LECTURE NOTES

ON

PRECISION ENGINEERING

B.TECH V SEMESTER
(IARE – R16)

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UNIT-1

ACCURACY AND ALIGNMENT TESTS

The performance of a measuring instrument is represented by the terms precision and accuracy. A good instrument must be precise and accurate.

Precision

Precision of an instrument is the extent to which the instrument repeats its result while making repeat measurement on the same unit of product. It is the repeatability of the measuring process. It refers to the repeat measurement for the same unit of product under identical condition. It indicates to what extent the identically performed measurement agree with each other. If the instrument is not precise it will give widely varying results for the same dimension when measured again and again. The set of observations will scatter about the mean. The scatter of these measurement is designated as (= the standard deviation) it is used as an index of precision. The less the scattering the more precise is the measurement. Thus lower the value of the more precise is the measurement.

Accuracy

Accuracy of an instrument is the extent to which the average of a long series of repeat measurement made on the same unit of product differs from the true value of the product. The difference between the true value and the measured value is known as error of measurement. It is practically difficult to measure exactly the true value. Therefore a set of observation is made whose mean value is taken as the true value of the quality measured, The distinction between precision and accuracy is represented with the help of following figures.

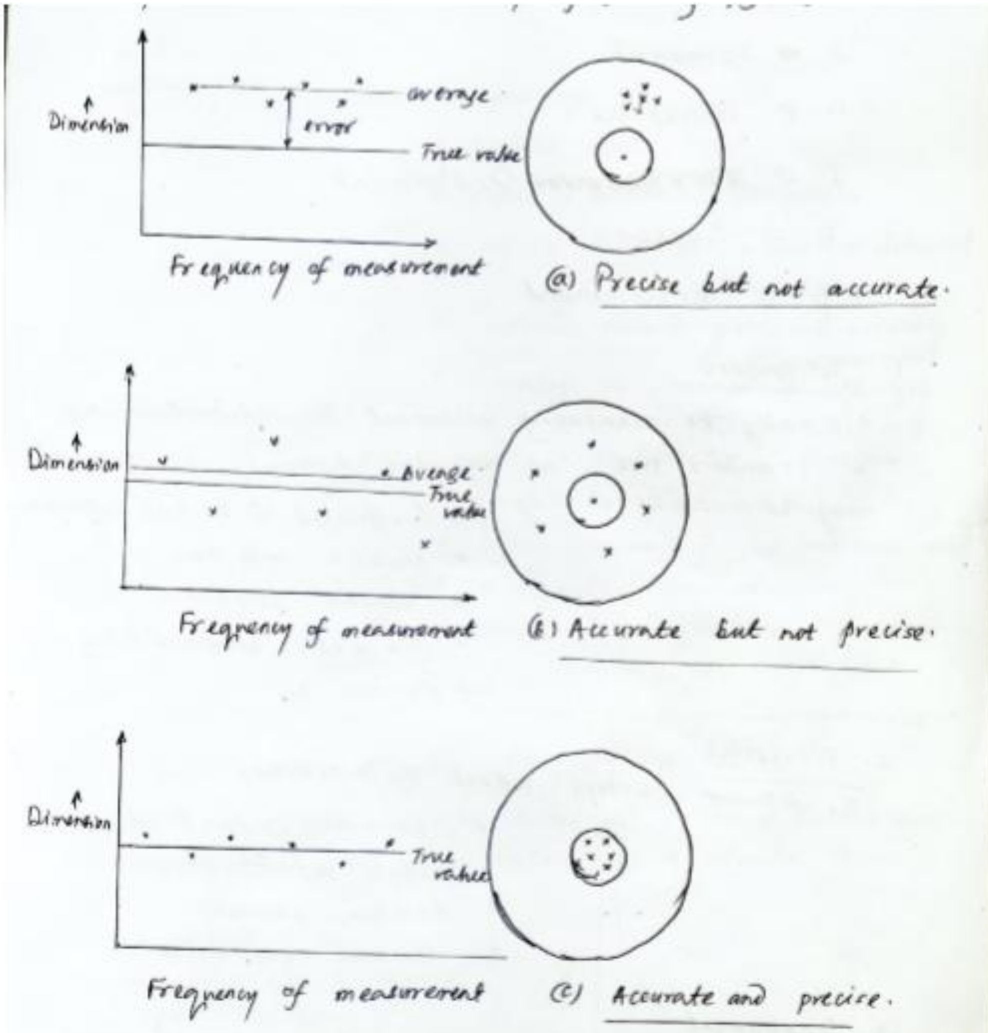


Fig 1.10: Precision and Accuracy

FACTORS AFFECTING ACCURACY OF A MEASURING SYSTEM:

The accuracy of an instrument depends on 5 basic elements (SWIPE) S- Standard W- Workpiece I- Instrument P= Person E- Environment

1. Standard Normally: The measuring instrument is calibrated with a standard are at regular interval. The standard may be affected by

1. Coefficient of thermal expansion
2. Stability with time
3. Elastic properties
4. Geometric compatibility
5. Position etc

2. Work piece: The following factors affect the accuracy

1. Cleanliness surface finish etc.
2. Surface defects
3. Hidden geometry
4. Thermal equalization etc

3. Instrument:The inherent characteristics of the instrument which affect the accuracy are

1. Inadequate amplification
2. Scale error
3. Effect of friction backlash hysteresis etc
4. Deformation while handling heavy w/p
5. Calibration error
6. Repeatability & readability
7. Person The factors responsible for accuracy are
8. Training skill
9. Sense of precision appreciation
10. Ability to select measuring instrument & standard
11. Attitude towards personal accuracy achievement
12. Planning for measurement technique to have minimum just with consistent in precision.

5. Environment: The environmental factor is:

1. Temperature press humidity
2. Clean surrounding and minimum vibration
3. Adequate illumination
4. Temperature equalization between standard w/p & instrument.

Higher accuracy can be achieved if all 5 factors are considered & steps are taken to eliminate them. The design of a measuring system involves proper analysis of cost accuracy consideration the general characteristics of cost of accuracy

C.Method of estimating accuracy &precision:

The mean value and the standard deviation of a set of measurement on a single product represent the repeatability or precision of the measuring process.

Standard deviation:

The actual value is only one however the measured value may varies from one measurement to another due to various sources of errors. Method of estimating the accuracy and precision can be explained by the following. The plan meter experiment is an excellent demonstration for estimating accuracy and precision. Suppose that there is a standard are and unknown area U which are alternately traced. From each such pair of tracings an individual measurement of the unknown area can be obtained. Of course the procedure may be altered such as S-U-U-S-S-U-U-S etc.

It is highly unlikely that the results from all such pairs will be agreement if they are it is because not enough care has been taken in estimating the fraction of divisions in reading the dials of the plan meter. It this is the case the ultimate in the measuring process has not being achieved. Assuming that the results are in disagreement the mean or average may be calculated. Also the standard deviation. This yields information about the repeatability or precision of the measuring process. Now in doing this the question arises. Have the uncertainties in the measurement procedure been fully explored? It the outlines of the unknown and the standard were always traced in a clockwise direction would the same results have been obtained by tracing them in a counter clock wise direction.

Let us try this. It is likely that the results from the two procedures clockwise and counter clock wise will be different but are they significantly different? There are statistical tests which help to decide this question if the axiom of a likeness between the standard and the unknown has been adhered to perhaps it could not be achieved completely. As a check the shapes of the areas can be varied. If the unknown area is roughly rectangular in shape the standard area can be made triangular. Are the measurement now the same or significantly different as determined by practical test. This will show how closely the principle of a likeness must be adhered to in order to achieve the accuracy desired in measuring the unknown area in terms of constructed standards. If it is desired to achieve an area measurement accurate to one percent in terms of standard. A procedure must be selected which yields a standard deviation for a series of measurement.

Somewhat smaller than this for minor variation in the conditions such as clockwise counter clockwise direction and sizes and shapes of the standard as compared with unknown. If large variations in these conditions do not yield appreciably different standard deviations or mean value from one series of measurement to another considerable confidence may be had in the trust worthiness of the procedure but if they do a careful study of the procedure but if they do a careful study of the procedure is necessary to reveal systematic errors. It should be noted here that is the index of precision. A measurement process with a standard deviation of is said to be more precise than another with a standard deviation of it is smaller than .

Standard and their evaluation In order to make informality in the measurement through outthe would a standard is followed. Definition of standard A standard is something that is setup and established by authority as a rule for measurement of quality and value etc. Throughout the world generally 2 standards are followed for linear measurement is (i) British/English (yard) (ii) Metric (metrs) followed by most of the countries due to convenience .

Introduction Machine Tools are used to remove material from components and produce the required shape and dimensional size with required surface finish at optimum cost. There are different methods in metal removing processes. In this paper the metal removal by Boring Process is studied and analyzed on typical Horizontal Machining Centers (HMC). The quality of the bored component is seen in terms of Circularity, Cylindricity and Surface Finish. These parameters largely depend on the spindle rotational accuracy of the machine tool spindle. To understand the concept of rotational accuracy of spindle, the authors studied and conducted experiments on run out and error motion of the spindle and tried to establish the relationship between rotational accuracies of spindle and bore accuracies on the components.

Spindle Rotational Accuracy

In Horizontal Machining Centers, HMCs, like in most of other types of machine tools, assembled main spindles units are routinely inspected for its rotational accuracy. It is understood this is an important factor and efforts are accordingly made to achieve finer run out accuracies through maintaining highest precision on the individual spindle shaft dimensions and geometry, in the selection and fitment of super precision bearings and related spacers, pre loading nuts and other related parts and following careful assembling and testing procedures.

Run out (TIR) Measurement of spindle

Run out is the classical method of measuring spindle rotational accuracy. Runout is also called Total Indicator Reading (TIR). The run out of machine tool spindle is measured by using precisely cylindrical mandrel. The mandrel is clamped in machine tool spindle taper bore and the spindle is slowly rotated by hand. The run out measurements on mandrel surface are recorded using precise dial gauges placed on machine table. As per Murthy [1], this classical method of measuring spindle rotation error reads pure eccentricity of a reference surface of the spindle while such an eccentricity has really no influence on the error of the work piece. Mere Run out or TIR as representing Spindle Rotation error is hence defective and inadequate to provide information on the component bore accuracies expected for certain measured levels of classical Run Out figures. However, in the machine tool industry, generally, the spindle is checked routinely only for its TIR values in the classical method.

Error Motion

Alternately we can subject the spindle to Error Motion Analysis. As opposed to Run out or TIR value, the Error motion is unintended relative displacement in the sensitive direction between the tool and the work piece. Error motions are specified as location and direction as shown in Fig. (1) and do not include motions due to axis shifts associated with changes in temperature, load or rotational speed. In ideal condition, the Rotation of spindle axis of centerline would remain stationary or in other words not shift theoretically. But, in practical working situations, the spindle rotational axis of centerline keeps on changing as instantaneous center of rotational axis changes. Hence, three Error Motions exist. They are pure radial error, pure axial error and tilt error. Error motion definitions are referred from ISO 230-7[2].

Pure Radial error motion. It is defined as motion in which the axis of rotation remains parallel to the axis average line and moves perpendicular to it in the sensitive direction. The sensitive direction is direction perpendicular to the perfect work piece surface through the instantaneous point of machining or measurement.

Axial error motion Axial error motion is error motion coaxial with the axis average line. This error motion may be measured as the motions, in the axial direction along the axis average line, of the surface of a perfect flat disk or spherical test artifact with its centerline coincident with the axis of rotation.

Tilt error motion

Tilt error motion is the error motion in an angular direction relative to the axis average line. This motion may be evaluated by simultaneous measurements of the radial error motion in two radial planes separated by a distance along the axis average line.

Error Motion versus Runout

Measurement of error motion is different from runout measurement and it is very important to understand the differences. Jemielniak and Chrzanowski [3] explained in their paper that it is important to measure the change of the axis rotation position during rotation at high speeds, because the runout test is conducted at low rotational speed. Spindle running contain both roundness error of spindle and centering error of axis of rotation. Radial Run out (as in the classical method) will be identical to radial error motion only if both of Roundness Error and Centering Error are removed, Jinho Kim et al [4], David J Whitehouse .To understand these mechanical phenomena, the authors conducted the experiments.

Instructional objectives :

1. At the end of this lesson, the students will be able to
2. State how the cutting tools fail
3. Illustrate the mechanisms and pattern of tool wear
4. Ascertain the essential properties of cutting tool materials
5. Define and assess tool life (v) Develop and use tool life equation.

(i) Failure of cutting tools:

Smooth, safe and economic machining necessitate • prevention of premature and catastrophic failure of the cutting tools • reduction of rate of wear of tool to prolong its life To accomplish the aforesaid objectives one should first know why and how the cutting tools fail. Cutting tools generally fail by : i) Mechanical breakage due to excessive forces and shocks. Such kind of tool failure is random and catastrophic in nature and hence are extremely detrimental. ii) Quick dulling by plastic deformation due to intensive stresses and temperature.

This type of failure also occurs rapidly and are quite detrimental and unwanted. iii) Gradual wear of the cutting tool at its flanks and rake surface. The first two modes of tool failure are very harmful not only for the tool but also for the job and the machine tool. Hence these kinds of tool failure need to be prevented by using suitable tool materials and geometry depending upon the work material and cutting condition.

But failure by gradual wear, which is inevitable, cannot be prevented but can be slowed down only to enhance the service life of the tool. The cutting tool is withdrawn immediately after it fails or, if possible, just before it totally fails. For that one must understand that the tool has failed or is going to fail shortly. It is understood or considered that the tool has failed or about to fail by one or more of the following conditions :

(a) In R&D laboratories • total breakage of the tool or tool tip(s) • massive fracture at the cutting edge(s) • excessive increase in cutting forces and/or vibration • average wear (flank or crater) reaches its specified limit(s)

(b) In machining industries • excessive (beyond limit) current or power consumption • excessive vibration and/or abnormal sound (chatter) • total breakage of the tool • dimensional deviation beyond tolerance • rapid worsening of surface finish

(ii) Mechanisms and pattern (geometry) of cutting tool wear:

For the purpose of controlling tool wear one must understand the various mechanisms of wear, that the cutting tool undergoes under different conditions. The common mechanisms of cutting tool wear are : i) Mechanical wear • thermally insensitive type; like abrasion, chipping and delamination • thermally sensitive type; like adhesion, fracturing, flaking etc. ii) Thermochemical wear • macro-diffusion by mass dissolution • micro-diffusion by atomic migration iii) Chemical wear iv) Galvanic wear In diffusion wear the material from the tool at its rubbing surfaces, particularly at the rake surface gradually diffuses into the flowing chips either in bulk or atom by atom when the tool material has chemical affinity or solid solubility towards the work material.

The rate of such tool wear increases with the increase in temperature at the cutting zone. Diffusion wear becomes predominant when the cutting temperature becomes very high due to high cutting velocity and high strength of the work material. Chemical wear, leading to damages like grooving wear may occur if the tool material is not enough chemically stable against the work material and/or the atmospheric gases. Galvanic wear, based on electrochemical dissolution, seldom occurs when both the work tool materials are electrically conductive, cutting zone temperature is high and the cutting fluid acts as an electrolyte. The usual pattern or geometry of wear of turning and face milling inserts are typically.

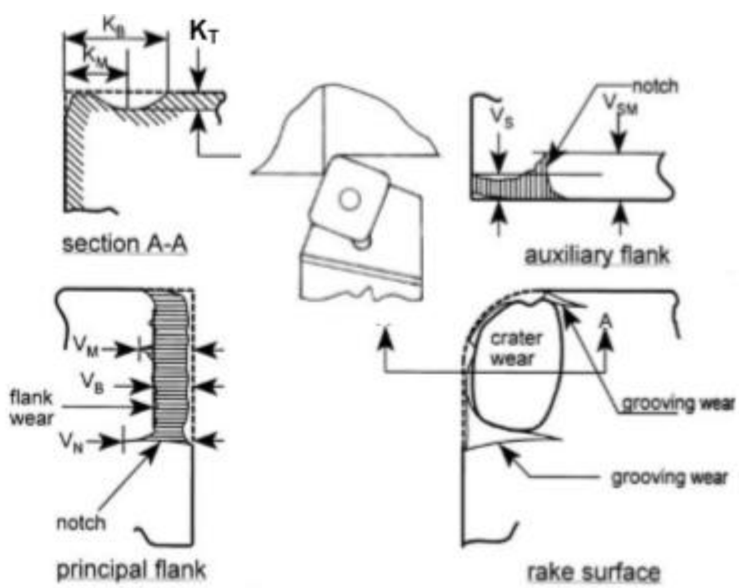


Fig. 3.2.1 (a) *Geometry and major features of wear of turning tools*

In addition to ultimate failure of the tool, the following effects are also caused by the growing tool-wear increase in cutting forces and power consumption mainly due to the principal flank wear • increase in dimensional deviation and surface roughness mainly due to wear of the tool-tips and auxiliary flank wear (Vs) • odd sound and vibration • worsening surface integrity • mechanically weakening of the tool tip.

(iii) Essential properties for cutting tool materials

The cutting tools need to be capable to meet the growing demands for higher productivity and economy as well as to machine the exotic materials which are coming up with the rapid progress in science and technology. The cutting tool material of the day and future essentially require the following properties to resist or retard the phenomena leading to random or early tool failure :

1. high mechanical strength; compressive, tensile, and TRA
2. fracture toughness – high or at least adequate
3. high hardness for abrasion resistance
4. high hot hardness to resist plastic deformation and reduce wear rate at elevated temperature
5. chemical stability or inertness against work material, atmospheric gases and cutting fluids
6. resistance to adhesion and diffusion
7. thermal conductivity – low at the surface to resist incoming of heat and high at the core to quickly dissipate the heat entered
8. high heat resistance and stiffness
9. manufacturability, availability and low cost.

iv) Tool Life :

Definition – Tool life generally indicates, the amount of satisfactory performance or service rendered by a fresh tool or a cutting point till it is declared failed. Tool life is defined in two ways:

(a) In R &D : Actual machining time (period) by which a fresh cutting tool (or point) satisfactorily works after which it needs replacement or reconditioning. The modern tools hardly fail prematurely or abruptly by mechanical breakage or rapid plastic deformation. Those fail mostly by wearing process which systematically grows slowly with machining time. In that case, tool life means the span of actual machining time by which a fresh tool can work before attaining the specified limit of tool wear. Mostly tool life is decided by the machining time till flank wear, VB reaches 0.3 mm or crater wear, KT reaches 0.15 mm.

(b) In industries or shop floor : The length of time of satisfactory service or amount of acceptable output provided by a fresh tool prior to it is required to replace or recondition.

Assessment of tool life :

For R & D purposes, tool life is always assessed or expressed by span of machining time in minutes, whereas, in industries besides machining time in minutes some other means are also used to assess tool life, depending upon the situation, such as • no. of pieces of work machined • total volume of material removed

Measurement of tool wear:

The various methods are :

1. By loss of tool material in volume or weight, in one life time – this method is crude and is generally applicable for critical tools like grinding wheels.
2. By grooving and indentation method – in this approximate method wear depth is measured indirectly by the difference in length of the groove or the indentation outside and inside the worn area
3. Using optical microscope fitted with micrometer – very common and effective method
4. Using scanning electron microscope (SEM) – used generally, for detailed study; both qualitative and quantitative
5. Talysurf, specially for shallow crater wear.

(v) Taylor's tool life equation.

Wear and hence tool life of any tool for any work material is governed mainly by the level of the machining parameters i.e., cutting velocity, (VC), feed, (so) and depth of cut (t). Cutting velocity affects maximum and depth of cut minimum. The usual pattern of growth of cutting tool wear (mainly VB), principle of assessing tool life and its dependence on cutting velocity are schematically. The tool life obviously decreases with the increase in cutting velocity keeping other conditions unaltered as indicated in Fig. 3.2.3. If the tool lives, T1, T2, T3, T4 etc are plotted against the corresponding cutting velocities, V1, V2, V3, V4 etc as shown in Fig. 3.2.4, a smooth curve like a rectangular hyperbola is found to appear. When F. W. Taylor plotted the same figure taking both V and T in log-scale, a more distinct linear relationship appeared as schematically shown in Fig. 3.2.5. With the slope, n and intercept, c, Taylor derived the simple equation as VTn = C where, n is called, Taylor's tool life exponent. The values of both 'n' and 'c' depend mainly upon the tool-work materials and the cutting environment (cutting fluid application). The value of C depends also on the limiting value of VB undertaken (i.e., 0.3 mm, 0.4 mm, 0.6 mm etc.)

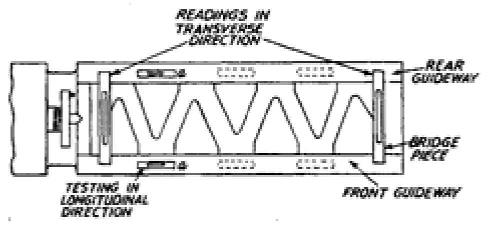
Alignment tests

Levelling of the Machine:

Before the various tests on any machine tool are carried out, it is very essential that it should be installed in truly horizontal and vertical planes. In horizontal plane, both longitudinal and transverse directions are equally important. If, say, any long lathe bed is not installed truly horizontal the bed will undergo a deflection, thereby producing a simple bend and undesirable stresses will be introduced. If the bed is not installed truly horizontal in transverse direction, twist will be introduced. Thus the movement of the saddal can't be in a straight line and true geometric cylinder can't be generated.

For proper installation and maintenance of its accuracy, a special concrete foundation of considerable depth must be prepared. Also this must be insulated from the surrounding floor by introducing some form of damping.The level of the machine bed in longitudinal and transverse directions is generally tested by a sensitive spirit level. The saddle is kept approximately in the center of the bed supportfeet. The spirit level is then placed at a-a , the ensure the level in the longitudinal direction. It is then traversed along the length of bed and readings at various places noted down. For test in transverse direction the level is placed on a bridge piece to span the front and rear guideways and then reading is noted. It is preferable to take two readings in longitudinal and transverse directions simultaneously so that the effect of adjustments in one direction may also be observed in the other. The readings in transverse direction twist or wind in the bed.

It may be noted that the two guideways may be perfectly leveled in longitudinal direction, but might not be parallel to each other. This is revealed by the test in transverse direction.

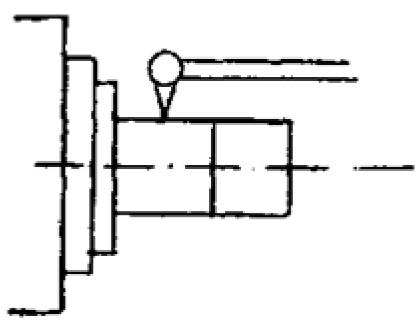


The straightness of bed in longitudinal direction for the long beds can also be determined by other methods, e.g., using straight edges, autocollimators or by taut wire method. But the test in transverse direction can be carried out only by spirit level.

It is desired that the front guideway should be convex only as the cutting forces and the weight of carriage act downward on it. If the front guideways are concave, then the effect will be cumulative. The tendency of the carriage, under cutting forces is to lift upwards from the rear and this is prevented by a gib placed underneath the guideways. With the result, an upward force acts on the rear guideways ; which must, therefore, be made concave.Transverse level may be in any direction, but no twist can be tolerated.

True Running of Locating Cylinder of Main Spindle:

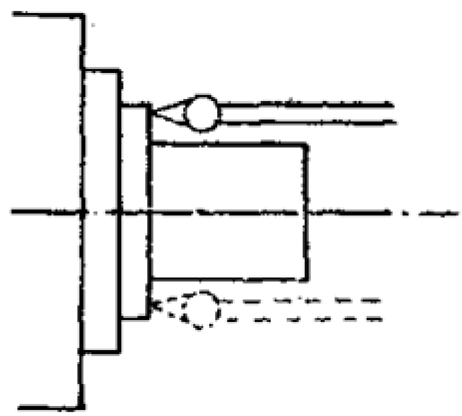
Locating cylinder is provided to locate the chuck or face plate. However locating surface can’t be threaded one as threads get worn out soon and thus introducing play in face plate or chuck. Thus locating surface is cylindrical and this must run truly; for only then the face plate etc., can run truly. The dial indicator is fixed to the carriage (or any other fixed member) and the feeler of the indicator touches the locating surface. The surface is then rotated on its axis and indictor should not show any movement of needle.



Axial Slip of Main Spindle and True Running of Shoulder Face of Spindle Nose:

Let us first distinguish between the axial play and the axial slip. Axial play means the indispensable freedom of spindle movement in axial direction to prevent it fromseizing by heating. The spindle is supported between two bearings. Due to running of spindle, there will be a rise in temperature and thermal expansion of spindle would be there. If no axial play is allowed, it would try to bend. Thus there will be no adverse effect of axial play if the direction of cutting forces remains same. If the direction of cutting force changes, there would be some error introduced due to movement of spindle axially in either direction. Under such conditions, therefore, it is advisable to cut threads in one direction only.

Axial slip is defined as the axial spindle movement whichfollows the same pattern and is due to the manufacturing error. Actually this test is meant to check this error. To test this the feeler of the dial gauge rests on the face of the locating spindle shoulder and the dial gauge holder is clamped to the bed . The locating cylinder is then rotated and the change in reading noted down. The readings are taken at two diametrically opposite points. The total error indicated by the movement of the pointer includes three main sources of errors.



1. Axial slip due to error in bearings supporting the locating shoulder, i.e., the bearings are not perpendicular to the axis of rotation and due to it a point on the shoulder will move axially in and out at diametrically opposite points.
2. Face of the locating shoulder not in a plane perpendicular to axis of rotation. (Hi) Irregularities of front face.Due to axial slip, in screw cutting, the pitch will not be uniform due to periodic movement of the spindle. This, however, is not important while turning.

True Running of Headstock Centre:

Headstock centre is live centre and the workpiece has to rotate with this centre. If it is not true with the axis of movement of the spindle, eccentricity will be caused while turning a work, as the job axis would not coincide with the axis of rotation of main spindle. For testing this error, the feeler of the dial indicator is pressed perpendicular to the taper surface of the centre, and the spindle is rotated. The deviation indicated by the dial gauge gives the trueness of the centre.

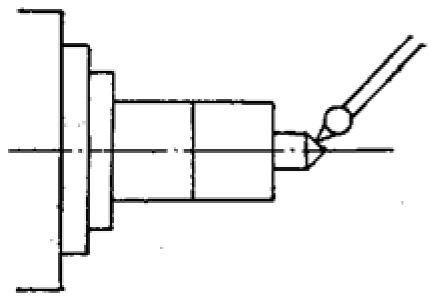


Fig. 16.4

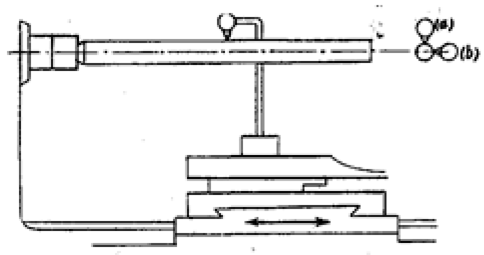
Parallelism of the Main Spindle to Saddle Movement:

This has to be checked in both vertical and horizontal planes. In this we require the use of mandrel. An important precaution in the use of mandrels and dial indicator is mentioned here. The mandrel must be so proportioned that its overhang does not produce appreciable sag, or else the sag must be calculated and accounted for. The rigidity indicator set up is also very important and must be carefully watched. Otherwise variations in readings are recorded by pointer may be solely due to deflection of the indicator mounting in different positions and it becomes very difficult to detect and isolate the spurious deflection from the true variations.If axis of the spindle is not parallel to bed in horizontal direction, a tapered surface is produced.

Any deviation from parallelism of spindle axis from bed in vertical axis will produce a hyperboloid surface. For this test, a mandrel is fitted in the taper socket of the spindle. Mandrel has a concentric taper shank which is close fit to the spindle nose taper. The feeler of the dial indicator is pressed on the mandrel and the carriage is moved. The indication in horizontal plane is given by dial (b) and in vertical plane by dial (a) (Fig. 16.5). In vertical plane the mandrel should be rising towardsthe free end in order to counteract the weight of mandrel and job. But for counter-acting cutting forces, it should be lower towards free end. In horizontal plane, mandrel should be inclined in a direction opposite to the direction of tool pressure.

True running of taper socket in main spindle:

If the axis of tapered hole of the socket is not concentric with the main spindle axis, eccentric and tapered jobs will be produced. To test it, a mandrel is fitted into the tapered hole and readings at two extremes of the mandrel are taken by means of a dial indicator as shown in Fie. 16.6.



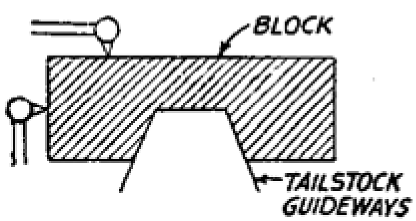
Parallelism of tailstock guideways with the movement of carriage:

Sometimes the job is held between head-stock and tail stock centre for turning. In that case the job axis must coincide with the tailstock centre. If the tailstock guideways are not parallel with the carriage movement there will be some offset of the tailstock centre and this results in taper turning.

To check the parallelism of tailstock mideways in both the planes i.e., horizontal and vertical, a block is placed on the guideways and the feeler of the indicator is touched on the horizontal and vertical surfaces of the block. The dial indicator is held in the carriage and carriage is moved. Any error is indicted by the pointer of dial indicator.

Movement of upper slide parallel with main spindle in vertical plane:

The dial indicator if fixed in the tool post. A mandrel is fitted in the spindle of the dial gauge is pressed against the mandrel in vertical plane and the upper slide is moved longitudinally. This error is not tested in horizontal plane because there is swiveling arrangement for taper turning.



Parallelism of tailstock sleeve to saddle movement:

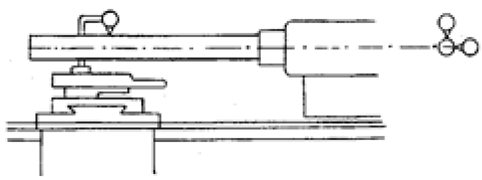
If the tailstock sleeve is not parallel to the saddle movement, the height of dead centre would vary as varying lengths of sleeve are taken out. For the jobs held between two centres, it is necessary that the central axis of the dead centre be coaxial with the job axis in both the planes. If it is not so, the jobmay be tilted up or down or in sideways due to the support of the dead centre. The test is carried out by fixing the dial indicator on the tool post and pressing the plunger against the sleeves first in vertical and then in horizontal plane . The carriage is moved along the full length of the sleeve and deviations as indicated by dial indicator are noted down. Tailstock sleeve should be rising towards the free end in vertical plane and should be inclined towards the tool pressure in horizontal plane.

Parallelism of tailstock sleeve taper socket to saddle movement:

A mandrel is put in the sleeve socket. The dial gauge is fixed on the tool post and plunger is pressed against the mandreland saddle is moved from one side to the other. This test is carried out in both the horizontal and vertical planes.

Alignment of both the centres in vertical plane:

Besides testing the parallelism of the axes individually (main spindle axis and tailstock axis) it is-necessary to check the relative position of the axes also. Both the axes may be parallel to carriage movement but they may not be coinciding. So when a jobis fitted between the centres, the axis of the job will not be parallel to the carriage movement. This test is to be carried out in vertical plane only. A mandrel is fitted between the two centres and dial gauge on the carriage. The feeler of the dial gauge is pressed against the mandrel in vertical plane asand the carriage is moved and the error noted down.



Pitch accuracy of lead screw:

The accuracy of the threads cut on any machine depends upon the accuracy of its lead screw. Thus it is very essential that pitch of the lead screw throughout its length be uniform.Test for this is performed by fixing a positive stop on the lathe bed. Against the stop, the length bars and slip gauges can be located. An indicator is mounted on the carriage and first it makes contact against the calculated length of slip gauges. The initial loading of the dial gauge against the slip gauge is noted. The slip gauges are then removed and the carriage is connected to the lead screw and lead screw is disconnected from the gear train. An indexing arrangement is utilised for rotating the lead screw and lead screw is given some revolutions so that distance travelled by carriage is equal to the length of slip gauges. The reading of the dial indicator against the stop is noted down in this position. It it is same as before, there is no error, otherwise it can be recorded. In this method, care must be taken not to disturb the datum location when changing the gauges for testing different pitch lengths.

A suitable method for recording the progressive and periodic errors is by using a suitably divided scale, which is placed close to the line of centres. A microscope is rigidly mounted on the carriage in a convenient position to note the readings on the scale.

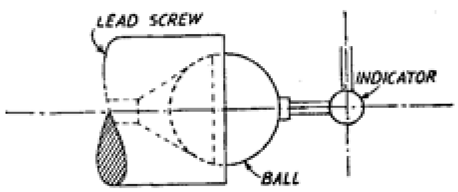
Alignment of lead screw bearings with respect to each other:

The alignment of the bearings decides the position of the lead screw. Misalignment of lead screw i.e., it not being parallel to the bed in vertical plane or horizontal plane can cause additional stresses due to bending, when carriage is moved. Due to it the lead screw might get damaged and the precision of the machine is reduced .Alignment of lead screw bearing with split nut in both the planes is also essential.

Axial slip of lead screw:

The thrust face and the collars of the lead screw (or the abuttment collar and the thrust bearing of the screw) must be exactly square to the screw axis, otherwise a cyclic endwise movement is set up which is of the same nature as the axial slip in the main spindle. Thus a periodic pitch error will be additional to any true periodic errors in the pitch of the screw.

For testing the axial slip in lead screw, a ball is fitted in the end of lead screw and the feeler of the dial gauge is pressed against the ball. The lead screw is rotated and deviation, if any, in any direction is noted down.



Practical tests:

These tests consist of the actual turning of some jobs on the machine. The job is made under prescribed condition of cutting speed, feed and depth of cut. The test piece is then measured for its geometry and surface finish and results compared with the standards as prescribed by the manufacturer. These tests are designed to reveal the combined effects of possible errors in alignment accuracy and the rigidity of machine.

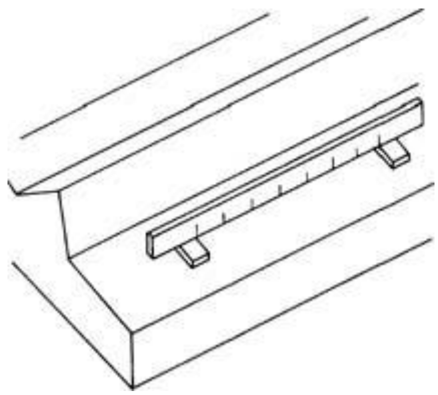
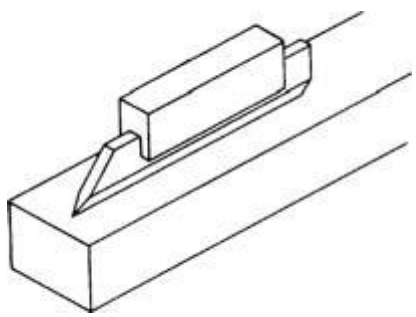
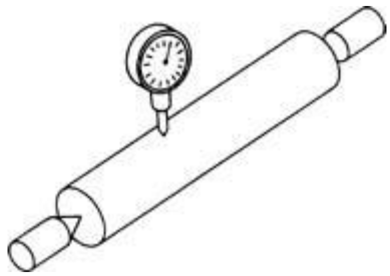
The various jobs to be made as prescribed by M/s Hindustan Machine Tools are givenbelow.

(i) Working accuracy of machine of cylindrical turning (chucking). S' should be as small as possible.

(ii) Working accuracy of machine facing : Permissible error=0.02 mm over the diameter of test workpiece, which is taken as 300 mm for swing over bed of up to500 mm, and 400 mm for swing over 500 mm.(Hi) Working accuracy of cylindrical turning, the job held between centres.

STRAIGHTNESS AND ALIGNMENT MEASUREMENTS

The straight line represents the path of all linear dimensions. Considering the premise that the shortest distance between two points is along a straight line, that path is not necessarily present in a physical sense on the part being measured for size, but it must be incorporated in the length measuring instrument. Straightness, which is a fundamental concept of linear measurements, is also a functionally important condition of many engineering products. As an introduction to the discussion of straightness measurements, a survey of a few basic methods is made.

OPERATING PRINCIPLES	**TYPICAL INSTRUMENTS**	**DIAGRAM**	**DISCUSSION**
Straightness of a surface element determined by its parallelism to a straight edge of known accuracy	Straight edge and gage blocks		Unequal height of the supporting elements create a controlled deviation from true parallelism. Gage blocks are used to check whether the digressions from the parallel at intermediate points correspond to the calculated values.
The straightness of a surface element inspected by direct contact with a tool of calibrated straightness	Knife edge rule		A knife edge rule brought to bear against the surface element to be inspected will indicate by the presence and width of light gaps the lack of contact caused by deficient straightness.
Straightness of a shaft determined by rotation on fixed supports and measuring the runout of its surface	Bench centers or Vee-blocks and indicator stand		Using the part's axis (between centers) or its surface...

TESTS ON MACHINE-TOOL ELEMENTS FOB. AOCUEAGY:

The object of these tests is to determine whether the various parts or elements of machine-tools have been made accurately and so fit and work together as to produce satisfactory results in the operation of the machines. In other words, to determine whether they are made so that the machine as a whole is capable of turning out work which is accurate within certain specified limits. It may be safely assumed that no machine-tool—no matter what the nature of its particular work may be—is able to produce work which is more accurate than itself.

Therefore, since the general accuracy of a machine-tool is dependent absolutely upon the accuracy of its component parts or elements, it follows that this latter accuracy is the one to be considered. Now, these accuracy tests are of two kinds, namely, those in which the degree of inaccuracy cannot be stated as a quantity, and those in which the error or departure from the truth can be so stated. The first kind of test is purely a qualitative test, and is only generally useful when the adjustment of a part is possible. The other is strictly a quantitative test, and as such is far more valuable and useful than the former not exclusively, used in connection with the testing of machine-tool parts which are in course of construction, machining, or fitting ; the latter is, in the majority of cases, the only test which is applied in the case of the finished machine with all the parts in their correct places.

Bed-levelling Tests:

The function of such tests is to determine whether the machine as placed down on its foundation is in such a position that its main element, namely the bed, is in a perfectly horizontal position or not ; and, if not, to check. Anyadjustment of its position until the required positionhas been secured. In such tests it is the bed of the.lathe which is worked on, and usually the top ofthis. The tests for straightness and levelness or planeness which are made when the bed is being scraped to shape also belong to this class, there being a close connection between the two.

Spirit Levels

One method of performing this test—and the usual one—involves the employment of a spirit level. The essential feature of a spirit level is a hermetically sealed glass vial of circular section and a more or less curved interior. This vial contains spirit in which is trapped a bubble of air. This bubble, which has a density much less than that of the spirit, always tends to rise to the highest part of the vial, which is so arranged that when it is perfectly horizontal its highest point and middle point coincide. In this case the bubble occupies a position in the middle of the vial which is plainly indicated. Now, as is perhaps not generally known, the internal surface of the vial is curved in the direct tip of the length of the vial and it is to the top of this surface that the bubble of air always tends.

In ordinary practice this curvature^which is practically of a circular character — can be imparted to the internal surface of the vial in either of two ways, that is, either by bending the tube from which the vial is made, or by grinding the vial internally so as to make it barrel shaped therein. The two forms of vial, namely, the ground and the bent fcms, are represented in Pig. 1, the ground form beiug shown at A, and the bent form at B. In all high-class spirit levels it is the ground form of vial which is used, since in the process of grinding it is possible to secure a higher degree of accuracy in regard to the curvature of the surface and also in regard to the regularity of the surface. The vial is fixed in a frame—being firmly embedded in special cement or plaster.

The nature of the frame varies considerably, such materials as castiron, brass, aluminium, boxwood, ebony, and mahogany being in considerable use. In any case, however, whatever the nature of the frame, the base of the frame should be made of a fairly hard metal, and the frame, when made of wood, firmly braced to prevent buckling or bending as the result of changes of temperature or other atmospheric conditions. The relation between the vial and the base of the instrument is such that the air bubble or 2index is in the middle of the vial about the ^eromark when the base is quite horizontal. This condition is, of course, realised in the testing of the level during manufacture.

The overall lengths of these levels vary from about two inches to thirty inches, but for ordinary machine tool bed levelling, both these lengths are unsatisfactory, a more suitable range extending from sixteen inches to twenty inches. When spirit-levels have to be used on shafts or other parts of circular or curved section, it is better if their bases are provided with vee'd or curved grooves, so that the user of the instrument can place it on the shaft and be quite sure that the axis of the instrument is parallel to the axis of the shaft.Some spirit-levels are equipped with cross vials for transverse testing, whilst others have additionalvials for vertical testing. In other forms, an additional vial is mounted on a hinged or pivoted arm which works over a graduated scale, this being useful in cases wherein it is desired to set a part in a definite angular position or to test the accuracy of such a position.

Spirit-level Graduation:

The vials of spirit levels can be marked or graduated in a variety of ways. The two commonest ways are to mark the vial or its frame at the middle of the air- bubble when the base of the instrument is quite horizontal, and to mark the vial or its frame at the two ends of the bubble when the same condition has been realized. On such vials there are no graduations, and the levels which contain them can only be used for qualitative work, though this is all that is required in the machine. Graduated vials can be marked -out in at least four different ways. These are

(1) in fractions of an inch,ormilliinetres

(2) in fractions of a degree, or minutes,or seconds

(3) in inches or fractions of an inch per foot ; and

(4) in binary or vulgar fractions vrith unity as the numerator in every case.

Vials which are graduated in the first way are generally provided with markings or graduations of either ^ in. or Jjj in., or 1 millimetre, such a system of marking usually giving no indication of the value of each division so far as inclination of the level is concerned, though by means of a test it is always possible to determine this relationship. Very sensitive vials when graduated in the second way read in units of two seconds or four seconds, whilst less sensitive ones read in one-minute or five minute divisions.

By means of this system of marking the actual inclination of a plane surface can be read off directly. The third form of graduation also gives the actual inclination, but in this case it is represented by the rise of the inclined plane per foot length of the base of the plane. In other words, it gives, a dimension which is proportional to the tangent of the angle of inclination.

In the metric system of measurement, the corresponding form of graduation is millimetres per decimetre or per metre. The- binary or vulgar fraction which is the basis of the fourth method of graduation is really equal to the tangent of the angle of inclination with unity as the numerator. Belations between Spirit-level Graduations.— Let I — the length of each graduation of the first form measured in, say, inches.

Hydrostatic Level:

In this form of levelling instrument the fact that water always tends to find its own level is made use of. It consists essentially of two exactly similar graduated cylinders with a flexible connecting tube between them. The two sets of cylinder graduations should be exactly alike and related in exactly the same way to the bases of the cylinders; otherwise the instrument is practically worthless. In any case, however, unless some form of magnifying apparatus (such as a microscope) is employed in connection with the readings, the results which are obtainable do not compare with those which are obtainable with the ordinary spirit-level. With this instrument the difference in level between the two points or places tested equals the difference between the heights of water in the two cylinders, the higher cylinder showing the lower head of water.

Gravity or Pendulum Level:

The principle of action of this instrument is based on the fact that the bob of a heavy pendulum when left to itself always occupies its lowest position, so that the longitudinal axis of the pendulum is thus always perfectly vertical. If such a penduluin is supported in a pase, the position of it in the case will vary with any variation in the direction of the base with respect to the horizontal. In one form of this instrument, the motion of the pendulum is transmitted through toothed gear wheels to a pivoted needle or pointer which works over a graduated dial. The graduations of the dial can be in degrees of inclination, inches per foot, or fractions of an inch per inch.

Norton Pendulameter:

This is a precision level which works on the pendulum principle. It is an American instrument, and was originally designed for the testing of the beds and ways of grinding machines for straightness, evenness, and parallelism. It can, however, be used in ordinary levelling tests. In this instrument the pendulum bob consists of a lead weight, weighing some 40 lb. avoirdupois, this being supported at the end of a piece of fine steel piano wire of a length of 10 ft. The movement of the bob is communicated to a long pivoted needle, which moves over a graduated scale, the total magnification (which consists of two distinct parts) being in the neighbourhood of 500 times. The degree of sensitiveness of this instrument is of the order of 0-00025 in., that is, dimensional and surface variations of this magnitude can be discovered by the use of this instrument. For the determination of transverse variations a second needle is provided, the magnifying power of this being of the order of 433 times, and the degree of sensitiveness equal to that of the other needle. The pendulum supporting wire is encased in a mast of seamless steel tubing, whilst the needles (which are made from thin aluminium sheet) are protected from the influence of air currents by beingsurrounded with light sheet-steel guards. The principle of action of this instrument is illustrated.

It will be observed from this diagram that the angle through which the pendulum swings is exactly equal tothe inclination of the base of the instrument, so that the movement of the bob of the pendulum will be to the rise of the high side or edge of the base in the ratio of the length of the pendulum to the length of the base. This ratio is 50 to 1 in one direction and 43-3 to 1 in the other. The average magnifying power of the needle alone is- 10 to 1, the total magnifying power of the instrument being equal to the productof these ratios.

Tests:

These tests may be divided into two classes : general and local level tests. The former test has respect to the general horizontality of the ways of the bed from end to end and from front to back when it is placed on a solid foundation, as every lathe bed should be before the final scraping operations to remove the tool marks and to correct any machining inaccuracies are performed. This test can be performed by means of any one of the instruments described above, though the commonest instrument which is employed is undoubtedly the spirit-level. The level used should be accurately made and marked and fairly large, and provided with a metal base or metal base-inserts so as to reduce the possibility of wear on the base. A level which is provided with longitudinal and cross vials can be employed at one setting to test the bed for horizontality in both the longitudinal and the transverse direction general horizontality of the bed has been realized in each aforementioned direction.

This test is thus a qualitative one, and does not admit of the making of measurements or of the obtainment of data of a quantitative nature. In some cases it may be found necessary, owing, say, to the limited capacity of the spirit-level, to have recourse to the use of parallel strips or parallel straight-edges on which to place the level. Such pieces of apparatus, if used, should be accurately made and reliably parallel. Parallel strips are, generally, of two forms ; these being distinguishablefrom one another by the difference in their sections. The first form is the block or prismoidal form, having a square or rectangular section. The other is usually of I section. Both are made of steel or seasoned cast iron. Parallel straight-edges are invariably longer than parallel blocks or strips.

They are made of steel in the majority of cases, and exist in the several different sections. 4. For the majority of ordinary operations, the forms A and B are equally suitable, though when the straight-edge has to be used as a parallel strip, preference should be given to the form A. In regard to the transverse testing of beds provided with raised inverted vee ways, it should be noted that, unless there are two vees of precisely the same height or unless a compound level is employed, a difficulty may be experienced.

This can, however, usually be overcome by making use of a packing.strip or small parallel strip of the same height as to rest the level on. A rather unusual method of testing a lathe bed for general horizontality is indicated diagrammatically in Kg. 5. In this case use is made of the physical fact that the level of still water is always horizontal. The water is contained in a long, fairly shallow vessel T-^such as, for example, a length of channel iron provided with ends.

This vessel is supported in some convenient manner, though there' is no need to set it in an exactly horizontal position. The position of the vessel with respect to the bed of the lathe is, as is indicated in the figure, approximately parallel. On the bed of the lathe (which is lettered B in the figure) a plane surface plate, P, is used, the plate being turned over so that it rests on the bed with its plane surface on the underside. A horizontal arm is attached to the plate, this arm carrying a simple microscope, M, of medium power. The axis of collimation of the microscope—that is, the axis of the tube of the microscope — should be arranged as nearly vertical as possible.

In the test, when the plate P is at one end of the bed, the microscope is adjusted until the surface of the water is brought into focus. The plate is then moved along the bed of the lathe to the other end.If the surface of the water is still in focus the surface of the bed is generally horizontal. If not, then the distance through which the collimator tube of the microscope has to be raised or lowered in order to bring the surface of the water into focus again represents the difference in level between the ends of the bed.

Ordinarily, however, this dimension is of no value whatever, so that the setting of the microscope is not altered but, instead of this, the end of the bed is raised or lowered, whichever is required, until the surface of the water is again brought into focus. This method is a reliable one, but it is not as easy to apply as the spirit-level method. Local bed-levelling tests are only made during the process of construction and erection of a lathe they are practically never made when the lathe is fully equipped and ready for service.

These tests can be divided into two classes made during the process of finishing the bed either by scraping or grinding, and those which are made on the finished bed as a final check ; and though both are desirable there are machine-tool manufacturing works in which the first at least is not applied, the scraping being done without the aid of any gauge and implicit confidence placed in the work of the planing or milling machine. This latter practice is not, however, very satisfactory, since it is practically impossible to machine on the planing or milling machine long parallel surfaces sufficiently accurate for fitting without any correction.

Surfaces which have to be horizontal are tested for local truth by means of a plane surface plate, this being run over the surfaces more or less lightly, the location of high and hard places being indicated by the use of a marking of red lead or Venetian red between the two surfaces. In certain cases, also, the general flatness of the surface (apart entirely from general horizontality) can be tested by means of a straight-edge, one form of which has already been described. Another and superior form for this kind of work is represented in fig. 6. This 'is a straightedge, which is made of fine-grained cast iron, and has a test surface rather than a test edge.

This surface is shown at S in the figure. The back of the instrument is curved more or less parabolieally in order to prevent or resist the distorting influence of its weight on the test surface. On the back are cast two lugs with plane surfaces, these being used to support the straight-edge when it is not in use. On some edges these lugs are replaced by hard wood feet. The back of the straight-edge is in the form of a flange which is connected to the flange S by a web of a reasonable thickness, this web being stiffened by anumber of cross ribs disposed uniformly from end to end of the straight-edge. Between consecutive ribs the web is centred to reduce its weight without impairing its resisting power.

Squareness

First we shall be dealing with the squareness of straight lines and planes and then the perpendicularity of motion. Two planes, two straight lines or a straight line and a plane are said to be perpendicular when the error of parallelism in relation to a standard square does not exceed a given value. The reference square may be a metrological square or a right angle level or may consists of kinematic planes or lines. The permissible errors are specified as ‘Errors relating to the right angle: ± … ^ or mm on a given length’ and if the error is determined in relation to another part of the machine then the permitted direction of error should also be specified, such as, 'Free end of spindle inclined only towards the support'. We shall be considering the following cases for the measurement of squareness of lines and planes.

Squareness of an axis of rotation with a given plane

For this test the dial indicator is mounted on an arm which is attached to the spindle representing the axis of rotation. The plunger of the dial indicator is adjusted parallel to the axis of rotation and made to touch the plane. As the spindle revolves, the dial gauge (or the end of plunger if revolving freely into air) describes a circumstances, the plane of which is per- pendicular to the axis of rotation. When no testing plane is specified the dial gauge is rotated by 360° and the variation in the readings of instrument represents the deviation of parallelism between the plane of the circumstances and the plane to be tested. However, if planes are specified (e.g. planes 1 and 2) then the difference of the readings in the position of the dial gauge, 180° apart is noted for each of these planes (Fig) The deviation is expressed in relation to the diameter of the circle of rotation of the instrument. The effect of periodical axial slip of the spindle can be eliminated by repeating the above test after moving the dial gauge through 180° relative to the spindle and average of two sets taken. The effect of minimum axis play can be eliminated by means of a suitable axial pressure.

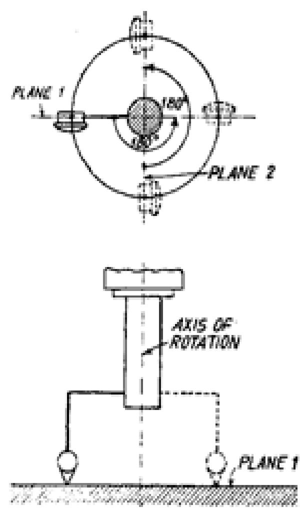
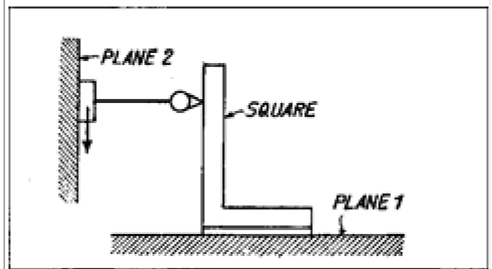
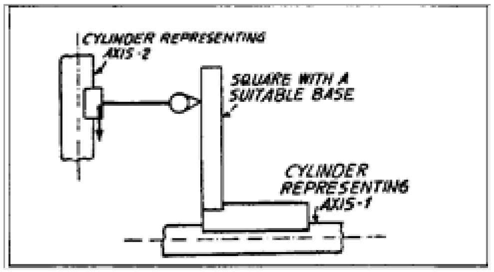
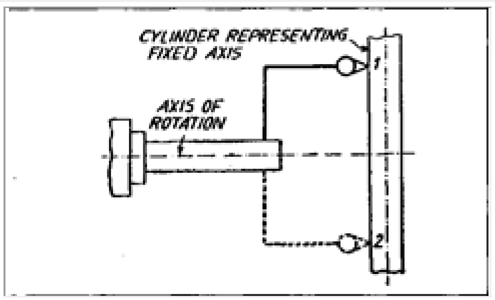
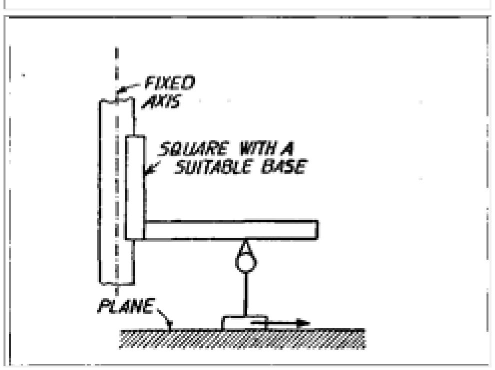
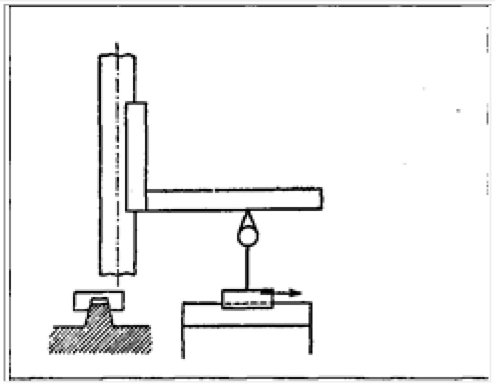
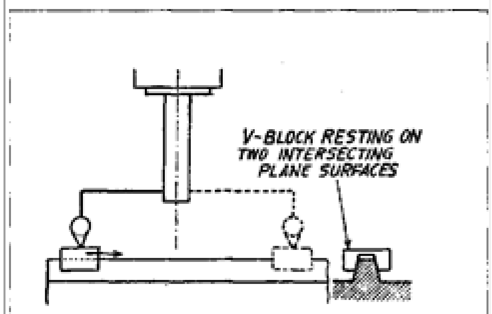
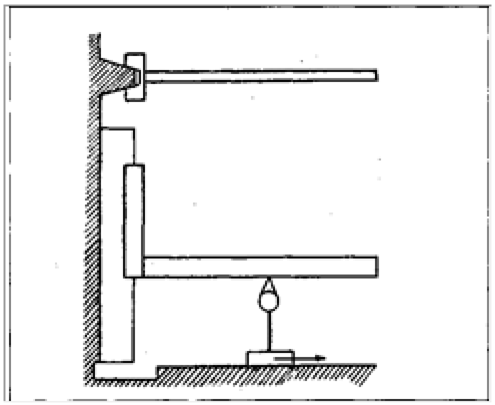
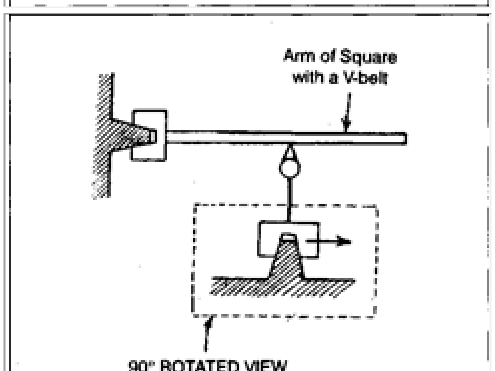


Fig :Testing squareness.

Indicator Method

This method is particularly suitable for checking the squareness of a block whose opposite faces are supposed to be parallel. It is assumed that the squareness of the block has already been assured to a reasonable accuracy by the use of square etc., as otherwise the full sensitivity of the method can't be obtained. The instrument for this purpose is designed by N.P.L. and is very suitable for checking squareness while manufacturing a square block. The instrument consists of parallel strip (framework) and a flat base. A knife edge and some form of indicator is mounted on the framework as shown in Fig. 7.21. The other tests of squareness of lines and planes are given below in the tabular form.

<table>
<tr><th>Condition</th><th>Test set up</th><th>Method in brief</th></tr>
<tr><td>(i) Two planes (1 and 2) at 90° to each other</td><td>
</td><td>Squareness of two planes 1 and 2 is checked by placing the square on one plane and then checking the parallelism of 2nd plane with the free arm of the square by sliding the dial indicator (mounted on a base) along 2nd plane and its feeler moving against free arm of the square.</td></tr>
<tr><td>(ii) Two axes at 90° to each other
(a) Both axes fixed</td><td>
</td><td></td></tr>
<tr><td>(b) One axis being axis of rotation and other fixed.</td><td>
</td><td>The dial gauge mounted on arm and fixed on the mandrel is brought into contact with the cylinder representing fixed axis at two points 1 and 2,180° apart and deviation expressed in relation to distance between 1 and 2.</td></tr>
<tr><td>(c) Both the axes being axes of rotation.</td><td></td><td>The test is conducted in the same way as (ii)-(b) but the cylinder representing 2nd axis of rotation is brought into the mean position of the run out in the plane of measurement.</td></tr>
<tr><td>(iii) An axis at 90° to a plane.
(a) axis is fixed.</td><td>
</td><td>Test set up is self explanatory, but the test is carried out in two perpendicular directions.</td></tr>
<tr><td>(h) Axis being the axis of rotation.</td><td></td><td>This test has already been described.</td></tr>
</table>

(iv) An axis at 90° to the intersection of two planes. **(a)** Axis is fixed.		The test set up is self explanatory.
(b) Axis being the axis of rotation.	 	First reading is taken by making the feeler of the dial indicator to touch on a V-block resting on two intersecting plane surfaces. (The dial indicator is mounted on the spindle). The second reading is noted by rotating the spindle along with dial by 180° and moving the V-block so as to bring the feeler into contact with the same point on the block.
(v) Intersection of two planes is at 90° to another plane.		In this test, either the square or the dial indicator fitted with a suitable base is allowed to rest on the intersecting planes and the dial indicator is moved with its feeler resting against the arms of dial gauge. The test is made in two perpendicular planes.
(vi) Two straight lines, each formed by the intersection of two planes, are at 90° to each other.	 	Test is self explanatory.

Circularity

Introduction

In the assembly of circular parts, only the dimensional tolerances on diameter will not suffice the requirements, but it is the geometrical accuracy (accuracy of form) that needs closer attention. If cylindrical parts are measured from devices having diametrically opposite contacts such as micrometer etc., though they may be found to be within the dimensional tolerances and still may not be perfectly circular, which would be noticed during the assembly of parts. (Fig.). Thus the method of circularity measurement has to be such which detects the various possible errors of circularity and this is always done by rotating a part and not measuring static diameter alone.

Fig. Errors in circularity.

Different types of Irregularities of a Circular Part.

The errors of circularity at a cross-section can be of the following nature :

(i) Ovality (There is some difference between the major and minor axes.) Fig.

(ii) Lobing (In this case the diameters at any two opposite points are constant, but still it is not circular form). [Refer Fig]

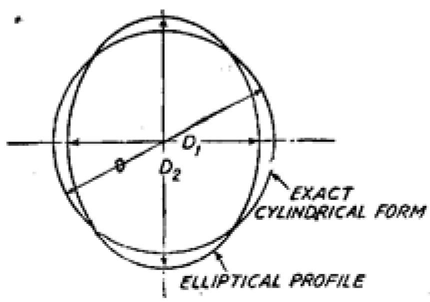


Fig. Ovality, i.e. DX*D2* D.

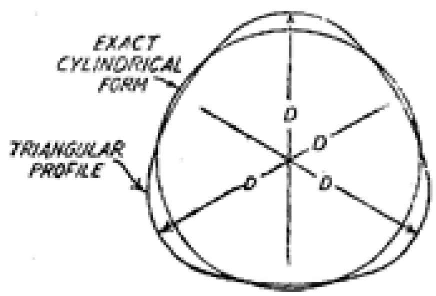


Fig. Lobing : Diameters at places equal, but still not circular form.

Diametral Method.

In this method, the measuring plungers are located 180° apart and the diameter is measured at several places. This method is suitable only when the specimen is elliptical or has an even number of lobes. Diametral check does not necessarily disclose effective size or roundness. This method is unreliable in determining roundness.

Circumferential Confin-ing Gauge. The principle of this method.

It is useful for inspection of roundness in production. However, this method requires a separate highly accurate master for each size part to be measured. The clearance between part and gauge is critical to reliability. This technique does not allow for the measurement of other related geometric characteristics, such as concentricity, flatness of shoulders, etc. The values obtained are dependent on the shape of the specimen.

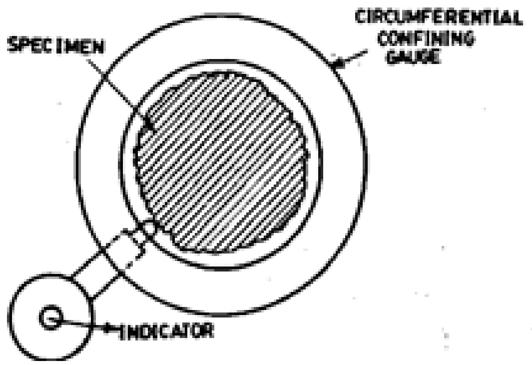


Fig Circumferential confining gauge.

UNIT II

INFLUENCE OF STATIC STIFENESS, THERMAL EFFECTS

Introduction

Beds, bases, columns and box type housings are called "structures" in machine tools. In machine tools, 70-90% of the total weight of the machine is due to the weight of the structure. In this chapter classification and functions of machine tool structure is described. Researchers have worked with different types of materials like cast iron, mild steel, granite and epoxy concrete for machine tool structure for different applications. Profile of the machine tool and selection of different stiffeners/ribs are suggested by researchers. Quality of the job produced on these machine tools depends directly on the quality and performance of machine tools. To develop good products, design engineers need to study how their designs will behave in real-world conditions.

The limitations of physical model techniques have led to the development of mathematical models representing a variety of mechanical structures. As in this approach, whole structure is divided into finite elements, it is known as 'Finite Element Analysis'.

The FEA is a very useful tool in engineering today and same has proved to be an important technique in machine tool structural analysis. Thus, Computer is an invaluable tool for a designer in his task for evaluating alternative designs to arrive at the optimum design and also predicting the static, dynamic and thermal behavior of the machine before arriving at the final design.

Functions of Machine Tool Structure and Their Requirements:

Machine tool parts, such as beds, bases, columns, box-type housings, over arms, carriages, table etc. are known as structures. Basic functions of machine tool structure are as follows:

1. To provide rigid support on which various subassemblies can be mounted i.e. beds, bases.
2. To provide housings for individual units or their assemblies like s gear box, spindle head.
3. To support and move the work piece and tool relatively, i.e. table, carriage, tail stock etc.

Machine tool structures must satisfy the following requirements:

1. All important mating surface of the structures should be machined with a high degree
    a. of accuracy to provide the desired geometrical accuracy;
2. The initial geometrical accuracy of the structures should be maintained during the
    a. whole service life of the machine tool; and
3. The shapes and sizes of the structures should not only provide safe operation and maintenance of the machine tool but also ensure that working stresses and deformations do not exceed specific limits; it should be noted that the stresses and deformations are due to mechanical as well as thermal loading.

4. Efficient thermal control on machine element such as spindle, ball screw and bearings for better part accuracy.
5. Faster tool change system.
6. Very high rapid traverse rates of round 40-60 m/min for faster tool positioning and very high cutting feed rates for increased metal removal rates.

The design features that provide for ease of manufacture, maintenance, etc. are peculiar to each structure and will, therefore, be discussed separately for different structures. However, there are two common features, which are fundamental to the satisfactory fulfillment of above requirements for all structures.

These are:

1. Proper selection of material.
2. High static and dynamic stiffness.

Classification of Machine Tool Structure :

Classification of machine tool structures which can be subdivided by various characteristics into the following groups:

a) By purpose into:

1. Beds, frameworks, carrying bodies.
2. Bases, bedplates etc.
3. Housing, boxes, columns, pillar, brackets.
4. Castings and covers.

b) By the method of manufacture into:

1. Cast.
2. Welded.
3. Combined cast and welded.

c) By functions they perform:

1. Beds and bases, upon which the various subassemblies are mounted.
2. Box type housings in which individual units are assembled.
3. Parts those serve for supporting and moving work piece and tool i.e. table, carriage etc.

Materials of Machine Tool Structure :

The structure of a machine tool forms the vital link between the cutting tool and work piece on a metal cutting machine. The machine tool's metal removal rate, accuracy, overall cost, method of production and lead times, depend upon the type of structural material and its properties. The commonly used materials for machine tool structures are cast iron and steel. While in some applications Granite and 'Epoxy Concrete', newly developed material, is also introduced. Cast iron structures were almost exclusively used in machine tools till a decade or so ago, but lately welded steel structures are finding wider application due to advances in welding technology. The choice of whether the structure should be made from cast iron or steel depends upon a number of factors, which are discussed as follows:

Material Properties :

Important material properties of relevance are as under: • Modulus of elasticity: For high stiffness it is necessary to choose materials with a high value of E. For instance, the high strength nodular graphite cast iron has doubled the modulus of elasticity than the normal cast iron, apart from its high internal damping. All steels have practically the same E and therefore mostly the non-expensive good commercial quality steel is used for machine tool structures.

Specific stiffness:

Material should have high specific stiffness.

• Damping:

Cast iron has higher inherent damping properties, damping in steel structures occurs mainly in welds, if welded joints are properly designed, the damping of steel structure may approach that of cast iron.

• Long-term dimensional stability:

The machine tool structural material must also have a good long-term dimensional stability. Locked in stress levels should be reduced to as close to zero as possible to achieve this.

• Coolant resistance:

The material should be unaffected by coolant.

• Wear rate and frictional properties:

Material should have low wear rate and low coefficient of friction.

• Thermal expansion coefficient:

The material used should have a reasonably low coefficient of expansion. If several composite materials are used, each should have the same coefficient of expansion to avoid thermal bending/distortion.

Different Materials Used for machine tool structure :

As already stated, commonly used materials for machine tool structure are cast iron and steel. While in recent times, granite and epoxy concrete are also developed and used for structures. These materials are discussed here:

1. Cast Iron: From early times cast iron has been the most commonly used material for

machine tool structures. It may be cast into complex and intricate shapes. It is easilymachined and may be hand-scraped and lapped to a high degree of accuracy. It has fairly good damping properties and also has reasonably good antifriction properties helped by the graphite contained in it. It can be given very good long-term dimensional stability by giving it a special long cycle stress relief annealing treatment. Cast iron should be preferred for complex structures subjected to normal loading, when these structures are to be made large in numbers.

It does, however, have several disadvantages. One major disadvantage is the time and cost taken to produce a finished casting. Again care has to be taken at design stage to ensure no abrupt changes in section thickness. Most manufacturing stages involve the moving of the component either in or outside the factory.

2. Mild steel weldments:

since 1950's mild steel weldments have been used more and more as a machine tool structural material. They have a high stiffness and the strength is also high. Values of properties of steel are listed in table. It has lower weight compare to cast iron. If necessary, in mild steel structures thin wall sections can be used. While with cast iron the wall thickness is limited by the accuracy of casting. Steel should be preferred for simple, heavily loaded structures, which are to be manufactured in small numbers; this is due to the fact that in lightly loaded structures the higher mechanical properties of steel cannot be fully exploited. This material too has some disadvantages.

The material damping is low and mild steel weldments have a marked tendency to 'ring'. Friction points are sometimes built-in friction is high and cast iron or plastic insets have to be used to reduce friction to avoid 'pick-up'. Again for this material, manufacturing times are long. This material will rust, too. Long-term dimensional stability has not been verified to the same degree as cast iron. Finally, combined welded and cast structures are becoming popular, now days. They are generally used where a steel structure is economically suitable but is difficult to manufacture owing to the complexity of some portions; these complex portions are separately cast and welded to the main structure

3. Granite:

Granite is used for surface tables and measuring machine structures. Its internal damping is better than that of cast iron. Its wear properties are good. It is reputed to be very stable dimensionally. Granite has a number of disadvantages. It is becoming more and more scarce. It takes a long time to cut it out to size, grind and lap it to shape. There are many types of granite, but most absorb water and the surrounding air humidity affects its dimensional stability and thus geometrical accuracy.

4. Epoxy concrete:

It is a new material specifically developed over the past two decades for high precision machine tool structure. It is the mixture of binding agent reaction resin and the hardener together with carefully selected and mixed aggregates. It is completely new technology as compared with those of the materials mentioned above. Epoxy concrete offers great design freedom, similar to cast iron. It has outstanding damping properties – better than traditional concrete. It costs approximately the same as steel reinforced concrete or even less. Epoxy concrete does not expand and contract with change in humidity, as does ordinary concrete. Again various material properties can be controlled in epoxy concrete by the type of mixture chosen. Epoxy concrete has a very high long-term dimensional stability. Values of some properties and comparison of above discussed material.

5 Manufacturing Considerations, Problems and Constraints :

Another important factor for deciding the choice of material concerns the problems of manufacturing that are associated with the use of steel or cast iron structures.Wall thickness: For a given weight of the structure, high strength and stiffness can be achieved by using large overall dimensions and small wall thickness. Thus walls of minimum possible thickness should be employed. Generally, reduction of wall thickness in cast iron structures is restricted by process capability and depends upon the size of the casting in case of cast iron. cast structures as the technological constraints are much less.

Steel structures in which the wall thickness is less than that of the cast structure by up to 50% are known as thickwalled structures. They are made of 10-12 mm thick plates and are easy to manufacture, but they are not particularly effective from point of view of economy of metal. Walls of different thickness can be welded more easily than cast structure, transition from one thickness to another (if $t1/t2 < 1.5$) is accomplished by means of a fillet radius, of proper value.

Machining allowance for cast structures are generally larger than for weld steel structures, this is essential to remove the hardened skin of casting and also to account for casting defects, such as inclusions, scales, drops, etc., that result due to the falling of sand into the mould cavity. A welded structure can, if required, be easily repaired and improved. Any corrections in a cast structure are much more difficult. This property of steel structures is particularly useful in preparing a prototype.

Economic considerations

The final selection of material for structure will in most cases rest upon which of them provides for a lower cost of the structure. Correct selection can be made only on the basis of a comprehensive analysis of various factors, some of which are listed below: Economy of metal: Here it is important to remember that although the weight of the finished steel structure may be low, the actual metal consumption may be high; this is due to the fact that whereas holes in castings are obtained with the help of cores, those in welded structures have to be machined. This results not only in scrap but also in additional labor cost. • Cost of pattern and welding fixtures. Cost of machining.

Basic Design Procedure for Machine Tool Structure :

In order to design a particular machine tool structure, it is first essential to draw up its design diagram. Machine tool structures have, as a rule, highly complicated profiles. In designing the structure of a machine tool a number of requirements must be respected. These are the possibility of placing the whole range of work pieces into the machine, the necessary ranges of travel, sufficient room for chips, room for all mechanisms and for hydraulic, electric and other equipment, the possibility of easy assembly of the structure and of its parts and of subsequent dismantling, easy access for the operator wherever necessary, and the limitation of thermal distortions of the structure. Further, it is necessary to design all parts of the frame with such shapes and of such dimensions as to ensure suitable rigidity of the frame.

According to various kinds of forces, which occur during the machining operation, various specifications of requirements on stiffness may be stated. These forces will be classified into four groups corresponding to four different criteria.

1. Deformations caused by weight forces:

During the movement of the individual parts of the structure the distribution of their weights and of the weight of the work piece varies. Consequently the deformations of the frame vary. The criterion is that any deviations arising do not disturb the prescribed geometric accuracy of the machine tool.

2. Deformations caused by cutting forces :

During the operation the cutting force varies and its point of application moves. In consequence, the deformations of the frame will vary causing deviations of the form of the machined surfaces. This effect may be limited by decreasing the cutting conditions and consequently the output of the operation. Cutting force depends upon the work piece material; machining parameters, wear of cutting tool etc. For a designer a knowledge about the nature and direction of the force and the point where it acts on the structure is often more important than a very precise knowledge of its magnitude.

3. Forced vibrations :

In the machine tool disturbing periodic forces occur. They are caused mainly by the unbalance of rotating parts and by errors of accuracy in some driving elements. They excite forced vibrations, which result in the waviness of machined surfaces. The criterion is to limit forced vibrations so as to achieve to the required surface quality.

4. Self-excited vibrations :

Under certain conditions, generally connected with the increase of the machining rate self-excited vibrations occur and these are energized by the cutting process. They cause unacceptable waviness of the machined surface and endanger the strength and life of the parts of the machine and of the tools. The criterion is that in the required range of operations and of cutting conditions self-excited vibrations shall not occur and the cutting process must be stable.

The individual criteria are almost independent of one another. Nevertheless, experience shows that criterion 4 prevails and if it is satisfied then criterion 2 and often also criterion 1 and 3 are more than fulfilled. The problem of stability of the frame against self-excited vibrations energized by the cutting process is not only the most important one but also the most difficult. All four criteria determine requirements on some resulting stiffness, static or dynamic, between the tool and the work piece. By analyzing this resulting stiffness, requirements on the individual parts of the frame may be derived.

Members of cutting machine tools are designed mainly on the basis of stiffness and stability. And thus deflection and deformation of all components along the line of action of forces should be a minimum. As already stated, machine tool structure can be broadly divided into three groups. In drawing the design diagrams for structures of each group the following guidelines may be useful:

Group 1: Structures like beds and columns with fully or partially closed thin box profiles or consisting of two walls connected by parallel and diagonal stiffeners may be analyzed as statically indeterminate thin-wall bars.

Group 2: Closed box type structures like housing of speed and feed boxes are designed for forces perpendicular to the walls, as the latter have sufficient stiffness in their own plane.

Group 3: Supporting structures like tables knees, etc. which are generally loaded normal to their base plane analyzed as plates. Under general conditions of compound loading, most of the machines tools structures are analyzed as elements subjects to bending in two perpendicular planes and torsion. It was pointed out earlier also that the basic design requirement of machine tools is their stiffness. The common design strategy for machine tool structures can therefore be summed up as:

1. Design for bending stiffness,

2. Designing for torsional stiffness, and

3. Checking dimensions for sufficient strength due to bending and torsion.

The design of a structural member is determined by its use. There are three principal cases:

1. The structural member is to be designed with respect to stiffness for which shape is the criterion. From the viewpoint of strength the member may then be over dimensioned. Several members in machine tools fall in this group i.e. bed, column etc. for those parts which are designed on the basis of stiffness, the dynamic behavior is of special importance i.e. chatter in cutting machine tools.
2. The structural member is to be designed with respect to strength. Deformations must remain within allowable limits.
3. The structural member is to be designed with respect to both stiffness and strength.

Profiles of Machine Tool Structures

During the operation of the machine tool, a majority of its structures are subjected to compound loading and their resultant deformation consists of torsion, bending and tension or compression. Under simple tensile or compressive loading, the strength and stiffness of an element depend only upon the area of cross-section. It is known from classical mechanics of elastic bodies that in the case of bending and torsion it is possible to decrease the requirement on material by a suitable choice of the form of the cross-section, by increasing the second moment of area at constant area of the cross section i.e. at constant weight of the element. Another typical feature of machine tools is the rather small value of the length to width ratio of their parts. Shape and strength are interrelated and when this fact is disregarded, damage often occurs. However, the deformation and stresses in elements subjected to torsion and bending depend additionally, upon the shape of the cross-section. A certain volume of metal can be distributed in different ways to give different values of inertia and sectional modulus. The shape that provides the maximum moment of inertia and sectional modulus will be considered best as it will ensure minimum values of stresses and deformation.

Factors Affecting Stiffness of Machine Tool Structure and Methods to Improve It :

In order to support the work piece and position it correctly with respect to the cutter under the influence of cutting forces it is necessary for the structure to have high static and dynamic stiffness values. Stiffness of the structure is related to its shape of cross-section, cuts and apertures in walls of structures cover plates, arrangement of ribs internally as well as externally etc.

Effect of aperture on torsional stiffness

In the most of the cases machine tools structures cannot be made of complete closed box type profile. There must be apertures, openings for free flow of chips and other purposes. Thus the actual machine tool profile is quite different from closed box profile. The apertures and openings in the structure have an adverse effect upon its strength and stiffness. The effect of aperture on the torsional stiffness of a box-type structure. It can be seen that a circular hole of diameter d affects a length of approximately twice the diameter, i.e. affected length ,P=2Q. An elongated aperture affects the stiffness even more. The reduction in the static and dynamic stiffness of a structure can be partially compensated by using suitable cover plates. Results using cover plates. However, the effect on the torsional stiffness is significant and cover plates do not help much in improving it. For symmetrically placed apertures, the effects can be taken into account by multiplying the torsional stiffness with a reduction coefficient.

Effect of stiffeners (ribs) on stiffness of structure

In a machine tool higher production rate together with good machining accuracy and surface finish can be achieved by aiming at a structural design that ensures a large stiffness to weight ratio. Accordingly, lightweight structures possessing large stiffness can be designed by employing box sections of large overall dimensions and very thin walls. Only limitation being there load carrying capacity in view of increased danger towarping and buckling. This problem, however, alleviated to a large extent by the use of suitable ribbing designs. The stiffness of structures can be improved by using ribs and stiffeners. However, it should be noted that the effect of the ribs and stiffeners depends to a large extent upon how they are arranged. Sometimes, an increase in rigidity due to partitions is negligible and does not compensate for the additional consumption of material and labor required for fabrication. Stiffness/weight ratio is an important factor in deciding the ribbing arrangements.

Effect of End Cover plate on stiffness of structure

Provision of an end cover plate reduces considerably, the deflections in y and z directions of a thin walled column in torsion Fig. 3.4, while in case of bending no significant improvement is observed. Thickness of end cover plate is varied and behavior of structure is observed and after analysis optimum thickness of end cover plate should be taken. The behavior of column with varying thickness of end cover plate. It can be observed that thickness of end cover plate equal to the wall thickness is giving reasonably good result compare to thicker end cover plates.

Effect of ribs arrangement in closed box structure

For the purpose of direct comparison, different ribbing arrangement in case of closed box-structure.It is evident from Table 3.7 that only stiffeners used as shown in arrangements 5 and 6 provide significant improvement in the bending and torsional stiffness of box-type structures . But the most effective arrangement of ribs is ‘diamond shaped ribs’, which is not shown in above table. The results of above table can be realized with graphical plots.

Effect of Vertical Stiffeners

The columns having internal and external vertical stiffeners, which have been analyzed. Each side of stiffener cross section is kept equal to wallthickness of the column. In both cases, vertical internal and external stiffeners, depth of the stiffeners, denoted by ‘a’, is varied in order to analyze effect on performance.

Effect of Horizontal stiffeners

The positions of internal and external horizontal stiffeners. Depth ‘a’ of stiffeners is varied in steps, which also shows results of combination of horizontal and vertical stiffeners, to analyze its effect on performance of structure. Large improvement in torsional rigidity by these stiffeners is due to their resistance to rotation of the column. But under bending loads these stiffeners are less effective. Columns having internal horizontal stiffeners are stiffer than those having external horizontal stiffeners. As earlier said, these stiffeners have very high torsional rigidity, while under bending loads they are less effective.

Improving Stiffness of Open Structures

The stiffness of open structures, such as lathe beds where two plates of structures, top and bottom, connected by ribs, also get affected by arrangement of ribs. The torsional rigidity of open structures has been compared under different stiffener arrangements and the results. The results of table indicate that only arrangements 4 and 5 are effective in terms of stiffness-to-weight ratio of the structure. Arrangements 4 consisting of two parallel shears, which are connected by diagonal ribs, is commonly used in machine tool beds. Finally, stiffness to weight ratio is important factor in deciding the ribbing arrangements. Higher values of stiffness to weight ratio is desirable. Because ribs increase stiffness of structure but it also increase weight on other hand. So to arrive at final arrangement of ribs, one has to see value of stiffness to weight ratio. Again increasing no. of ribs means adding material and so adding cost, finally.

The significance of joints and their orientation upon the overall stiffness of structure:

It is well established that one of the great obstacles to a complete understanding of the static and dynamic behavior of machine tool structure is the inability to take the effects of the joints fully into account. Contribution of various parts of structure in overall flexibility of machine tool, and actual machine tool behavior, as a whole, differs. This is because during analysis of individual structural elements, joint properties of machine tool are not specified; however, it is of much importance. Because resultant force will transfer from one part to another through contact area, which is nothing but a joint, either “fixed” or “sliding”.

Evaluation of Machine Tool Structure

The analysis of static rigidity and dynamic characteristics of machine tool structures is one of the most important factors in designing high-precision and highefficiency machines. In present work, an attempt is made to explore the meaning of analysis, both static and dynamic. In order to evaluate operational efficiency and accuracy of machine tools at the design stage, and finally to optimize the machine structures with respect to the performance, structural analysis using computer programming/software must be conducted.

The extent to which the behavior of the various elements of the machine contributes to its overall performance is by no means fully understood. However, the results of research together with the experience of the user form the basis for the design procedures currently available. The aim of this chapter is to present systematic procedures for the analysis of the machine tool structure – a prerequisite of the sound systematic design. It is useful to know how the actual design will work in actual condition. To achieve perfection in machine tool structure design, one has to check the design alternates for both the conditions, i.e. statically, which considers only time independent parameters, and dynamically, which takes care of dynamic behavior of structure, during actual machining. So in short, we arrive at.

a) Static analysis, and

b) Dynamic analysis of machine tool structure.

Static Analysis

Forces of an essentially static nature result from the static component of the cutting force, the weight of the various machine elements and thermal stresses. The latter source of stressing is not considered here although the methods to be discussed are adaptable to the thermal problem. Thus the static problem is defined as that of obtaining a measure of the deformed shape of the structure under the action of both the cutting force and the distributed gravity force.

Although the changing distribution of the gravity force, due to the movement of the machine carriages and the variable magnitude and direction of the cutting force add to the complexity of the problem this is by far outweighed by simplifications arising from the linear behavior of the stressed structure. If only the static deformation of the structure is of interest it is generally adequate to obtain a measure of the three orthogonal displacements of each selected node.

Whilst a knowledge of the relations of the nodes would lead to a more accurate construction of the deformed shape this is usually unnecessary. However, the formulation of the static characteristics represents the first requirement of more general dynamic analysis and where this is required the inclusion of node rotations will lead to a more accurate assessment of the frequencies and modes of natural vibrations. This is especially critical for the higher modes involving significant rotations of the elements.

Wear of cutting tools

Failure of cutting tools: Smooth, safe and economic machining necessitate prevention of premature and catastrophic failure of the cutting tools • reduction of rate of wear of tool to prolong its life To accomplish the aforesaid objectives one should first know why and how the cutting tools fail. Cutting tools generally fail by, Mechanical breakage due to excessive forces and shocks.Such kind of tool failure is random and catastrophic in nature and hence are extremely detrimental. Quick dulling by plastic deformation due to intensive stresses and temperature. This type of failure also occurs rapidly and arequite detrimental and unwanted. Gradual wears of the cutting tool at its flanks and rake surface.

The first two modes of tool failure are very harmful not only for the tool but also for the job and the machine tool. Hence these kinds of tool failure need to be prevented by using suitable tool materials and geometry depending upon the work material and cutting condition. But failure by gradual wear, which is inevitable, cannot be prevented but can be slowed down only to enhance the service life of the tool. The cutting tool is withdrawn immediately after it fails or, if possible, just before it totally fails. For that one must understand that the tool has failed or is going to fail shortly.

It is understood or considered that the tool has failed or about to fail by one or more of the following conditions. In R&D laboratories ,total breakage of the tool or tool tip(s), massive fracture at the cutting edge(s) excessive increase in cutting forces and/or vibration ,average wear (flank or crater) reaches its specified limit(s) (b) In machining industries ,excessive (beyond limit) current or power consumption ,excessive vibration and/or abnormal sound (chatter) ,total breakage of the tool , dimensional deviation beyond tolerance , rapid worsening of surface finish, adverse chip formation.

Mechanisms and pattern (geometry) of cutting tool wear

For the purpose of controlling tool wear one must understand the various mechanisms of wear, that the cutting tool undergoes under different conditions.

The common mechanisms of cutting tool wear are :

i) Mechanical wear

- thermally insensitive type; like abrasion, chipping and delamination
- thermally sensitive type; like adhesion, fracturing, flaking etc.

ii) Thermochemical wear

- macro-diffusion by mass dissolution
- micro-diffusion by atomic migration

iii) Chemical wear

iv) Galvanic wear

In diffusion wear the material from the tool at its rubbing surfaces, particularly at the rake surface gradually diffuses into the flowing chips either in bulk or atom by atom when the tool material has chemical affinity or solid solubility towards the work material.

The rate of such tool wear increases with the increase in temperature at the cutting zone. Diffusion wear becomes predominant when the cutting temperature becomes very high due to high cutting velocity and high strength of the work material. Chemical wear, leading to damages like grooving wear may occur if the tool material is not enough chemically stable against the work material and/or the atmospheric gases. Galvanic wear, based on electrochemical dissolution, seldom occurs when both the work tool materials are electrically conductive, cutting zone temperature is high and the cutting fluid acts as an electrolyte.

In addition to ultimate failure of the tool, the following effects are also caused by the growing tool-wear increase in cutting forces and power consumption mainly due to the principal flank wear increase in dimensional deviation and surface roughness mainly due to wear of the tool-tips and auxiliary flank wear (Vs) odd sound and vibration worsening surface integrity mechanically weakening of the tool tip

Essential properties for cutting tool materials

The cutting tools need to be capable to meet the growing demands for higher productivity and economy as well as to machine the exotic materials which are coming up with the rapid progress in science and technology. The cutting tool material of the day and future essentially require.

The following properties to resist or retard the phenomena leading to random or early tool failure :

i) high mechanical strength; compressive, tensile, and TRA

ii) fracture toughness – high or at least adequate

iii) high hardness for abrasion resistance

iv) high hot hardness to resist plastic deformation and reduce wear rate at elevated temperature

v) chemical stability or inertness against work material, atmospheric gases and cutting fluids

vi) resistance to adhesion and diffusion

vii) thermal conductivity – low at the surface to resist incoming of heat and high at the core to quickly dissipate the heat entered

viii) high heat resistance and stiffness

ix) manufacturability, availability and low cost.

Tool Life Definition:

Tool life generally indicates, the amount of satisfactory performance or service rendered by a fresh tool or a cutting point till it is declared failed.

Tool life is defined in two ways : In R & D : Actual machining time (period) by which a fresh cutting tool (or point) satisfactorily works after which it needs replacement or reconditioning. The modern tools hardly fail prematurely or abruptly by mechanical breakage or rapid plastic deformation. Those fail mostly by wearing process which systematically grows slowly with machining time. In that case, tool life means the span of actual machining time by which a fresh tool can work before attaining the specified limit of tool wear. Mostly tool life is decided by the machining time till flank wear, VB reaches 0.3 mm or crater wear, KT reaches 0.15 mm.

In industries or shop floor: The length of time of satisfactory service or amount of acceptable output provided by a fresh tool prior to it is required to replace or recondition.

Measurement of tool wear The various methods are :

i) By loss of tool material in volume or weight, in one life time – this method is crude and is generally applicable for critical tools like grinding wheels.
ii) By grooving and indentation method – in this approximate method wear depth is measured indirectly by the difference in length of the groove or the indentation outside and inside the worn area .
iii) Using optical microscope fitted with micrometer – very common and effective method
iv) Using scanning electron microscope (SEM) – used generally, for detailed study; both qualitative and quantitative .
v) Talysurf, specially for shallow crater wear.

Taylor's tool life equation

Wear and hence tool life of any tool for any work material is governed mainly by the level of the machining parameters i.e., cutting velocity, (VC), feed, (so) and depth of cut (t). Cutting velocity affects maximum and depth of cut minimum. The usual pattern of growth of cutting tool wear (mainly VB), principle of assessing tool life and its dependence on cutting velocity.The tool life obviously decreases with the increase in cutting velocity keeping other conditions unaltered as indicated. If the tool lives, T1, T2, T3, T4 etc are plotted against the corresponding cutting velocities, V1, V2, V3, V4 etc a smooth curve like a rectangularhyperbola is found to appear. When F. W. Taylor plotted the same figure taking both V and T in log-scale, a more distinct linear relationship.

Errors due to variation of cutting force

A body behaves as if all its mass in concentrated at its center of mass

A body supported by bearings, behaves as if all the bearings are concentrated at the center of stiffness

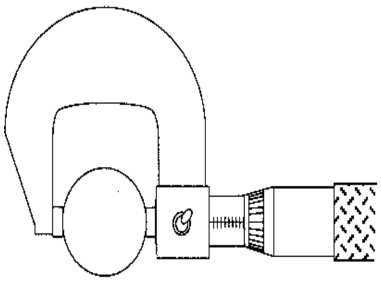
- The point at which when a force is applied to a locked-in-place axis, no angular motion of the structure occurs
- It is also the point about which angular motion occurs when forces are applied elsewhere on the body
- Found using a center-of-mass type of calculation (K is substituted for M)

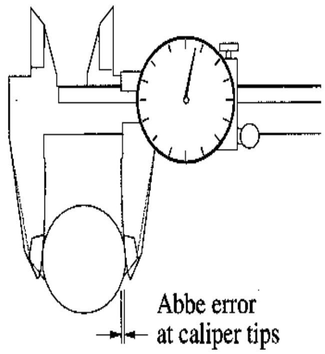
Errors act through the There are MANY types of errors that can affect machine accuracy

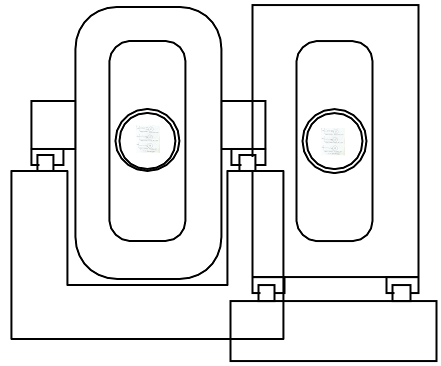
- Abbe (Sine) Errors
- Cosine Errors
- Linear Motion Axis Errors
- Rotary Motion Axis Errors
- Rolling Element Motion Errors
- Surface Finish Effect Errors
- Kinematic Errors
- Load Induced Errors
- Thermal Growth Errors

Abbe(sine) Errors

- ***Thermal: Temperatures are harder to measure further from the source***



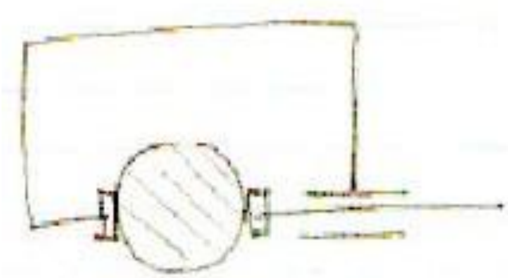


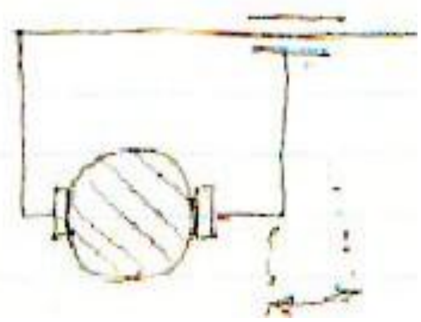


- Geometric: Angular errors are amplified by the distance from the source

- Thinking of Abbe errors, and the system FRs is a powerful catalyst to help develop DPs, where location of motion axes is depicted schematically

Example: Stick figures with arrows indicating motions are a powerful simple means of depicting strategy or concepts



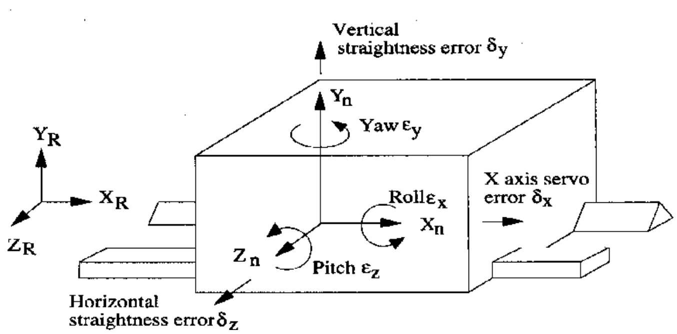


Cosine Errors

- ***Cosine errors have much less effect than Abbe errors, but they arestill important, particularly in large systems***

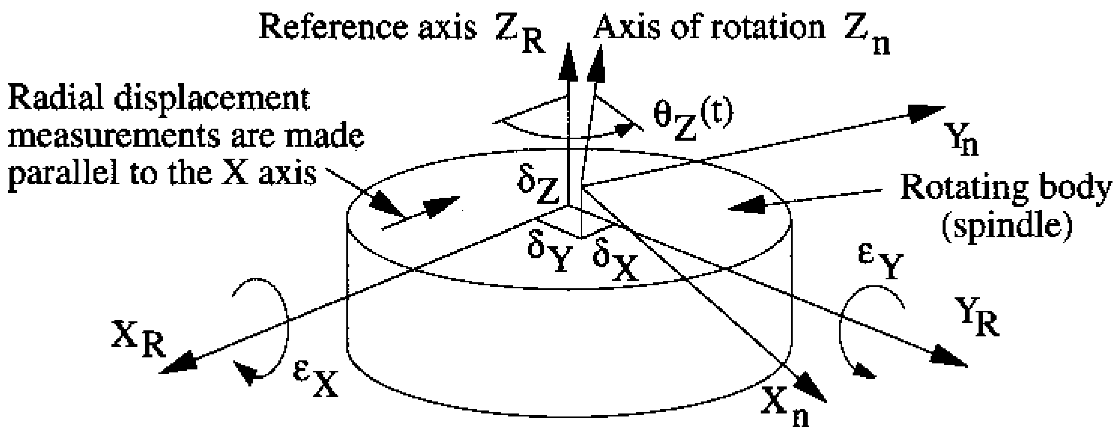
Linear Motion Axis Errors

Every linear motion axis has one large degree of freedom, and five small error motions



Rotary motion Axis Error

Every rotary motion axis has one large degree of freedom, and five small error motions

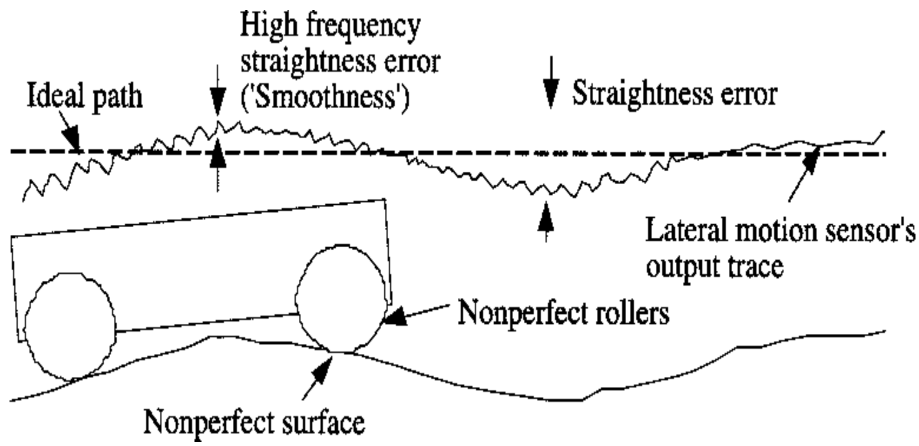


Rolling Element Motion Errors

Rolling element bearings average out surface finish errors by their numbers

-Separators can reduce error (noise) by a factor of 5 or more

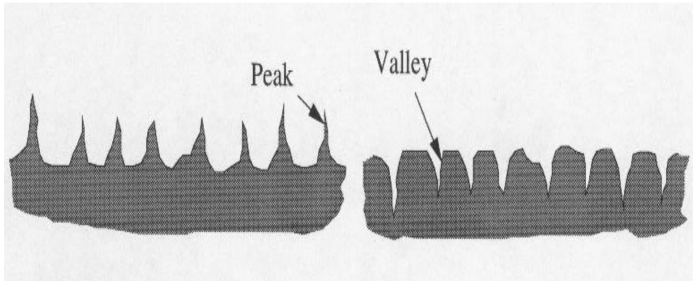
Rolling element bearings are still subject to form errors in the surface



Surface Finish Effect Errors

- Surfaces with sharp peaks wear quickly (positive skewness)
- Surfaces with valleys wear slowly
  - Both surfaces below have equal average roughness (Ra values)

- Ask machine element suppliers to provide part samples….measure the



surfaces and compare!

- ***Sliding contact bearings tend to average out surface finish errors and wear less when the skewness is negative***
  - The larger the positive skewness, the greater the wear-in period
- ***Hydrostatic and aerostatic bearings are insensitive to surface finish effects Surface finish should be at least 10x greater (e.g., 1 μm) than the bearing clearance (e.g., 10 μm).***

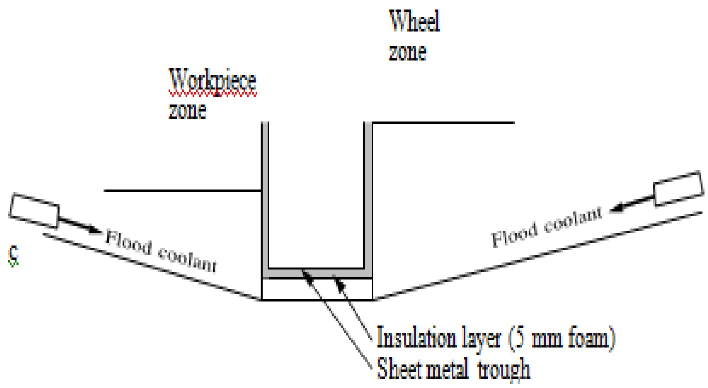
Thermal Growth Errors

- ***Very troublesome because they are always changing***
- Very troublesome because components' heat transfer coefficients vary from machine to machine
- Design strategies to minimize effects:
  - Isolate heat sources and temperature control the system
  - Maximize conductivity, OR insulate
  - Combine one of above with mapping and real time error correction
- May be difficult for thermal errors because of changing boundary conditions.
  - Combine two of the above with a metrology frame

Conduction

- Use thermal breaks (insulators)
- Keep the temperature the same in the building all year!
- Channel heat-carrying fluids (coolant coming off the process) away

- ***Convection: Use sheet metal or plastic cowlings***
- Radiation:
  - Plastic PVC curtains (used in supermarkets too!) are very effective at blocking infrared radiation
  - Use indirect lighting outside the curtains, & never turn the lights off!
- ***Always ask yourself if symmetry can be used to minimize problems***
- ***62.5 grams of prevention is worth a kilo of cure!***


Wheel
zone
Workpiece
zone
Flood coolant
Flood coolant
Insulation layer (5 mm foam)
Sheet metal trough

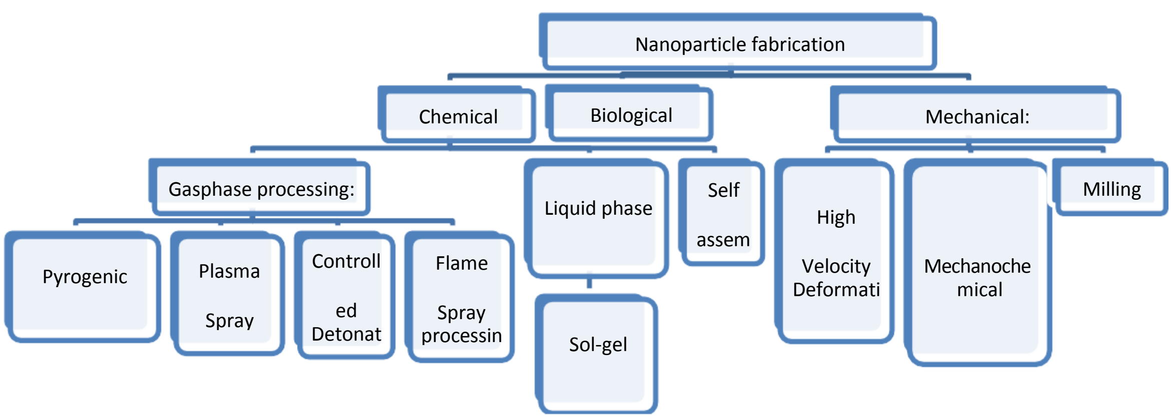
UNIT-III

PRECISION MACHINING

Nanotechnology has been steadily receiving significant attention during the past decades both in scientific and engineering communities as well as in popular media. Nanometer-scale materials or nanomaterials often have distinctly different physical and chemical properties in comparison to their bulk form. Indeed several size-dependant phenomena makes nanomaterials attractive in terms of potential applicability compared to their bulk form, justifying the importance and attention such research is receiving.

Methods of obtaining nanomaterials vary and mostly depend on the material, its morphology and also the targeted applications. Currently physical techniques are usually limited to specialized vapor deposition techniques for obtaining epitaxial deposition of thin layers and clusters of materials with precision down to atomic layers on various substrates. Other techniques extensively involve solution chemistry and are favored when synthesis of large quantities of nanomaterials at relatively lower costs is required.

In the past decades chemical routes for nanomaterials fabrication have matured and there is a very good control over the size, shape and thus the properties of nanomaterials. Applications of nanomaterials cover a wide range of fields including bio-medicine, electronics, Optoelectronics, water purification, automobile industry etc. Traditionally nanomaterials investigated for electronic applications were fabricated by variations of vapor deposition techniques. Various methods used for fabrication of nanomaterials



Fabrication of nanomaterials

Overview of the two methods:-

The focus of this paper is to investigate the fabrication of nanomaterials by using various techniques and to evaluate their merits and demerit shows the two different approaches used for synthesis of nanomaterials.

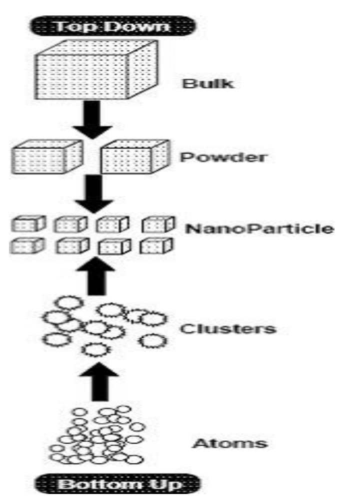
Top-Down Method:

Mechanicanosynthetic Methods *:-* Mechanical methods offer the least expensive ways to produce nanomaterials in bulk. Ball milling is perhaps the simplest of them all. Ball milling produces nanomaterials by mechanical attrition in which kinetic energy from a grinding medium is transferred to a material undergoing reduction. *Compaction and consolidation* is an industrial scale process wherein nanomaterials are "put back together" to form materials with enhanced properties. Metallic alloys can be made this way. Many top-down mechanical methods are utilized by industry.

Thermal methods form a nebulous category and we try and focus on those that provide heat to a fabrication process. Of these, *electro spinning* is a means to form nanothread materials. *High energy methods* are those that require an excessive input of energy– whether in the form of heat, electricity or solar energy. *Arc discharge* was the first controlled means of making carbon nanotubes. *Laser ablation* and *solar flux* also work well. The problem is control of quality and potential upscale. We include *plasma methods* in this category. Plasmas are created in high-energy situations (high potential bias, etc.).

The problem with this and other high- energy methods is upscale potential– with the possible exception of solar flux methods as sunlight is easily available. Top-down *chemical fabrication* methods are always easy to upscale and many, such as *anodizing*, are widespread industrial processes. *Lithographic methods*, as we all know quite well, although energy intensive and requiring expensive equipment and facilities, are top-down methods capable of producing for the most part micron-sized features. Lithography is the means of making printed circuits and computer boards for several decades now.

The push to miniaturize in the future is a costly venture as more powerful sources (high energy electron beams and shorter wavelength sources), support equipment and facilities are required. *Nanoimprint lithography* (NIL) is lithography but not according to typical standards. It is more like *template synthesis*. A template material is made first and then stamped into a soft polymeric material to form a pattern. The template stamp is formed by top-down method as is the stamped material. Nanosphere lithography utilizes latex spheres that form a template matric. So, we can call these techniques template process as well.



Top down and bottoms up approach

Bottom-Up Method:

Bottom-up methods start with atoms or molecules to form nanomaterials. *Chemical vapor deposition* is a gas-phase process by which reactive constituents react over a catalyst or pre-templated surface to form nanostructure materials. The economical synthesis of carbon nanotubes is by CVD. Precursors in the form of methane or acetylene or other carbon source gases are passed over Co, Fe or Ni catalyst. Once decomposed into carbon, nanotubes are formed by the catalyst particle. *Atomic layer deposition* is an industrial process that is capable of coating any material, regardless of size, with a monolayer or more of a thin film. *Molecular beam epitaxy* and *MOCVD* are other industrialized processes that are considered to be bottom-up.

Liquid phase methods are also numerous. It is within the liquid phase that all of *self-assembly* and synthesis occurs. Liquid phase methods are upscalable and low cost.*Electrodeposition* and *electroless deposition* are very simple ways to make nanomaterials (dots, clusters, colloids, rods, wires, thin films). *Anodizing* aluminium to make a porous oxide structure is a simple way to make nanomaterials. The porous structure is a nanomaterial as well as any material synthesized within. Porous membranes are in many ways the ultimate template. A new generation of nano bottom-up methods have made the scene. Many of the new methods are both inexpensive and offer high throughput. Disadvantages include establishment of long-range order. The new methods include nanolithography (dip pen method) and nanosphere lithography

Current semiconductor manufacturing is at a cross- road: optical lithography will face tremendous dif- ficulty as it approaches 50 nm critical dimensions, and projection tools become prohibitively expensive. In addition, to match the continually shrinking crit- ical dimensions and increasing complexity, three- dimensional (3D) multi-level nano-device architecture becomes a necessity to increase the speed and to reduce the budget of power consumption and com- munication delay. These challenges call for a fundamental change in the nano-manufacturing paradigm.

Along with the development of photo-lithography process, continuous efforts have been devoted to explore the alternative nano-manufacturing technologies. Several key technologies, such as X-ray lithography, e-beam lithography, near-field optical lithography, and multi-photon optical lithography, have been developed but yet to be matured before large-scale industrial applications, due to the inherent drawbacks of high cost or low through- put of these technologies. Imprint lithography is targeting to solve the cost and throughput issues of the nano-manufacturing. It has been developed to allow patterns on a wafer to be stamped from a master with high resolu- tion and throughput. This well-developed technology has been used to fabricate nanoscale devices and cir- cuits.

However, the intrinsic drawbacks of imprinting are apparent: it is hard to achieve reliable resolution down to <20 nm (for soft lithography, the resolution is even poorer due to the elastic nature) more importantly, nanoimprint is mostly limited to 2D fabrication, due to the high pressure involved dur- ing the imprinting. A competing approach, bottom-up fabrication such as chemical self-assembly, is based on molecular recog- nition and uses molecules/nano-dots rods as ‘building blocks’. Two main drawbacks of the self-assembly process are evident: it is a homogeneous process and cannot make complex patterns for devices, and it generates defects due to its thermodynamic nature.

To tackle the above mentioned challenges, the Center for Scalable and Integrated NAno-Manufacturing (SINAM) sets its goal to establish a nano-manufacturing paradigm that will combine fundamental science and technology in nano- manufacturing, and will transform laboratory science into industrial applications in nano-electronics, biomedicine, and in traditional industries. Clearly, the wide range and high complexity of nano-engineered systems and products requires an integrated multidis- ciplinary nano-manufacturing research strategy. To embark on this important mission, SINAM is founded among six partner institutes – including UCLA, UC Berkeley, Stanford, UCSD, UNCC, and HP labs (Figure 1) – and the center has developed a strategic network with other participants from industry, govern- ment laboratories/institutes, other peer NSF centers, professional associations, as well as business analysis firms. On the basis of the strategic network, SINAM will further establish a consortium to closely inter- act with industry partners. SINAMs research efforts will not only focus on top-down nano-manufacturing aiming toward critical resolution of 1–10 nm, but also emphasize on exploring novel hybrid approaches, in combining the top-down and bottom-up technologies to achieve massively parallel integration of hetero- geneous nanoscale components into higher-order structures and devices. As the ultimate goal, SINAM will develop system engineering strategies to scale up the nano-manufacturing technologies.

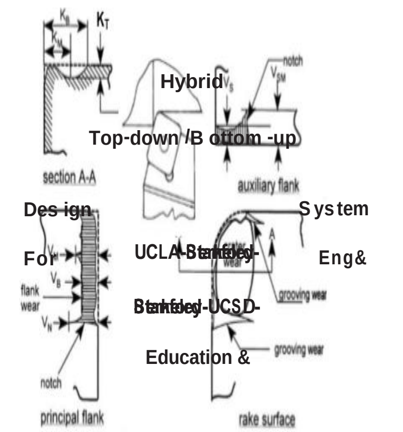


Fig. 3.2.1 (a) Geometry and major features of wear of turning tools

Theme organization of SINAM.

Top-down nano-manufacturing:

Amazingly surface plasmons at visible frequencies can have wavelengths down to nanometers. SINAM will develop a revolutionary approach, plasmonic imag- ing lithography (PIL). In PIL, surface plasmon optics and lenses open up an exciting avenue for ultrafine resolution imaging. These plasmonic lenses convert free space waves into surface waves, thus allowing unprecedented resolution of 1–10 nm in the final opti- cal image. In effect, the plasmonic elements will act as the final objective lens for imaging a mask in a geometrical optical imaging system. These surface plasmonic waves can then be used to expose photo- resist at resolution of 10–50 nm. SINAM will develop 3D nano-manufacturing based on layer-by-layer PIL approach for various materials and structures.

It is well established that the resolution is determined by the wavelength of the light used in the lithography. However, less recognized is the fact that optical wavelength can be changed; for example, in glass wave- length is shorter than in vacuum. Moreover, it can be much shorter indeed when light forms a surface wave (plasmon) on metals. We could be misled into believing that the Rayleigh optical resolution criterion is limited by the vacuum wavelength, but it is actually the modal wavelength of the propagating lightwave that is deci- sive. Frequency *versus* wave-vector and wavelength for surface plasmons are indicated in Figure 2.

The preliminary feasibility of plasmonic lithogra- phy with 150 nm resolution has been demonstrated in Figure 3 (Werayut et al., 2003). Given a modest writing speed of 200 µm/s, we expect the PIL will be capable of producing 20–40 wafers of 12 in. diameter per hour, compared with 10–20 wafer/h throughput in today's optical lithography in semiconductor foundries. This will make the PIL a highly competitive nanofabrication technique of high-speed, high-resolution, and low-cost compared with other techniques.

In addition, an ultra-molding and imprinting (UMIL) technology is proposed which promises the nano-manufacturing at 1 nm resolution. The key to investigate UMIL is the usage of epitaxially grown superlattices to make 1–10 nm molds in 2D appli- cations that require molecular level resolution. A multi-layered Si/SiGe superlattice can be deposited sequentially onto the substrate followed by a CMP planarization on the side wall. SiGe layers are then selectively etched back from a Si/SiGe superlattice, leaving the silicon fins as an imprinting mold. The advantage of UMIL technique is that the width and pitch of the lines are precisely defined by the epitax- ial layer with thickness ranging from 0.5 to 20 nm. As shown in Figure 4, the preliminary results of 4–8 nm imprinted feature has been demonstrated.

Top down and Bottom up Engineering are two different design methodologies used for design of complex engineering systems. You probably use one, both or a combination of these methods on a daily basis without consciously thinking about it. Both design methods have their individual advantages and disadvantages when applied to Systems Engineering. Understanding the differences can help select the most cost effective approach or, if the approach has already been selected for you, help you identify what issues you are likely to expect.

In short bottom up engineering is probably simpler and initially more flexible to change. It allows a faster initial learning curve on the basics and can be great whilst getting some base level knowledge. Top down engineering is more reusable and repeatable with lower whole of life costs. It has greater initial complexity but enables faster design iterations with less ongoing engineering requirements. Perhaps it's a kick back to our university days ("Bottoms Up!") or perhaps because engineers like solving problems more than planning on solving problems, that the Bottom Up approach is our usual first tactic. However bottom up engineering becomes more difficult and costly to change the further into a design you go.

Top Down Engineering

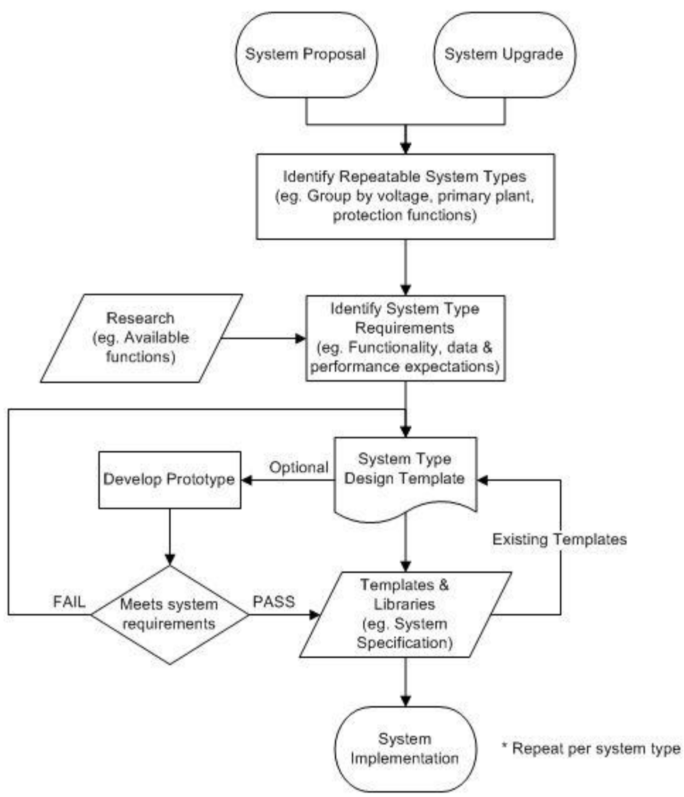
As mentioned Top Down design is more about being reusable and repeatable with lower whole of life costs. It has greater initial complexity and starts with the big questions like:

- What does the end product look like in terms of layout and functionality?
- Can the overall system be broken down into repeatable/reusable subsystems or components?
- Can these subsystems be broken down further describing their functionality?

- What are the performance requirements of the individual subsystems?
- What data is expected out of the system and how should it look (including naming, timing and precision specifications)?

As top down is more interested in the "What" than the "How" it typically has greater flexibility for changing subsystem components and implementation tools later. eg. swapping one IED model for another that better implements your specified functionality. Top down sets firm goal posts for pass/fail criteria during product research, procurement, prototyping and commissioning stages.

- Methodical more efficient design approach
- Simplification of design iterations
- Reduced whole of life costs
- Repeatable/reusable engineering process
- Results can be simulated early to meet requirements
- Increased initial costs
- Increased initial design time
- More easily applied to greenfield sites



Example of Top Down Engineering Flow

Templates can be used as building blocks for larger Templates by repeating the process to create a library of products that meet the functional specifications. Modular systems could be implemented from multiple templates.

Bottom Up Engineering

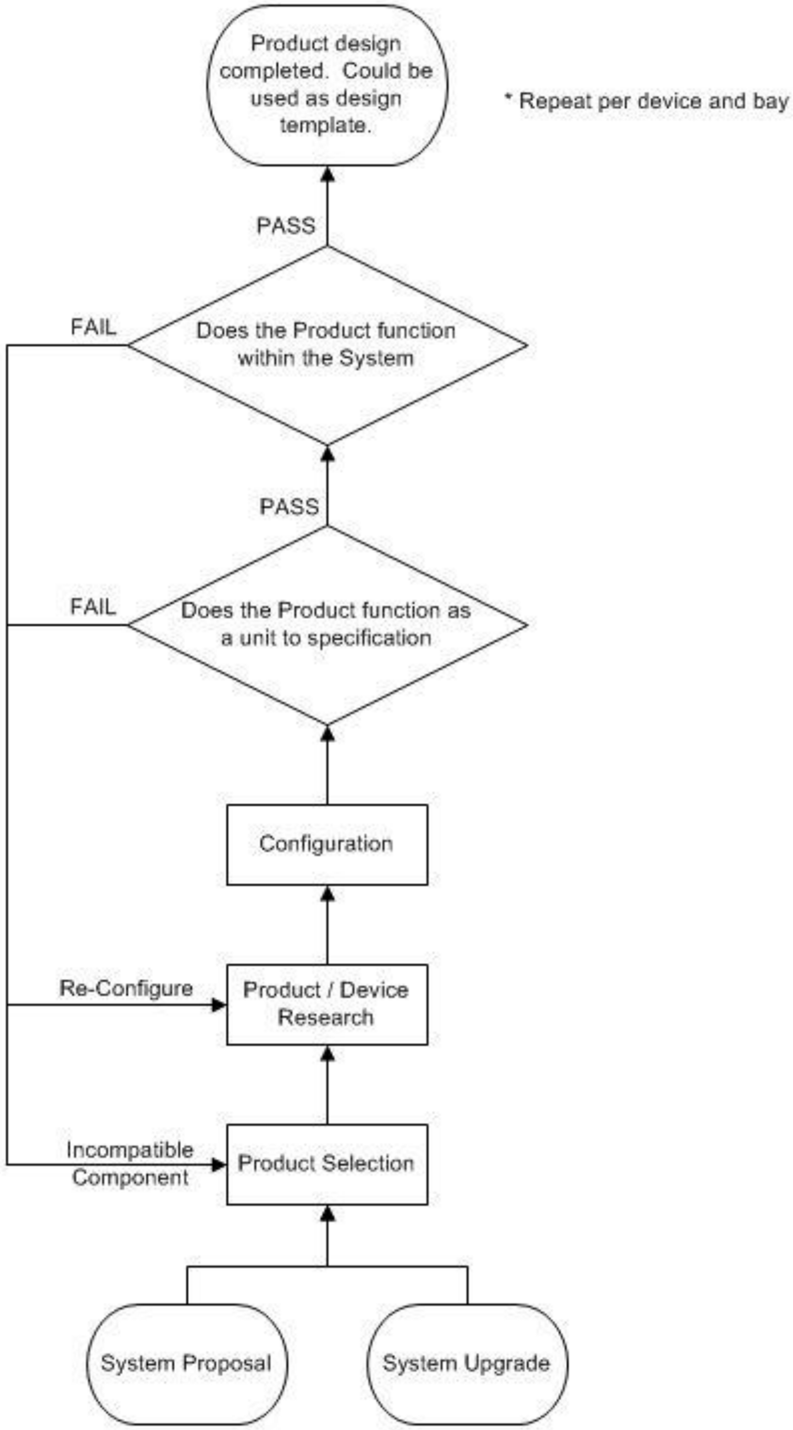
Most Bottom Up projects start with a conversation along the lines of "We have this old relay that has failed and we want to replace it with this new one. Can you make it work?" They will even put extra emphasis on the words **old** and **new** to make one sound the villain and the other the hero. The bottom up engineering method is essentially a "start with a product and make it work" approach. On occasions when issues are discovered late in the process you may find yourself committed to a product and then end up negotiating system performance requirements with stakeholders that are less than ideal.

Some initial questions that can lead you down the Bottom Up approach are:

- Are we replacing a product that has failed in service? The device that was here was performing fine.
- I don't really know much about this product and I'm not sure what I want but how do I make it work?
- Is there a System Specification in place that we just need a new product for?
- Is this a minor system upgrade with no System Specification for the current implementation?
- Do we need to reverse engineer the legacy system to confirm documentation and performance criteria?

The Bottom up Engineering approach commences with System Integration of a lower level component via an iterative approach into a more complex system. Iterations tend to be evaluated via a pass/fail approach on perceived or specified performance criteria. This approach is ideal for a minor System Engineering upgrade or replacement (with or without a previously developed System Specification) and legacy systems that are often lacking adequate records and documentation. In some circumstances reverse engineering may be necessary to discover data and analysis of the System being upgraded or replaced.

- Design begins with the practical application of the project
- Best applied to brownfield sites or "one offs" (in most cases)
- Informal learning environment (practical problem solving)
- More rapid results on simplistic designs
- Good for product familiarity and product research (depending on how soon you discover "features" of a product)
- Reduced implementation costs for minor projects
- Change management for engineering standards is significantly more difficult (if possible at all)
- Changes to the system architecture increase impact (costs) the further into the design you go (sometimes significantly)
- Completed system results are not available until late in the design



Example of Bottom up Engineering Flow

Methods to Synthesis of Nanomaterials:
In general, top-down and bottom-up are the two main approaches for nanomaterials synthesis.

a. Top-down: size reduction from bulk materials.
b. Bottom-up: material synthesis from atomic level.

Top-down routes are included in the typical solid –state processing of the materials. This route is based with the bulk material and makes it smaller, thus breaking up larger particles by the use of physical processes like crushing, milling or grinding. Usually this route is not suitable for preparing uniformly shaped materials, and it is very difficult to realize very small particles even with high energy consumption. The biggest problem with top-down approach is the imperfection of the surface structure. Such imperfection would have a significant impact on physical properties and surface chemistry of nanostructures and nanomaterials. It is well known that the conventional top-down technique can cause significant crystallographic damage to the processed patterns.

Bottom –up approach refers to the build-up of a material from the bottom: atom-by-atom, molecule-by-molecule or cluster-by-cluster. This route is more often used for preparing most of the nano-scale materials with the ability to generate a uniform size, shape and distribution. It effectively covers chemical synthesis and precisely controlled the reaction to inhibit further particle growth. Although the bottom-up approach is nothing new, it plays an important role in the fabrication and processing of nanostructures and nanomaterials.

Evolution of Nanotechnology in India

The 9th Five-Year Plan (1998-2002) had mentioned for the first time that national facilities and core groups were set up to promote research in frontier areas of S&T which included superconductivity, robotics, neurosciences and carbon and nano materials. Planning Commission supported number of such R&D programmes under basic research (GOI 1998).

However, the thrust came with the launch of "Programme on Nanomaterials: Science and Devices" in 2000 by the Department of Science and Technology (DST). DST launched special initiative to generate and support some end-to-end projects leading to tangible processes, products and technologies after realizing the importance of nanomaterials and their far-reaching impact on technology (DST 2001). In 2001-2002, the DST set up an Expert Group on "Nanomaterials: Science and Devices".

The Government identified the need to initiate a Nanomaterials Science and Technology Mission (NSTM) in the 10th Five Year Plan (2002-07) after taking into consideration the developments in nanotechnology. A strategy paper was evolved for supporting on a long-term basis both basic research and application oriented programmes in nanomaterials (DST 2001).The Tenth Five Year Plan (2002-2007) document identified various areas for mission mode programmes such as technology for bamboo products, drugs and pharmaceutical research, instrument development including development of machinery and equipment, seismology, and also nano science and technology (GOI 2002).

Subsequently, the National Nanoscience and Nanotechnology Initiative (NSTI) was launched in October, 2001 under the aegis of the Department of Science and Technology of the Ministry of Science. The motive of launching NSTI in 2001 was to create research infrastructure and promote basic research in nanoscience and nanotechnology. It focused on various issues relating to infrastructure development, basic research and application oriented programmes in nanomaterial including drugs/drug delivery/gene targeting and DNA chips. Nanotechnology was heralded as a revolutionary technology with applications in almost every aspect of life.

Overwhelmed by the promising prospects of nanotechnology applications and in order to further enhance the visibility of India in nano science and technology, a Nano Science and Technology Mission (NSTM) was envisioned to give desired thrust to research and technology development in this area (DST 2006). The Eleventh Five-Year Plan (2007-2012) categorically mentioned projects to create high value and large impact on socio-economic delivery involving nano material and nano devices in health and disease. The generous Eleventh Five Year Plan Budget allocation of Rs. 1000 crore was earmarked for the Nano Mission when it was launched in 2007 (GOI, 2007).

The scale of nanotechnology's operation has raised concerns over nanotechnology risk and safety aspects with respect to environment and health safety (EHS) as well as its ethical, legal and social implications (ELSI). The World over, countries are vying to establish a regulatory framework to address these concerns. The initiatives in this regard comprise enacting new regulations or amending existing regulations/laws for nanotechnology; enforcing safety guidelines for researchers/workers in the laboratories in universities/research centres or companies; and establishing a global standard.

In the US, the Environmental Protection Agency (EPA), under the Toxic Substances Control Act (TSCA), has been mandated to regulate nanomaterials. A task force on nanotechnologies has been active within the Food and Drug Administration (FDA) since 2007. The general approach to nanoregulation of FDA is that the existing regulation adequately covers nano forms of substances, though a careful review is generally devoted to nanotech products.

In Canada and Australia, environmental health and safety (EHS) and regulatory issues are receiving increasing resources within their national strategies for nanotechnologies, and the need to adopt a precautionary approach is explicitly stated. There is a growing involvement of authorities in different sectors that are working to develop regulatory, product-specific guidance documents for nanomaterials. The lack of a definition of nanomaterials is considered one of the key gaps to enable regulatory actions.

In Japan, the Ministry of Economy, Trade and Industry (METI), since 2008, has supported a voluntary gathering initiative related to risk management of nanomaterials at industry level. Research reports on occupational health and safety (OHS) issues of nanomaterials have been published by the National Institute of Occupational Safety and Health Japan (JNIOSH).

The Republic of Korea is developing the National Nano-safety Strategic Plan (2011-2015). Moreover, a specific Risk Management platform Technology for Nanoproducts is also at development stage and aims at providing a certification system for nano-related products. Several research programmes on EHS and ELSI.

In Taiwan, within the framework of their Strategic Plan for Responsible Nanotechnology (2009-2014), the Nanomark Certification System has been active since 2004. This is a voluntary reporting and certification scheme that aims to increase public confidence in nanotechnology products.

In Thailand, nanosafety is among the priorities of the national policy on nanotechnologies. A strategic plan on safety and ethical issues is expected to be proposed to the government by the National Nanotechnology Center. This will include plans for the creation of an industrial standards certification for nanotechnologies related products (called NanoQ)

Applications of Nanotechnology with Examples

Sl. No.	Applications	Examples
1.	Energy storage, production, and conversion	• Novel hydrogen storage systems based on carbon nanotubes and other lightweight nanomaterials • Photovoltaic cells and organic light- emitting devices based on quantum dots • Carbon nanotubes in composite film coatings for solar cells • Nanocatalysts for hydrogen generation • Hybrid protein-polymer biomimetic membranes
2.	Agricultural productivity enhancement	• Nanoporous zeolites for slow-release and efficient dosage of water and fertilisers for plants, and of nutrients and drugs for livestock • Nanocapsules for herbicide delivery • Nanosensors for soil quality and for plant health monitoring • Nanomagnets for removal of soil contaminants
3.	Water treatment and remediation	• Nanomembranes for water purification, desalination, and detoxification • Nanosensors for the detection of contaminants and pathogens • Nanoporous zeolites, nanoporous polymers, and attapulgite clays for water purification • Magnetic nanoparticles for water treatment and remediation • TiO_2 nanoparticles for the catalytic degradation of water pollutants
4.	Disease diagnosis and screening	• Nanoliter systems (Lab-on-a-chip) • Nanosensor arrays based on carbon nanotubes • Quantum dots for disease diagnosis • Magnetic nanoparticles as nanosensors • Antibody-dendrimer conjugates for diagnosis of HIV-1 and cancer • Nanowire and nanobelt nanosensors for disease diagnosis • Nanoparticles as medical image enhancers

5.	Drug delivery systems	• Nanocapsules, liposomes, dendrimers, buckyballs, nanobiomagnets, and attapulgite clays for slow and sustained drug release systems
6.	Food processing and storage	• Nanocomposites for plastic film coatings used in food packaging • Antimicrobial nanoemulsions for applications in decontamination of food equipment, packaging, or food • Nanotechnology-based antigen detecting biosensors for identification of pathogen contamination
7.	Air pollution and remediation	• TiO_2 nanoparticle-basedphotocatalytic degradation of air pollutants in self- cleaning systems • Nanocatalysts for more efficient, cheaper, and better-controlledcatalytic converters • Nanosensors for detection of toxic materials and leaks • Gas separation nanodevices
8.	Construction	• Nanomolecular structures to make asphalt and concrete more robust to water seepage • Heat-resistant nanomaterials to block ultraviolet and infrared radiation • Nanomaterials for cheaper and durable housing, surfaces, coatings, glues, concrete, and heat and light exclusion • Self-cleaning surfaces (e.g., windows, mirrors, toilets) with bioactive coatings
9.	Health monitoring	• Nanotubes and nanoparticles for glucose, CO 2 , and cholesterol sensors and for in-situ monitoring of homeostasis
10.	Vector and pest detection and control	• Nanosensors for pest detection • Nanoparticles for new pesticides, insecticides, and insect repellents

Accordingly, on 3 May 2007, a Mission on Nano Science and Technology (Nano Mission) was launched by the DST to foster, promote and develop all aspects of nanoscience and nanotechnology which have the potential to benefit the country. The Mission is steered by a Nano Mission Council (NMC) under the Chairmanship of Prof. CNR Rao. The technical programmes of the Nano Mission are also being guided by two advisory groups, viz. the Nano Science Advisory Group (NSAG) and the Nano Applications and Technology Advisory Group (NATAG). The primary objectives of the Nano-Mission are:

- Infrastructure Development for Nano Science and Technology Research
- Public Private Partnerships and Nano Applications and Technology Development Centres
- Human Resource Development
- International Collaborations

- Academia-Industry partnerships to be nurtured under these programmes (DST 2008).

PrecisionandMicroMachining:

Manufacturing technologies offer plenty of opportunities to improve sustainability by reducing environmental impact or by the more efficient use of resources. Possible improvements in sustainability are related to processes, machines or the overall system. To realize the idea of green manufacturing, all production technologies have to be examined with respect to their possible contribution to improved sustainability.

Sustainability is achieved when the actual consumption rate matches the sustainable rate. Life Cycle Assessment helps to investigate the potential for improvement in order to bridge the gap between today's consumption rates and the needed consumption rate to reach a sustainable state postulated the concept of "technology wedges" that reduce the current consumption rate stepwise aiming at the fulfillment of the sustainability requirements.This approach relies on the basic idea that the sum of many small changes or improvements is equivalent to a major change.

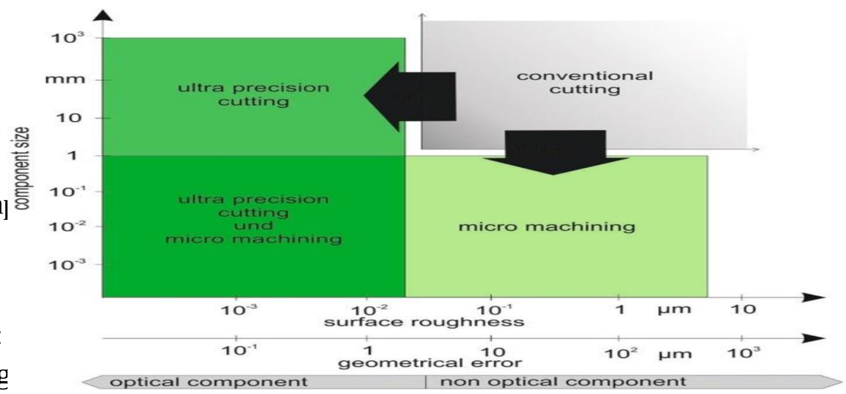
Ultra precision and micro manufacturing are playing a significant role in advanced manufacturing technology. The applications of ultra precision cutting and micro machining are increasing in the last decades and keep fueling market economy. Ultra precision processes allow to achieve surface roughness down to the nanometer scale and are applied for example to manufacture optical components. Micro machining processes on the other hand are adequate technologies to manufacture micro components, micro features, and micro structures.

To the best knowledge of the authors, no comprehensive overview of the sustainability aspects of ultra precision and micro machining has been published. only considered conventional machining processes in their review. The aim of this work is therefore to provide this overview. First, the necessary terminology is defined, followed by an inventory analysis in connection with the explanation of the most relevant factors of sustainability.

Ultra Precision and MicroMachining

Definitions for ultra precision machining and micro machining processes are provided by Mativenga and Brinksmeier in the CIRP Encyclopedia of Production Engineering. Mativenga defined micro machining as a manufacturing technology that involves the use of mechanical micro tools with geometrically defined cutting edges in the subtractive fabrication of devices or features with at least some of their dimensions in the micrometer range (1–999 μm)".

Ultra precision manufacturing is a dynamic field of research whose application possibilities are already enor- mous and yet more to explore.. Furthermore, UPM is increasingly applied in the field of consumer products such as portable electronic devices or automotive fuel-injection devices under high accuracy and tight tolerances. Sophisticated optical parts with high surface finish are for example: optical glancing mirrors for X-ray telescopes, elliptical cylinder mirrors for synchrotron orbital radiation, and electroplated copper memory disks for computers widely used for commercial and industrial applications. Another challenge and opportunity for ultra precision manufacturing lies in manufacturability of new materials.



Com[illegible] ;

For example: [illegible] ry, satellite bearing, inertia navi- g [illegible] not only lowers the cost of optical parts themselves but also for mold cavities of mass production lenses. For example, the production cost of contact lenses both soft and hard can be reduced by manufacturing mold cavities in an ultra precision machining process compared to polishing processes.

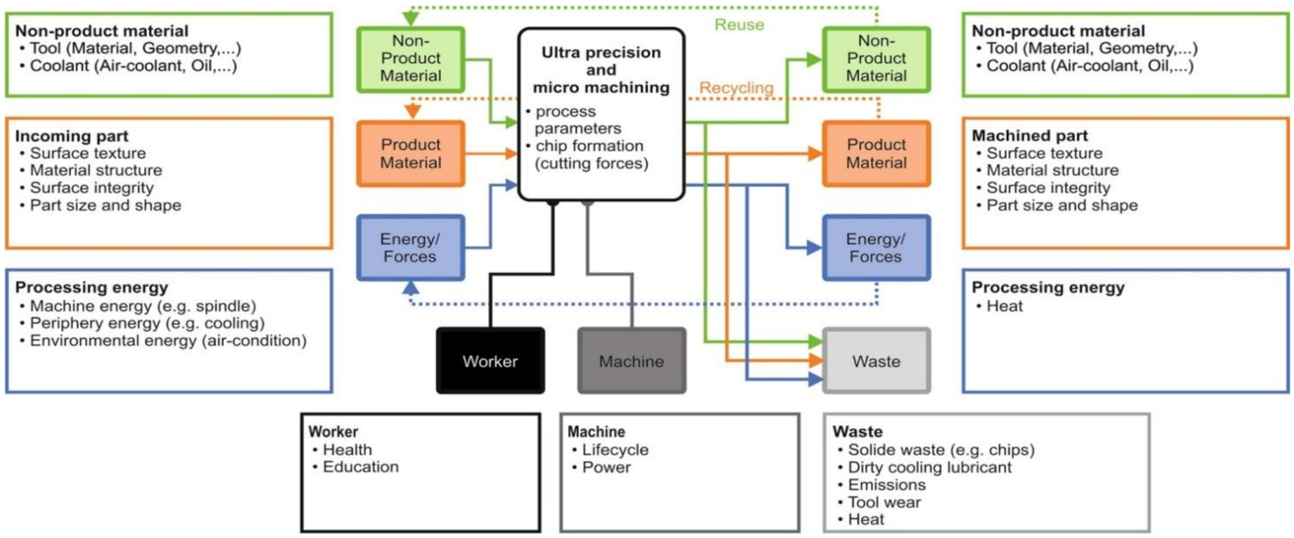
Size Effects

The findings of conventional machining processes cannot simply be scaled down to the dimensions of ultra precision and micro machining. For those, aspects like roundness errors or spindle eccentricities become much more dominant than for the conventional processes. Non scalable effects are commonly referred to as size effects. Vollertsen defined size effects as deviations from intensive or propor- tional extrapolated extensive values of process characteris- tics which occur, when scaling the geometrical dimensions". Size effects can be classified in three categories. The clas- sification of size effects is based on the considered prop- erty, which is responsible for the existing effects and held constant. The three categories are density, shape and microstructure size effects.

An example of density effects are defects contained in the material. Considering conventional workpieces sizes, the number of defects in different workpieces is large so that the mechanical properties are not influenced and deemed to be constant. For very small workpiece sizes on the other hand,the mechanical properties of different workpieces can vary due to few defects. Shape effects result from the fact that certain properties are hinged on the volume or the size of the surface. For example, while the surface of a spherical work- piece is proportional to the square of the radius, the volume is proportional to the cube of the radius. A size effect hence occurs when the regarded property depends on surface and volume. The last category of size effects is based on the fact that it is technologically impossible to scale all micro struc- tural values at the same time in the same magnitude.

Sustainability Aspects in Ultra Precision and Micro Machining

A suitable way to study the sustainability of manufacturing processes is the life cycle inventory analysis. Based on the procedure proposed by Linke to investigate grind- ing, input and output quantities of ultra precision and micro machining.



In- and output diagram of ultra precision and micro machining

Diamond Turning of Parts to Nanometer Accuracy

The use of special machine tools with single-crystal diamond-cutting tools to produce metal optics is called diamond turning. The manufacture of optical surfaces by diamond turning is relatively new compared to the traditional optical-polishing methods. In terms of geometry and motions required, the diamond-turning process is much like the step of ‘‘generating the optical surface’’ in traditional optical fabrication.

However, the diamond- turning machine is a more sophisticated piece of equipment that produces the final surface, which typically does not need the traditional polishing operation. But surface quality produced by the ‘‘best’’ diamond turning does not yet match the best conventional- polishing practice. Yet , the limits of diamond turning for both figure and surface finish accuracy have not yet been reached . There are several important advantages of using diamond turning , including the ability to produce good optical surfaces to the edge of the element , to fabricate soft ductile materials difficult to polish , to eliminate alignment in some systems , and to fabricate shapes difficult to do by other methods If the advantages of diamond turning suggest this fabrication method , then it is important to determine early in the design phase of a project whether the material specified is appropriate for diamond turning.

THE DIAMOND-TURNING PROCESS:

The diamond-turning process produces finished surfaces by very accurately cutting away a thin chip or layer of the surface. Thus, it is generally applicable to ductile materials that machine well rather than to hard brittle materials traditionally used for optical elements. (However, by using a grinding head on a diamond-turning machine in place of the tool , hard brittle materials can be finished .) At very small ef fective depths of cut, brittle materials behave in an apparently ductile manner. This attribute allows fracture-free grinding of glasses and ceramics as well as diamond turning of optical surfaces on materials such as gemanium , zinc selenide , and potassium dihydrogen phosphate (KDP) . In diamond turning, both the figure and surface finish are largely determined by the machine tool and the cutting process. Note, however, that materials characteristics such as grain size , inclusion size , etc . Limit the ultimate surface finish achievable. The tool has to be very accurately moved with respect to the optical element to generate a good optical surface, and the edge of the diamond tool has to be extremely sharp and free of defects.

THE ADVANTAGES OF DIAMOND TURNING:

The advantages of diamond turning over the more traditional optical fabrication technique of lapping and polishing

- It can produce good optical surfaces clear to the edge of the optical element . This is important , for example , in making scanners , polygons , special shaped flats , and when producing parts with interrupted cuts .
- It can turn soft ductile materials that are extremely dif ficult to polish . $ It can easily produce of f-axis parabolas and other dif ficult-to-lap aspherical shapes .
- It can produce optical elements with a significant cost advantage over conventional lapping and polishing where the relationship of the mounting surface—or other feature—to the optical surface are very critical . Expressed dif ferently , this feature of diamond turning of fers the opportunity to eliminate alignment in some systems .
- The fabrication of some optical shapes , such as axicons and x-ray telescopes , would be extremely difficult by methods other than diamond turning

COMPARISON OF DIAMOND TURNING AND TRADITIONAL OPTICAL FABRICATION:

In diamond turning , the final shape and surface of the optical produced depends on the machine tool accuracy , whereas , in traditional optical fabrication , the final shape and surface of the optical element are produced by lapping and polishing with an abrasive- loaded lap . The dif ferences between diamond turning and traditional optical fabrication can be summarized by describing diamond turning as a displacement - controlled process versus a force - controlled process for traditional optical fabrication . 9 The goal in diamond turning is to have a machine tool that produces an extremely accurate path with the diamond tool , hence a displacement-controlled machine . A traditional polishing machine used for optical fabrication depends on the force being constant over the area where the abrasive-loaded lap—or tool—touches the surface being worked . Selective removal of material can be produced by increasing the lap pressure in selected areas or by use of a zone lap . The stif fness of a diamond-turning machine is important because , to control the displacement , it is important that cutting forces and other influences do not cause unwanted displacements . Feeds , speeds , and depth of cut are typically much lower in diamond turning than conventional machining , thus giving lower forces . However , the displacements of concern are also much lower . Thus the stif fness required is as much , or more , of a concern than conventional machining even though the total force capability may be lower for diamond turning.

MACHINE TOOLS FOR DIAMOND TURNING:

In general , the machine tools used for diamond turning are very expensive compared to the equipment needed for traditional optical fabrication . The precision required for diamond turning is beyond the capability of conventional machine tools, thus some of the first diamond-turning machines for fabricating optics were built adapting Moore measuring machines. Although there are some records of machine tools being used to generate optical surfaces as early as the 17th century , most of the effort is modern , accelerated in the 1960s and 1970s with the advent of computer-based machine tool controls and laser interferometer systems used as positional feedback devices . Evans11 has documented much of the history of diamond turning and provides an extensive reference list. Some of the research in metal cutting related to diamond turning and associated machine tools is summarized by Ikawa.Two commercial diamond-turning machines are. Such machines may generally be configured to operate in a normal facing lathe mode (with the tool stationary and the part rotating), as a milling machine (part stationary, tool rotating), or, on occasion, as an optical generator—both part and tool rotating—with the addition of a second

BASIC STEPS IN DIAMOND TURNING:

Much like the traditional optical-fabrication process , the diamond-turning process can be described as a series of steps used to make an optical element . The steps used in diamond turning are

Preparing the blank with all the required features of the element with an extra thickness of material (generally 0 . 1 mm extra material or plating is adequate) on the surface to be diamond turned

1. Mounting the blank in an appropriate fixture or chuck on the diamond-turning machine
2. Selecting the diamond tool appropriate for material and shape of optical component
3. Mounting and adjusting the diamond tool on the machine
4. Machining the optical surface to final shape and surface quality
5. Cleaning the optical surface to remove cutting oils or solvents

Mounting the optical element blank on a diamond-turning machine is extremely important. If a blank is slightly distorted in the holding fixture, and then machined to a perfect shape on the machine, it will be a distorted mirror when released from the fixture. Therefore, fixtures and chucks to hold mirrors during diamond turning need to be carefully designed to prevent distortion. Often the best way to hold a mirror during machining is to use the same mounting method that will be used to hold the mirror in service. It is advantageous in many applications to machine a substrate of an aluminum or copper and then plate on a surface to be diamond turned. The design and application of platings is part science and part art. Many aspects of the platings as related to diamond turning were covered at the ASPE Spring 1991 Topical Meeting. Tool setting—the mounting and adjusting of the diamond-tipped cutting tool—is often accomplished by cutting a test surface , either on the actual mirror blank to be later machined over , or by placing a test piece on the machine just for tool setting . If the cutting tool is too high, or too low, a defect at the center of a mirror is produced. It is possible, using reasonable care and patience, to set the tool height within about 0.1 mm of the exact center. Setting the tool in the feed direction after the height is correct is somewhat more difficult.

SURFACE FINISH IN DIAMOND-TURNED OPTICS:

Surface structure is different for diamond-turned surfaces compared to conventionally polished surfaces. A diamond-turned surface is produced by moving a cutting tool across the surface of the turning component. Therefore, diamond-turned elements always have some periodic surface roughness , which can produce a dif fraction- grating effect , whereas polished optical surfaces have a random roughness pattern . The traditional ‘‘scratch and dig’’ approach to describing surfaces is not meaningful for diamond-turned surfaces. The machining process produces a periodic surface structure directly related to the tool radius and feed rate. The theoretical diamond-turned surface. The formula displayed in the figure for calculating the height of the cusps is

$$\mathbf{h = f^2 / 8R}$$

where , h is the peak-to-valley height of the periodic surface defect , usually expressed in microinch , micrometer , nanometer , or angstrom units—the units have to be consistent with other parameters of the formula but any units will work . f is the feed per revolution , expressed for example in mm per revolution , or thousandths of inch per revolution . R is the tip radius of the tool , expressed for example in mm , fractions of an inch , or thousandths of an inch.

MEASURING DIAMOND-TURNED SURFACES:

The measurement of diamond-turned surfaces presents some difficulties not encountered in conventional optics. In general, all methods used to measure optical surfaces are used on diamond-turned components. Bennett20 presents a complete discussion of surface- roughness measurement. The microscope is an excellent means of qualitatively evaluating diamond-turned surfaces. The illustrate the periodic machined structure of a diamond-turned surface. The feed rate used in producing the surface causes the periodic structure to be about 8 mm per revolution. The measurement of the roughness of optical surfaces is performed by a number of different instruments, both stylus types and optical systems. If a surface is measured with an instrument that produces a profile, several different statistical methods can be used to describe the surface. Figure 6 illustrates a profile and some of the statistical parameters used in describing surfaces. The term peak-to-valley is often used in the diamond-turning shop to mean the difference between the highest and lowest points in any surface trace. The rms and Ra are also used to quantify a measured surface finish.

Although the rms roughness is generally used to describe the finish of optical surfaces , the ay erage roughness Ra is normally used for roughness of machined surfaces . Ra is simply the average of the absolute values of the surface height variations zi measured from the mean surface level. Expressed in equation form, this is

$$R_a = \frac{1}{N}\sum_{i=1}^{N}|z_i|$$

If a surface has a profile that contains no large deviations from the mean surface level , the values of d and Ra will be similar . However , if there are appreciable numbers of large ‘‘bumps’’ or ‘‘holes , ’’ thlargest values of the zi ’s will dominate the surface statistics and d will be larger than Ra.

Diamond turning has been used for many years to commercially produce infrared optics . Some visible and ultraviolet applications are now possible . Moreover , the limits of diamond turning for both figure and surface finish accuracy have not yet been reached . Taniguchi and others have shown that precision in both conventional machining and ultraprecision machining , such as diamond turning , has steadily improved for many decades , with roughly a factor of three improvement-in-tolerances possible every ten years . If this trend continues , we could expect diamond-turning machines with accuracies below 10 nm by the year 2000 . Yet , it is important to remember that it becomes increasingly dif ficult to push the capabilities in this regime . Research in the field of nanofabrication— working with dimensions on the order of molecules , or tenths of nm—may help extend diamond turning into the nanometer range . The technology developed for diamond-turning optics in some industries is now beginning to impact the precision machining of nonoptical components . In the future , the improvement of all machine tools will likely be driven by both optical and nonoptical applications , with diamond-turning machines possibly reaching the accuracy level that will allow visible and ultraviolet optics to be fabricated by machining or grinding without postpolishing.

Stereo microlithography :

In (micro-)stereo lithography a product is created layer by layer by illuminating a photocurable liquid polymer. Where the light hits the liquid, it is transformed into a solid polymer. Stereo lithography processes are limited in terms of resolution, speed of construction and processibility of materials, all of which have restricted broader application for Rapid Manufacturing productivity, material, process and equipment must be specially developed per application. The RM group of TNO has a vast experience in these kind of developments.

Most stereo lithography devices build a product at an average speed of 100 layers per hour. At a layer thickness of 0.1 mm this means that 10 mm of product height is built per hour. Higher resolutions (thinner layers) reduce the building speed even more. The micro-stereo lithography system developed by TNO has a building speed of up to 1200 layers per hour, which means that even at resolution of up to 0.025 mm high construction speed is 60 mm per hour.

Especially for products that require very high precision or surface finish, TNO has developed a process with a resolution of 0.005 mm, making it possible to manufacture small complex products with high-tech product properties. The difference in surface quality between parts built on this system and injection moulded parts can no longer be seen with the naked eye. TNO also develops special materials for micro-stereo lithography, which makes it possible to optimise materials in terms of the functional product requirements. Important aspects are high resolution, construction speed, mechanical properties and durability. TNO also has experience with developing biocompatible and ceramic materials, and materials for lost pattern casting.

The present invention uses micro stereo lithography to provide a new method to fabricate 3D micro or nano structures that can be used for a wide variety of devices such as micro/nano-electronics, biotechnology, MEMS, biomedical devices and in the manufacture of optical devices such as lenses and mirrors. The invention is based on using advanced dynamic mask projection stereo micro-lithography on a photo resist to form a layer, building an object layer by layer, to achieve ceramic micro-stereo lithography for the first time. A 3D solid image, which may be a model designed by CAD software at a PC, is sliced into a series of 2D layers, each 2D layer being displayed at the dynamic mask via micro-mirror deflections projected onto the photoresist.

Machining of micro-sized components:

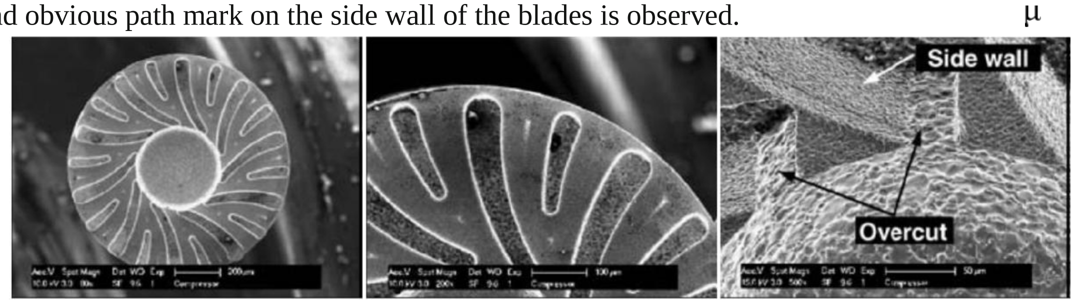
There is a growing demand for industrial products with increased number of functions and of reduced dimensions. Micro-machining is the most basic technology for the production of such miniature parts and components. Micro machining is defined as the ability to produce features with the dimensions from 1 m to 999 m or when the volume of the material removed is at the micro level. Lithography based micro-machining technology uses silicon as material to produce integrated circuitry components and microstructures. However, these methods, in general, lack the ability of machining three-dimensional shapes because of poor machining control in the Z axis. Fabrication using hard and difficult-to-machine materials such as tool steels, composites, super alloys, ceramics, carbides, heat resistant steels and complex geometries for demanding aerospace, mechanical or biomedical applications requires alternative novel methods.

APPLICATIONS OF MICROMACHINING

In recent years, manufacturing industry has witnessed a rapid increase in demand for micro-products and micro-components in many industrial sectors including the electronics, optics, medical, biotechnology and automotive sectors. Examples of applications include medical implants, drug delivery systems,diagnostic devices, connectors, switches, micro-reactors, micro-engines, micro- pumps and printing heads. These micro-system-based products represent key value-adding elements for many companies and, thus, an important contributor to a sustainable economy (Brousseau et al. 2010). As a result of the current trend towards product miniaturization, there is a demand for advances in micro- and nano- manufacturing technologies and their integration in new manufacturing platforms. These platforms must enable both function integration (i.e. combination of different functions) and length-scale integration (i.e. mixing of the macro-, micro- and nano-dimensions) in existing and new products and, at the same time, their cost effective manufacture in a wide range of materials.

Production of Micro-Compressor

It is a two-and-a-half dimensional structure, machined on the tip of a 1-mm diameter cylinder. The Materials used for electrode and work-piece are tungsten carbide and stainless steel, respectively. The centre hole with diameter 0.3 mm is micro-EDM drilled directly with a purchased electrode. The blades are micro- EDM milled with the same tool after it is reduced to a diameter of 40 m by WEDG. The incremental depth for each micro-EDM milling layer is 0.5 m. All the blades show good consistency, and the examined shape accuracy is less than1 m. Furthermore, no taper angle and obvious path mark on the side wall of the blades is observed.

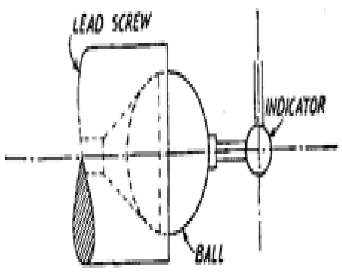


A micro-compressor on a Ø1 mm cylinder: top and detail views

Production of Micro-Turbine Impeller

Another application example is micro-EDM milling of Si3N4-TiN ceramic composite into a miniature three dimensional gas turbine impeller which serves as a key component for a micro power generation system. A close view of the manufacturing process is illustrated in Figure 1.2. The milling of each cavity starts with a Ø1mm WC tool for pocketing using the roughing regime to remove the bulk of the material, then followed by a Ø 0.7 mm tool for wall finishing using the semi-finishing regime.

Due to the extremely low machining speed of the finishing regime, only two steps are performed. The same layer-by-layer machining strategy is applied and the layer thickness for pocketing and wall finishing are 8 and 3 m, respectively. The shape and geometrical accuracy of the cavity is measured on a Coordinate Measuring Machine. All the machined products show good consistency compared to the original CAD model. However, even with rather high MRR, the total machining time for one cavity takes around 20 hours.

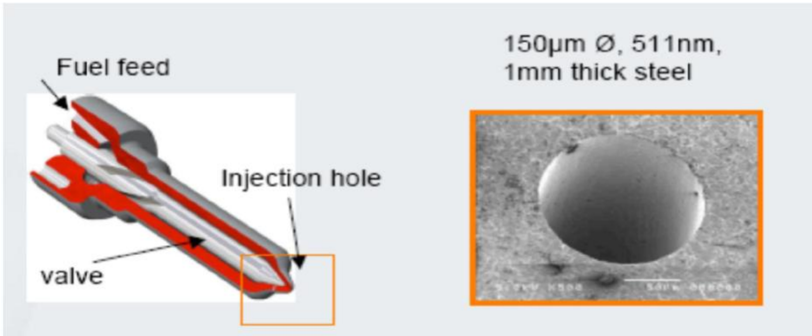


Close views of the Micro-EDM milling process and a finished

Nozzle for Diesel Fuel Injectors

Machining capability of micro-EDM, in conductive materials with high precision regardless of material hardness, creates a wide range of application area with the increasing demand for miniaturized parts and components such as holes, nozzles, and gears. Fuel injector nozzles machined by EDM.

Fuel Injection Nozzle drilling



Inkjet Printer Manufacturing

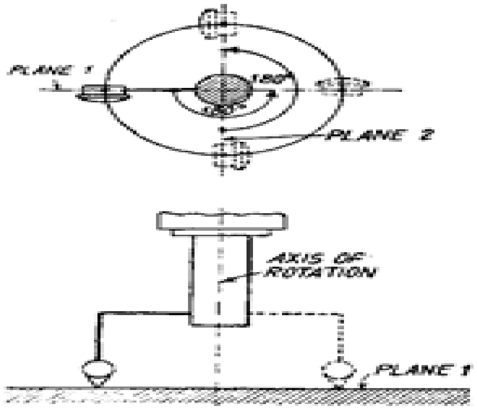
Electroformed nozzles are presently used in number of commercially produced ink-jet printers. The nozzle plate of ink-jet printer head is electroformed. The electroformed nozzles are formed by plating nickel on a mandrel (mould), which defines the pattern of the nozzle, and then the finished product is removed (Bhattacharyya et al 2004). The pulsating current/voltage holds better control over EMM of thin films and foils in the applications of micro fabrication. Through-mask EMM is used to fabricate a series of flat-bottomed conical nozzles in a metal foil as shown in Figure .4. The process is applicable to various materials including high strength corrosion resistant materials such as conducting ceramics.

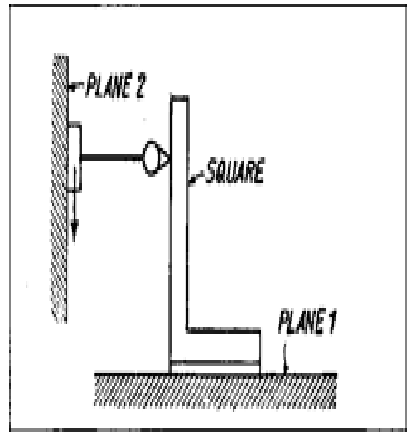
Cooling Holes in Turbine Blades

The main objective of turbine blade cooling is usually to achieve maximum heat transfer coefficients while minimizing the coolant flow rate. Usually the turbine blades are made of a super alloy with a very high melting temperature. By using the lost wax method, these cavities are cast. With this technique, it is possible to produce cavities with a serpentine shape. The other method employs drilling to provide the blades with cooling holes.

These holes are placed in the span wise direction of the turbine blades. In both the cases, the walls of the passage have ribbed surfaces. Although the technique of casting has been improved tremendously over the years, it is still very difficult to develop cavities over large parts. Therefore blades with longitudinal holes are produced using the drilling technique. Since the holes have such a complex shape and their diameter is of only a few millimeters, conventional drilling techniques are not suitable. Moreover the surface of the hole has to be ribbed and the material is very hard. Therefore an electrochemical drilling technique is preferred the high accuracy microholes in turbine blades for generating cooling effect.

Cooling holes in turbine blades





Mirror Grinding Of Ceramics

As ultra-precision parts made of hard and brittle materials are increasingly used these days, the machining of structural ceramics, electronic ceramics, optical glass and heat treated steel has become an important research area. However, the grinding of these hard and brittle materials using conventional grinding wheels is difficult, with ultra-precision grinding even more difficult. Single point cutting tools which have been used effectively in the cutting of ductile materials cannot be used in the machining of hard and brittle materials.

Diamond or CBN (cubic boron nitride) wheels may be used in the grinding of these materials, if submicron precision is not required. Recently, the ultra-precision grinding of these materials has become possible by the development of the cast-iron fiber bonded diamond wheel and the electrolytic in-process dressing (ELID) method. Using this method, a mirror surface of hard and brittle material was achieved. The surface roughness and form accuracy of the machined surface by this method have been realized with nanometer and submicron level, respectively, providing the grinding machine tool has suitable static and dynamic performances.

Therefore, it is important to develop a ultra-precision grinding machine with high stiffness and high accuracy for the mirror surface grinding of hard and brittle materials. Also, the determination of parameters for ELID machining process suitable for specific ceramics and machine tools is important because machine tools for ultra-precision grinding are composed of sophisticated elements, such as ball screws and linear motion guides . In this study, the mirror surface grinding of ceramics, such as Si_3N_4 and AI_2O_3-TiC, was performed. For the grinding operation, a prototype three-axis ultra-precision CNC grinding machine was designed and manufactured. Since the bed of a machine tool contributes much to the overall dynamic stiffness, a resin concrete bed was designed and manufactured to improve the dynamic performance. The characteristics of the grinding machine tool were evaluated by vibration testing as well as by the grinding of hard and brittle materials.

Design of the Grinding Machine Tool:

The spindle and the feed mechanism for the ultra-precision machine tool should have high stiffness and low frictional resistance for high rotational accuracy and smooth feed motion. Also, the structural material must have high stiffness and high damping. Since aero-static spindles have been widely used for ultra-precision machine tools owing to theirs rotating accuracy. High rotating speed and low friction, in this study the air spindle chosen has the driving motor inside of its spindle housing was used. The built-in type motor removes the difficulty of assembling the spindle and the driving motor, although there is a tendency of the spindle to increase in temperature. The strokes of the machine tool are 400 mm along the x-axis, 250 mm along the y-axis and 300 mm along the z-axis, respectively.

The maximum power and speed of the spindle are. l kW, at 3,400 and 10,000 rpm, respectively. The speed of the spindle is changed by frequency converting. The failure load of the air film of the spindle is 600 N in the radial direction and 430 N in the axial direction. Since the cutting force, during grinding with the cast-iron fiber bonded (CIFB) diamond wheel employing ELID dressing, was in the range of 20-50 N, it was decided that the spindle was suitable for mirror surface grinding machine with ELID dressing. Ball screws and linear motion guides were used for the feed mechanisms . The positions of the three axes were controlled by the AC servo motor and the CNC controller, both manufactured by FANUC Co. of Japan. The relative coordinate type was used for the control of the servo motors. The 50,000 pulses per revolution for the table and the saddle and 100,000 pulses per revolution for the headstock were used.

Dynamic Performance Test of the Grinding Machine :

The dynamic characteristics of the spindle and the headstock including the spindle were measured by giving impulse signals and measuring responses . The devices used for the vibration test were the FFT analyzer, impulse hammer, accelerometer and signal amplifier. Figure 3 shows the schematics of the measuring system for the vibration test. The vibration tests of the main spindle were performed in two cases: one case where the accelerometer was mounted on the spindle housing and the other case where the accelerometer was mounted on the spindle nose.

The vibration tests of the two cases gave similar results. When the supplied air pressure was higher than 0.5 MPa, the first natural frequency of the main spindle was 815 Hz, which was much higher than the rotational frequency of the spindle in the working range and then the damping factor of the spindle was 1.1%. spindle. The first natural frequencies in the x- and z-directions were 50 and 142.5 Hz, respectively. Therefore, the occurrence of resonance is expected when the workpieces are machined at a rotating speed of the spindle around 3000 rpm.

To avoid the resonance, the machining of materials was performed at the rotating speed of the spindle away from 3000 rpm. Since it was found that the stiffness of the manufactured machine tool was slightly low, it was concluded that six linear motion guide blocks rather than four blocks which supported the headstock should be used or the next larger size, four linear motion guide blocks, should be used. Also, it was found that the overhang length of the headstock should be decreased a little, in order to increase the bending stiffness of the headstock, which decreases the working envelope. The first natural frequency of the table was 545 Hz, which was much higher than both the rotating speed range of the spindle and the feed rate of the table.

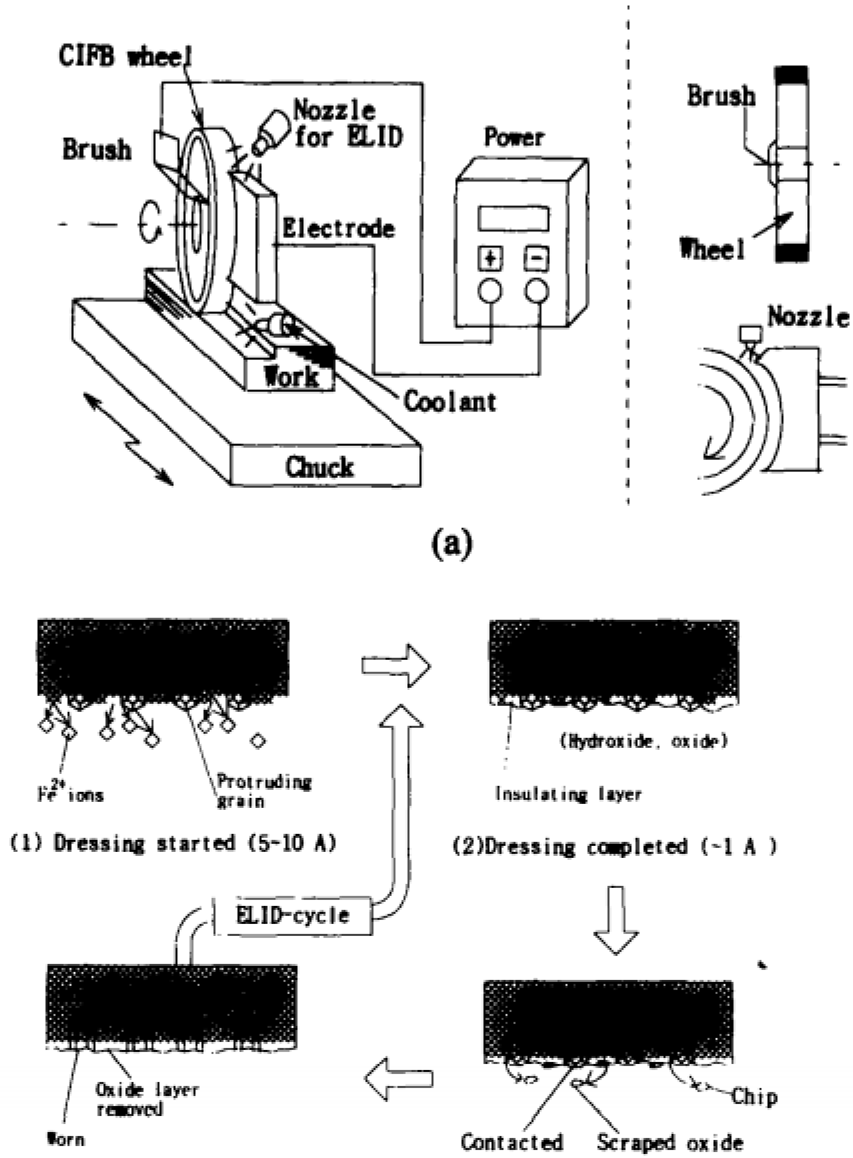
Machining Performance Test:

The grinding process is generally composed of truing, dressing and grinding. The truing and dressing are most important because they affect the wheel performance. However, there are few studies on precision truing and dressing for mirror surface grinding. In this study, a truing process, to precisely correct the roundness and straightness of the wheel, was developed. After the dressing conditions were experimentally evaluated, the grinding tests using the manufactured machine tools were performed. Grinding process for effective dressing of the fine diamond grit grinding wheel, the ELID grinding process was used.

The principle of the ELID grinding process in which the wheel with a smoothly contacted brush has a voltage of +Vc and the electrode fixed below has a voltage of -Vc. In the small clearance of approximately 0.1 mm between the -V~ and the +Ve poles, electrolysis occurs upon supply of conducting grinding fluid (adequate fluid). Figure 5(b) shows a schematic illustration of the mechanism of the ELID-grinding process. During ELID-grinding, the grains are worn out as the grinding process is continued. Also, the oxide layer (Fe203) wears out because the strength of the oxide layer is less than that of the workpiece and then the current between the wheel and electrode is increased owing to the reduction the nonconductor thickness of electricity. Thus, the electrolysis increases and the oxide layer is recovered, which decreases the electrolysis.

Therefore, the protrusion of the grains remains constant during this steady-state electrochemical action. Since the ELID works most effectively when there is a balance between the etched layer and the protrusion of grits on the wheel surface, the cycle described should be optimised according to the grain size of the employed wheel. 4.2. Truing process of the cast-iron fiber bonded diamond wheel The truing of a resinoid bonded diamond wheel is usually performed with a diamond dresser, however, the truing of a cast-iron fiber bonded wheel cannot be done this way because the strength of the cast-iron fiber bonded material is very high. Therefore, the truing process of the cast-iron bonded diamond wheel must be developed for ultra-precision grinding. In this study, a 60 mesh C (carborundum) resinoid bonded grinding wheel were used as the brake truer.

Figure shows a schematic illustration of the brake truer and the truing process using the brake truer, where the truer axis is tilled relation to the grinding wheel axis is also done with the same tilt angle (helical scan grinding). If the feed velocity of the wheel is uniformly maintained during the truing process, both edges of the wheel are rounded. This phenomena is caused by the variation of the normal force between the wheel and the C resinoid bonded wheel due to the contact area between the wheel and the brake truer changing during truing. In this study the velocity of the wheel was changed during truing using an NC program to generate uniform surface of the grinding wheel. Figure shows the stages and velocity profiles of the truing process. From the truing operation, it was found that the wheel was rounded 4 - 5/zm at both edges for case 1, the wheel was rounded 4 p,m at the front edge for the case 2 and the wheel were corrected within 1 txm of the roundness and straightness for the case 3. Figure 8 shows the profile of the wheel section in each case. The roundness and straightness of the wheel were measured by a 1/zm accuracy mechanical-type dial indicator with 1/~m tip radius manufactured by Mitutoyo Co. of Japan.



Basic principle and dressing cycle of the ELID grinding: (a) basic principle; (b) dressing cycle.

The mirror surface grinding of ceramics such as Si3N,~ and AI2Oa-TiC was achieved with surface roughness average (Ra) less than 10 nanometers. For the grinding operation, a three-axis CNC grinding machine tool with resin concrete bed for improved dynamic performances, was designed and manufactured. The performances of the grinding machine tool were evaluated using vibration tests and the grinding of hard and brittle materials.

Ultra precision block Gauges:

Gauge blocks (also known as gage blocks, Johansson gauges, slip gauges, or Jo blocks) are a system for producing precision lengths. The individual gauge block is a metal or ceramic block that has been precision ground and lapped to a specific thickness. Gauge blocks come in sets of blocks with a range of standard lengths. In use, the blocks are stacked to make up a desired length.

An important feature of gauge blocks is that they can be joined together with very little dimensional uncertainty. The blocks are joined by a sliding process called *wringing*, which causes their ultra-flat surfaces to cling together. A small number of gauge blocks can be used to create accurate lengths within a wide range. By using 3 blocks from a set of 30 blocks, one may create any of the 1000 lengths from 3.000 to 3.999 mm in 0.001 mm steps (or .3000 to .3999 inches in 0.0001 inch steps). Gauge blocks were invented in 1896 by Swedish machinist Carl Edvard Johansson. They are used as a reference for the calibration of measuring equipment used in machine shops, such as micrometers, sine bars, calipers, and dial indicators (when used in an inspection role). Gauge blocks are the main means of length standardization used by industry

Gauge blocks are available in various grades, depending on their intended use. The grading criterion is tightness of tolerance on their sizes; thus higher grades are made to tighter tolerances and have higher accuracy and precision. Various grading standards include: JIS B 7506-1997 (Japan)/DIN 861-1980 (Germany), ASME (US), BS 4311: Part 1: 1993 (UK). Tolerances will vary within the same grade as the thickness of the material increases.

- reference (AAA): small tolerance (±0.05 μm) used to establish standards
- calibration (AA): (tolerance +0.10 μm to −0.05 μm) used to calibrate inspection blocks and very high precision gauging
- inspection (A): (tolerance +0.15 μm to −0.05 μm) used as toolroom standards for setting other gauging tools
- workshop (B): large tolerance (tolerance +0.25 μm to −0.15 μm) used as shop standards for precision measurement

More recent grade designations include (U.S. Federal Specification GGG-G-15C):

- 0.5 — generally equivalent to grade AAA
- 1 — generally equivalent to grade AA
- 2 — generally equivalent to grade A+
- 3 — compromise grade between A and B

  and ANSI/ASME B89.1.9M, which defines both absolute deviations from nominal dimensions and parallelism limits as criteria for grade determination. Generally, grades are equivalent to former U.S. Federal grades as follows:

- 00 — generally equivalent to grade 1 (most exacting flatness and accuracy requirements)

- 0 — generally equivalent to grade 2
- AS-1 — generally equivalent to grade 3 (reportedly stands for American Standard - 1)
- AS-2 — generally less accurate than grade 3
- K — generally equivalent to grade 00 flatness (parallelism) with grade AS-1 accuracy

The ANSI/ASME standard follows a similar philosophy as set forth in ISO 3650. See the NIST reference below for more detailed information on tolerances for each grade and block size.

Calculating gauge block length from the data is done in 3 steps:

1. Calculation of wavelength, λtpf, at observed ambient conditions.
2. Calculation of the whole number of fringes in the gauge blocks length from its predicted length and the laser wavelength in ambient air.
3. Calculation of the gauge block length from the whole number of fringes, the observed fraction, wavelength in ambient air, gauge block temperature, and interferometric correction factors

The symbols used are:

λ0 = Vacuum wavelength in µm

λptf = Wavelength at observed conditions t,p,f

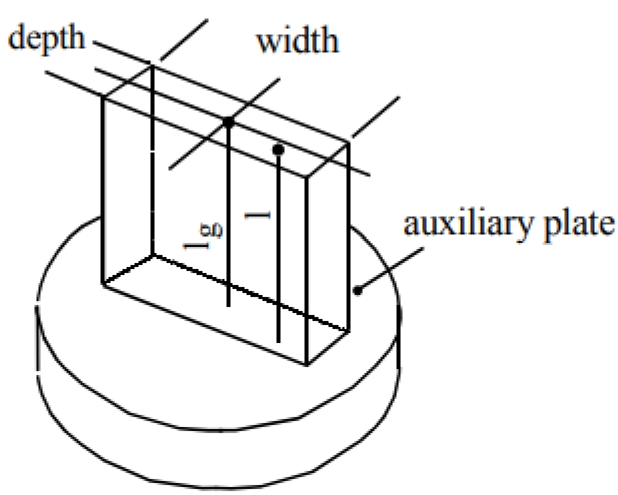
nptf = Index of refraction of air at t,p,f

p = Atmospheric pressure in Pa

t = Temperature in degrees Celsius

f = water vapor pressure in Pa

σ = 1/λ0 in µm.



The length of a gauge block is the distance from the gauging point on the top surface to the plane of the platen adjacent to the wrung gauge block.

Gauge blocks are usually made either from hardened alloy tool steels, ceramics or cemented carbides (such as tungsten carbide or tantalum carbide). Often the carbide has a hardness of 1500 Vickers hardness. Long series blocks are made from high-quality steel having cross section (35 × 9 mm) with holes for clamping two slips together. These are also available in carbon steel material. Steel blocks are hardened and tempered. The hardness is important because it slows down the gauge's rate of wear during use (this is why other kinds of gauges, such as pins, thread plugs, and rings, are also hardened.) The cutting of the blocks to size is accomplished with grinding followed by lapping. Usually no plating or other coating is involved. Blocks are kept very lightly oiled, and are stored and used in dry climate-controlled conditions; unplated, uncoated steel gauge blocks can last for decades without rusting.

How to Select a Gage Block Set:

1. Decide which system of measurement (inch or metric) is most appropriate.
2. Determine the range of measurements that might be made from the desired set.break down the measurements into ranges that are frequently made and infrequently made.
3. Determine the "comfortable range" of a set.
4. Choose a style of block: (Rectangular, Square, or Heavy Duty).
   Note: The choice of
   style may restrict the choice of material and grades.
5. Choose a gage block material.
6. Choose an accuracy grade

UNIT - IV
NANO-MEASURING SYSTEMS

In-process measurement of position of processing point

In order to process a work piece to nanometre-order accuracy, measuring and control techniques of nanometre accuracy or better are essential. Nanotechnology must therefore be considered as an integrated technology of processing, measurement, and control. The measurement techniques used in connection with precision processing measure many characteristics of machined work pieces and machine tool components.

The quantities measured are length, displacement, vibration, run out, figure, surface roughness, etc. The phenomena detected are sound, temperature, mechanical force, light, electromagnetic field, etc. Because of its widespread applications and present status, optical detection is the main theme here. This section discusses some advantages, the present potential, and the future of nanometre-order measurement techniques for in-process or in-situ mode. In process measurement will be desirable at the processing point if possible.

In-process measurement

Measurements for production processes can be classified as follows:

1. pre-process measurement
2. on-machine measurement (or process intermittent measurement, stop-and-measure, insitu measurement, etc.)
3. in-process measurement (or real-time measurement, on-line measurement, during-process measurement, etc.)
4. post-process measurement.

Today's measurement or inspection processes on production lines usually occupy locations between the machining processes or the assembly ones. Rejected parts or products have to be processed again for correction, or sometimes discarded. These inspection processes may be rigorous or brief, total or by sampling, and sometimes omitted. However, large losses may be suffered if rejection of a product happens in the later part of the production line.

So an appropriate arrangement of processes should be designed and operated. In spite of the desire to omit the inspection processes from the viewpoint of simple productivity, they are becoming essential as the requirement for machining accuracy increases. Process control with information from on-machine or in-process measurements will be essential for nanometer order production in the near future, to achieve better accuracy and to increase productivity.

On machine measurement means spatial unification of machine tool and measuring instrument, and in-process measurement means their temporal unification or simultaneous operation. These techniques will make the processing line simple and rational. Examples of in-process measurement and X machining control In-process measurement means measurement during processing and allow real-time control of the process from the measurement signal. For single-point diamond turning, the application of in-process measurement should be easier than for grinding or polishing, because of the simplicity of its form generation mechanism.

Seven laser interferometer position sensors, five differential capacitance gauges and one spindle encoder are used to control the famous LODTM (large optics diamond turning machine)(1). These sensors measure the positions of carriage, workpiece and tool during processing, as well as the angle of the spindle. As the LODTM requires accurate positioning during machining for attaining a machining accuracy of 25 nm, the positions of the machine tool elements are sensed with reference to the metrology frame with a resolution of up to 0.6 nm. Although errors exist in all machine tool elements, the turning accuracy may be determined eventually by the relative, not the absolute, positions of the workpiece and the cutting tool point.

'Workpiece referred form accuracy control' (WORFAC)2 is a simple method to control the relative positioning of workpiece and tool instead of trying to control all the mechanical elements, to increase their individual accuracies, and to improve environmental conditions such as temperature, humidity, and vibration. Figure.1 shows schematically an experiment to demonstrate the feasibility of WORFAC.

A non-contact surface sensor such as a HIPOSS optical stylus (see section 2.5) or a capacitance gauge detects the machined surface of a flat workpiece and feeds the information to a microtool servodrive which controls the tool position by means of a piezoelectric element. The effects of the control in the elimination of disturbances are shown in Fig.2. When the control is off, the machined surface has a profile with the same amplitude as a disturbance wave imposed artificially. This profile is suppressed completely when the servo loop is closed.

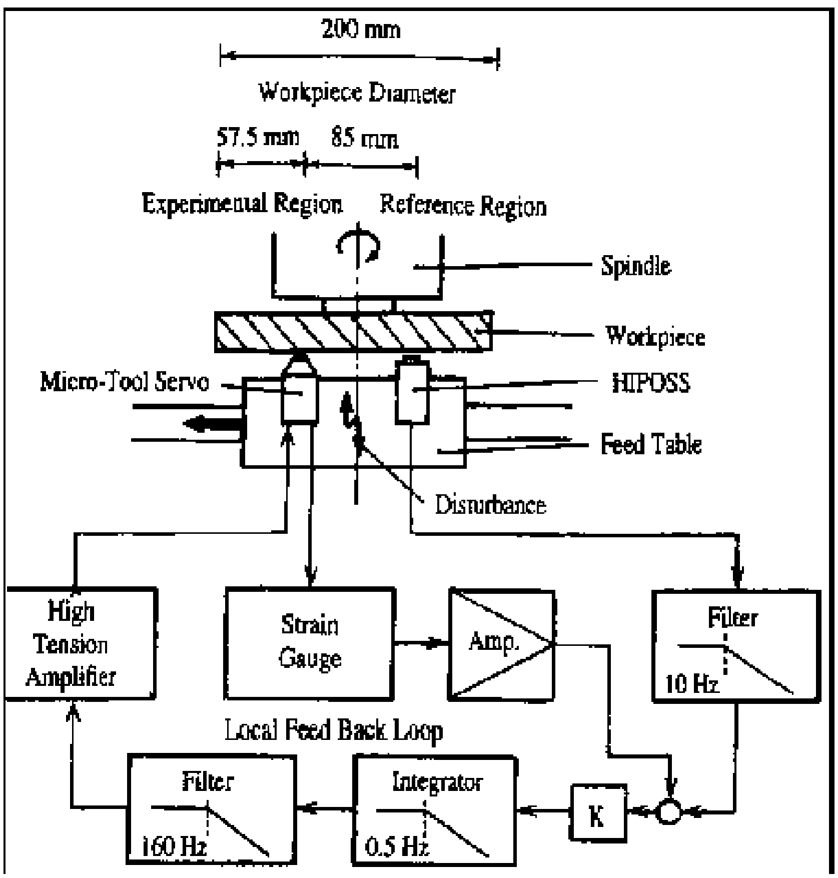


Fig.1. Block diagram of WORFAC experiment.

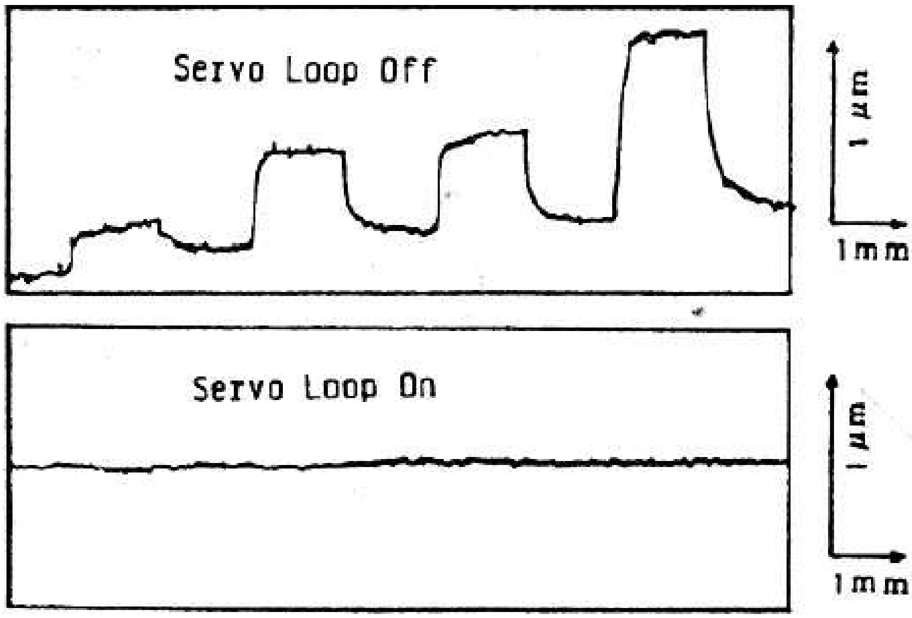


Fig.2 Results of WORFAC experiment: elimination of disturbances.

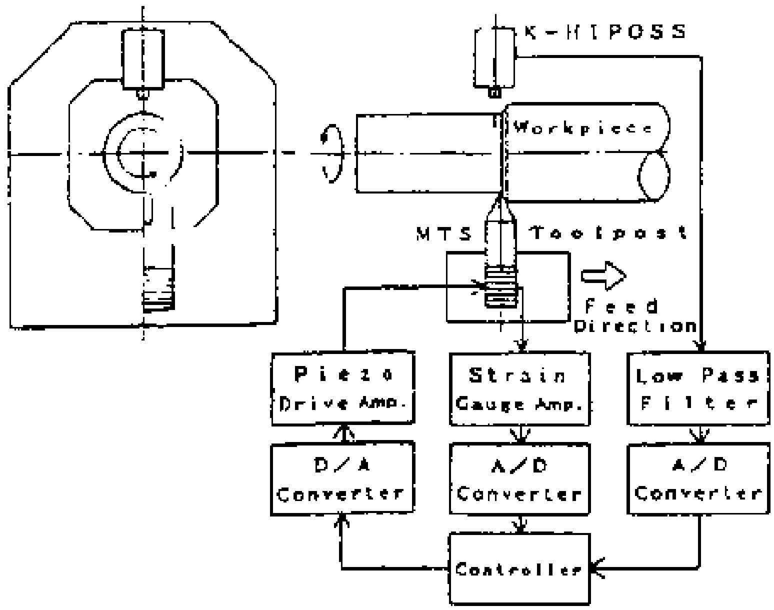


Fig.3. WORFAC experimental set-up for cylindrical turning.

Post-process and on-machine measurement of dimensional features

Post-process measurement is the quality testing of a machined workpiece, usually dimensional measurement such as length, outer and/or inner diameter, hole distance, surface roughness, and surface contour. Such measurements of nanometre accuracy have often been performed using high-accuracy measuring instruments on a vibration-isolated table in an air-conditioned room. However, on a mass production line, this is not a popular processing system and is time consuming.

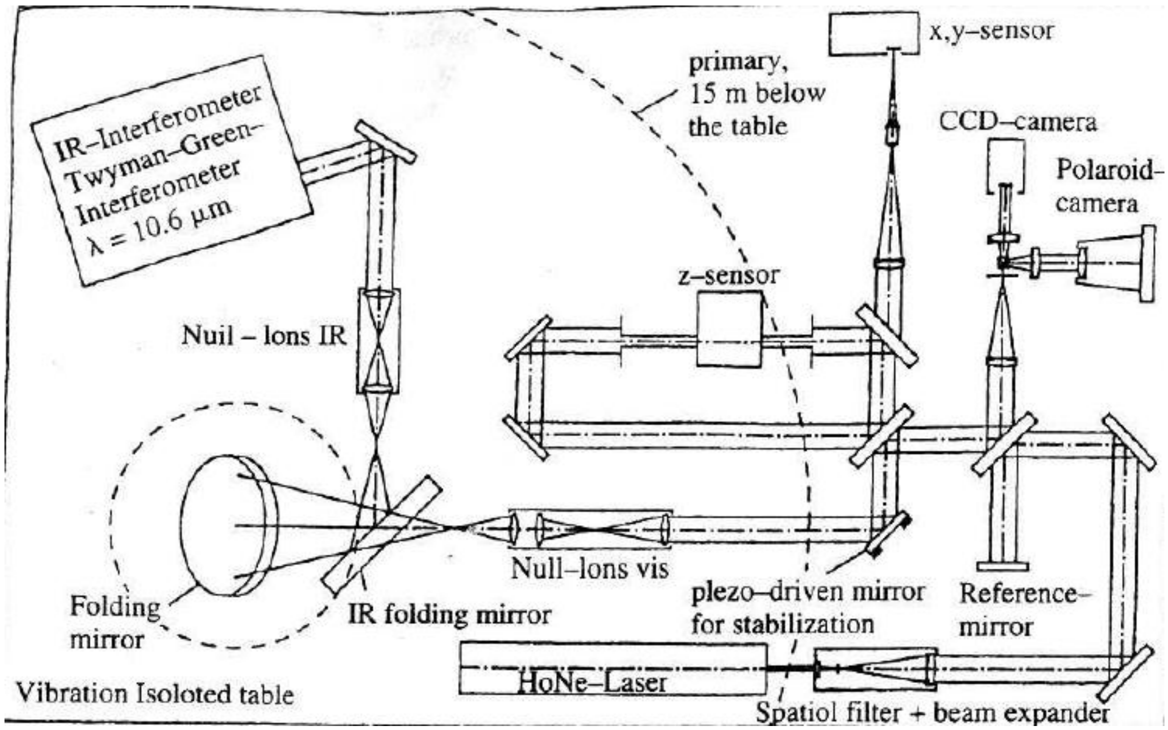


Fig.4 Zeiss system of stabilization of the interferogram for large optics measurement.

On-machine measurement is intermittent or stop- and; measure, in which the measuring instrument is placed on or unified with the machine tool. It is important to keep the workpiece held with a chuck during the measurement so as to be able to reprocess immediately if necessary.

Examples of on-machine measurement

On-machine measurement has been widely practiced in the manufacture of opitical parts. In the polishing of relatively small optical parts, Newton interference fringes formed between a test plate and a workpiece surface are sometimes observed to check the residual error in shape. For large optics, such as telescope primary mirrors, the stop-and-measure method is used from a tall tower.

Movements of the measuring instrument relative to the mirror and air turbulence are the main problems to be solved in order to perform measurements of nanometre-order accuracy, especially for interferometers with temporal scanning. Figure 4 shows a Zeiss solution to the problem(l).

To solve the 10 /tm-range vibration problem, adaptive optics and a new type of interferometer with DMI (direct measuring interferometry) are used simultaneously. The adaptive optics compensates three-axis displacement up to 1000 Hz by a piezo-driven mirror. This may be the first successful application of adaptive optics ever to compensate for air turbulence for practical precision measurement.

Unlike the well-known interferometers with fringe scanning, in which several interferograms are detected and processed to map a wavefront, the DMI interferometer uses only one interferogram with narrow-spaced fringes to calculate a phase map in real time. The phase is determined by calculating a video signal of fringes multiplied with sine and cosine signals at the carrier frequency and subsequent application of a low-pass filter.

Digital pipeline processing gives DMI some advantages, e.g. insensitivity to vibrations and ability to average a large number of wavefronts so as to reduce random errors such as errors from air turbulence. Profile correction for accurate aspherical lens or mirror surfaces is achieved by repeating a figuring cycle of geometrical measurement and corrective polishing.

The system effects corrective polishing by on-machine measurement. The CSSP omits the recheking process by adopting a figuring system having both the measurement and polishing units on a single baseplate. Figure 6 shows the measurement system for the Z-coordinate. The metrology frame from which all displacements, including the X- and Y-coordinates, are measured with interferometric sensors is placed above the measurement area of the baseplate.

A simple experiment has been conducted to make on-machine measurements of a metal mirror surface immediately after machining with an ultra-precision lathe. The cutting tool was removed and the HIPOSS optical stylus was set to make surface measurements. An example is shown in Fig.7, measured with the spindle stopped and the feed slide in operation. Because the slide motion of an ultra-precision lathe is now as accurate as that of the measuring instrument, reliable surface characteristics can be determined by on-machine measurement.

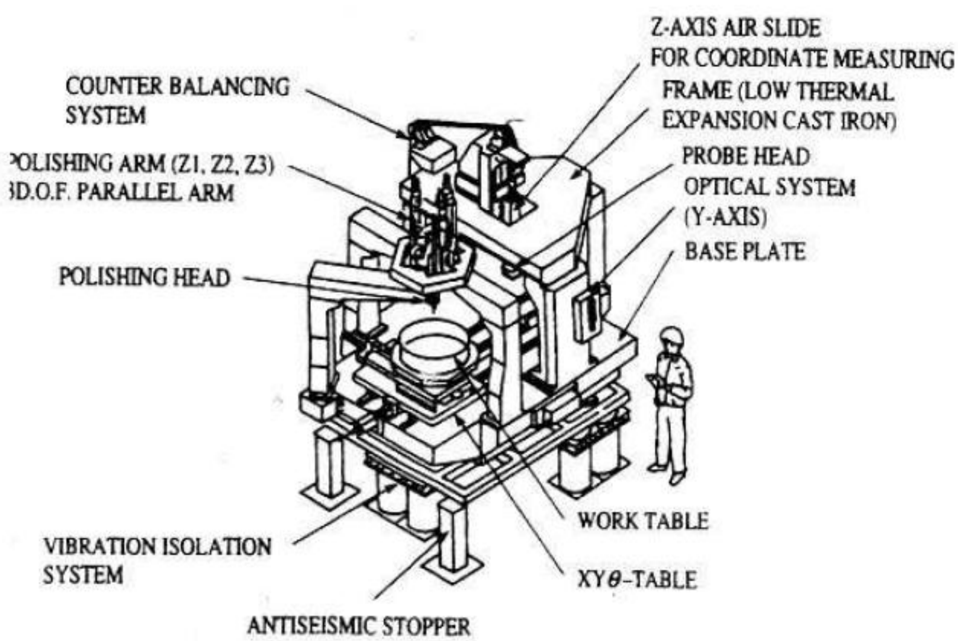


Fig.5. Diagram of the Canon super smooth polisher (CSSP).

To save time and avoid some errors, the CSSP (Canon super smooth polisher) system has been developed, as shown in Fig.5.

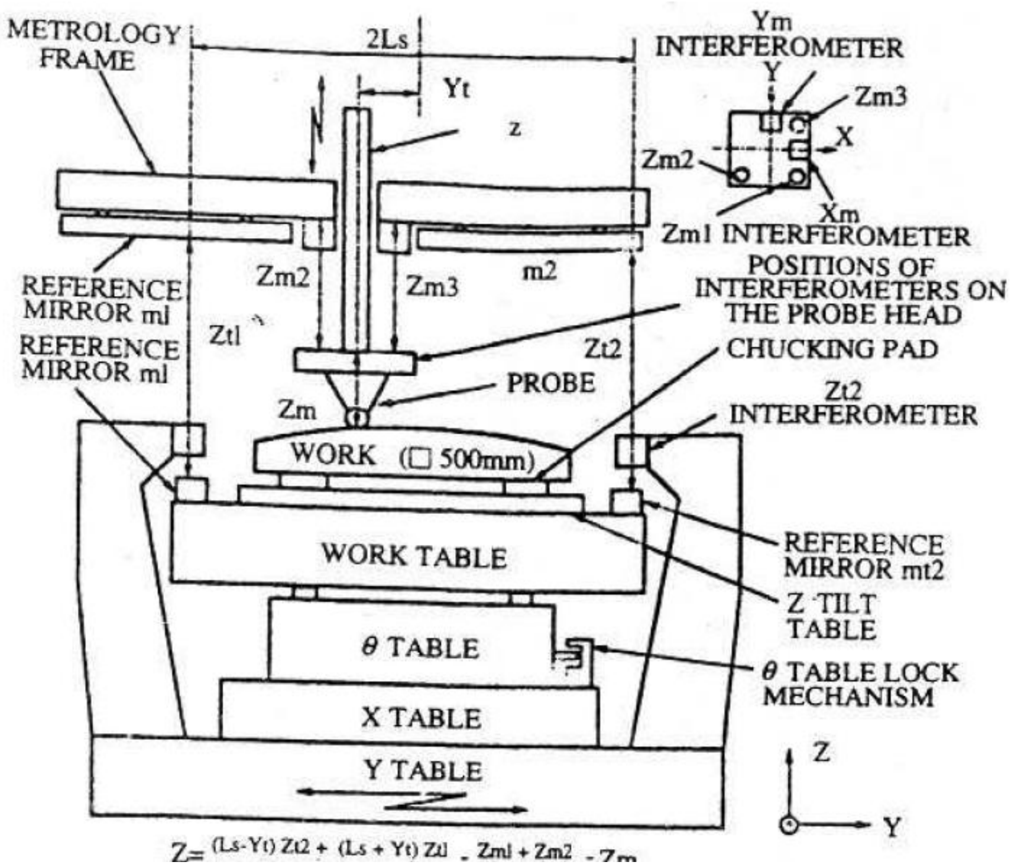


Fig. 6 Z-coordinate measurement system of the CSSP.

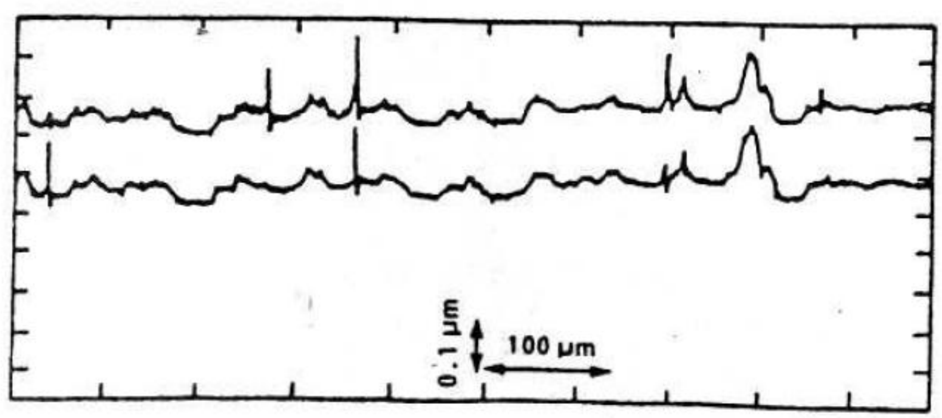


Fig.7. Repeatability of on-machine measurement with the HIPOSS.

Mechanical measuring systems

A mechanical measuring system is one that uses mechanical contact with a solid probe to measure the change in displacement or position (i.e. the mechanical quantity) of the part of a sample that we wish to measure (i.e. the measurement point). A mechanical measuring instrument, therefore, consists of a probe, a device to support the probe while converting its motion into an electrical quantity, and a device to analyse the measured results and display the evaluated value. A typical instrument is the high-agnification profile instrument, which successively measures the surface profile from the motion of a solid stylus. The displacement and position of the measurement point are given by the vertical movement and horizontal position, respectively, of the stylus.

In this section we describe the profile instrument in some detail, to highlight the typical features of mechanical measuring systems. In addition, mechanical displacement measuring instruments and capacitance-type sensors with maximum resolutions < 10 nm are mentioned in the discussion on conversion methods for the mechanical quantity.

Features of mechanical measuring systems

Because the mechanical quantity at the measurement point is directly measured in a mechanical measuring system, such a system has the advantages that the measurement procedure is straightforward and the measurement accuracy and resolution can be directly inspected. On the other hand, if the mechanical quantity at the measurement point is measured directly as an electrical or optical quantity, a mechanical-to-electrical/optical conversion takes place; hence the measurement is affected by the electrical or optical characteristics of the surface material of the measured specimen.

In mechanical systems, a measurement force is needed to maintain contact between the probe and measurement point to transfer the mechanical quantity accurately. This force causes deformation at the measurement point. Although this deformation is usually an elastic one, plastic deformation can occur in soft metals, resulting in surface damage. Nevertheless, the causes of measurement errors are relatively easy to identify, in comparison with other measuring methods, and measurements are affected less by environmental factors.

Therefore as long as measurement conditions pertaining to the problematic factors have been spelled out, one can obtain highly stable and reliable measurement results with good repeatability using mechanical measuring systems. It is also relatively easy to manufacture instruments that have identical performances. Since the probe's minute movements must ultimately be converted into an electrical quantity, the detection and conversion system must not disturb those movements. For this purpose, compact and lightweight units that respond linearly by non-contact methods have been developed. Thus in modem mechanical measuring systems, the change in mechanical quantity at the measurement point is mechanically extracted and then measured by a non-contact measuring system.

Features of the high-magnification profile instrument

In profile measurement, a record of the magnified surface profile is obtained by allowing the detector unit which houses the stylus to scan mechanically over the measured surface in one direction to measure the coordinates of consecutive points on the surface profile. Other surface properties are also evaluated. Thus the horizontal scanning line provides the measurement standard, the distance of which from each measured point is measured by the stylus to give the height (i.e. vertical) dimension such as surface roughness.

At the same time, the position of the measured point is measured by the feed distance (i.e. horizontal direction). A high-precision feed device is necessary, since the accuracy (i.e. straightness) of the feeding motion directly affects that of the vertical measurement, while the readout accuracy of the feed distance directly affects the horizontal accuracy. Thus there is a vertical and a horizontal measurement resolution.

There are other instruments that also mechanically scan the detector unit to determine coordinates of consecutive surface points, such as a device that uses an optical stylus, or the scanning tunnelling microscope; these are basically similar in structure to the above profile instrument.

Vertical resolution of profile instrument

(a) Historical advances in vertical resolution

A method that uses optical levers to magnify microscopic movements of the stylus was developed in the 1920s and used until the early 1950s. It achieved a vertical resolution of ~ 0.1 gm. Research on ways to accomplish magnification by electrical means began in the 1930s, and ever since 1935, when Rank Taylor Hobson Ltd announced the Talysurf Model 1, electrical magnification has become the more usual method.

In electrical magnification, a transducer is used to convert the movement of the stylus into electrical signals, which are then amplified. Several countries undertook research in this field, with the result that a vertical resolution of 0.5 nm was achieved in the 1960s, improving 0.1 nm by the mid-1980s and 0.03 nm by the late 1980s.

(b) Measurement requirements and functions of the instrument

The major requirements for making measurements of ~ 1 nm are discussed below.

(1) Radius of curvature of stylus tip and measurement force In general, if Fs is the static load or measurement force at the mean position when the stylus and sample surface are in contact, the maximum dynamic measurement force of the stylus continually tracing the surface profile can be approximated(1) by 2Fs. This measurement force causes elastic deformation at the contact point.

(2) If the tip radius of the stylus is sufficiently small, however, the maximum pressure at the contact point will be large enough to cause plastic deformation in soft materials such as aluminium. Moving the stylus horizontally in this state will result in a scratch. To prevent this, the stylus assembly must have a small mass, and a coil- or plate-spring mechanism must be installed to exert an upward force to reduce the measurement force within the measurement range. Generally a stylus with 2 µm tip radius is used with a measurement force of 0.7 mN; however, for measurements of surface features of □10 nm, a stylus with a tip radius of 0.5 or 1.0 µm is used with a measurement force of 0.01-0.3 mN.

(3) Tracking characteristic of stylus when the measurement point makes vertical up/down motions, the limiting frequency at which the contacting stylus is able to track the measurement point faithfully is called the tracking characteristic. This characteristic is inversely proportional to the square root of the amplitude of the measurement point's vertical motion, and roughly proportional to the square root of the measurement forced. In general, when the surface profile curve has small amplitudes (i.e. height of protuberances), its wavelengths are also small, giving a large number of waves per unit length. Hence when measuring a surface with a low surface roughness, the feed velocity should be kept low so as not to exceed the stylus's tracking characteristic. For measurements of profile features of < 10 nm, a feedspeed of 2-100 µm s-1 is used; the accuracy of the feed motion achieved in these cases is normally a straightness of 50 nm per 25 mm to 3 nm per 3 mm.

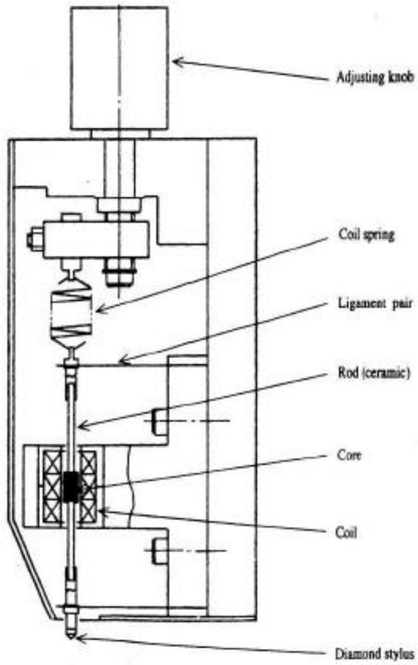


Fig. 8 Surfcorder ET (Kosaka Laboratory Ltd). Stylus—transducer assembly, showing stylus support mechanism.

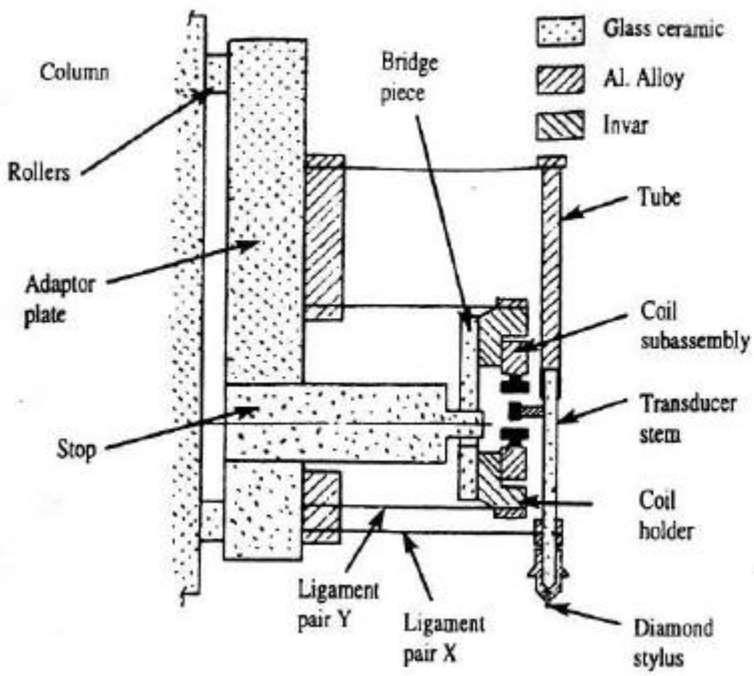


Fig. 9 Nanostep (Rank Taylor Hobson Ltd). Transducer assembly, showing materials used in measurement loop.

(4) Examples of detector units Figure 8 shows a high-magnification detector unit (Kosaka Laboratory, Japan), which has a measurement force of 0.2 mN for the mean stylus position, and a maximum tracking characteristic of ~100 Hz for a surface roughness of 3 pm. The smallest vertical resolution is 0.5 nm. Figure 9 shows the construction of the detector unit for the Nanostep (Rank Taylor Hobson, UK). Its newest features include the use of a glass ceramic with a low thermal expansion coefficient for its major parts to minimize the effects of temperature changes. The Nanostep which incorporates this unit achieves a maximum vertical resolution of 0.03 nm, with a system accuracy of ± 3 -4% of the measured result.

(c) Horizontal resolution of profile instrument

The feed unit consists of a high-precision linear guide mechanism (or circular guide for out-of roundness measurements), which provides the measurement standard for the vertical direction, and the readout unit for the horizontal position of the stylus. When the horizontal range of measurement is large or when the specimen is large in volume and mass, a feed unit which horizontally moves the detector unit itself is commonly used. Conversely, when measuring vertical displacements of ~ 1 nm, the horizontal measurement range tends to be small and the specimen itself small and lightweight, so it is better, in terms of both construction and accuracy, to move the sample

(a) Feed unit for detector unit and horizontal resolution

An example of a feed (or traverse) unit is given in Fig.10 The guide mechanism consists of a precision-machined sleeve and guide rod; the sleeve, which holds the detector unit, slides along the fixed guide rod and reads the feed distance on a digital scale. The feed motion has a straightness given by the formula 0.05 + 1.5L/1000 μm, where L (mm) is the feed distance (i.e. Measurement). The maximum horizontal resolution is 0.1-0.05 μm.

(b) Feed unit for sample and horizontal resolution

The advantage of this kind of feed unit is that it can be designed and fabricated as a separate unit. It is connected to the instrument's main body by a three- point mounting so as to minimize force and heat deformations. A special material is used for the guide plane to provide smoother sliding, and measures have been taken to prevent vibrations that accompany the feed motions. Since these units have a small range of movement, sometimes an encoder is used to determine the feed distance through the feed rotation angle, instead of taking direct measurements of the feed distance. In these units too the horizontal resolution of the feed distance is 0.1 μm, limited by the resolution of position detection.

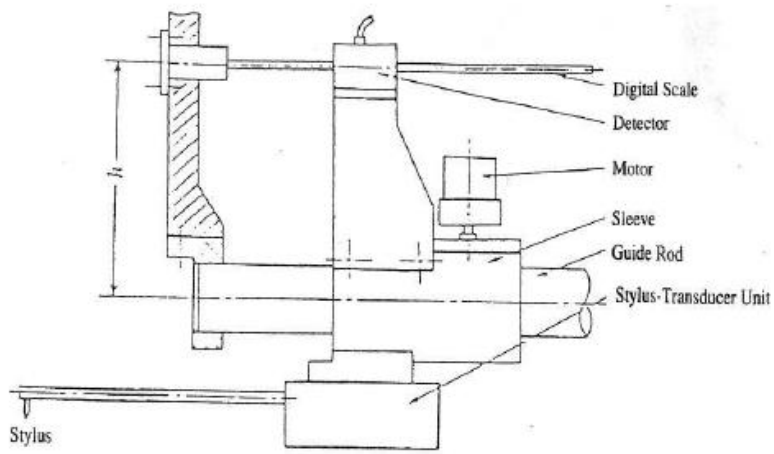


Fig. 10 Surfcorder SE (Kosaka Laboratory Ltd). Mechanism of traverse unit.

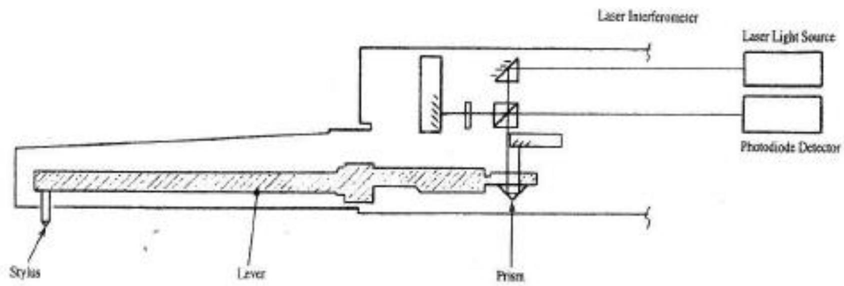


Fig. 11 From Talysurf S5 (Rank Taylor Hobson Ltd.) Schematic diagram of laser pickup

Other methods of converting the mechanical quantity

(a) Vertical displacements

With a small transducer, it is possible to measure only a narrow range. To overcome this limitation, an instrument (Form Talysurf Model S5) that converts the vertical movement of the stylus into motion of interference fringes has been developed. It can measure a range of 6 mm with a vertical resolution of 10 nm. As shown in Fig. 2.4.4, when the stylus, which is connected to a small prism, moves vertically, the optical path length in the laser interferometer changes, causing the interference fringes to move. This movement is measured to determine the distance travelled by the stylus.

(b) Detection of horizontal position

One commercial product makes measurements with 8 nm resolution by allowing a semiconductor laser to impinge on a hologram grating and then utilizing the resulting interference of the diffracted light.

(c) Capacitance-type sensors

Non-contact capacitance-type sensors are now often used for position measurements in precision transfer devices and measurements of the dynamic characteristics of rotating samples.

A schematic drawing of such an active-probe sensor (ADE Corporation, USA) is shown in Fig.12

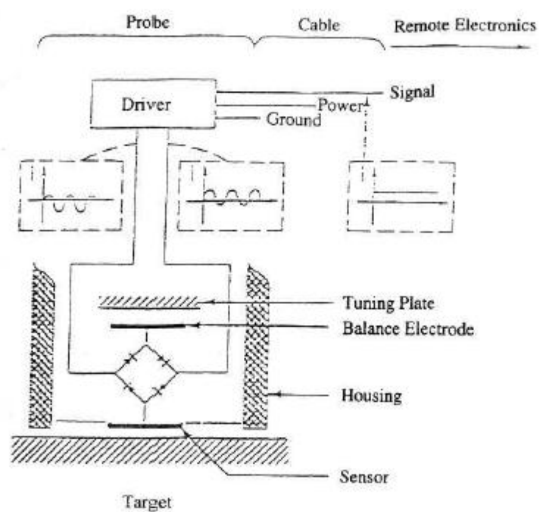


Fig. 12 Micro Sense-Active Probe (ADE Corporation). Simplified schematic diagram of 'active probe'.

It houses a sensor electrode and a balance electrode which provides the reference capacitance; the capacitance difference is used to make measurements. This probe yields an output inversely proportional to the distance between the sensor electrode and specimen surface (mean surface). This output is linearized (with a standard linearity of ±0.2%) by a linearizer circuit and then displayed. Although the static resolution is generally considered to be 10 nm at the most, in one instance in which the transfer position for a precision transfer device was measured, a resolution of 1 nm was obtained.

Optical measuring systems

Precision measurement is essential for almost all nanometre-order processing. Non-contact, especially optical, measuring systems are now greatly needed in this particular field.

(1) Laser interferometer

Most ultra-precision processing systems have their own high-precision scales integrated with the machine tool or stand-alone measuring instruments in the inspection room. Some types of laser interferometer are used widely as typical precision scales with nanometre-order resolution. Inprocess or on-machine positioning control of machine tools, semiconductor production systems and three-dimensional measuring instruments are typical applications. The coherence of laser sources permits fringe counting systems with a range up to 50 m. Over the lifetime of the laser tube, the laser wavelength can remain stable to one part in 108 or better.

The most popular type of laser interferometer uses a heterodyne method with a two-wavelength Zeeman laser or an AO (acousto-optical) element to obtain accurate phase information. Another length-measuring interferometer using a1/8 phase plate in one arm and a polarization beam splitter detects three or four signals with phases mutually differing by 90 or 180 degrees(1). The length displacement is calculated from these signals as accurately as it is by a heterodyne interferometer. The main drawback of interferometer systems of nanometre accuracy used in the free atmosphere is the necessity to correct for the refractive index of the air, which can change by one part in 105 under the usual conditions.

Calculation of and correction for the refractive index by simultaneous measurement of air temperature, pressure, humidity, etc. may be an effective means of overcoming this problem to some extent, but a better way of reducing this source of uncertainty is to use a gas refractometer. If the atmosphere is uniform along the light path, the uncertainty will be reduced to one part in 108 by the correction.

(2) Optical figure-measuring instruments

For measurement the figure of ultra-precision machined surfaces, optical interference wavefront detectors are widely used. They are mainly based on the Michelson, Fizeau, Mach-Zehnder, or Young interferometers or holography. The Fizeau-type interferometer with a laser source as shown in Fig.13 gives a relatively stable interferogram and is one of the most useful instruments in optical and precision machining workshops.

Besides the heterodyne technique mentioned in connection with the length-measuring interferometer, the figure-measuring interferometer uses another technique, fringe scanning(2), in which the reference surface is scanned by means of piezoelectric drives. All the interferograms in every scanning position are detected by a CCD camera and processed in a digital computer to obtain a figure map of nanometre-order resolution.

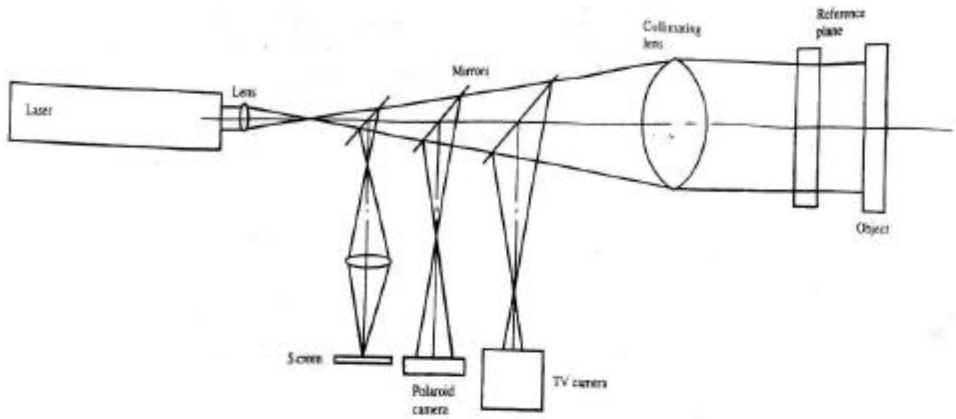


Fig.13. Laser interferometer for figure measurement

For accurate phase measurements of large optics over long optical paths, as explained above. Temporal fringe scanning interferometer has certain weak points arising from mutual displacement, vibration and air turbulence between the interferometer and the surface under test. Like the DMI interferometer, the simultaneous phase shift interferometer (SPSI) of Michelson type(3), shown in Fig. 13, has the ability to make accurate phase measurements in dynamic environments where fringe patterns are rapidly changing.

The SPSI uses a stabilized single frequency He—Ne laser and four CCD cameras. Interference fringes at each of the four cameras are phase-shifted 90 degrees relative to one another using polarization techniques. Pixels of the four CCD cameras are aligned with each other exactly. A shutter synchronized to 0.1 ms creates four high- contrast fringes simultaneously, even with severe vibration. The Micro PMI compact Fizeau interferometer with the same principle as the SPSI can measure surface height to better than 10 nm accuracy and is now commercially available.

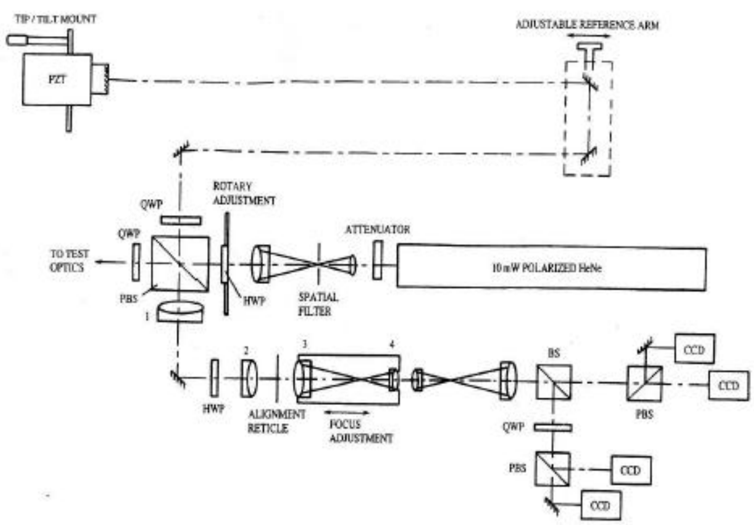


Fig. 14 Optical layout of the simultaneous phase shift interferometer (SPSI).

(3) Optical surface roughness-measuring instruments

Hitherto, surface roughness has been measured primarily by stylus instruments, as a convenient and versatile method. However, it has been criticized because, it is relatively slow and may damage the surface of soft materials or the function of semiconductors. Several non-contact methods are now being developed and used extensively. Optical stylus focus error detection and optical interferometers seem the most promising techniques for practical applications. Astigmatism, critical-angle, and knife-edge methods are typical examples of the optical stylus technique, and micro-Fizeau, Mirau, and Michelson instruments are typical interference profilometers.

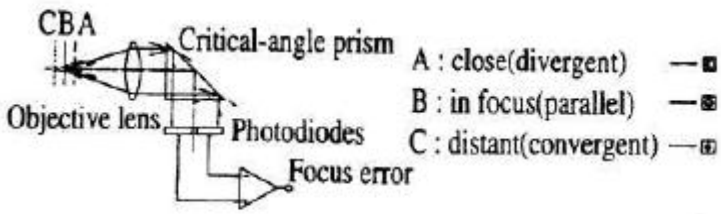


Fig. 15 Principle of the critical-angle method.

The principle of the optical stylus using the critical- angle method is shown in Fig.15 If the surface under test is at the focus of the lens at B, the laser light passing through the objective lens is converted into parallel flux. A total-reflection prism is positioned to reflect the light at the critical angle and thus the same level of light is incident on the two photodiodes. Consequently the out-of-focus signal becomes zero.

When the object surface is at position A close to the lens, the light diverges after passing through the lens. The light on the upper side of the optical axis shown in the figure strikes the prism at an angle smaller than the critical angle. This causes the light to be refracted and pass out of the prism, whereas the light on the lower side of the optical axis is totally reflected at the large incident angle.

As a result, a difference in the output of the photodiodes is created, thereby producing an out-of-focus signal. At position C, far from the lens, the opposite phenomenon to that at A occurs and a signal with the reverse sign is obtained.

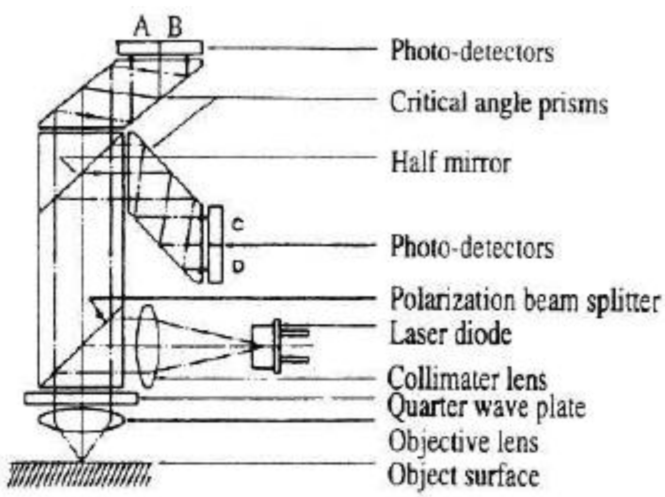


Fig. 16 Optical path of the high-precision optical surface sensor (HIPOSS).

As shown in Fig. 16 the high-precision optical surface sensor (HIPOSS)(4) has a half-mirror to split the optical path into two total-reflection prisms and split detectors so as to avoid any effects of object surface inclination on the measured result.

The resolution of the HIPOSS with a 0.6 NA (numerical aperture) objective is better than 0.2 nm r.m.s over a linear range of 2 gm. Besides its use as a profilometer, the HIPOSS has practical applications in inprocess and on-machine measurement as described in Sections 2.1 and 2.2.

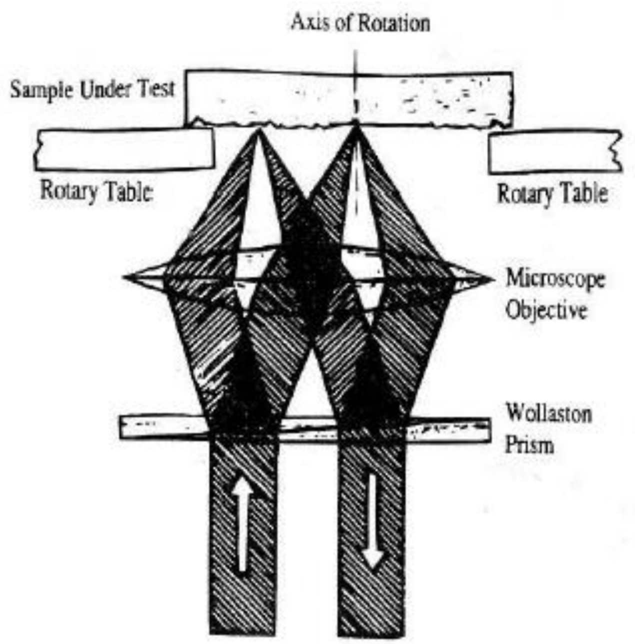


Fig.17 Schematic diagram of circular-path inter-ferometer.

Figure 17 shows a circular scanning heterodyne laser interferometer^ with better than 0.1 nm vertical resolution. A Wollaston prism divides a Zeeman split two-wavelength laser beam by polarization into two beams. The measuring beam is focused on a point on a circular rotating surface, while the reference beam is fixed on the centre of rotation. The reflected beams are recombined at the prism and create an interference signal arising from the beam path difference.

Electron beam measuring systems: / SEM and TEM

- Since the electron beam has a short wavelength, it provides a much higher resolution than light when used in a microscope. This excellent spatial resolution is taken advantage of in the use of the scanning electron microscope (SEM) and transmission electron microscope (TEM) for measurements.

- The line-width measurement system and the electron beam tester are established measuring systems using electron beams, both of which were developed for the semiconductor industry. When ‘measurement system’ is defined to include surface analysis systems and microscopes, EPMA (electron probe microanalyser), SAM (scanning auger microscope), SEM and TEM are all measurement systems effectively used in the field of industrial measurement.

- This section describes the line-width measurement system and the morphology inspection system for wafers (here after called ‘wafer inspection systems’) as examples of measurement systems using electron beams. It describes some electron optical technologies adopted to improve resolution, which directly influences the measurement accuracy.

- It also describes some applications of the TEM as an inspection system for the internal structures of semiconductor devices. This section mostly describes applications in the semiconductor field, which is only natural in view of the fact that semiconductor devices were the first nanotechnological products into which nanometre- order structures were incorporated practically.

Wafer inspection systems

(a) Required resolution

As is well known, large-scale integration of devices and improvement of their functions and performance have taken place rapidly in the semiconductor industry. Along with this progress, the minimum-sized unit for device design (called the ‘design rule’) is becoming smaller year by year. For example, with the 256M DRAM now under development, this size is ~ 0.2µm. The size of defects or errors that influence the electrical properties of devices is said to be 1/10 of the design rule. Therefore it is necessary to control the dimension of each part of a device to an accuracy of 1/10 of the design rule. Moreover, wafer inspection systems require a measuring accuracy of ¼ to 1/6 of the fabrication accuracy. Hence for a 256M DRAM a system with a resolution of < 10 nm is required.

(b) Need for low accelerating voltage and its influence on resolution

Wafer inspection systems carry out dimensional measurements and morphological observations on resist patterns and etching patterns formed on Si wafers. Since the wafer surface is mostly covered with insulators, it will be negatively charged during the observation with high accelerating voltages that are used by ordinary SEM (i.e. 10-20 kV). Moreover, when a highenergy electron beam is targeted on an MOS transistor, a major component in today’s semiconductor devices, the electrical properties of the transistor deteriorate or are destroyed. To alleviated these problems, wafer inspection systems are used exclusively at low accelerating voltages, ~1 kV.

The SEM’s probe size d (which determines the resolution) can be approximately expressed by the following equation(2):

$$d^2 = \left(\frac{2}{\pi\alpha}\sqrt{\frac{1}{B}}\right)^2 + \left(\frac{1.22\lambda}{\alpha}\right)^2 + \left(C_c\alpha\frac{\delta V}{V}\right)^2 + \left(\frac{1}{2}C_s\alpha^3\right)^2$$

where α is the illumination angle of the probe, δV is the full-width half-maximum of the initial energy of the electrons (V) at the electron source, B is the brightness of the electron gun, which is proportional to the accelerating voltage V, I is the probe current, □ is the wavelength of the electron beam, which is proportional to $1/\sqrt{V}$ and C_s, C_c are the spherical and chromatic aberration coefficients respectively. As is clear from the dependence of the above equation on V, lowering V increases ail the terms except for spherical aberration. With the SEM using a conventional thermal electron gun (TEG), if the accelerating voltage is lowered to 1 kV, d is ~40 nm.

(c) Field emission electron gun (FEG)

The field emission electron gun is characterized by high brightness and small energy spread. The brightness is as high as 10^8 A cm^{-2} sr^{-1} even at 1 kV (in contrast to about ~ 103 for a TEG).

Therefore, under typical operating conditions (I = 10 pA, α = 5 mrad), the first term of eqn is 0.4 nm, which can be neglected compared with the other terms. δV is ~ 0.3 V for a cold FEG and ~0.5 V for a thermal FEG. These values are 1/7 and ¼ of that of a TEG. Hence the use of the FEG makes it possible to improve considerably the resolution at low accelerating voltages.

(d) Improvement of objective lens aberrations

Since the conventional SEM is designed for multipurpose use, its objective lens is not optimal at low accelerating voltages. If the objective lens is specifically designed for use at low accelerating voltages, this creates more room for design improvements. For the magnetic lens it is known that the larger the excitation parameter (J2/V), where J is the number of ampere- turns, the higher is the lens performance. At low accelerating voltages, a large J2 / V value can be obtained with a relatively small J. Thus the magnetic circuit can be made thin and small, with a simpler cooling method or without cooling. Furthermore, an extreme modification of lens shape becomes possible.

Transmission electron microscope (TEM)

The TEM is the only instrument that allows observations of the internal structure of a specimen obtained with an electron beam line-width measurement system incorporating the lens shown in Fig. 18 and thermal FEG (V = 0.8 kV). Average line width of five measurements marked + is 1.173 µm. Edge detection was done automatically by the threshold method with atomic resolution. TEM resolutions, require thin-sectioning of the specimen, so the instrument has rarely been used for the inspection of the internal structures of semiconductor devices. With the recent advent of focused ion beam (FIB) equipment, however, a selective thinnning technique has been developed for TEM observation. Hence major efforts are now' being made to use the TEM to inspect the internal structures of semiconductor devices.

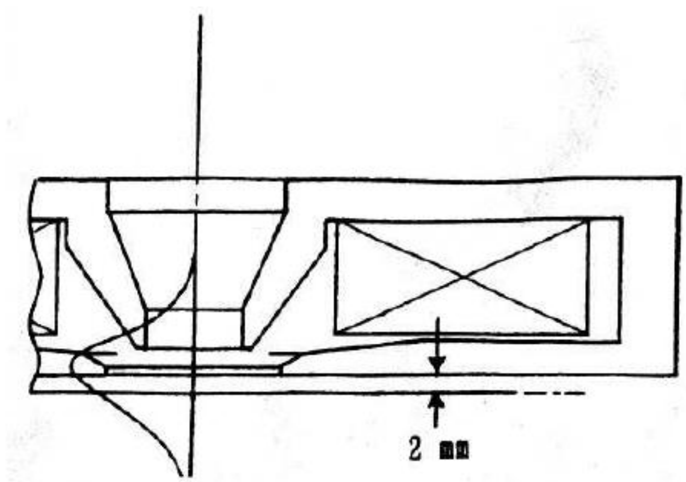


Fig. 18 Objective lens for line-width measurement system. Cs = 3.2 mm, Cc = 3.4 mm (at working distance 2 mm), Jmax = 986 (at 3 kV).

Pattern recognition and inspection systems

Basic concept of pattern recognition systems

Pattern recognition is the technology of analysing pictorial information using digital computers. Although it was once a very specialized and expensive technology, with rapid advances in digital computers, pattern recognition technology has emerged from the research laboratory and is being used in a wide array of applications such as FA (factory automation), OA (office automation), CG (computer graphics), medical systems, publishing, security, remote sensing, and the arts. A basic pattern recognition system is shown in Fig. 19. In general, such a system consists of an illumination source, a sensor, an image processor and a display unit. How the image processing unit handles the data is shown in Fig. 20. This system consist of an A—D (analogue—digital) converter, image mem-ory, image processor, D—A converter, CPU, program memory and keyboard. Image data observed by a camera are digitized by the A—D converter and stored in the image memory. The data are then transferred to the image processor to be processed by an algorithm, and are reconverted to analogue form by the D—A converter and displayed.

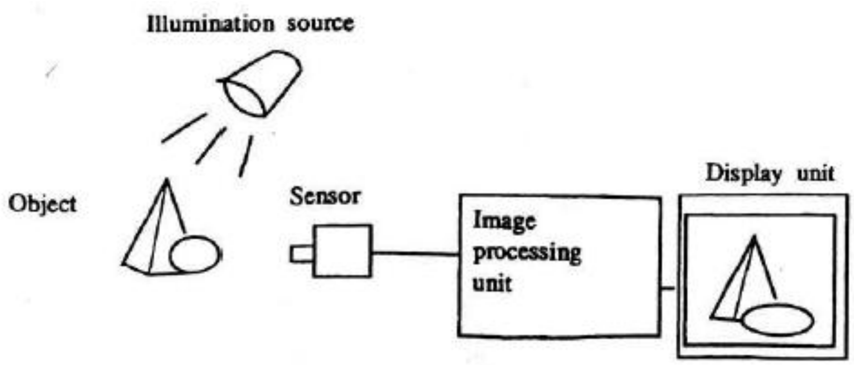


Fig.19. Pattern recognition system.

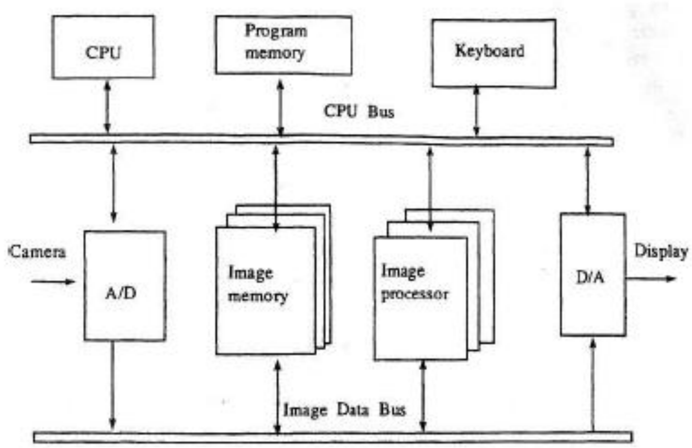


Fig.20. Block diagram of image processing unit.

The image data consist of two-dimensional numerical data corresponding to an observed image. The pixel is the minimum sampling unit for digitization; one pixel has two dimensional position data and one numerical datum which represents the observed brightness, as shown in Fig. 21. In the computer, the image data are represented by a two-dimensional M x N matrix as shown in Fig. 22. The elements in the matrix represent the brightness data. Generally the image processing algorithm can be divided into pre-processing and main processing algorithms. The pre-processing algorithm accomplishes normalization by geometrical transformations, sharpening by filtering, and contrast enhancement by grey- level transformations, and elimination of noise by smoothing. The main algorithm analyses or evaluates the pre-processed input image for feature extraction including edge detection, clustering, segmentation, texture analysis, and pattern matching. The main algorithm also carries out basic operations such as binarization, affine transformation, grey-level transformation, filtering, two-dimensional Fourier transformation, and pixel operations for addition, subtraction, multiplication, and division.

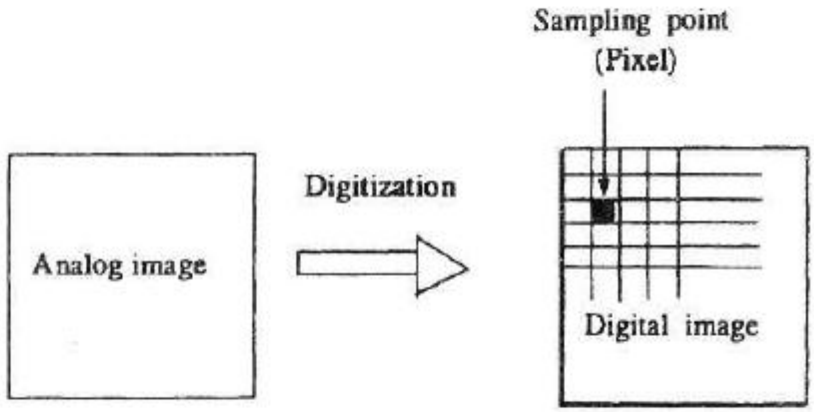


Fig. 21. Representation of image data.

Examples of image processing algorithms

Figure 22 shows the visual images of an ARI (assembly robot with intelligence). The ARI has two vision systems, corresponding to the left and right eyes. The pair of stereo images from the two vision systems are analysed together. The edges and vertices of an object are extracted and a pair of two- dimensional object descriptions is generated. The three-dimensional information is then created by combining the two-dimensional descriptions. In this example, white lines represent the perceived edge positions.

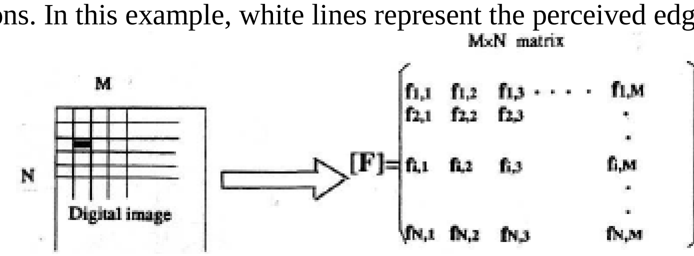


Fig.22. Image data representation by an M x TV matrix.

A second example shows how a combination of image processing algorithms is used to detect small defects on printed-circuit boards.

UNIT V
LITHOGRAPHY

Introduction about Photolithography

Since photolithography was first applied to semiconductor circuit fabrication, the performance of semi-conductor circuits has been extended up to ULSI. Photolithography is the most important and key Technology in the semiconductor fabrication system. Photolithographic technology has been improved in accordance with the demands of higher circuit integration, and now lines of width several hundreds of nanometres have been fabricated by photolithography.

The light source for photolithography mainly determines the resolution achievable. The wavelength of the light source has been successively shortened, from the g-line (436 nm) of the high-pressure mercury arc lamp to its i-line (365 nm), the 248 nm radiation of the KrF excimer laser, and now the 193 nm radiation of the ArF excimer laser. The optical wafer stepper, referred to simply as the stepper, is used on almost all production lines for mass production of ULSI as the photolithographic device. The stepper involves many of the most advanced component technologies, including nanotechnology.

Optical configuration of the stepper

The optical system of the stepper is shown in Fig1 The key component is the projection lens for imaging the mask pattern on to the wafer with some reduction ratio.

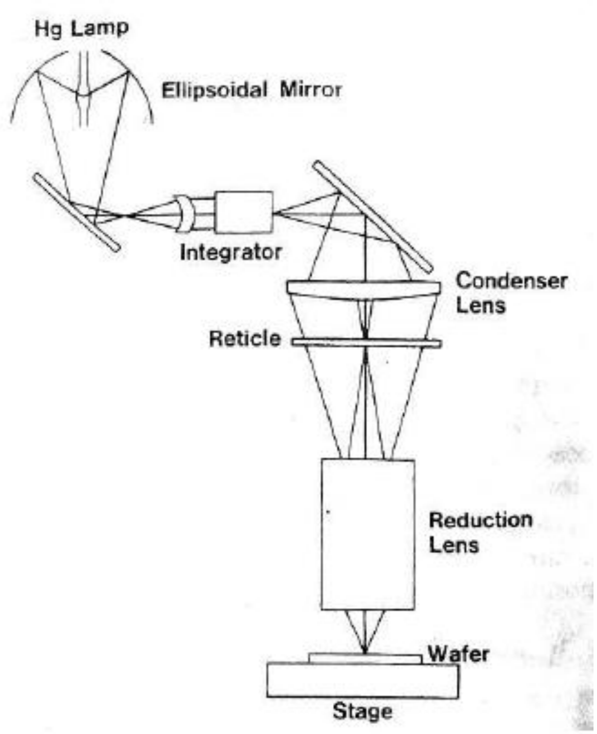


Fig.1 Optical system of water stepper.

Theoretically, the resolution of the lenses is defined by the formula

R = K. λ/ NA

where R is the resolution (nm), AT is a process factor, a constant defined by the process of pattern duplication and equal to 0.8 under production conditions and 0.65 in R & D, λ is the wavelength of the light source (nm), and NA is the numerical aperture (= 1/ cosθ, where θ is the angle formed by the optical axis and the outermost light beam to the image). Hence the resolution of the optical system is higher, the shorter the wavelength or the larger the NA. The development of lens design and fabrication technology has improved the lens system so that shorter wavelengths and a larger NA can be used.

A lens system is made up of about 30 component lenses, each of which has a maximum diameter of 250 mm and a maximum mass of 10 kg. The total mass of the whole lens system is up to 500 kg. A stepper which uses an excimer laser as the light source for exposure is called an excimer stepper. The excimer laser is used to obtain higher resolution, having a shorter wavelength in the far ultraviolet region than the g-line or i-line in the ultraviolet region.

The basic configuration of the excimer stepper is almost the same as the ordinary stepper except for the light source. A KrF excimer laser (248 nm) is now in use for test production of ICs, and an ArF excimer laser (193 nm) is under development. It is necessary to involve features such as a narrow waveband of the radiation generated high stability of light power, and long operating life when using an excimer laser for photolithography. A kind of optical monochromator is inserted in the cavity of the laser to achieve a narrow bandwidth.

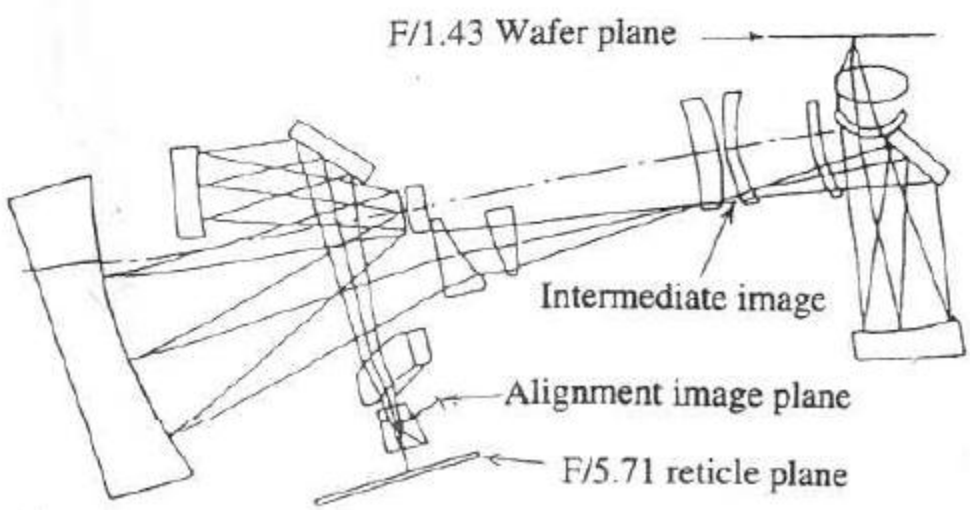


Fig.2. Optical system of mirror projection optics (Micrascan, Perkin-Elmer Co.).

by small dust particles in the light path, owing to the high coherence of the laser beam(l). A laser beam direction distributor should be inserted in the light path in the illumination system to reduce coherence. In some systems, the distributor is a swinging mirror which is driven synchronously with the excimer laser pulses. Multiple exposure with different directions of illumination hides the speckle noise pattern.

Shorter wavelengths allow less material to be used in excimer laser projection lenses, owing to the low transparency of the materials at the excimer laser wavelength. Typical optical glassesgreen soda-lime glass and white crown glass (BK7) - cannot be used in the ultraviolet region. Quartz (SiO_2) and fluorspar (CaF_2) are possible candidates.

A combined system using reflecting mirrors has been developed to reduce the number of lenses. An example is shown in Fig.2. A problem is the small exposure area with this system, so scanning methods have to be used, as in subsection 4.2.1.5.

Alignment system

Integrated circuits are fabricated by applying some 10 to 15 different pattern masks for the multilayered structure. The alignment between a previously exposed pattern on a wafer and the succeeding pattern on a mask that will be exposed on the wafer is a critical factor determining the minimum pattern width. The stepper has a number of alignment systems, each with a certain attainable accuracy. Wafer pre-alignment is achieved by means of two rolling pins fitting the facet of the wafer within ±3 μm

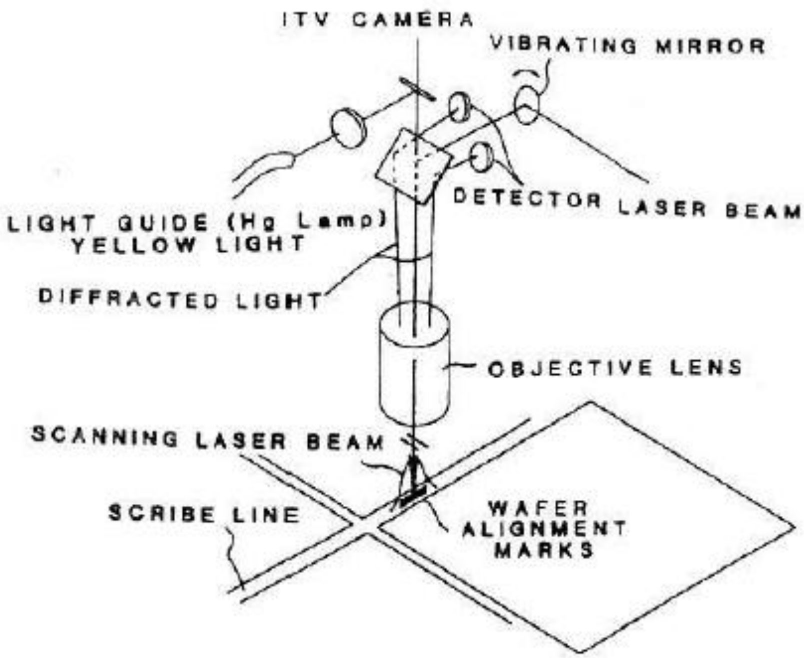


Fig. 3. Principle of a wafer alignment system.

mechanically. The wafer alignment system aligns the wafer itself to the reference line of the stepper stage motion; this is also called global alignment. For more accurate alignment, chip alignment is applied. Each chip on the wafer is aligned with the optical axis of the stepper lenses or mask alignment mark, depending on the alignment method.

Essentially, alignment is achieved by detection of the centre of the alignment pattern and adjustment of the position of either wafer or mask so as just to overlap each other. The detection of the centre of the alignment pattern is analogous to the technique used to detect the centre of the line on the standard scale of a photoelectric microscope. The same technique is used in the alignment system of IC steppers, although some improvement has been achieved.

An example of the wafer alignment system is shown in Fig.3. A beam from an He-Ne laser illuminates the pattern on the wafer through an alignment microscope. A vibrating mirror in the light path as shown modulates the illuminating position on the wafer sinusoidally. The signal reflected from the wafer varies, depending on the reflectivity of each point on the pattern and the unpattemed surface, and the waveform of the signal changes according to the relative positions of the pattern and the centre of deflection of the vibrating light beam.

The signal from a photo detector is amplified and fed to a phase-sensitive detector (PSD). The discriminated signal varies depending on the displacement of the alignment pattern from the axis. The centre of the pattern can be estimated from the zero-voltage point of the signal. The position-sensing repeatability of this method is within 10 nm. The alignment patterns are formed as a grating as shown in Fig.3 to obtain a better signal-to-noise ratio.

An example of the chip alignment system is shown in Fig.4. The laser beam illuminates the chip alignment pattern through the projection lens. The diffracted light from the wafer returns along the same optical path and is split by the beamsplitter to the detector. The spatial filter stops the zero-order diffracted light to eliminate effects due to the strong beam containing error factors through surface rough-ness or pattern irregularity.

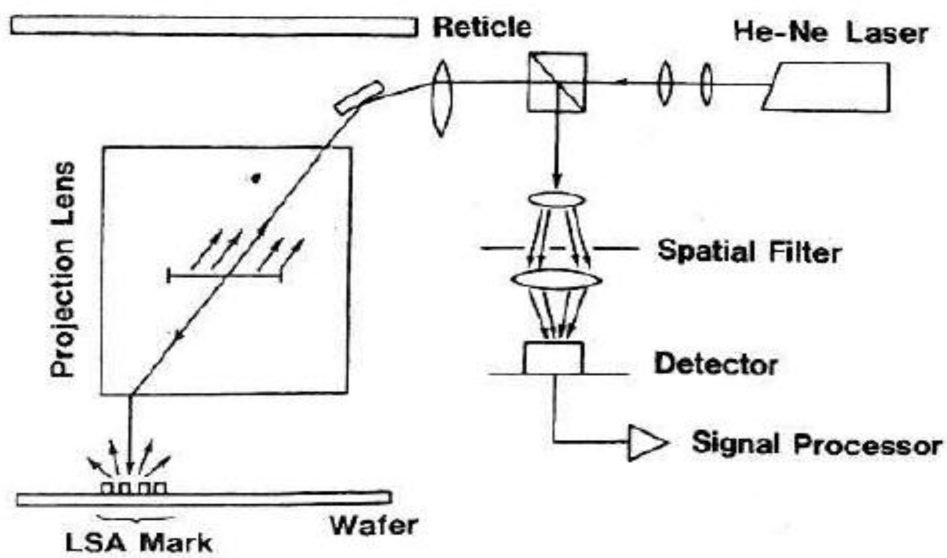


Fig.4 Principle of a chip alignment system.

The mark is scanned by the stage motion. The signal from the detector shown in Fig.5 is interpolated by the fringe signal of the stage interferometer, allowing the accurate centre of the pattern to be detected. The total configuration of the alignment system is shown in Fig. 5.

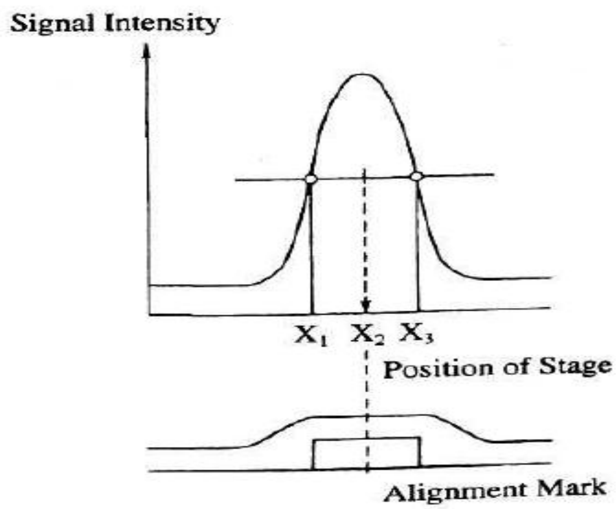


Fig 5. Chip alignment signal processing.

As already mentioned, the alignment accuracy determines the minimum pattern width of ICs. Improvement of the alignment system is a crucial factor in developing higher-resolution steppers.

A new alignment sensor has been devised using a diffraction and frequency-heterodyning method[(2)]. The configuration of the laser interferometric alignment (LIA) system is shown in Fig.7, and the optical signal processing principle in Fig 8. Two different laser beams are modulated by an AOM (acoustic optical modulator) with frequencies f1 and f2. The two beams are reflected through the projection lens below the reticle and imaged on to the wafer. The alignment pattern in grating form on the wafer is thus illuminated by two laser beams from two different directions as shown in Fig. 8. The beams diffracted by the grating, +1 order of f1 and -1 order of f2 interfere and frequency-heterodyning takes place.

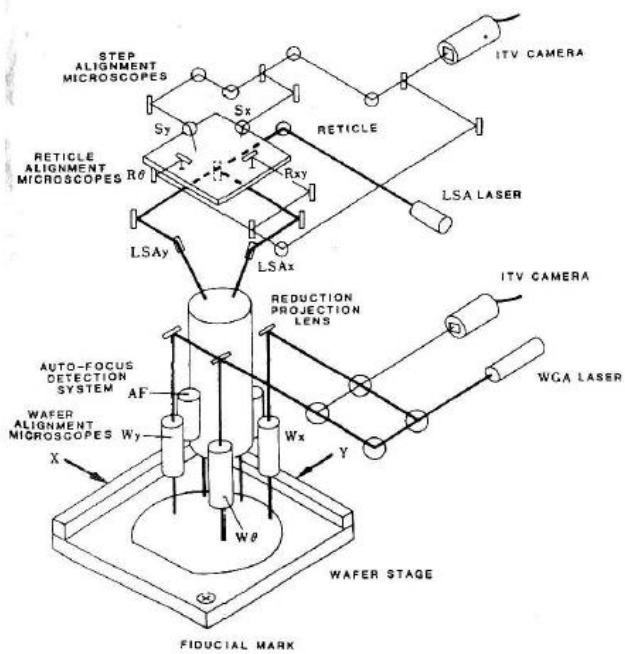


Fig 6

From phase modulation theory, the phase of the heterodyne frequency fh h 1 2 □ f f □ f □ f varies according to the displacement of the relative positions of the alignment pattern and the laser beam. On the other hand, the reference signal fr is processed by the reference signal generator as shown in Fig.7. The phase difference between fr and fh corresponds to the displacement of the alignment mark from the fiducial position. The stage is moved to reduce the phase difference to zero and thus achieve alignment.

This heterodyne method allows greater disturbance to be tolerated from surface roughness of the mark, low step dimension of the mark, and high reflectivity of materials such as aluminium. The alignment accuracy has been found to be from 43 to 85 nm for various alignment marks. The results of an alignment test are shown in Fig.9 for two types of alignment mark.

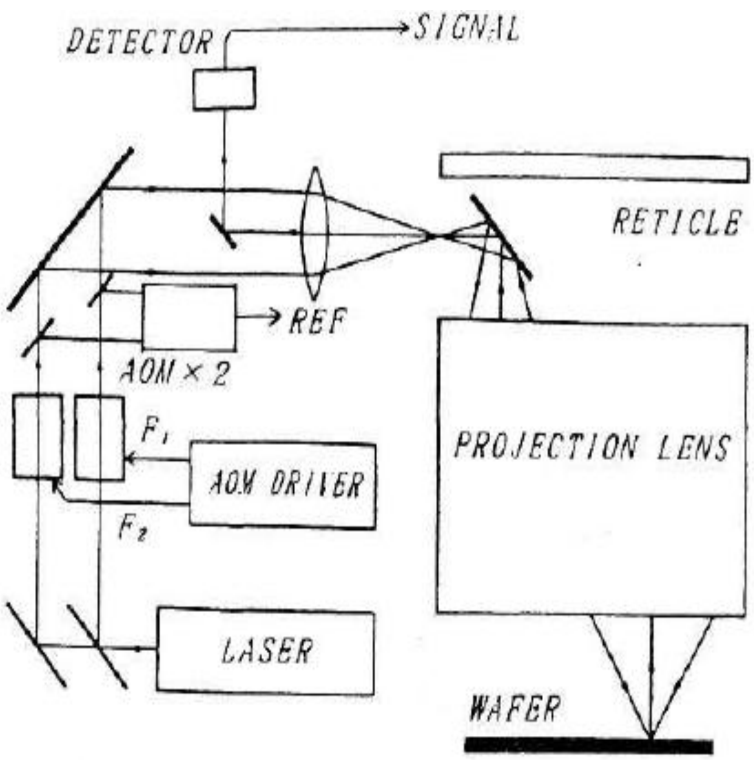


Fig.7. Interferometric alignment system.

Autofocus, auto-levelling system

The depth of focus at which a specific resolution can be obtained is defined by

$$DOF = k.1/\lambda.(NA)^2 \qquad (5.2.2)$$

Since high-NA lenses are used for high-resolution imaging, focusing is very critical. Line-width variation with out-of-focus displacement is shown in Fig. 10. Autofocusing systems are used in almost steppers.

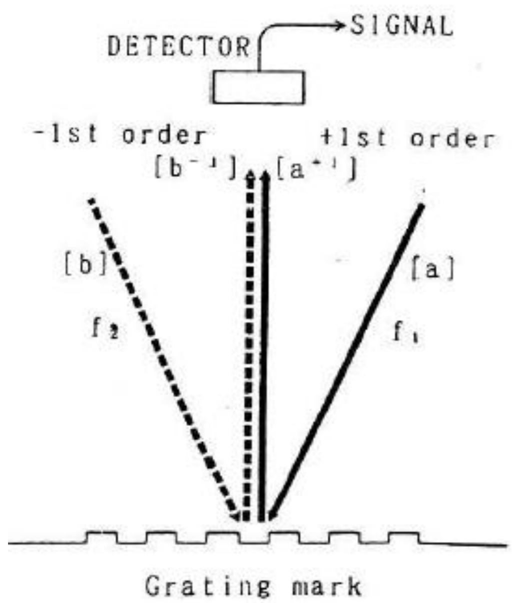


Fig. 8. Principle of LIA optical signal processing.

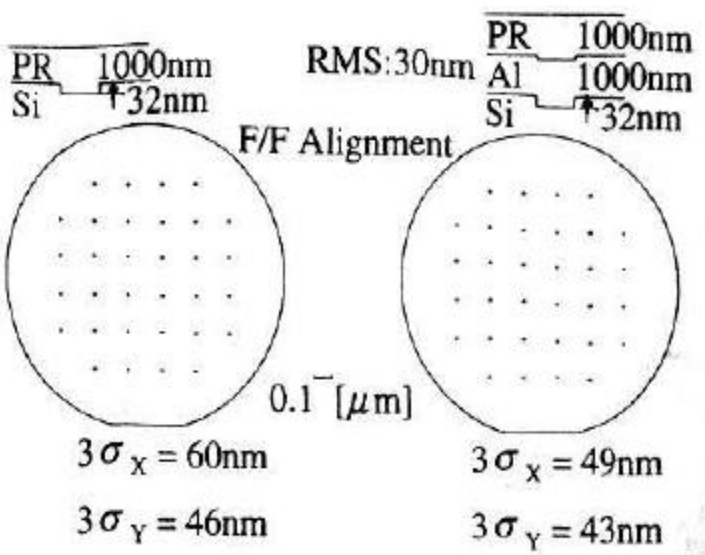


Fig.9 Results of LIA tests.

The principle of the stepper autofocus system is shown in Fig. 4.2.11. This system is an application of the photoelectric microscope used for pattern alignment. A photo detector senses the horizontal shift of the projected line of the laser beam on the wafer depending on the vertical position of the wafer.

The error signal from the photoelectric sensor is fed back to a control amplifier to drive the motor positioning the wafer stage on its vertical axis. This error signal decreases to zero as the vertical position approaches and finally reaches the focus point. The focus point can be controlled within 0.1 µm.

Hitherto the level of the wafer surface has been regulated only once, at the start, before exposure. However, a large wafer with a diameter of up to 200 mm cannot be allowed only one initial adjustment of level, since the surface is not at the same height throughout. Hence a level control system for adjustment of each chip has been designed for a recently developed stepper which has a high resolving power and can handle large wafers. The principle of the system is that of the auto-collimator. The system may be imagined from the autofocusing system shown in Fig.11 with the right-hand section of the autofocusing system replaced by the projection side of the auto-collimator and the left-hand section by its receiving side. The wafer corresponds to the mirror of the auto-collimator.

Mechanical stage for wafer stepping and alignment

The stage carrying the wafer needs to have both speed and high positioning accuracy to attain high resolution and high throughput. Positioning accuracy is determined by two major technical components: the accuracy of construction of the mechanical stage, and that of position control. The wafer supported by the stage is very light, but the required accuracy of wafer positioning means that the stage must be very rigid and heavy: its mass is up to 50 kg.

The moving table is driven by an electric motor through a precision lead screw and nut system. The guide system is composed of a V-flat guide and needle bearing or a bar and roller guide and double flat needle bearing. In an early state of the development, the stage was composed of coarse and fine tables driven by two motors, one for each table. However, the need for high throughput led to a change to a one-motor system to reduce positioning time.

Position control is achieved as follows; a position command is given by a computer and the stage position is sensed by a laser interferometer with feedback to the controller, which drives the motor until the error between command and stage position is reduced to zero. After positioning is completed,

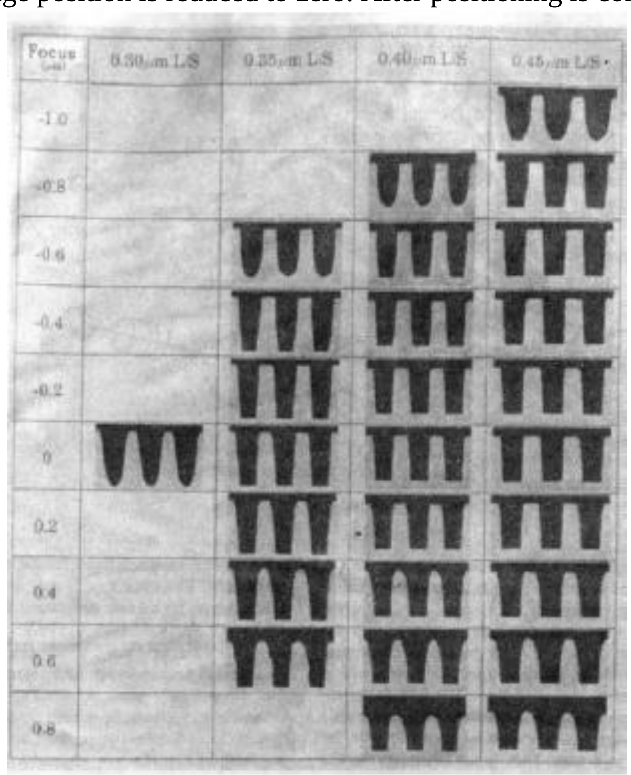


Fig.10. Line patterns as a function of focusing conditions (i-line, 365 nm, NA 0.57, photoresist PFi-28 1.06 pm, normal incidence illumination) for some line and space (L/S) values.

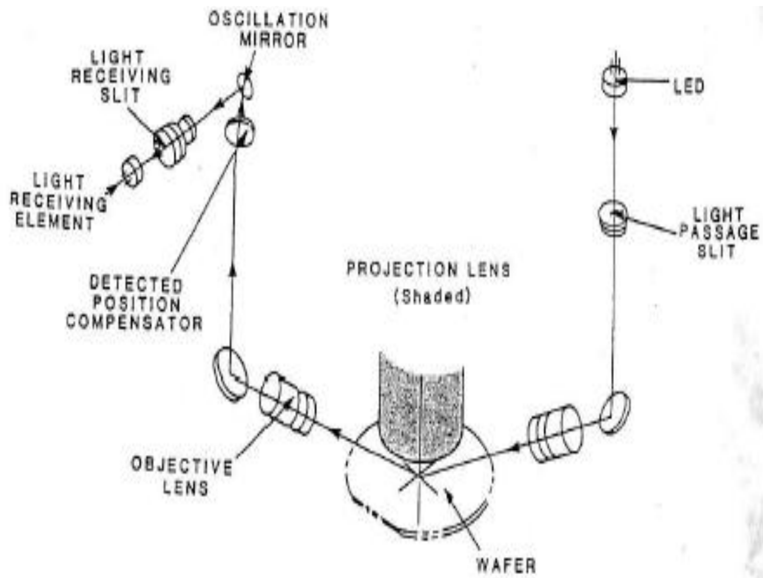


Fig.11. Configuration of an autofocus system.

focusing, alignment, and exposure are achieved for one chip. This process is repeated step by step, hence its name 'step-and-repeat'.

With a higher-resolution stepper, the step-and- repeat system cannot be used, because the exposure area is not able to cover a whole chip area with a resolution better than 0.25 μm. The lens or mirror projection system will be able to achieve imaging only in the slit zone covering part of a chip of size for example 22x4 mm. Then a slit-like image on the mask is projected on to the wafer, and the full image of the mask is exposed after scanning of the mask and wafer synchronously over a chip. For this purpose, a

Resolution enhancement technology

To obtain higher resolution with a normal light source and projection lenses, a number of resolution enhancement methods have been developed.

A modified illumination method has been developed and used in a production stepper(3). When a narrow line and space pattern is illuminated, transmitted light is diffracted by the slit composed of lines as shown in Fig.12(a) according to Fresnel diffraction theory. The diffraction angle θ is given by

$$\sin\theta = \lambda / p$$

where λ is the wavelength of the illuminating light and p is the pitch of the lines and spaces. If p is larger than the mask-side aperture of the projection lens, zero-order light and diffracted ±1- order light pass through the lens and focus the image of the mask on the wafer.

But if p is smaller than the critical value for the aperture, the ±1-order light beam is stopped by the aperture. The focused image is impaired because the ±1-order light beam does not contribute to the image. However, if the illuminating angle is made oblique as shown in Fig.12(b)

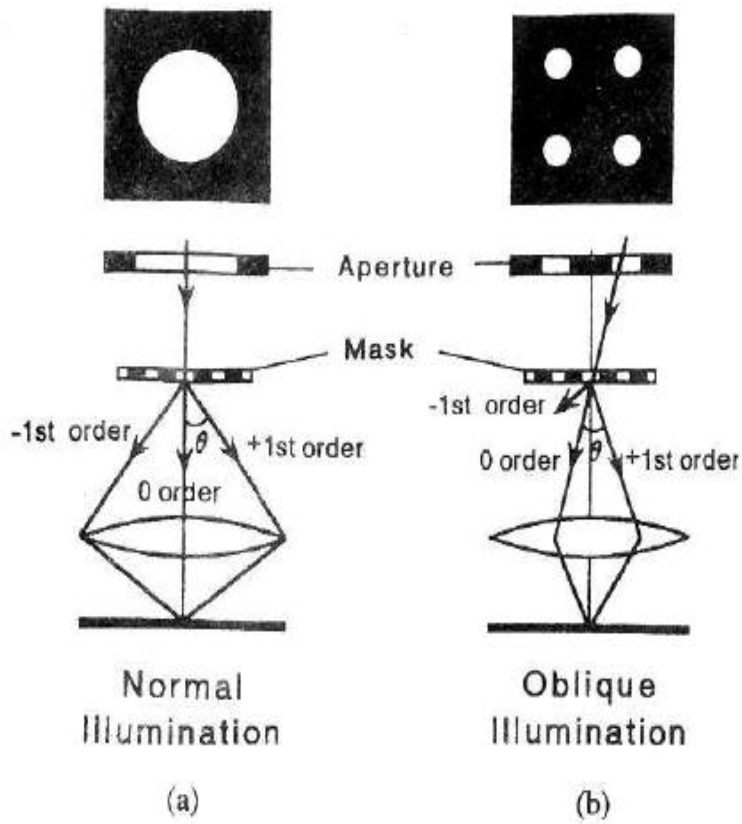


Fig.12. Principle of the oblique illumination system.

zero-order light and either the +1-order or the -1- order light can pass through the aperture. The image is then better than that composed by only the zero-order light. Oblique illumination is achieved by means of the aperture plate shown in Fig.12. This method has been applied in a Nikon commercial stepper, under the acronym SHRINC (super-high resolution by illumination control).

Another resolution enhancement method is the phase-shifting mask method. A phase-shift mask can be formed with a line and space pattern and a phase-shifter covering the spaces in the pattern as shown in Fig.13(a). The phase of the light passing through the phase-shifter is changed by 180°. As a result, the contrast of the light intensity on the wafer is better than that with no phase shifter, as shown in Fig.13(b).

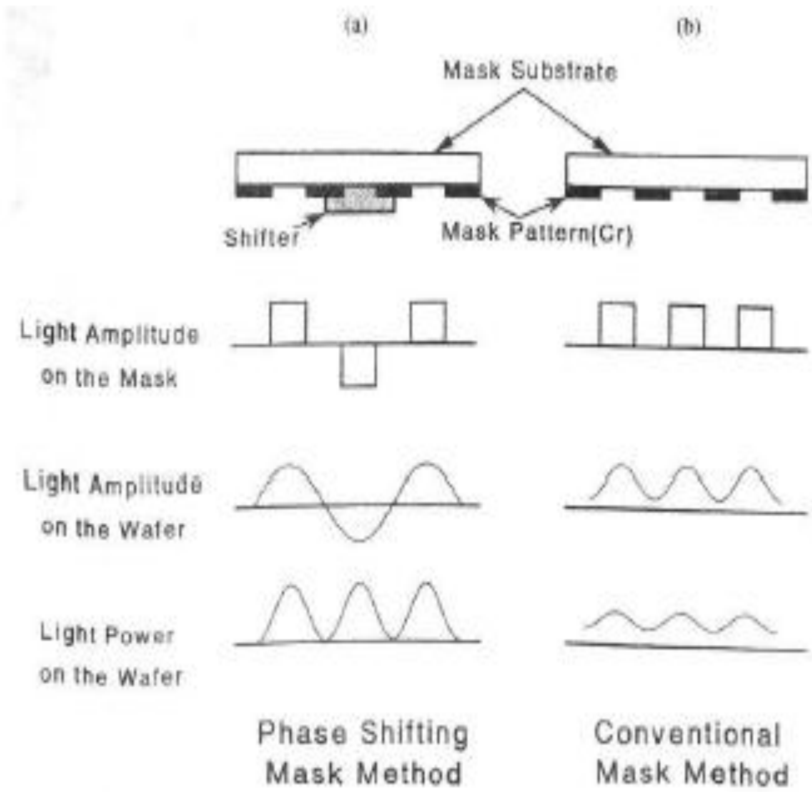


Fig.13. Principle of the phase-shifting mask method.

Electron beam lithography Introduction

Electron beam (EB) lithography has been an essential mask fabrication technology for ULSI devices since Bell Laboratories developed a high-throughput and reliable EB system, EBES1. Mask fabrication technology is now very important for ULSI miniaturization, because a phaseshifting mask improves the resolution of optical lithography.

It has been forecast that progress in the miniaturization of ULSI devices achieved by the revolution in optical lithography will result in a 1 Gbit DRAM (dynamic random access memory) with a size of 0.15 µm by about the year 2000. However, since optical lithography for a size of 0.25 pm is still under development, optical lithography is not always used in the development of 256 Mbit to 1 Gbit DRAM devices. Although the EB system throughput is very low, it is sufficient for use in R & D on devices because of its high-resolution capability.

The problem is that it is impossible for optical lithography to fabricate a pattern smaller than 0.15¬0.1 µm, owing to its resolution limitation. EB lithography, in addition to X-ray lithography, is a promising technique for such smaller patterns. The key features to be developed for a production-stage EB system are throughput and writing accuracy.

EB lithography for masks

Figure14 shows a lithography scheme. Nowadays the main lithography technique is for an optical projection printing machine to duplicate a pattern from a mask of several fold magnification (reticle) on to a Silicon (Si) wafer. The reticle or mask is fabricated by the EB writing process. So far, a Gaussian beam system has been used for reticle-making in most mask shops. Figure 15 shows an example of a writing method for a reticle EB system, EBM-130/40, produced by Toshiba Machine Co[2]. The stage moves continuously in one direction, while the beam is scanned in a direction perpendicular to the movement. LSI data are divided into addresses represented by a 1 or a 0.

The electron beam is on or off according to whether the address is 1 or 0 respectively. The data transfer rate is 40 MHz. The Gaussian beam spot size has to be reduced for ULSI miniaturization, as shown in Table 5.3.1. The throughput is > 1 h^{-1} for a 4 Mbit DRAM-class reticle when writing with a 0.5 μm spot size. However, the throughput decreases to 0.05 h^{-1} for a 64 Mbit DRAM-class reticle, since the spot size has to be reduced to 0.1 μm.

Furthermore, the reticle writing speed is reduced by proximity effect correction such as a GHOST exposure method[3], by an increase in reticle size from 125 to 150 mm and also by phase- shifting mask writing, which requires about double exposure. A high-speed reticle writing system is therefore strongly required. MEBES (ETEC Co.) has been developed as a high-speed reticle writing system which adopts a Zr-O-W thermal field-emission electron gun.

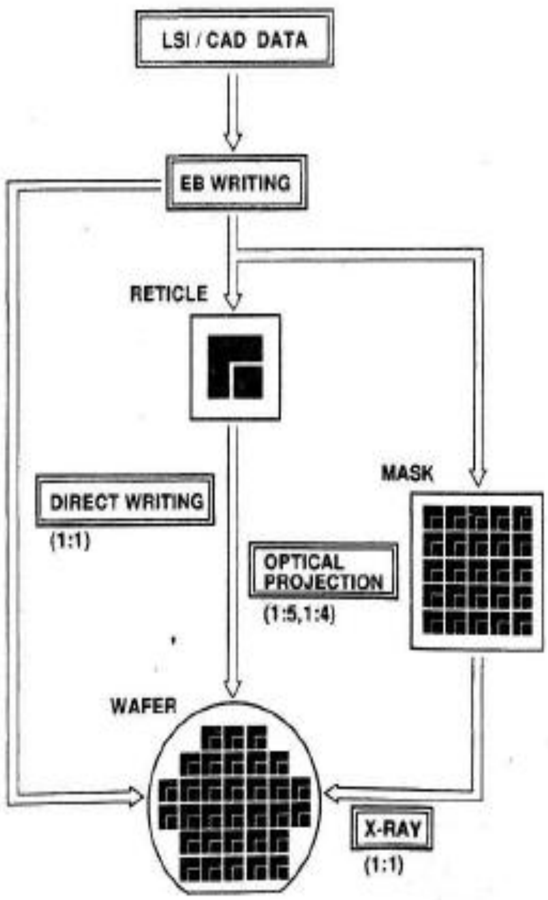


Fig.14. Lithography scheme

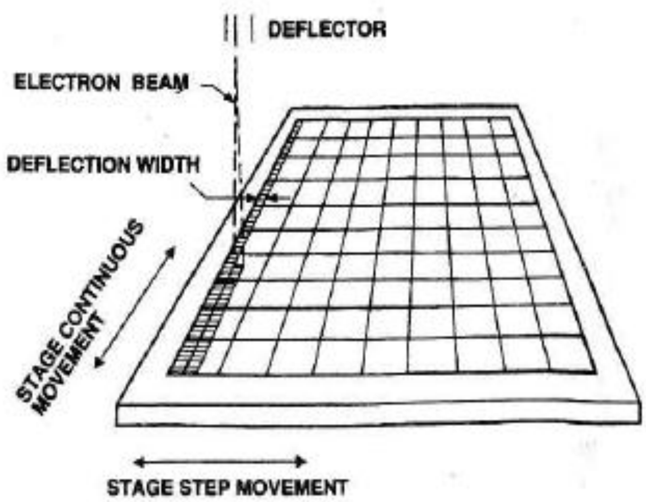


Fig. 15 Writing method for reticle writing

DRAM capacity	Reticle pattern size (x5) (μm)	Beam diameter (μm)	Throughput (h^{-1})
4M	3.5	0.5	1.3
16M	2.5	0.25	0.3
64M	1.5	0.1	0.05
256M	1.25	0.05	0.0125
1G	0.75	0.05	0.0125

of 10 kV, and the data transfer rate 160 MHz. The writing speed of MEBES is four times that of EBM-130/40, resulting in a reticle writing time of ~ 5 h for a 64 Mbit DRAM class. The EBES4 developed by Bell Laboratories is similar in concept, using a thermal field-emission electron gun(5). The spot size is 0.125 µm, the current density 1600 A cm-2 at an acceleration voltage of 20 kV, and the data transfer rate 230 MHz.

Another method of achieving a high throughput system is to adopt the variably shaped beam (VSB) concept. The writing method for the EX-8 (Toshiba Co.) is shown in Fig. 4.3.4, which adopts VSB, a continuously moving stage, and vector scanning (beam flies from pattern to pattern[6]. The EX-8 has the ability to write a 1 Gbit DRAM-class reticle pattern, because the address size, corresponding to the beam size in a Gaussian beam system, is 0.01 µm.

[The EX-8 can generate triangular beams and rectangular beams from 0.1 to 2.56 µm by using a key hole type second shaping aperture. LSI patterns are composed of slanting-angle patterns in addition to x-y patterns. A conventional VSB-type EB system approximates a slanting angle by small rectangles. On the other hand, the EX-8 writes a slanting-angle pattern with a combination of triangular and rectangular beams, which results in a higher throughput than with conventional VSB-type EB systems. The throughput is ~ 2 h^{-1} for a 64 Mbit DRAM-class pattern. Moreover, the EX-8 is equipped with an alignment function using marks on a glass plate, which enables it to write a Levenson-type phase-shifting mask[7]. It is also equipped with a fully automatic glass plate loading system, as shown in Fig. 4.3.5. A robot takes a glass plate from a cassette magazine and puts it into the I/O chamber. After the I/O chamber has been evacuated, the glass plate moves to the loading chamber, from where a shuttle takes it to the writing chamber.

Writing accuracy, as well as throughput, is very important for a reticle writing system. The required reticle accuracy is indicated in Table. Figure shows pattern errors appearing in a pattern written by a VSB and continuous stage-moving system. The patterns dimensional accuracy is limited by the resist process in addition to problems inherent in EB lithography, for example the proximity effect and resist heating. Stitching accuracies are composed of shaped beam stitching, sub-field stitching caused by sub-deflection, and stripe stitching caused mainly by the main deflection and stage movement. The improvement of stripe stitching accuracy is the most difficult among stitching accuracies. A stripe stitching error arises from residual distortion of the main deflector after distortion correction, stage attitude control error, mechanical vibration between the electron optical column and the substrate, electrical noise, and beam drift. Moreover, stripe stitching overlaps beam stitching and sub-field stitching. The only way to reduce stripe stitching error is to discover the origin of the error factors and to eliminate them one by one. Long-range dimensional accuracy is related to the difference in writing position from the ideal position. The accuracy has to be better than 5×10^{-7}, since the required long-range dimensional accuracy is ~ 0.05 μm per 100 mm.

Furthermore, long-term stability of accuracy is required. It needs great effort to maintain an accuracy of 5×10^{-7} for a long time[8]. Many monitoring systems for acceleration power supply, stage temperature, beam size, beam drift, and so on have been developed. Generally, an EB system is very complicated, which poses a problem to be solved in the future.

Data conversion from LSI/CAD data to EB system data is essential for large-volume LSI data. VSB systems are used in parallel to conventional Gaussian beam systems in most mask shops. Data conversion from conventional Gaussian beam system data to the VSB system data is therefore necessary. An example of a data conversion system, in which the EX-8 VSB-type system and the EBM-130/40 Gaussian beam-type system are used, is shown in Fig. LSI/CAD data are converted to EBM-format data for the EBM-130/40. It takes about two days for 16 Mbit DRAM- class pattern data to be converted from LSI/CAD' to EBM format, because data compaction using a hierarchical structure of the LSI data cannot be applied effectively to EBM data. EBM data are converted to VSB data (EX-8 data) in a very short time. The reticlemaking speed is not so high, because it is limited by conversion from LSI/CAD data to EBM data in spite of the high writing speed of the EX- 8 and high-speed data conversion from EBM

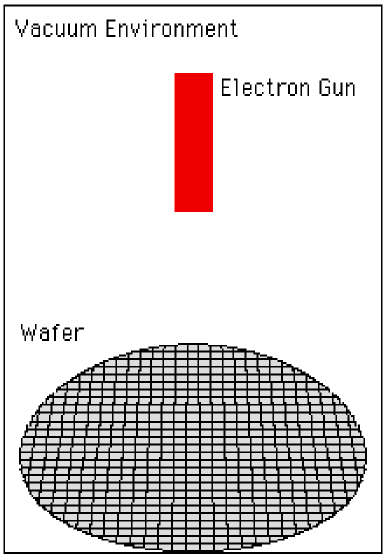
data to VSB data. A high-speed data conversion system from LSI/CAD data to VSB data has therefore been developed using a hierarchical structure of the LSI pattern data and a parallel computer processing method[9]. The data conversion time is ~ 30 min for a 64 Mbit DRAM-class pattern

Ion Beam Lithography

Description:

This is a variation of the electron beam lithography technique, using an focused ion beam (FIB) instead of an electron beam. In a similar setup to scanning electon microscopes, an ion beam scans across the substrate surface and exposes electron sensitive coating. A grid of pixels is superimposed on the substrate surface, each pixel having a unique address.

The pattern data is transfered to the controling computer, which then directs the electron beam as to realize the pattern on the substrate pixel by pixel. The ion beam used is either a Guassian round beam or Variable Shaped Beam (VSB). There are two methods of scanning the beam over the substrate surface to write the pattern data. With raster scan, the electron beam is scanned across lines of pixels and the wafer is shifted to the next line. With vector scan, an area of an individual chip is selected, and the beam draws out the features in that area one-by-one.



Advantages:

- Computer-controlled beam
- No mask is needed
- Can produce sub-1 µm features
- Resists are more sensitive than electron beam resists
- Diffraction effects are minimized
- Less backscattering occurs
- Higher resolution
- Ion beam can detect surface features for very accurate registration

Disadvantages:

- Reliable ion sources needed
- Swelling occurs when developing negative ion beam resists, limiting resolution
- Expensive as compared to light lithography systems
- Slower as compared to light lithography systems
- Tri-level processing required

Optical Lithography

The name optical lithography comes from the early application where the exposing energy was visible light. While those wavelengths can still be used, the push to reduce the size of feature sizes has lead to the use of shorter wavelengths to increase resolution. Ultraviolet (UV) and deep ultraviolet (DUV) sources are now used. Such sources include excimer lasers which operate at wavelengths of 248 nm, 193 nm, and less. Visible wavelengths end in the red at about 400 nm. At these shorter wavelengths, particularly 193 nm, optical materials and even air absorb the energy very well and there are still many problems to be overcome when using this wavelength. The process steps described below are superficial and require advanced levels of technology to be fully effective. There are many references available which more completely describe each process step.

The first step in optical lithography is to create a mask. The mask substrate is commonly borosilicate glass or more recently fused-silica because of its lower thermal expansion coefficient and higher transmission at lower wavelengths. The next step is to apply a resist coating to the mask substrate. This is done using a spinner which spins the mask substrate as a small amount on liquid resist is applied at the center. This results in a uniform coating of the liquid resist on the substrate. To mechanically "fix" the resist, it undergoes a prescribed baking operation.

The next step is to pattern the resist with a pattern generator. In photography, the negative is patterned by the scene being photographed. In lithography, the pattern is made by moving a small spot of light over the resist to "write" the desired pattern. The source for traditional optical lithography is a mercury arc lamp which has an output with spectral energy peaks at particular wavelengths. The resist is commonly tailored to be most sensitive at one or more of these wavelengths.

For DUV mask patterning, lasers are used. The mask resist may also be patterned by electron beam lithography which can shape the beam to be square or rectangular. The much shorter wavelength of the electrons is one reason for increased resolution using e-beam lithography. After patterning, the mask is developed and a metal coating (commonly chromium) is applied. The chromium fills the voids in the developed resist, as well as on top of the undeveloped resist. The resist is then stripped away leaving a pattern of chromium on the mask substrate. Prior to use, the mask must be inspected, measured, and if necessary repaired.

A similar process is performed on the substrate and resist to be patterned for the final structures. For microelectronics, the substrate is silicon or gallium-arsenide. For silicon-based MEMS (microelectro mechanical systems), the substrate is also silicon. The mask is then used analagous to a photographic negative and the mask pattern is transferred into the resist carried on the substrate. Normally, the mask is held in very close proximity to the substrate and resist in what is termed proximity or shadow printing.

The resolution of the transferred pattern is governed by the diffraction equations for the incident light.

Proximity and Contact Printing

$$\text{Resolution} = \sqrt{\lambda\,\{\text{gap between mask and resist} + \text{resist thickness}\}}$$

where λ is the wavelength of the illuminating radiation

Projection Printing

$$\text{Resolution} = \{Ka * \lambda\} / \{NA\} \quad ; \quad \text{Depth of Focus} = \{Kb * \lambda\} / \{NA^2\}$$

where Ka is process constant ~ 0.75
Kb is a process constant ~ 0.5
NA is the numertical aperture of the optical system

LIGA Process

LIGA is a German acronym for Lithographie, Galvanoformung, Abformung (Lithography, Electroplating, and Molding) that describes a fabrication technology used to create high-aspect-ratio microstructures

LIGA consists of a three min processing steps; lithography, electroplating and molding. There are two main LIGA-fabrication technologies, X-Ray LIGA, which uses X-rays produced by a synchrotron to create high-aspect ratio structures, and UV LIGA, a more accessible method which uses ultraviolet light to create structures with relatively low aspect ratios.

The notable characteristics of X-ray LIGA-fabricated structures include:

- high aspect ratios on the order of 100:1
- The parallel side walls with a flank angle on the order of 89.95°
- smooth side walls with = 10 nm, suitable for optical mirror
- structural heights from tens of micrometers to several millimeters
- structural details on the order of micrometers over distances of centimeters.

X-Ray LIGA

X-Ray LIGA is a fabrication process in microtechnology that was developed in the early 1980s [1] by a team under the leadership of Erwin Willy Becker and Wolfgang Ehrfeld at the Institute for Nuclear Process Engineering (Institut für Kernverfahrenstechnik, IKVT) at the Karlsruhe Nuclear Research Center, since renamed to the Institute for Microstructure Technology (Institut für Mikrostrukturtechnik, IMT) at the Karlsruhe Institute of Technology (KIT). LIGA was one of the first major techniques to allow on-demand manufacturing of high-aspect-ratio structures (structures that are much taller than wide) with lateral precision below one micrometer.

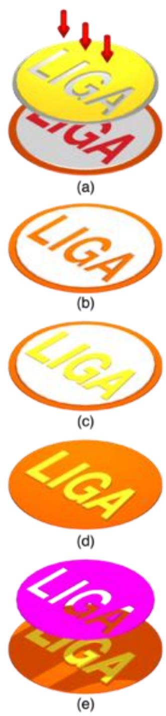
In the process, an X-ray sensitive polymer photoresist, typically PMMA, bonded to an electrically conductive substrate, is exposed to parallel beams of high-energy X-rays from a synchrotron radiation source through a mask partly covered with a strong X-ray absorbing material. Chemical removal of exposed (or unexposed) photoresist results in a three-dimensional structure, which can be filled by the electrodeposition of metal. The resist is chemically stripped away to produce a metallic mold insert. The mold insert can be used to produce parts in polymers or ceramics through injection molding.

The LIGA technique's unique value is the precision obtained by the use of deep X-ray lithography (DXRL). The technique enables microstructures with high aspect ratios and high precision to be fabricated in a variety of materials (metals, plastics, and ceramics). Many of its practitioners and users are associated with or are located close to synchrotron facilities.

UV LIGA

UV LIGA utilizes an inexpensive ultraviolet light source, like a mercury lamp, to expose a polymer photo resist, typically SU-8. Because heating and transmittance are not an issue in optical masks, a simple chromium mask can be substituted for the technically sophisticated X-ray mask. These reductions in complexity make UV LIGA much cheaper and more accessible than its X-ray counterpart. However, UV LIGA is not as effective at producing precision molds and is thus used when cost must be kept low and very high aspect ratios are not required.

Process details



The LIGA-fabrication process is composed of exposure (a), development (b), electroforming (c), stripping (d), and replication (e).

Mask

X-ray masks are composed of a transparent, low-Z carrier, a patterned high-Z absorber, and a metallic ring for alignment and heat removal. Due to extreme temperature variations induced by the X-ray exposure, carriers are fabricated from materials with high thermal conductivity to reduce thermal gradients.

Currently, vitreous carbon and graphite are considered the best material, as their use significantly reduces side-wall roughness. Silicon, silicon nitride, titanium, and diamond are also in use as carrier substrates but not preferred, as the required thin membranes are comparatively fragile and titanium masks tend to round sharp features due to edge fluorescence. Absorbers are gold, nickel, copper, tin, lead, and other X-ray absorbing metals.

Masks can be fabricated in several fashions. The most accurate and expensive masks are those created by electron beam lithography, which provides resolutions as fine as 0.1 µm in resist 4 µm thick and 3 µm features in resist 20 µm thick. An intermediate method is the plated photomask which provides 3 µm resolution and can be outsourced at a cost on the order of $1000 per mask.

The least expensive method is a direct photomask, which provides 15 µm resolution in resist 80 µm thick. In summary, masks can cost between $1000 and $20,000 and take between two weeks and three months for delivery. Due to the small size of the market, each LIGA group typically has its own mask-making capability. Future trends in mask creation include larger formats, from a diameter of 100 mm to 150 mm, and smaller feature sizes.

Substrate

The starting material is a flat substrate, such as a silicon wafer or a polished disc of beryllium, copper, titanium, or other material. The substrate, if not already electrically conductive, is covered with a conductive plating base, typically through sputtering or evaporation.

The fabrication of high-aspect-ratio structures requires the use of a photoresist able to form a mold with vertical sidewalls. Thus the photoresist must have a high selectivity and be relatively free from stress when applied in thick layers.

The typical choice, poly(methyl methacrylate) (PMMA) is applied to the substrate by a glue-down process in which a precast, high-molecular-weight sheet of PMMA is attached to the plating base on the substrate. The applied photoresist is then milled down to the precise height by a fly cutter prior to pattern transfer by X-ray exposure. Because the layer must be relatively free from stress, this glue-down process is preferred over alternative methods such as casting. Further, the cutting of the PMMA sheet by the fly cutter requires specific operating conditions and tools to avoid introducing any stress and crazing of the photoresist.[citation needed]

Exposure

A key enabling technology of LIGA is the synchrotron, capable of emitting high-power, highly collimated X-rays. This high collimation permits relatively large distances between the mask and the substrate without the penumbral blurring that occurs from other X-ray sources. In the electron storage ring or synchrotron, a magnetic field constrains electrons to follow a circular path and the radial acceleration of the electrons causes electromagnetic radiation to be emitted forward. The radiation is thus strongly collimated in the forward direction and can be assumed to be parallel for lithographic purposes. Because of the much higher flux of usable collimated X-rays, shorter exposure times become possible. Photon energies for a LIGA exposure are approximately distributed between 2.5 and 15 keV.

Unlike optical lithography, there are multiple exposure limits, identified as the top dose, bottom dose, and critical dose, whose values must be determined experimentally for a proper exposure. The exposure must be sufficient to meet the requirements of the bottom dose, the exposure under which a photoresist residue will remain, and the top dose, the exposure over which the photoresist will foam. The critical dose is the exposure at which unexposed resist begins to be attacked. Due to the insensitivity of PMMA, a typical exposure time for a 500 µm thick PMMA is six hours. During exposure, secondary radiation effects such as Fresnel diffraction, mask and substrate fluorescence, and the generation of Auger electrons and photoelectrons can lead to overexposure.

During exposure the X-ray mask and the mask holder are heated directly by X-ray absorption and cooled by forced convection from nitrogen jets. Temperature rise in PMMA resist is mainly from heat conducted from the substrate backward into the resist and from the mask plate through the inner cavity air forward to the resist, with X-ray absorption being tertiary. Thermal effects include chemistry variations due to resist heating and geometry-dependent mask deformation.

Development

For high-aspect-ratio structures the resist-developer system is required to have a ratio of dissolution rates in the exposed and unexposed areas of 1000:1. The standard, empirically optimized developer is a mixture of tetrahydro-1,4-oxazine (20 %), 2-aminoethanol-1 (5 %), 2-(2-butoxyethoxy)ethanol (60 %), and water (15 %). This developer provides the required ratio of dissolution rates and reduces stress-related cracking from swelling in comparison to conventional PMMA developers. After development, the substrate is rinsed with deionized water and dried either in a vacuum or by spinning. At this stage, the PMMA structures can be released as the final product (e.g., optical components) or can be used as molds for subsequent metal deposition.

Electroplating

In the electroplating step, nickel, copper, or gold is plated upward from the metalized substrate into the voids left by the removed photoresist. Taking place in an electrolytic cell, the current density, temperature, and solution are carefully controlled to ensure proper plating. In the case of nickel deposition from NiCl2 in a KCl solution, Ni is deposited on the cathode (metalized substrate) and Cl2 evolves at the anode. Difficulties associated with plating into PMMA molds include voids, where hydrogen bubbles nucleate on contaminates; chemical incompatibility, where the plating solution attacks the photoresist; and mechanical incompatibility, where film stress causes the plated layer to lose adhesion. These difficulties can be overcome through the empirical optimization of the plating chemistry and environment for a given layout.

Stripping

After exposure, development, and electroplating, the resist is stripped. One method for removing the remaining PMMA is to flood expose the substrate and use the developing solution to cleanly remove the resist. Alternatively, chemical solvents can be used. Stripping of a thick resist chemically is a lengthy process, taking two to three hours in acetone at room temperature. In multilayer structures, it is common practice to protect metal layers against corrosion by backfilling the structure with a polymer-based encapsulant. At this stage, metal structures can be left on the substrate (e.g., microwave circuitry) or released as the final product (e.g., gears).

Replication

After stripping, the released metallic components can be used for mass replication through standard means of replication such as stamping or injection molding.

Dip pen nanolithography (DPN)

Dip pen nanolithography is a scanning probe lithography technique where an atomic force microscope (AFM) tip is used to create patterns directly on a range of substances with a variety of inks. A common example of this technique is exemplified by the use of alkane thiolates to imprint onto a gold surface. This technique allows surface patterning on scales of under 100 nanometers. DPN is the nanotechnology analog of the dip pen (also called the quill pen), where the tip of an atomic force microscope cantilever acts as a "pen," which is coated with a chemical compound or mixture acting as an "ink," and put in contact with a substrate.

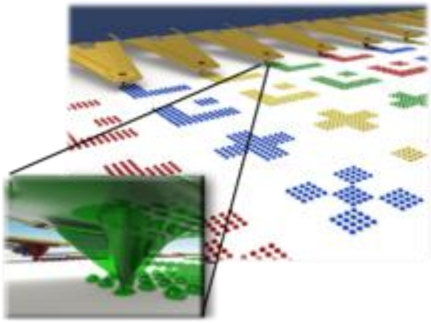
DPN enables direct deposition of nanoscale materials onto a substrate in a flexible manner. Recent advances have demonstrated massively parallel patterning using two-dimensional arrays of 55,000 tips. Applications of this technology currently range through chemistry, materials science, and the life sciences, and include such work as ultra high density biological nanoarrays, and additive photomask .

Deposition material

Molecular inks

Molecular inks are typically composed of small molecules that are coated onto a DPN tip and are delivered to the surface through a water meniscus.[citation needed] In order to coat the tips, one can either vapor coat the tip or dip the tips into a dilute solution containing the molecular ink. If one dip-coats the tips, the solvent must be removed prior to deposition. The deposition rate of a molecular ink is dependent on the diffusion rate of the molecule, which is different for each molecule. The size of the feature is controlled by the tip/surface dwell-time (ranging from milliseconds to seconds) and the size of the water meniscus, which is determined by the humidity conditions (assuming the tip's radius of curvature is much smaller than the meniscus). Water meniscus mediated (exceptions do exist) Nanoscale feature resolution (50 nm to 2000 nm) No multiplexed depositions. Each molecular ink is limited to its corresponding substrate Examples Alkane thiols written to gold Silanes (solid phase) written to glass or silicon

Liquid inks



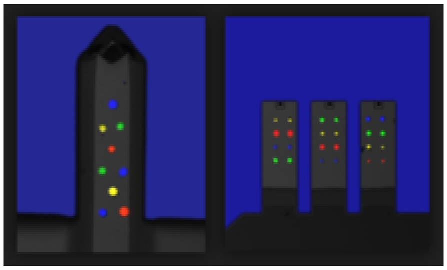
Liquid ink deposition mechanism

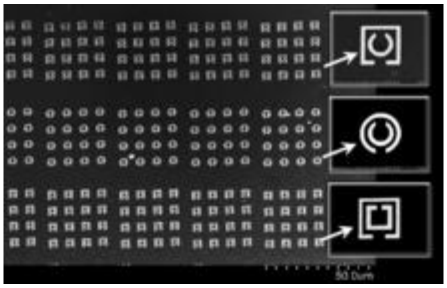
Liquid inks can be any material that is liquid at deposition conditions. The liquid deposition properties are determined by the interactions between the liquid and the tip, the liquid and the surface, and the viscosity of the liquid itself. These interactions limit the minimum feature size of the liquid ink to about 1 micrometre, depending on the contact angle of the liquid. Higher viscosities offer greater control over feature size and are desirable. Unlike molecular inks, it is possible to perform multiplexed depositions using a carrier liquid. For example, using a viscous buffer, it is possible to directly deposit multiple proteins simultaneously.

Applications

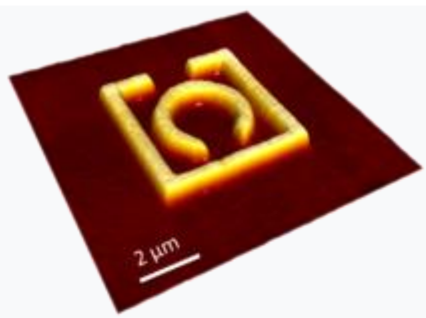
In order to define a good DPN application, it is important to understand what DPN can do that other techniques can't. Direct-write techniques, like contact printing, can pattern multiple biological materials but it cannot create features with subcellular resolution. Many high-resolution lithography methods can pattern at sub-micrometre resolution, but these require high-cost equipment that were not designed for biomolecule deposition and cell culture. Microcontact printing can print biomolecules at ambient conditions, but it cannot pattern multiple materials with nanoscale registry.

The following are some examples of how DPN is being applied to potential products.





DPN is a direct write technique so it can be used for top-down and bottom-up lithography applications. In top-down work, the tips are used to deliver an etch resist to a surface, which is followed by a standard etching process.[18] In bottom-up applications, the material of interest is delivered directly to the surface via the tips.



Gold on silicon metastructure fabricated with top-down DPN methods

Advantages

Directed Placement - Directly print various materials onto existing nano and microstructures with nanoscale registry

- Direct Write - Maskless creation of arbitrary patterns with feature resolutions from as small as 50 nm and as large as 10 micrometres
- Biocompatible - Subcellular to nanoscale resolution at ambient deposition conditions
- Scalable - Force independent, allowing for parallel depositions

Thermal dip pen lithography

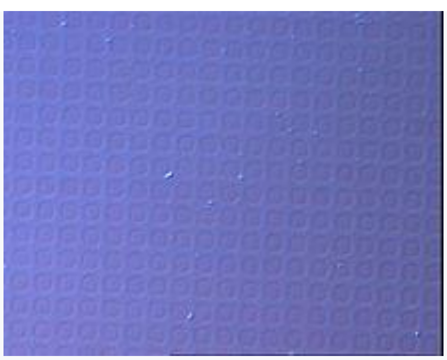
A heated probe tip version of Dip Pen Lithography has also been demonstrated, thermal Dip Pen Lithography (tDPL), to deposit nanoparticles.[21] Semiconductor, magnetic, metallic, or optically active nanoparticles can be written to a substrate via this method. The particles are suspended in a PMMA or equivalent polymer matrix, and heated by the probe tip until they begin to flow. The probe tip acts as a nano-pen, and can pattern nanoparticles into a programmed structure. Depending on the size of the nanoparticles, resolutions of 78-400 nm were attained. An O_2 plasma etch can be used to remove the PMMA matrix, and in the case of Iron Oxide nanoparticles, further reduce the resolution of lines to 10 nm.[21] Advantages unique to tDPL are that it is a maskless additive process that can achieve very narrow resolutions, it can also easily write many types of nanoparticles without requiring special solution preparation techniques. However there are limitations to this method. The nanoparticles must be smaller than the radius of gyration of the polymer, in the case of PMMA this is about 6 nm. Additionally, as nanoparticles increase in size viscosity increases, slowing the process. For a pure polymer deposition speeds of 200 μm/s are achievable. Adding nanoparticles reduces speeds to 2 μm/s, but is still faster than regular Dip Pen Lithography.

Beam pen lithography

A two dimensional array of (PDMS) deformable transparent pyramid shaped tips are coated with an opaque layer of metal. The metal is then removed from the very tip of the pyramid, leaving an aperture for light to pass through. The array is then scanned across a surface and light is directed to the base of each pyramid via a micromirror array, which funnels the light toward the tip. Depending on the distance between the tips and the surface, light interacts with the surface in a near-field or far-field fashion, allowing sub-diffraction scale features (100 nm features with 400 nm light) or larger features to be fabricated.

Common misconceptions

Direct comparisons to other techniques



The criticism most often directed at DPN is the patterning speed. The reason for this has more to do with how it is compared to other techniques rather than any inherent weaknesses. For example, the soft lithography method, microcontact printing (μCP), is the current standard for low cost, bench-top micro and nanoscale patterning, so it is easy to understand why DPN is compared directly to microcontact printing. The problem is that the comparisons are usually based upon applications that are strongly suited to μCP, instead of comparing them to some neutral application. μCP has the ability to pattern one material over a large area in a single stamping step, just as photolithography can pattern over a large area in a single exposure. Of course DPN is slow when it is compared to the strength of another technique.

DPN is a maskless direct write technique that can be used to create multiple patterns of varying size, shape, and feature resolution, all on a single substrate. No one would try to apply microcontact printing to such a project because then it would never be worth the time and money required to fabricate each master stamp for each new pattern. Even if they did, microcontact printing would not be capable of aligning multiple materials from multiple stamps with nanoscale registry.

The best way to understand this misconception is to think about the different ways to apply photolithography and e-beam lithography. No one would try to use e-beam to solve a photolithography problem and then claim e-beam to be "too slow".

Directly compared to photolithography's large area patterning capabilities, e-beam lithography **is** slow and yet, e-beam instruments can be found in every lab and nanofab in the world. The reason for this is because e-beam has unique capabilities that cannot be matched by photolithography, just as DPN has unique capabilities that cannot be matched by microcontact printing.

Connection to atomic force microscopy

DPN evolved directly from AFM so it is not a surprise that people often assume that any commercial AFM can perform DPN experiments. In fact, DPN does not require an AFM, and an AFM does not necessarily have real DPN capabilities. There is an excellent analogy with scanning electron microscopy (SEM) and electron beam (E-beam) lithography. E-beam evolved directly from SEM technology and both use a focused electron beam, but no one would ever suggest that one could perform modern E-beam lithography experiments on a SEM that lacks the proper lithography hardware and software requirements.

It is also important to consider one of the unique characteristics of DPN, namely its force independence. With virtually all ink/substrate combinations, the same feature size will be patterned no matter how hard the tip is pressing down against the surface.[24] As long as robust SiN tips are used, there is no need for complicated feedback electronics, no need for lasers, no need for quad photo-diodes, and no need for an AFM.

Deep-UV Microlithography

In recent years, deep-UV exposure tools have been designed and built using KrF excimer laser light sources that have a peak intensity at 248 nm. Conventional photoresists are not appropriate for use with these new deep-UV tools due to deficiencies in sensitivity and absorption properties of the materials. For most resists, the quantum yield is significantly less than 1, and since the new lithographic tools in general have low brightness sources, high sensitivity resists are required. In addition, the absorption of conventional photoresists is too high to allow uniform imaging through practical resist film thicknesses (~1 pm).

Thus new resists and processes will be required after photolithography has reached its limits (~0.5fim). One approach to improving sensitivity involves the concept of chemical amplification pioneered by Ito and Willson which employs the photogeneration of an acidic species that catalyzes many subsequent chemical events such as deblocking of a protecting group or crosslinking of a matrix polymer. The overall quantum efficiency of such reactions is thus effectively much higher than that for the initial acid generation.