down. The dial indicator base is mounted on the carriage. The deviation should be within acceptable limits.

Axial slip of main spindle The spindle should have true running in a direction parallel to its axis. This is easily checked by placing the dial indicator feeler against the spindle face and giving slight rotation to the spindle. The deviations should be within acceptable limits. The test is repeated at a diametrically opposite location to ensure that the spindle does not have an axial slip.



True running of headstock centre The headstock centre is the live centre of the machine; if it is not true, accuracy of the work piece will suffer. The work piece will develop eccentricity if the error is too much. The feeler of the dial indicator is pressed perpendicular to the taper surface of the centre, and the spindle is rotated. The deviation indicates the trueness of the headstock centre. The test procedure is illustrated in Figure.

Parallelism of main spindle Parallelism of the spindle is crucial for generating accurate dimensions. Any error in parallelism will result in a tapered surface after machining. In order to test parallelism, a test mandrel is made use of. It is fitted into the spindle bore and dial gauge readings are taken over a specified length, as shown in Figure. Two readings are taken, one in a horizontal plane and the other in a vertical plane, on one of the sides of the mandrel. It is important to see that excess overhang of the mandrel does not result in a sag due to its own weight.



True running of head stock center

parallelism of main spindle

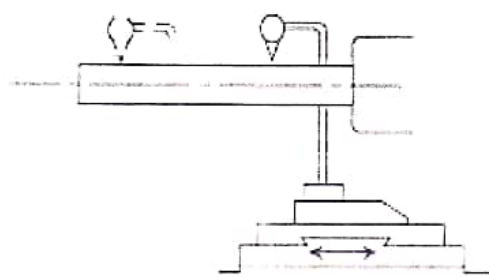
true running of spindle taper bore

True running of taper bore of main spindle The lathe spindle bore has a standard taper. Unless this taper is concentric with the spindle axis, work pieces will have undesired taper or eccentricity. A test mandrel is fitted to the tapered bore of the spindle, and dial gauge readings are taken at the two extreme ends of the mandrel. This value should be well within the allowable limits.

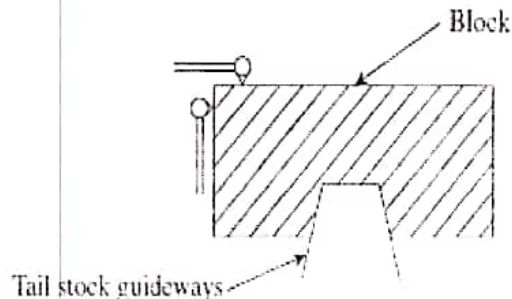
Parallelism of tailstock sleeve to carriage movement A tailstock is generally used to hold long work pieces. The dead centre of the tailstock is mounted on the end of the sleeve, which moves in an axial direction. The sleeve surface should be perfectly parallel to the movement of the carriage. A mandrel is put in the sleeve socket and dialling is done by mounting the dial gauge base on the tool post, as shown in Figure. The test should be carried out in both the horizontal and vertical planes.

Parallelism of tailstock guide ways to carriage movement The tailstock guide ways should be parallel to the movement of the carriage. Whenever long jobs are being turned, it becomes necessary to shift the tailstock along its guide ways. While doing so, the job axis should

perfectly coincide with the tailstock centre. If this condition is not satisfied, the work piece will develop an undesirable taper. A test block, specially designed for the purpose, is placed on the guide ways, as shown in Figure. The dial indicator base is mounted on the carriage and the feeler is made to contact the work piece. The carriage is moved for the specified distance and the deviation is noted down. The test is carried out in both the horizontal and vertical planes.



Parallelism of a tail stock sleeve



Parallelism of a tail stock guide ways

Practical tests Actual machining is carried out in order to ascertain not only the accuracy of alignment but also the rigidity of the machine tool. At least three turning operations are mandatory, namely chucking (using the chuck only), turning between centres, and facing. The operations are performed with prescribed values of cutting speed, feed rate, and depth of cut. Table illustrates the recommended ways of conducting practical tests on lathes.

Operation	Workpiece diameter (mm)	Permissible error (mm)
Chuckling	50-100	0.01
Turning between centres	100-200	0.02
Facing	100-200	0.02

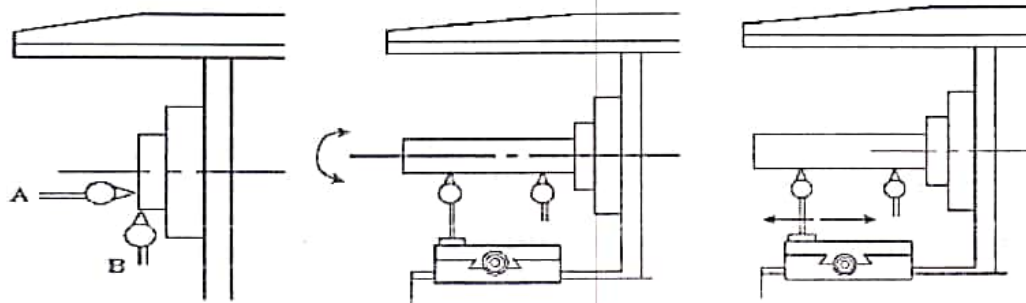
Recommended practical tests

Acceptance Tests for Milling Machines

It is presumed that the student is aware of the various types of milling machines. However, we will deal with some of the important tests conducted on a horizontal milling machine in order to provide the student with a fair knowledge of the methodology.

Axial slip of spindle A spindle may have an axial slip, which is the axial movement of the spindle during its rotation. Axial slip may occur due to the following reasons: errors due to worn-out spindle bearings, face of the locating shoulder of the spindle not being in a plane perpendicular to the axis of the spindle, and irregularities in the front face of the spindle. Figure 10.25 illustrates the test for measuring the axial slip of the spindle. The feeler of the dial gauge is held against the front face of the spindle and the base is mounted on the table. The position

of the dial gauge (in order to measure axial slip) is denoted by A in the figure. The spindle is gently rotated by hand and the dial gauge reading is noted down. The test is repeated at a diametrically opposite spot. The maximum deflection should be well within the prescribed limits.



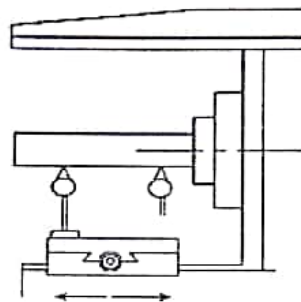
Measuring axial slip of spindle true running of spindle taper parallelism of work table to spindle axis

Eccentricity of external diameter of spindle Position B of the dial gauge shown in Figure is used to determine the eccentricity of the external diameter of the spindle. The feeler is made to contact the spindle face radially, and the dial gauge base is mounted on the machine table. The spindle is gently rotated by hand and the dial gauge deviation is noted down. The maximum deviation gives the eccentricity of the external diameter of the spindle, and it should be well within specified limits.

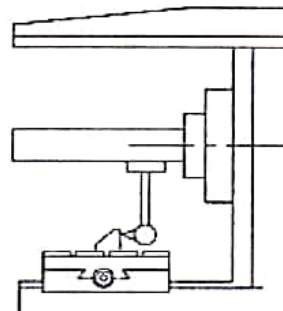
True running of inner taper of spindle The spindle of a milling machine is provided with a standard taper, which matches with the tooling used on the machine. The axis of the taper should be perfectly coincident with the axis of the spindle. Otherwise, the work pieces will develop undesired taper or eccentricity after machining. This condition is checked by using a test mandrel that fits into the spindle taper. The dial gauge is mounted on the machine table, and the feeler is made to contact the mandrel at one end of the mandrel, as shown in Figure. The maximum deviation of the dial gauge is noted by gently rotating the spindle by hand. The test is repeated at the other end of the mandrel.

Parallelism of work table surface to spindle axis Work pieces are clamped on the top surface of the work table of the machine. We should ensure that the work table surface is parallel to the spindle axis; otherwise, milled surfaces will not meet quality requirements. A test mandrel is fitted to the spindle. If the machine has an arbour, the arbour surface is checked for parallelism. The feeler of the dial gauge is made to contact the mandrel or arbour, as the case may be, and the base of the dial gauge is kept on the table surface. Now the dial gauge base is moved on the table surface in a direction parallel to the spindle axis till the extreme end, as

shown in Figure. The dial gauge deflection is noted down, which should be well within the permissible limits.



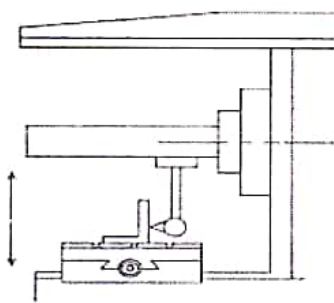
Parallelism of table movement with spindle axis



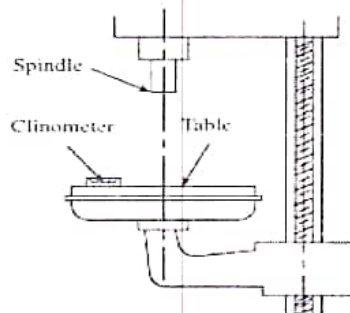
parallelism of T-slots with table movement

Parallelism of transverse movement of table to spindle axis The machine table is set in its mean position and the dial gauge base is mounted on the table. The feeler is made to contact the mandrel and the table is given motion in the transverse direction. The test is carried out both in the horizontal and vertical planes of the mandrel. The deviation on the dial indicator should be within permissible limits.

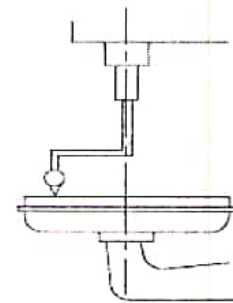
Parallelism of T-slots to table movement A number of T-slots are provided on the machine table to enable accurate clamping of work holding devices, which in turn hold the work pieces. The vertical surfaces of the T-slots should be perfectly parallel to the longitudinal axis of the machine in the horizontal plane. Generally, the test is carried out for the central T-slot, and an accessory, namely a Tenon, is used. A Tenon is a 150 mm long simple bracket, which fits into the T-slot. While sitting in a T-slot, a butting surface projects out, which is parallel to the vertical surface of a T-slot. The dial gauge base is mounted on the spindle and the feeler is made to contact the Tenon, as shown in Figure. Now, the machine table is moved longitudinally while the tennon block is held stationary. Deviations from parallelism are noted from the dial gauge.



Squareness of T-slots with the spindle



flatness o table



Squareness of table with the Spindle axis

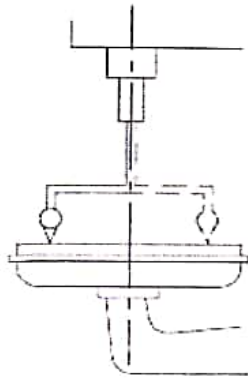
Squareness of T-slots with machine spindle Unless the T-slots are parallel to the spindle axis, slots or key ways cut on the work piece will not be aligned in the required direction. As in the previous case, this test is also generally carried out for the central T-slot. The table is approximately set in a mid-position, and a Tenon block is inserted in the T-slot. The dial gauge base is fixed to the mandrel and the feeler is brought in contact with the vertical surface of the Tenon. Now, the Tenon is moved towards one of the ends and the dial gauge swung to establish contact with the Tenon. The reading on the dial gauge is noted. The Tenon block is moved towards the other end and the dial gauge swung the other way in order to establish contact again. The difference in reading, which is a measure of the squareness error, is noted down. The preceding paragraphs provided some insight into the important acceptance tests carried out on a horizontal milling machine. It is recommended that 25–30 different tests be carried out on a milling machine before it can be accepted for production work. Only a few tests are highlighted here. The student is advised to visit the metrology laboratory in the institute and go through the detailed acceptance charts provided by the machine suppliers. Subsequent to the aforementioned tests, it is recommended to carry out practical tests by milling test pieces. One has to check for accuracy in surface milling, end milling, and slot milling before certifying the machine to be fit for use on a production shop floor.

Acceptance Tests for Drilling Machines

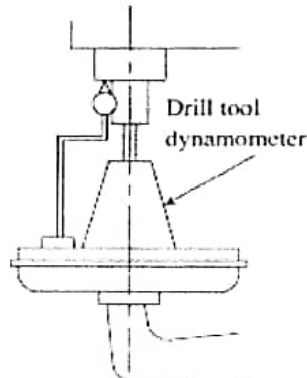
There are various types of drilling machines such as sensitive drilling machine, pillar-type drilling machine, and radial drilling machine. This section deals with the acceptance tests recommended for a pillar-type drilling machine.

Flatness of clamping surface of table This test is performed for the table of the milling machine. The table surface provides support to either clamp the work piece directly or to clamp a fixture that holds the work piece. The test is performed using a sensitive spirit level or a clinometer with good resolution. **Squareness of clamping surface of table with spindle axis** It is important to ensure that the clamping surface of the machine table is perfectly square with the axis of the spindle. Unless this condition is satisfied, the drilled hole will not be parallel to the spindle axis. The arrangement for the test is shown in Figure. The dial gauge base is mounted on the spindle, and the feeler is made to touch the machine table and set to zero. Now, the table is rotated slowly by 180° , without disturbing the dial gauge base, which is in the spindle. The change in reading is noted down; it is then checked to see if it is within the permissible limits.

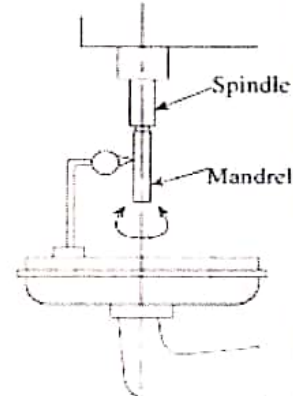
Squareness of spindle axis with table This is the corollary to the aforementioned test. Even though the mounting arrangement for the dial gauge is is the same, the spindle rather than the table is moved by 180°, in order to determine the error in squareness



Squareness of the spindle axis with the table

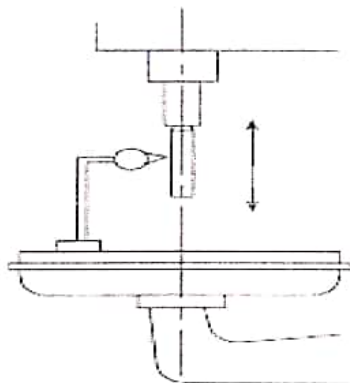


deflection of a spindle

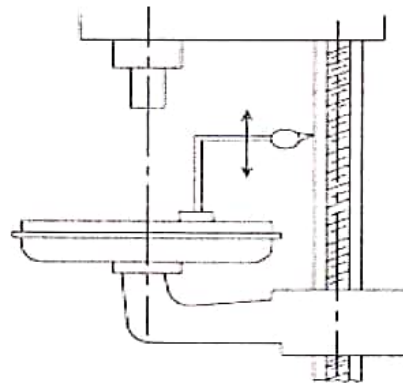


true running of a spindle taper

Total deflection of spindle During the drilling operation, the spindle experiences high axial force. The spindle should not deflect excessively due to this force. Otherwise, the drilled hole will have error of straightness and eccentricity. In order to evaluate deflection of the spindle, a drill tool dynamometer (DTD) is used. The DTD provides a means of applying a known amount of load on the spindle. The drill spindle is loaded by moving the drill head downwards and recording the value of force on the DTD display screen. The base of the dial indicator is placed on the machine table. The feeler is held against the spindle face. The recommended pressure is applied on the spindle and the dial gauge deflection is noted down.



Parallelism of a spindle axis with its vertical movement



Squareness of guide ways with table

True running of spindle taper The true running of a spindle taper is tested using a test mandrel. The test mandrel is loaded in the spindle and the dial gauge base is fixed on the machine table. The feeler is made to contact the mandrel surface and the spindle is gently rotated by hand. The dial indicator reading is noted down and it is ascertained if the reading is within permissible limits. The test is repeated at three different locations to ensure its validity.

Parallelism of spindle axis to its vertical movement While drilling holes, the spindle is given feed in the vertical direction, and therefore, it is necessary to ensure that the vertical movement of the spindle is parallel to its axis. The test setup is illustrated in Fig. 10.36. The mandrel is fixed in the spindle, and the dial gauge is mounted with the feeler making contact with the mandrel at the bottom. The spindle is moved vertically by hand feed and the dial gauge reading is noted down. The test is repeated in another plane by rotating the spindle through 90° . The total deflection shown by the dial gauge should be well within the allowable limits.

Squareness of drill head guide ways with table The drill head in a pillar-type machine moves up and down in order to accommodate various work piece sizes. This up and down movement is facilitated by guide ways. Therefore, it is important to ensure that this motion of the drill head is perfectly square with the clamping surface of the work table. If this condition is not met, the drilled holes will be skewed from the vertical axis and the work piece will fail to pass inspection.