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SURFACE FINISHING PROCESSES

16.1 INTRODUCTION

In a manufacturing plant, a product may be shaped, turned, milled or drilled, and left in that condition as being satisfactory for use. However, If a better finish is desired, for looks, for accuracy, for wearing qualities, or for any other reasons, one of the microfinishes that include lapping, honing, superfinishing, polishing, buffing, may be employed. In some cases other operations are done only to get durable finishes.

16.2 LAPPING

Lapping is an abrading process that is used to produce geometrically true surfaces, correct minor surface imperfections, improve dimensional accuracy, or provide a very close fit between two contact surfaces. Very thin layers of metal (0.005 to 0.01mm) are removed in lapping and it is, therefore, evident that lapping is unable to correct substantial errors in the form and sizes of surfaces. It is, however, low efficiency process and is used only when specified accuracy and surface finish cannot be obtained by other methods.

Abrasive powders (flours) such as emery, corundum, iron oxide, chromium oxide, etc., mixed with oil or special pastes with some carrier are used in lapping. Most lapping is done by means of lapping shoes or quills, called *laps*, that are rubbed against the work. The face of a lap becomes "charged" with abrasive particles. Charging a lap means to embed the abrasive grains into its surface. Laps may be made of almost any material soft enough to receive and retain the abrasive grains. They are made of soft cast iron, brass, copper, lead or soft steel. The method of charging a lap depends upon the shape of lap. When the lap is once charged, it should be used without applying more abrasive until it ceases to cut. Laps may be operated by hand or machine, the motion being rotary or reciprocating. Cylindrical work may be lapped by rotating the work in lathe or drill press and reciprocating the lap over the work in an everchanging path. Small flat surfaces may be lapped by holding the work against a rotating disc, or the work may be moved by hand in an irregular path over a stationary faceplate lap. In *equalizing lapping* the work and lap mutually inprove each others surface as they slide on each other.

There are three important types of lapping machines. The *vertical axis lapping machine* laps flat or round surfaces between two opposed laps on vertical spindles. The *centreless lapping machine* is designed for continuous production of round parts such as piston pins, bearing races and cups, valve tappets and shafts. The centreless lapping machine operates on the same principle as centreless grinding. The *abrasive belt lapping machine* laps bearings and cam surfaces by means of abrasive coated clothes.

16.3 HONING

Honing is grinding or a abrading process mostly for finishing round holes by means of bonded abrasive stones, called hones. Honing is therefore a cutting operation and has been used to remove as much as 3 mm of stock but is normally confined to amounts less than 0.25 mm. So honing is primarily used to correct some out of roundness, taper, tool marks, and axial distortion. Honing stones are made from common abrasive and bonding materials, often impregnated with sulphur, resin, or wax to improve cutting action and lengthen tool life. Materials honed range from plastics, silver, aluminium, brass, and cast iron to hard steel and cemented carbides. This method is mostly used for finishing automobile crankshaft journals.

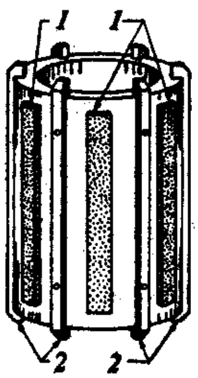


Figure 16.1 Honing tool-head for holes
1. Stones, 2. Guides

When honing is done manually the tool is rotated, and the workpiece is passed back and forth over the tool. For precision honing, the tool is given a slow reciprocating motion as it rotates. Honing stones may be loosely held in holders, cemented into metal shells which are clamped into holders, cemented directly in holders, or cast into plastic tabs which are held in holders. Some stones are spaced at regular intervals around the holder, while others are interlocking so that they present a continuous surface to the bore. A typical honing toolhead is shown in Fig.16.1. The honing tool may be so made that a floating action between the work and tool prevails and any pressure exerted in the tool may be transmitted equally to all sides. Coolants are essential to the operation of this process to flush away small chips and to keep temperatures uniform.

Honing is done on general purpose machines, such as the lathe, drill press, and portable drills, as an expedient. But more economical results can be obtained by honing machines for production work. There are two general types of honing machines : Horizontal and vertical. A honing machine rotates and reciprocates the hone inside holes being finished. The two motions produce round and straight holes that have a very fine surface finish of random scratches. Vertical honing machines are probably more common. Horizontal honing machines are often used for guns and large bores.

16.4 SUPERFINISHING

Superfinshing is an operation using bonded abrasive stones in a particular way to produce an extremely high quality of surface finish in conjunction with an almost complete absence of defects in the surface layer. A very thin layer of metal (0.005 to 0.02 mm) is removed in superfinishing. This operation may be applied for external and internal surfaces of parts made of steel, cast iron and non-ferrous alloys, which have been previously ground or precision turned. It is most frequently used to obtain very fine surface finish.

In superfinishing, a very fine grit (grain size 400 to 600) abrasive stick is retained in a suitable holder and applied to the surface of the workpiece with a light spring pressure. The stick is given a feeding and oscillating motion, and the workpiece is rotated or reciprocated according to the requirements of the shape being superfinished, In this process, the work rotational speed is low (2 to 20 m/min.) the longitudinal feed ranges from 0.1 to 0.15 mm per workpiece revolution, the abrasive stick oscillates rapidly in short strokes (2 to 5mm) with a frequency from 500 to 1,800 strokes per minute and the springs hold the stick against the work with a

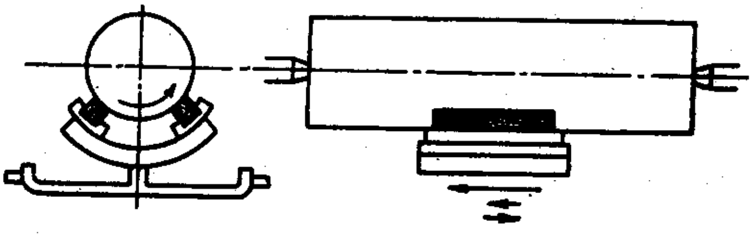


Figure 16.2 Schematic diagram of shaft superfinishing

force from 2 to 10 kg. A special lubricant, usually a mixture of kerosene and oil, is used to obtain a high quality of surface finish, A schematic diagram of shaft superfinishing is shown in Fig.16.2.

Special general-purpose machine tools are available for superfinishing. Other types of ordinary machines, in particular, lathes, are sometimes employed for this purpose. Single purpose machine tools for example, for finishing crankshaft journals, camshafts, etc. are also used.

16.5 POLISHING

Polishing is a surface finishing operation performed by a polishing wheel for the purpose of removing appreciable metal to take out scratches, tool marks, pits and other defects from rough surfaces. In polishing, usually accuracy of size and shape of the finished surface is not important, but sometimes tolerances of 0.025 mm or less can be obtained in machine polishing. Polishing wheels are made of leather, papers, canvas, felt, or wool. The abrasive grains are set up with glue or thermosetting resins on the face of the wheel, and the work is held against it and rotated to give the desired finish. Polishing may follow any of the machining methods except honing, lapping, or superfinishing. Commonly several steps are necessary, first to remove the defects and then to put the desired polish on the surface.

The polishing method is very similar to grinding, and the work may be pressed by hand to wheels mounted on floor stand grinders. For production many kind of machines have been built to bring the coated abrasive in contact with the workpiece. They may be broadly classified in two groups : the *endless-belt machines* and the *coated abrasive wheels.*

16.6 BUFFING

Buffing is used to give a much higher, lustrous, reflective finish that cannot be obtained by polishing. The buffing process consists in applying a very fine abrasive with a rotating wheel. Buffing wheels are made of felts pressed and glued layers of duck or other cloth, and also of leather. The abrasive is mixed with a binder and is applied either on the buffing wheel or on the work. The buffing wheel rotates with a high peripheral speed upto 40 m/sec. The abrasive may consist of iron oxide, chromium oxide, emery, etc. The binder is a paste consisting of wax mixed with grease, paraffine and kerosene, or turpentine and other liquids.

16.7 POWER BRUSHING

High speed revolving brushes can be used to remove burrs, fins, sharp edges or minute surface defects from manufactured components. Tough fibre wheels, wire bristle and Tampico are utilized to produce power brushes. These materials are flexible and can conform to irregular surfaces.

16.8 TUMBLING

Tumbling, often, is the least expensive process for removing rust and scale from metal parts. Parts configuration and size are the primary limitations of the process. Tumbling in dry abrasives (deburring compounds) is effective for removing rust and scale from small parts of simple shape. However, parts of complex shape, with deep recess and other irregularities, cannot be descaled uniformly by tumbling. It may require several hours of tumbling, if the method is used. The addition of descaling compounds instead of deburring compounds will often decrease the tumbling time by 75 per cent.

The operation is accomplished by placing workpieces in a drum or barrel, together with stars, jacks, slugs, or abrasive materials. The abrasive materials can be sand, granite chips, slag, or aluminium oxide pellets. In operation, the barrel is rotated, and the movement of the workpieces and the accompanying slugs or abrasive material against each other produces by friction a fine cutting action which remove the fins, flashes, and scale from the products.

16.9 PICKLING AND OXIDIZING

Pickling refers to the removal of surface oxides and scale from metals by acid solutions. Common pickling solutions contain sulphuric or hydrochloric acids and water and sometimes inhibitors which have been developed to reduce the harmful action of the acid fumes on plant equipment. Nitric and hydroflouric acids are used for some applications. In pickling, the parts must be perfectly cleaned before they are immersed in acid solution. After pickling, the parts must be rinsed and completely neutralized by an alkaline rinse, otherwise any trace of acid will corrode the material and harm paint or other subsequent coating.

Pickling is commonly done on rolled shapes, wires, sheets, heat treated steel parts, wrought and cast aluminum parts. In some applications, such as on aluminium, pickling is called *oxidizing*.

16.10 ELECTROPLATING

Electroplating is the most popular means of applying metallic coatings on the surfaces of metals and sometimes on non-metals. This is done for protection against corrosion or against wear and abrasion, for appearance, to re-work worn parts by increase in size, to make pieces easy to solder and to stop off areas on steel parts from being carburized during heat treatment. Common plating metals are chromium, nickel, copper, zinc, cadmium and tin. The more precious metals—silver, gold, platinum, and rhodium are also applied by plating.

Surfaces to be plated must be buffed smooth to eliminate scratches and unevenness. The work is then cleaned in suitable cleaning solutions to remove all grease, dirt, buffing compound, etc. After rinsing, the part is ready for plating.

The four essential elements of a plating process are the cathode, anode, electrolyte, and direct current. They are shown in Fig.16.3. The current leaves the anode, which is a bar of plating metal, and migrates through the electrolyte (water solution of salts of the metal to be applied) to the cathode, or part to be plated. As the ions are deposited on the cathode, they give up their charge and are deposited as metal on the cathode. Parts to be plated should be designed with generous fillets and radii instead of sharp corners, since current concentrations occur at sharp points, resulting in excessive deposits.

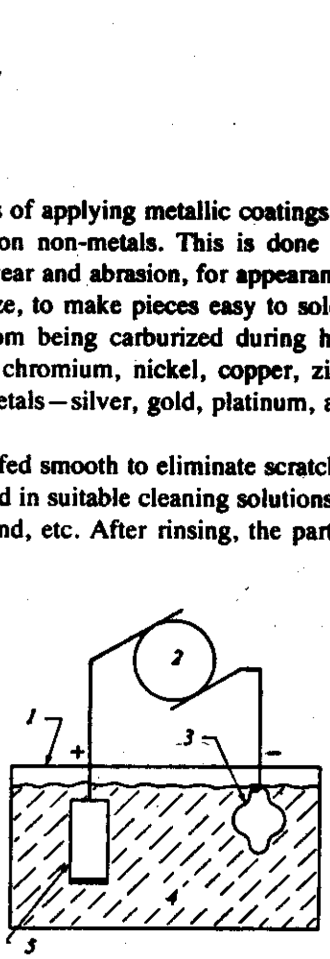


Figure 16.3 Electroplating
1. Plating tank, 2. D.C.source, 3. Workpiece, 4. Solution, 5. Anode (plating)

16.11 HOT DIPPING : GALVANIZING

A protective coating may be applied on metal pieces by dipping them into certain molten metals namely zinc, tin, or an alloy of lead and tin. Dipping is an economical way of putting on a heavy and enduring coating.

To obtain an even coating on small objects such as nuts, bolts, pins and washers, the objects are centrifuged, after being taken from the molten bath, until the coating is hard.

Zinc dipping, or hot galvanizing, is widely used on steel as an effective protection against corrosion. The parts are first cleaned and fixed in solution of zinc chloride and hydrochloric acid.

16.12 METAL SPRAYING

Metal spraying is basically intended to confer some physical property on a surface. The appearance of poor surfaces on castings can be improved by metal spraying. Sprayed metal can be decorative, like aluminum or bronze on cast iron. Some can even be coloured.

Metal spraying is done by melting a metal in an oxy-gas flame and blowing it from the nozzle of a spray gun. In most guns the metal in the form of wire is fed by powered rollers to the flame, but some guns use powder or granulated metal. The process uses compressed air to atomize fully the molten metal or oxides and project them against a prepared surface where they are embedded, assuring good mechanical adhesions. This is illustrated in Fig.16.4. The surface must be roughened first and be free of dirt, oil and grease. The compressed air helps cool the work parts, so that the coatings may be applied successively not only to metals but also to glass, wood, asbestos, and certain plastics.

A metal spray gun may be directed by hand or mounted on a machine.

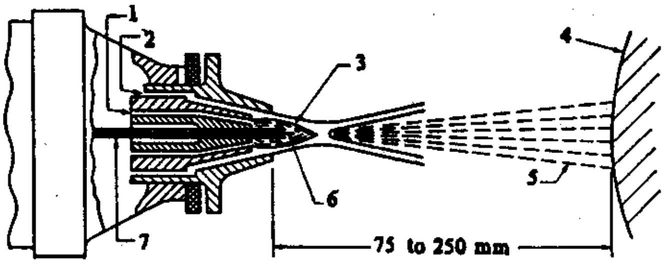


Figure 16.4 Metal spraying

1. Oxy-fuel gas, 2. Compressed air, 3. Flame, 4. Workpiece, 5. Atomized spray, 6. Melting, 7. Wire.

16.13 METALLISATION

Metallisation is an interesting application of the oxy-acetylene flame. This technique essentially consists in laying deposits which vary both in nature and in thickness, on to the widest variety of parts.

The principle is as follows : the material to be deposited is melted in a flame and subsequently pulverized and sprayed in fine droplets on to the part to be coated. The equipment used is a gun. It comprises a special torch, coupled with a compressed air pulverizing device and a system of feeding the product.

Any product can be sprayed : metal, ceramics, plastics, on to any metal, and under certain conditions on to many non-metallic supports : wood, plaster, plastics, etc. Metallised surfaces laid in a thin layer of from 40 to 200 microns (zinc and aluminium) provide a much stronger and longer lasting protection against corrosion than any other more or less composite film.

REVIEW QUESTIONS

1. Explain why surface finishing is an important manufacturing process.
2. Briefly explain the process of lapping.
3. What is honing ? How and why it is performed ?
4. What is superfinishing ?
5. Write short notes : (a) Polishing, (b) Buffing, (c) Electroplating.
6. What is pickling ? Why it is considered as a surface finishing process ?
7. Explain how metal spraying is done ?
8. Briefly explain : (a) Galvanizing (b) Metallisation.

17

ERECTING AND TESTING MACHINE TOOLS

17.1 INTRODUCTION

The accuracy in the form and relationship of machine tool elements have a great bearing on the accuracy and finish of the workpiece. Machine tools are, therefore, subjected to a rigid test during all stages of manufacture. The test covers the grade of accuracy of the machine tool itself, and whenever feasible, also its working accuracy.

Before proceeding to test a machine tool, the machine should be fixed upon suitable foundations on which it will later have to work and leveled in accordance with the instruction of the manufacturer. It will be logical, therefore, to start from the location, and foundation of machines.

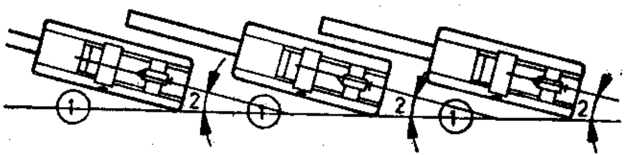


Figure 17.1 Arrangement of several machines
1. Working place of the turner, 2. Position of the lathes with respect to each other.

17.2 LOCATION

At first the space required by a properly functioning machine must be determined. In this connection it should be noted that work tables at machines normally must be conveniently accessible from all sides for the operator. For example, when selecting the location of a radial drilling machine, the operating range of the swivelling arm must be taken into consideration. Fig.17.1 shows a typical arrangement of several machines.

17.3 FOUNDATIONS

The foundation plays a most important part in testing machine tools. It carries and supports the weight of the machine, aligns the machine, and what is most important, it absorbs vibration produced by the unbalanced forces created by the reciprocating and rotating masses of the machine elements. But if the foundation is not properly made, i.e., if the foundation is made too light and is not extended to a sufficient depth, this will cause a continuous source of trouble.

For machines, where vibration occurs, a concrete foundation must be prepared. To enable this to be laid out the manufacturers generally prepare and issue a foundation plan. The plan shows the profile and size of the necessary concrete preparation and gives particulars as to recesses necessary to accommodate projections and holding-down bolts, etc. The foundation can be set down before the machine is delivered and will be ready for occupation as soon as it arrives.

The depth of the concrete foundation will depend on the weight of the machine, the amount of vibration involved and the character of the subsoil. The safe load vary from about 5,000 kg/m^2 for alluvial soil or wet clay to about 20,000 kg/m^2 for gravel, coarse sand, or dry clay. If the soil is marshy, it will not support even 5,000 kg/m^2. In that case, the base of the foundation will be required to form a mat or raft and concrete base should be reinforced with steel. For most machine tools, according to the weight and the subsoil, depth of concrete varying from 225 to 1200 mm should be sufficient.

17.4 ERECTION

After the foundation has been made, the machine may be placed in position for levelling and aligning. Before setting the foundation, a foundation bolt should be passed through each of the holding down holes in the base of the machine and allowed to remain loose with a nut on the end of the bolt. It should be noted that concrete normally requires a time of three to four days to set; for this time, a machine cannot be erected on it. Concrete needs more than 20 days to reach its full hardness.

Now comes the job of *levelling*. The machine is carefully put on the foundation bolts in the floor. Then the machine must be properly aligned. This means that the whole machine must be in a perfectly horizontal position. Spirit levels are used to check the position.

The first thing to do is to check the actual position of the machine. For this purpose, a spirit level is applied to certain measuring areas, in both longitudinal and cross direction, for example to the bed if lathes (Fig.17.2), to the work table of milling and grinding machines. If these measuring surfaces are out of the horizontal, wedges must be driven into the gap under the machine bed as shown in Fig.17.3. When the tests show satisfactory results the wedges should be examined to ensure that each one is tight and then the machine should be left to settle down for a day or two. After this time a further check for level should be made, and if this is acceptable the machine may be grouted in. The grouting is carried out by pourung a creamy mixture of almost pure cement so that it fills up all the voids between the base and the concrete and provides a large area of support. In a few days the grouted will be hard, when the wedges may be removed and the concrete at the edges of the base made good. The machine base is then tightly screwed to the foundation bolts as shown in Fig.17.4. After tightening the nuts, the correct position of the machine must once more be checked by means of the spirit level.

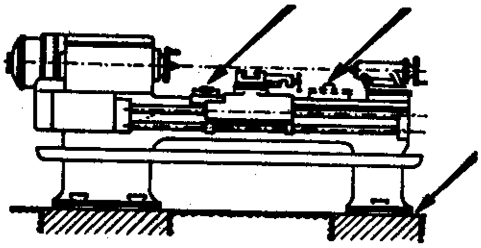


Figure 17.2 Checking a lathe for horizontal position by means of a spirit level

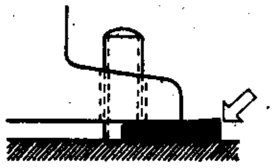


Figure 17.3 Wedges are driven into the gap between base and floor to align the machine

17.5 TESTING

The precision test cover the manufacturing accuracy of the machine tool itself and whenever feasible, also its working accuracy. The test carried out to know the grade of manufacturing accuracy of the machine is known as *alignment test* and the working accuracy as *performance test*. The *cceptance test* includes the alignment test and the performance test.

In general, the tests should be carried out at the manufacturer's works. This is because the machine is always carefully adjusted and aligned during assembly or on the test stand at the manufacturer's works. Also, at the

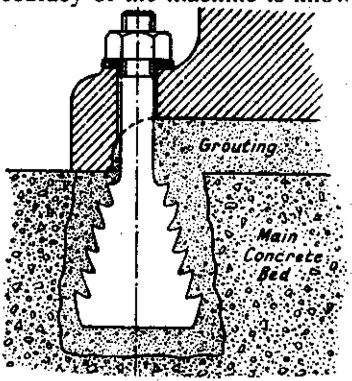


Figure 17.4 Machine base and foundation bolt after grouting

manufacturer's plant, skilled men are available together with the necessary equipment, which is only obtainable with difficulty outside the testing department.

Primarily, the degree of the manufacturing accuracy of the machine tool itself is to be tested, i.e. the accuracy with which machine has been assembled. This is measured when the machine is idle and free of any load. The reason for giving prominence to the manufacturing accuracy of the machine in the test procedure lies in the fact that it covers the whole machine and can be carried out unambiguously and without difficulty. The cutting test can only be carried out for random sizes and conditions, for otherwise the time necessary for their execution and their costs would be prohibitive.

The degree of working accuracy of the machine, besides depending on the machine itself, is also influenced by the following factors :

1. The type of cutting tool and its condition (rake angles, hardness, etc.)
2. The cutting speed, feed and depth of cut.
3. The material to be machined
4. The shape, size and rigidity of the job.
5. The tool holder.
6. The clamping equipment.
7. The skill of the operator.

It is therefore, not in every cases practicable to guarantee the obtainable degree of working accuracy. In the majority of the cases, working limits to be attained with the machine in operation are specified at the end of the *test charts*.

Testing the accuracy of machine tools is done by geometrical checks and practical tests.

Geometrical check means the checking of dimensions of forms and positions of components as well as the checking of their displacement relative to one another. They comprise all the operations which affect the components of the machine (the surface flatness, coincidence and intersection of axes, parallelism and perpendicularity of straight lines to straight lines, of flat surfaces to flat surfaces or of each to the other). They concern only sizes, forms, position and relative movements which may affect the accuracy of working of the machine.

Practical test means the machining of test pieces appropriate to the fundamental purposes for which the machine has been designed, and having predetermined limits and tolerances.

The Geometrical checks cover the manufacturing accuracy of the machine, whilst the practical tests check the accuracy of the finished components. Both measurements are practical and both form part of one indivisible whole. Neither the user nor the manufacturer can dispense with either of these tests.

17.6 PRACTICAL TEST

Practical tests should be carried out on pieces, the making of which does not require operation other than those for which the machine has been built. Practical tests to ascertain the precision of a machine tool should be the finishing operations for which the machine has been designed.

The number of workpieces or, as the case may be, the number of cuts to be made on a given workpiece, should be such as to make it possible to determine the average precision of working. If necessary, wear on the cutting tool used should be taken into account.

Checking of workpieces used in practical tests should be done by measuring instruments selected for the kind of measurement to be made and the degree of accuracy required.

17.7 GEOMETRICAL CHECKS

Geometrical checks include checking of the following :

1. Straightness.
2. Flatness.
3. Parallelism, equidistant and coincidence.
4. Rectilinear movements.
5. Rotations.

Straightness : The following geometrical checks for straightness should be conducted :

(a) ***Straightness of a line in two planes.*** A line is deemed to be straight over a given length when the variation of the distance of its points from two planes perpendicular to each other and parallel to the general direction of the line remains below a given value for each plane.

(b) ***Straightness of components.*** The conditions for the straightness of a component are the same as those for a line. For this purpose, the straightness of components relates particularly to sideways of machine tools.

(c) ***Straight line motion***. In the straight line motion of a component, the trajectory of a point on that component is parallel to a reference line parallel to the general direction of the motion.

Flatness : A surface is deemed to be flat within a given range of measurement when the variation of the perpendicular distance of its points from a geometrical plane parallel to the general trajectory of the plane to be tested remains below a given a value.

Parallelism, equidistance and coincidence :

Parallelism : This includes checking of the following :

(a) Parallelism of lines and planes.

(b) Parallel motion. The term "parallel motion" refers to the position of the trajectory of a moving part of the machine in relation to a plane (support or slideways), a straight line (axis, intersection of planes) and a trajectory of a point on another moving component of the machine.

Equidistance : This relates to the distance between the axis and a reference plane.

Coincidence or alignment : Here it refers only to two axes merged in each other or where one axis extends beyond the other.

Squareness : This includes the following :

(a) Squareness of straight lines and planes.

(b) Checking of perpendicularity of motion.

Rotation : The following geometrical checks for rotation should be conducted :

(a) ***Run out.***

(i) Out of round.

(ii) Eccentricity.

(iii) Radial throw of an axis at a given point.

(iv) Run out of a component in a given section.

(b) ***Periodical axial slip.*** This is the smallest value of possible movement, along the axis, of a rotating part, measured at rest at each of the several positions around its axis.

(c) ***Camming.*** Camming is the defect of a plane surface which, when rotating around an axis, does not remain in a plane perpendicular to this axis. Camming is given by the distance separating the two planes perpendicular to the axis between which the points of the surface are moving during the rotation.

17.8 MEASURING EQUIPMENT FOR TESTING

In the machine tool industry, there are three categories of measuring equipment which differ mainly in the accuracy to which they are made in order to fulfill the following functions :

Category A : Reference standards for use in standard rooms.
Category B : Measuring equipment for inspection purposes.
Category C : Measuring equipment for use during manufacture.

The equipment types of category B are used for testing machine tools. Different elementary testing equipment that are most frequently used in engineering workshops are : dial gauges, mandrels, straight edges, squares, measuring cylinders, and spirit levels. Testing of machine tool parts of large dimensions often requires the use of special device for convenience and speed.

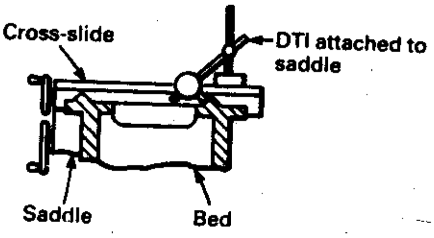


Figure 17.5 Testing the parallelism of slide-ways of a lathe

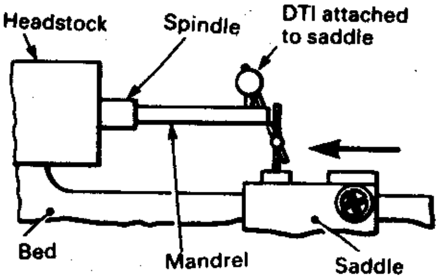


Figure 17.6 Testing the spindle axis of a lathe

Dial gauges : The dial gauge has been described in Vol-I. The graduations must be clear and normally need be finer than 0.01mm (0.0004 in). Finer graduations which are required in special cases should only be used if the measuring accuracy of instruments justifies it. In such cases graduations down to 1µ (0.00004 in) may be used. The dial gauge must be fixed to robust and stiff bases and bars in order to avoid displacements due to shock or vibration. Fig.17.5 shows the testing of parallelism of the slideways with saddle of an engine lathe. Fig.17.6 shows the testing of the spindle axix for parallism with the lathe bed.

Test mandrels : The most widely used inspection tool during manufacture and acceptance tests of new machine tools, and the repair of old ones, is the test mandrel. A test mandrel represents, within given limits, the axis which it is desired to check, either for out-of-true running or for position in relation to other elements of the machine tool.

Two types of test, mandrel used are :

1. Mandrels with a cylindrical measuring surface and a taper shank which can be inserted into the taper bore of the main spindle.
2. Cylindrical mandrels which can be held between centres.

Test mandrels have a conical shank for inserting in the socket of the machine to be tested, and a cylindrical body which is used as a reference surface for measurements. Mandrels are made of hardened steel left either unplated or plated with hard chromium.

The distance between the marks at the two ends of the cylindrical part represents the measuring length of the mandrel. This length may be 75, 150, 200, 300, or 500 mm.

Straightedges and squares : Straightedges of cast iron or steel should be heavy, well-ribbed and free of internal stresses. Their bearing surfaces should be as wide as possible. The error at the top of a standard square should be less than ± 0.01 mm (± 0.0004 in), of a precision square less than ± 0.005 mm (± 0.0002 in). A master square which would serve for checking squares in normal use is best made as a hardened steel cylinder, ground all over with the faces accurately square to the cylindrical surface. Master squares made of box sections are also useful.

Spirit levels : Levels shall be fitted with a micrometer screw or with graduation lines on the tube. In the first case, the changes in slope shall be read on the division of the micrometer and, in the second case, they shall be read directly or the graduation lines of the tube.

The sensitivity s of a level shall be the displacement of a bubble (or the micrometric device) for a tilt of 1 mm in 1 m, or for 200 seconds of arc. This sensitivity shall be equal to one thousandth of its radius of curvature expressed in metres. The constant of a level, or apparent sensitivity n, shall be the change in the tilt, expressed in mm per m (or in seconds of arc), which produces a displacement of the bubble by one division.

If λ is the length in mm of one division of the scale, then $\lambda = n \times s$.

For testing machine tools, levels should have an accuracy of 5 to

10μ per metre, and sensitivity of 30 to 50 mm, that is, when the length of a division is from 2 to 2.5 mm, and apparent minimum sensitivity of 10 seconds of arc, the bubble shall move through at least one division for a change of angle not greater than 0.05 mm per m. Fig.17.7 shows the testing of level of the table of a radial drilling machine both longitudinally and transversely.

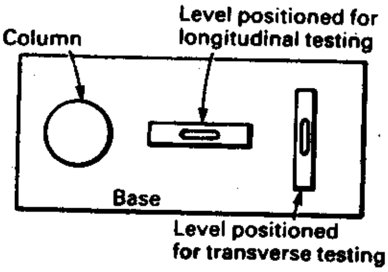


Figure 17.7 Testing of level of a radial drill machine table

17.9 MAGNITUDE AND DIRECTION OF TOLERANCES

Tolerance on a dimension is the algebraic difference between the upper and lower deviations (maximum and minimum limit). This is fully explained in Vol-I.

In the test chart, the tolerances are given in three different ways, viz :

1. As plus or minus tolerances (example: ± 0.03mm per 1,000mm).
2. As tolerances without signs (example: 0.03mm per 1,000mm).
3. As unilateral tolerances (example: 0 to 0.03mm per 1,000mm).

With plus or minus tolerances, the permissible error is allowed to occur in either direction within the specified reference length. The total range of error is, therefore, double the specified tolerance.

Tolerances without signs include the total range of error measures on the reference length, no matter in which direction the error appears.

With unilateral tolerances, the specified limits cover the total range of error across the total reference length, the direction of error being of great importance and always stated in the text of the respective test chart.

17.10 TEST CHARTS

The test chart is prepared to provide a convenient basis for the preparation of proforma for preparing test certificates. A short text in the chart describes each test, the chart being arranged in such a manner that at first the manufacturing accuracy of the machine is tested, and then the accuracy of its performance. Each test is further explained by a sketch in which the method of measurement is also indicated.

In a test chart, usually seven columns are drawn to incorporate seven items, such as serial No., test item, figure (sketch), measuring instruments used, permissible error in mm, actual error in mm, and instructions for testing.

REVIEW QUESTIONS

1. Explain why foundation of a machine tool is considered as a very important task in machine shop.
2. What is the procedure for erecting a lathe once foundation is complete ?
3. How a machine is tested ? Briefly describe.
4. How the measuring instruments / gauges are used in testing machine tools ? What types of testings are conducted ?
5. Describe the use of spirit level and dial gauge in testing.
6. What do you understand by geometric tests ? What are the checks ?
7. Outline the types of straightness tests conducted on machine tools.

18

KINEMATIC DESIGN OF MACHINE TOOLS

18.1 FUNDAMENTALS

"A metal cutting machine tool is a device in which energy is expended in deformation of material for shaping, sizing or processing a product by removing the excess material in the way of chips". Fig.18.1 schematically shows the basic principle involved in the above definition.

To fulfill the purpose of a machine tool, i.e., to generate forms and finished surfaces, an interference area is to be created by the relative path of motion between the cutter and workpiece. Depending on the nature of generated surface, choice of drive and cutter are to be made. Thus every machine tool is required to perform one or more of the following kinematics functions :

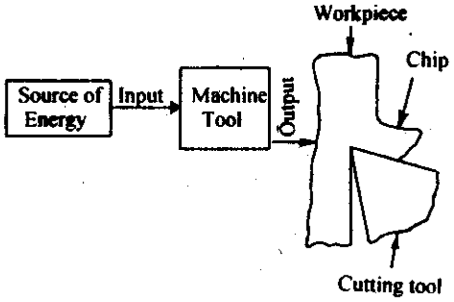


Figure 18.1 Basic principle of machine tool

1. To transfer motion from the input to the output spindle.
2. To transform motion from the rotation to translation or reciprocation and vice-versa.

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

The action of a metal cutting tool is based on the relative movement between the cutting edge and the surface to be cut. The relative motion of the workpiece past the cutting edge is "cutting speed" while the motion bringing in new uncut surfaces for machining is feed motion (Fig.18.2).

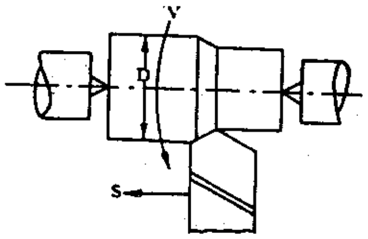


Figure 18.2(a) Cutting speed and feed in lathe work
D : diameter of work,
V : cutting speed, S : feed

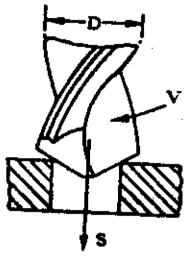


Figure 18.2 (b) Cutting speed and feed in drilling
D : diameter of drill,
V : cutting speed, S : feed

In mechanical drives for providing rotational movement of the spindles (carrying workpiece in lathes of carrying cutter in drilling, milling or grinding machines), a number of output speeds are necessary.

The reasons for such output speed steps are :

(a) For constant power utilisation, during the variation of torque demand, number of output steps might be necessary.

(b) It is known :

$$\text{Energy input} = \text{kW} = \frac{2\pi NT}{60\times 75\times 1\cdot 36} = \frac{NT}{974}kW$$

If energy input is constant, then :

$$\text{kW}_i = C_1 . N_i T_i = C_1 N_1 T_1 = C_1 N_2 T_2 = C_1 N_0 T_0$$

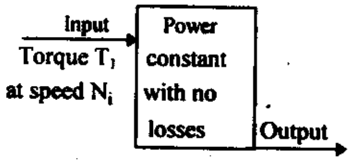


Figure 18.3 Number of output speed for constant power utilisation

Thus for constant power utilisation, a number of output speeds are necessary (Fig.18.3).

(b) Further, for constant desired tool life, depending on job-tool material pairing, cutting conditions and environment an allowable cutting speed is to be chosen. Thus :

$$V = \frac{\pi DN}{1{,}000} \text{ m/min.}$$

where, V = allowable cutting speed in m/min.

D = diameter of rotating element (job in lathe, and drill in drilling machine) in mm.

N = r.p.m. of rotating element.

Hence, for variation in V and D, a number of output speeds (N_n) are required.

Such variable output speeds can be obtained either by stepped or stepless drives (Fig.18.4a & b).

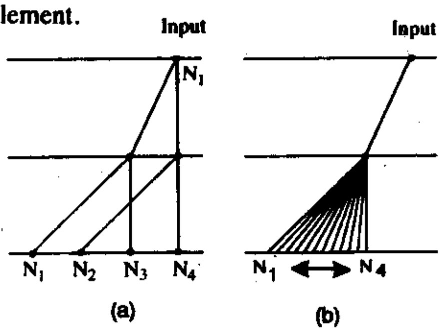


Figure 18.4 Stepped and stepless drive
(a) : stepped output, (b) : stepless output

Thus the one purpose of drive would be to deliver stepped or stepless output spindle speeds between two selected limits from an input source (Fig.18.5)

The next problem is how to design the spindle speeds at output requiring the fixation of :

(i) Limit speeds, i.e., greatest r.p.m. (N_g) and least r.p.m. (N_l).

(ii) A suitable manner of layout, which may be either in Arithmetic progression or in Geometric progression or in Logarithmic progression.

(iii) The number of stages (w) and subdivision in every stage (P) for obtaining required number (Z) output steps.

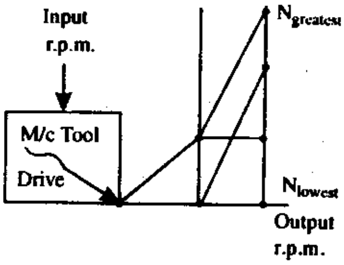


Figure 18.5 Stepped or stepless output between two limits

18.2 FIXATION OF LIMIT SPEEDS

The limit speeds depends on :

(i) Process capability of a given machine tool.
(ii) Size of machine.
(iii) Spectrum of tool-work pair covered.

For a given cutting speed, $N = 318\left(\frac{V}{D}\right)$

Now, N is the greatest when : $N_g = 318\left(\frac{V_{max}}{D_{min}}\right)$

N is the least when : $N_l = 318\left(\frac{V_{min}}{D_{max}}\right)$

Hence, the range of limit speeds is given by :

$$R_N = \frac{N_g}{N_l} = \left(\frac{V_{max}}{V_{min}}\right)\left(\frac{D_{max}}{D_{min}}\right) = R_V \cdot R_D$$

where, R_N = Range of spindle speeds,
R_V = Velocity range
R_D = Diameter range

TABLE 18.1 STANDARD VALUES OF RANGE (R_N)

Machine	R_N
Centre Lathe	40—60
Compromise Lathe	80—100
Automatic Lathe	8—10
Milling machine	30—50
Drilling machine	20—30
Shaping machine	10
Grinding machine	1—10

18.3 ON THE MANNER OF LAYOUT

The output speeds can be laid out in Arithmetic progression when :

$N_g = N_1 + (Z - 1)a$ where, Z = number of output steps
a = common difference

Hence, $a = \frac{N_g - N_1}{Z - 1}$

If the speed spectrum is constructed as in Fig.18.6, it is seen that speed-loss becomes a function of diameter and is larger at lower speeds. It is further seen that there is considerable crowding of speeds at higher speeds. To get around these difficulties, output spindle steps are often laid out in Geometrical progression, where :

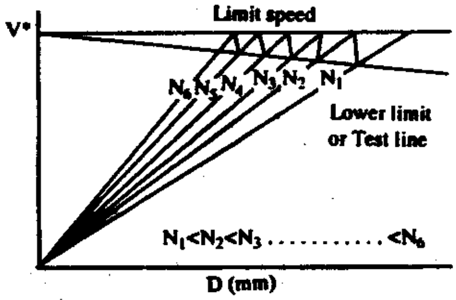


Figure 18.6 Speed spectrum in Arithmatic progression

$$N_g = N_1 . \phi^{z-1}$$

where, ϕ = common ratio

The speed spectrum shown in Fig.18.7 for Geometric progression shows that speed-loss is constant at all diameters and there is less crowding at higher speeds. Further, it has been proved that with speeds laid out in Geometrical progression, the cost of machine can be optimum. Often, the speeds in machine tools are laid in Geometric progression.

18.4 ON THE NUMBER OF OUTPUT STEPS (Z)

The output steps are often obtained by cluster of gears comprising of 1, 2 or 3 gears or by pulley blocks of 2, 3 or 4 pulleys. Thus the number of output steps (Z) is a function of the numerals 2 and 3 , which can be shown as :

$$Z = 2^{m_1} 3^{m_2}$$

where m_1 and m_2 are indices ranging from 0 to any integer.

The standard values of Z are,

2, 3, 4, 6, 8, 9, 12, 16, 18, 24, 32, 64, etc.

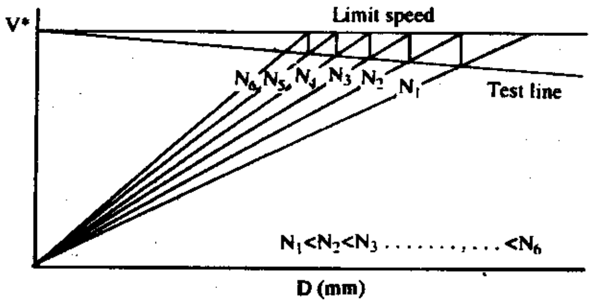


Figure 18.7 Speed spectrum in Geometric progression

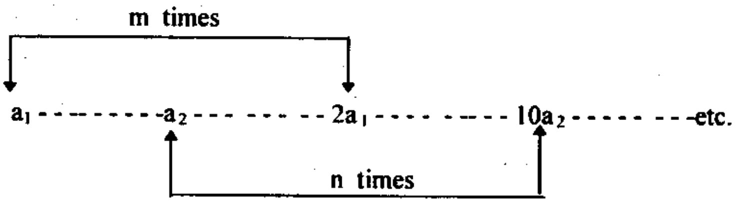


Figure 18.8 Series for determining standard value of (ϕ)

18.5 STANDARD VALUES OF COMMON RATIO (ϕ)

Often for various requirement, a series is to be chosen such that after *m* number of terms each figure is doubled and after *n* number of terms another figure becomes 10 times as shown in Fig.18.8.

Hence :

$$2a_1 = a_1 \phi^m$$

and

$$10a_2 = a_2 \phi^n$$

therefore,

$$\phi = \sqrt[m]{2} = \sqrt[n]{10}$$

Solving this equation, the standard values of ϕ are :

$$\phi_1 = \sqrt[3]{2} = \sqrt[10]{10}$$

$$\phi_2 = \sqrt[1.5]{2} = \sqrt[5]{10}$$

$$\phi_3 = \sqrt[6]{2} = \sqrt[20]{10}$$

$$\phi_4 = \sqrt[12]{2} = \sqrt[40]{10}$$

18.6 INTER-RELATION BETWEEN Z, ϕ AND R_N

For a standard Geometrical progression series,

$$N_g = N_1 . \phi^{z-1} \quad \text{or} \quad \frac{N_g}{N_1} = \phi^{Z-1}$$

$$\text{or} \quad \log(R_N) = (Z-1) \log \phi$$

$$\text{or} \quad Z = \frac{\log(R_N . \phi)}{\log \phi}$$

For standard values of Z, and ϕ, often adjustments are necessary for R_N, as shown in the semi-log plot of Fig.18.9.

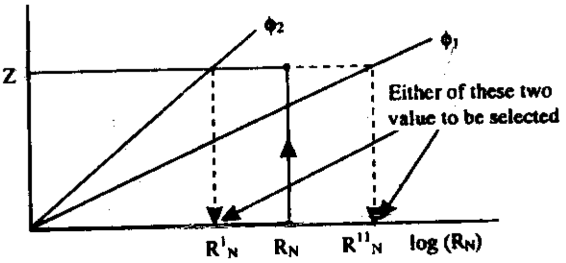


Figure 18.9 Semi-log plot

18.7 SOME CONSIDERATIONS FOR DESIGNING THE SPEED STRUCTURE

Most of the usual ray diagram for speed structure are unilateral (Fig.18.10A) or skewed (Fig.18.10B) .

While designing the best ray diagram, the following considerations must be made :

(i) Least number of shafts, levers and gears.
(ii) Maximum stage range is governed by the restriction : $R_N \leq \phi^x \leq 8$
(iii) Maximum gear ratio should be such that : G.R. $\leq$ 6 to 8
(iv) Minimum teeth in a gear is to be kept to for 17 for 20° pressure angle.
(v) Sum of shaft diameters of all stages should be minimum.

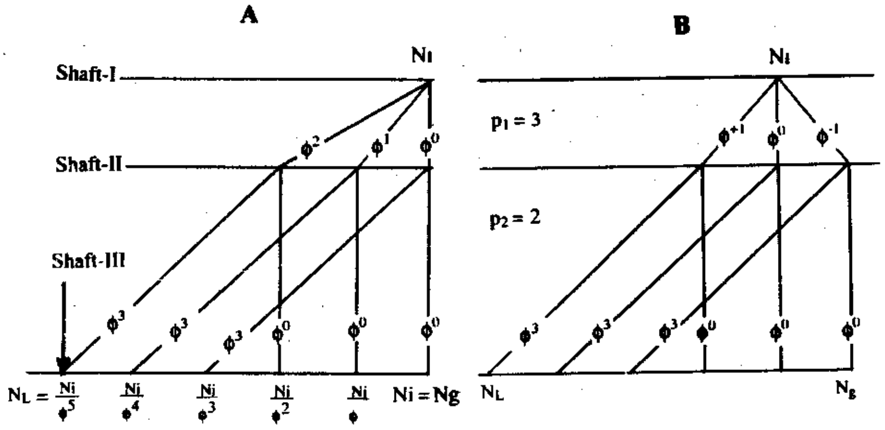


Figure 18.10 Ray diagram for speed structure
A : 2-stage 6-speed (3×2) unilateral ray diagram, B : 2-stage 6-speed (3×2) unilateral skewed ray diagram.

REVIEW QUESTIONS

1. What are the kinematic functions a machine tool must perform ?
2. Explain why a number of output speeds are necessary in any machine tool. How these variable speeds are obtained ?
3. What do you understand by stepped and stepless drive ?
4. On what basis output spindle speeds laid out in geometric progression is considered better over output spindle speeds laid out in arithmetic progression.
5. What are the factors on which limit speeds are fixed ? What is the range of ratios of max speed with minimum speed for an engine lathe ? Show and explain the speed spectrum in arithmetic progression.
6. Show and explain the speed spectrum in arithmetic progression.
7. What is a ray diagram ? Where it is used ?
8. Describe how standard value of common ratio is fixed for geometric progression.

19

NUMERICAL CONTROL OF MACHINE TOOLS

19.1 INTRODUCTION

·Numerical control has been developed out of the need for higher productivity, lower cost and more precise manufacturing. This is the latest machine tools control system since the industrial revolution and can be considered as the most sophisticated form of automation for controlling machine tools, equipment or processes.

In NC system, operation instructions are inputed to the machine as numbers which are suitably coded for storing on tapes. These instructions are then automatically carried out in the machine tool in predetermined sequence with pre-set or self-adjusted speed, feed, etc., without human intervention. Avoidance of human intervention, omission of conventional tooling and fixturing an quick-change capability of NC system are the primary factors considered to decide the level of acceptance of NC machine tools for a particular job. Other maintainable advantages identified of NC machine tools over conventional machine tools with automation are : (i) optimization of cutting tool life and quality of jobs, (ii) possibility of making parts which are impossible in conventional machining systems, and (iii) quick and more accurate inspection and detection of error in design and fabrication.

19.2 NC AND ITS COMPONENTS

Numerical control is a technique of automatically operating a productive facility, based on a code of letters, numbers and special characters. The complete set of coded instructions; responsible for executing an operation (or a set of operations) is called a part program. This program is translated into electrical signals to drive various motors to operate the machine to carry out the required operations. The components of a traditional NC machine is shown in Fig.19.1. The components are described in the following paragraphs.

1. **Program of instructions :** The program of instruction, often called part program is the detailed set of directions for producing a component by the

NC machine. Each line of instruction is a mixture of alphabetic codes and numeric data and is punched in a input media (usually paper tape) in a specified format. The input is read by a tape reader which transfers the instructions to a machine controller to operate the machine slides and to generate specific surfaces on the job.

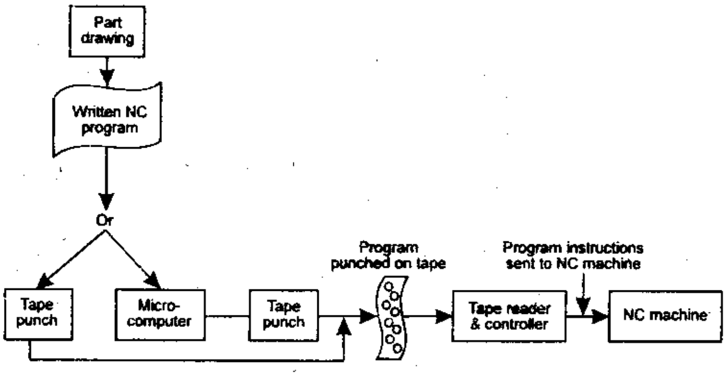


Figure 19.1 Components of a traditional NC system

2. **Tape punch** : Usually it is a paper tape of 1″ width. Paper-mylar, aluminium mylar or plastics are also used as tape materials. Paper tapes are cheap and popular but cannot last long. It is treated to resist oil and water. Mylar tapes are expensive but durable. Mylar tapes are still used by machine manufacturers to store informations as executive tapes. Punching machine (flexo writers) of various types are used to key in program instructions to tapes. Presently tapes are prepared by micro-computers by keying in the information from the manuscript. Once the entire program has been entered, it is checked and corrected if needed, and then the computer activates the tape punching unit to produce the tape. The computer can also generate the program print-out through its printer. Tape formats are discussed in section 19.12.

3. **Tape reader** : A tape reader reads the hole pattern on the tape and converts the patters to a corresponding electrical signal. Fig.19.16 shows the function of a tape reader in decoding the tape information.

4. **Machine controller** : Controller receives the electrical signals from tape reader or an operating panel and causes NC machine to respond. Fig.19.2 shows the function of a NC controller.

It contains a decoder/encoder, an interpolator and facilities to execute auxiliary functions which are machine dependent. The decoder/encoder receives the data and stores them in two separate memory locations. One for the part geometry data and the other for the process data. Process data includes switching functions for adjusting feed rates, spindle speeds, tool changes, cutting fluid applications etc.. Geometric data consists information about tool motions, tool length, tool radius, tool compensation etc.. As the machine is to shape complex surfaces at a constant feed rate, signals must be given to various slides and spindles so that the individual motions can be integrated to produce the required shape which can be represented by complex curve or simple lines. The interpolator breaks down these curves into small individual increments for each controlled motion of the machine tool. Controller also interfaces various machine units like drive motors, transducers and other control functions of the machine tools.

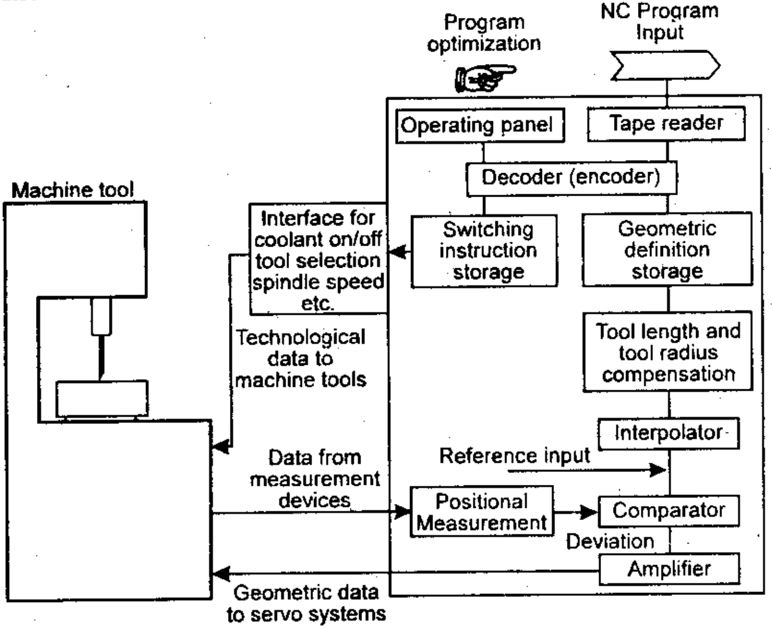


Figure 19.2 NC controller

5. NC machine : NC machine responds to the electrical signals from the controller. Accordingly the machine executes various slide motions and spindle rotations to manufacture a part. Any NC machine can be considered as a general purpose machine tool fitted with drive motors and other auxiliary functions of the machine. It consists as usual the work table, spindle and other hardwares as a general purpose machine contains. Transducers are fitted to feed back data on the positions of the slideways, for the r.p.m. of the spindle and for the amount of cut on the job. NC machine tools range from single spindle drilling machine to complex machines having multiple motions, tool changers, high capacity tool magazines and multi-axis control.

19.3 POSITION AND MOTION CONTROL IN NC MACHINE ; OPEN AND CLOSED LOOP

A group of devices, electrical, hydraulic or pneumatic are used to control the position of machine tool slides and spindle r.p.m. The most common are the open loop and closed loop systems.

Open loop system is a control system that has no means of comparing the output with the input for control purposes (no feed back). The working of open loop system in NC is described below.

The information stored in tape is decoded by the tape reader. Tape reader stores the information till the machine is ready to receive it. Tape reader converts the information into electrical pulses or signals which are sent to control unit. Control unit in turn energises the driving control unit which actuates D.C motors to perform the desired function, indicated in the tape by program instructions. Driving motors (stepping motor for open loop system) rotates proportionally with the number of electrical pulses received by it from the servo control unit. A precision lead screw coupled with the motor rotates, causing the machine table to slide.

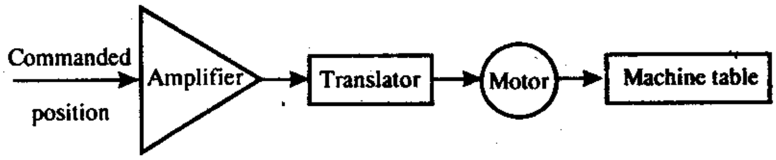


Figure 19.3 Open loop system

The pitch of the lead screw determines how much the table will move for one turn of motor. Each pulse of electrical signal rotates the motor by a fraction of revolution called stepping angle. For example if the lead screw is having 10 tpi and 100 number of electrical pulse rotates the motor by one revolution then a pulse will cause the machine table to move by $\frac{25.4}{10 \times 100}$ or 0.025 mm. Thus by controlling the number of pulse, the position of the machine table can be controlled. The motor controller sends back signals indicating the motors have completed the motion. (The feed back, however is not used to check how close the actual machine movement comes to exact movement programmed.) However in load condition, the stepper motor may have loss of one or more pulse, thus the desired position of table and actual position of table may not be same. This situation is depicted in Fig.19.3 as a open loop system; no correction for deviation is accepted here. Point-to-point positioning systems accept open loop control system. In close loop system along with the components of open loop system a feed back unit is added into the electrical circuit. A large varieties of feed back sensors are available for comparing the actual table movement with the desired table movement. For an error the corrective signal is fed back to the driving motor (usually a D.C servo motor) which makes necessary adjustment to compensate the deviation. In close loop NC systems, the accuracy is very high and one electrical pulse will cause machine table to slide about 0.0025 mm. Special motors called servos are utilized in closed loop system. Motor types include, A.C, D.C and hydraulic servos. Hydraulic servos are particularly used for large NC machines as they are powerful. The speed of A.C or D.C servo is variable and depends upon the current passing through it. For contouring NC system, close loop servo controls are preferred for this obvious reason. Fig.19.4 shows a closed loop system.

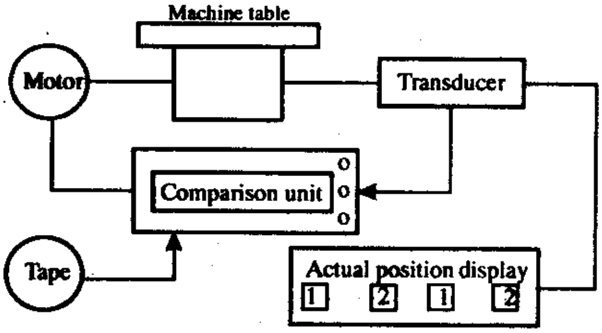


Figure 19.4 Closed loop system

19.4 MEASURING SYSTEMS FOR CONTROL

The measuring systems used for numerical control machine tools are, in effect, position transducer. Many kinds of transducers are available. Electric scales, electro-optical scales, magnetic scales, synchors, shaft digitizers, resolvers, laser types, linear or rotatory transducers, and many other types are used on numerical control.

Just as there is much that is common to all numerical control systems, all of the aforesaid devices have characteristics that can be categorized. Transducers may be analogue or digital.

Analogue control : This is the term used to refer to a quantity which resembles, in certain respects, another quantity. A slide rule is an analogue device, where the value of 4 on the scale might be 150 mm away from the zero mark on the scale. Therefore 4 can be said to be analogous to 150. In analogue control devices, an electrical unit such as voltage might be related to the position of the table (and hence the work) relative the cutter axis, in mm, i.e. 10 volts, for example, could indicate 250 mm of movements of the table. Analogue signals are continuous, modulated by events to provide the message, and proportional to the continuous movement of the table, rotation of the spindle, or movement of the spindle. They sense and constantly monitor variations in levels of voltage. The accurate positioning is achieved when the continuous input voltage is matched to the transducer output voltage. Analogue control systems are ideal for point-to-point positioning system.

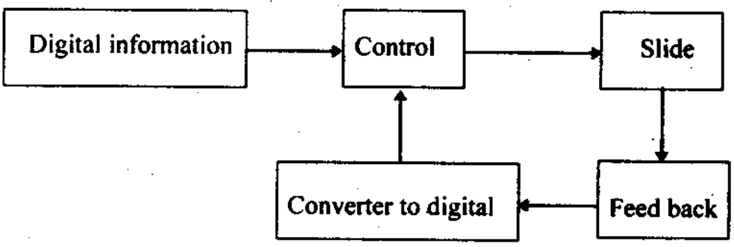


Figure 19.5 Digital control in servo-system

Digital control : In digital control, the amount of movement of the work-table is measured in discrete (separate) quantities. This is usually in the form of a voltage pulse where each pulse represents a basic length. Typical basic length is 0.01 mm. A telephone dial taps out digital signal. In this control, electrical pulses equivalent to the dimensional information are generated and used to drive the servo. The transducer in turn produces electrical pulses as the table moves and is compared with the input signal. This may be accomplished by counting the number of pulses needed for a given movement or by matching the pulses to the input signal. These quantities, or digits are counted at very high speeds. Therefore, digital feedback systems are ideal for continuous path control. Theoretically, the digital system is of a finite accuracy, while the analogue information can accept any value.

Both digital and analogue controls are used in NC systems of machine tools. To decide the control type may sometimes be a little difficult, as any digital control contains an analogue component and vice versa. The input to NC systems is always digital, as the dimensions that are taken from the drawings are given in numbers, which is a digital form. On the other hand, the output of NC system is always analogue, as the slides of the machine tools move in a continuous and smooth form. Therefore, each one of the system types contains an analogue and digital information unit. The conversion of one from the other is carried out in a *converter* as illustrated in Fig.19.5 and Fig.19.6. However, the type of control, digital or analogue, is called by the type of information appearing at the control loop inputs. Whenever a sequence of pulses is applied – the control is digital, and if the input is continuously variable – the control is analogue.

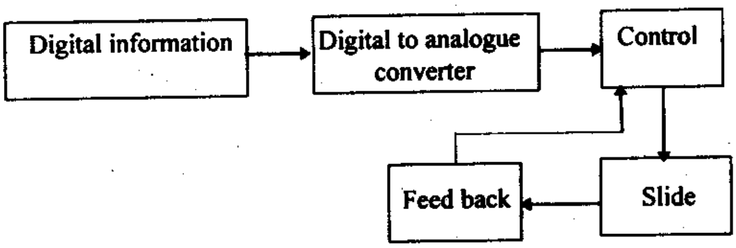


Figure 19.6 Analogue control in servo-system

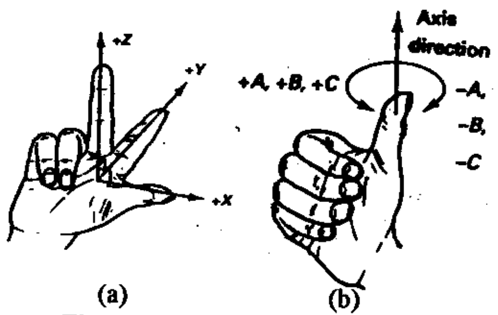
19.5 NC MACHINE–AXIS OF MOTION

The location of a NC tool at any point of time is controlled by Cartesian co-ordinate system. The system is composed of three directional lines, mutually intersecting at 90° with each other. The three axes are known as X,Y and Z axes. The manufacturers generally define the X,Y and Z direction of movement of slides. Present standards of machine axes are established by Electronic Industries Association (EIA). These are ;

1. Primary machine axis of movement follow right hand rule (Refer Fig.19.7(a))
2. Spindle movement is taken along Z axis.
3. Movement along the X-axis is the largest travel perpendicular to Z axis. Movement along the Y-axis is shorter compared to Z movement
4. Rotary motion directly follow right-hand rule (Refer Fig.19.7(b))

5. Rotation about an axis parallel to X axis is A, about an axis parallel to Y axis is B, and about an axis parallel to Z axis is C.
6. U, V, W axes are parallel to X, Y, and Z axes (Refer Fig. 19.8).

In NC machine tools, each axis of motion is equipped with a separate driving device which replaces the hand wheel.



(a) (b)

Figure 19.7 Right hand rule

19.6 CLASSIFICATION OF NC SYSTEM

There are three types of motion control of tools in NC systems. They are listed hereunder in increasing level of sophistication.

1. Point-to-point.
2. Straight - cut.
3. Contouring.

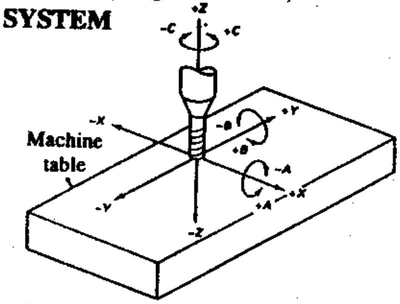


Figure 19.8 NC machine axis of motion

1. Point–to–point (PTP) system : Point-to-point system or positioning system refers to operations that require fast movement to a point followed by a manufacturing operation at that point. NC drill machine is an example of PTP system.

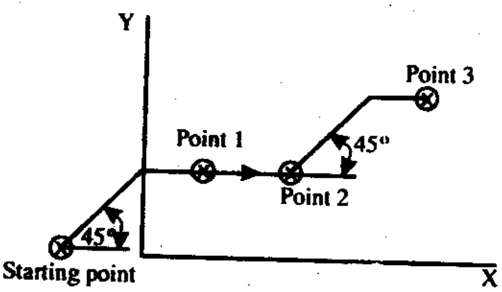


Figure 19.9 Point to point control in NC

Through PTP control the drill spindle is positioned at a particular location on the workpiece. The drilling operation is performed and tool is moved to the next location for the operation. The process continues till all the operations are completed. The tool moves parallel to one axes or it may move at the same rate for both X and Y axis simultaneously. Tool movement from point 2 to point 3 in Fig.19.9 is an example. The point to point NC machines are the simplest and least expensive and are commonly employed in drilling, boring, hole punching and some limited machining. Some point to point machines are equipped with milling capabilities also.

2. **Straight - cut NC :** In straight cut NC, the tool moves parallel to one of the major axis at a desired rate suitable for machining. It is quite appropriate for milling workpieces of rectangular configuration. However in this process no angular cuts on the workpiece is possible. Any NC machine tool capable of straight cut movement can perform point-to-point operation also. Fig.19.10 shows the system.

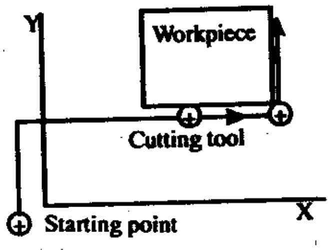


Figure 19.10 Straight cut control in NC

3. **Contouring system :** In contouring, or continuous-path system the tool follows the desired shape since the commands are far more descriptive than for the point-to-point system. The movement of the tool is precisely controlled at all times, in all planes. All axes of motion might move simultaneously, each one at a different speed, while this speed may be changed even within the path between two given points Thus, the displacement along one of the motions becomes a function of the displacement on the other, i.e. x is some function of y, designated $x = f(y)$. In contouring machines, the path of the cutting tool and its feed establish the desired contour of the part and at the same time the feed also affects the surface finish. Fig.19.11 shows the contouring control in NC.

Contouring NC machines have a complex circuitry which can feed and read information of the tool on a nearly instantaneous basis and they are normally programmed with the help of computers. This system is commonly used on milling machines.

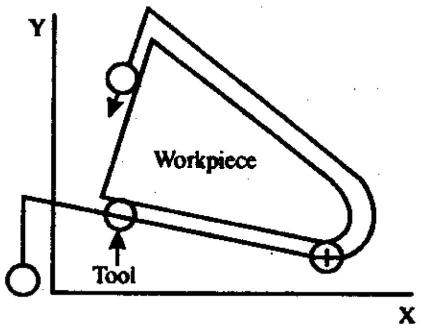


Figure 19.11 Contouring control in NC

19.7 TOOL POSITIONING MODES

Two types of programming modes, the absolute system and incremental system, are used in NC to locate tool positions. Most control system on machine tools built today are capable of handling with incremental, absolute or mixed.

Tool position	*Absolute*		*Incremental*	
	X	*Y*	*X*	*Y*
A	10	10	10	10
B	20	10	10	0
C	30	15	10	5

Absolute system : An absolute system is one in which all moving commands are referred to one reference point, which is the origin, and is called zero point. All position commands are given as absolute distance from that zero point. For example, suppose that two holes have to be drilled in the part shown in Fig.19.12. Their distances, as measured from the origin along the X-axis, are 10 and 20 mm respectively ; Y distances are same and equal to 10 mm for both.. The command for the second move would be to move by 20 mm in X direction and 15 mm in Y direction. The zero point may be defined as the point outside the workpiece, or at a corner of the part. If a mounting fixture is used, it could be a point on the fixture or on the machine table.

The zero point may be either a floating or fixed point. A *zero floating point* allows the operator, by pushing a button, to select arbitrarily the zero reference point at any point within the limits of the machine tool table.

As a matter of fact, absolute system may be subdivided into a pure absolute and absolute programming system. By the term *pure absolute* both programmed dimensions and feedback signals are referred to a single point.

It is estimated that considerably more than 90 per cent of point-to-point NC machines use absolute programming.

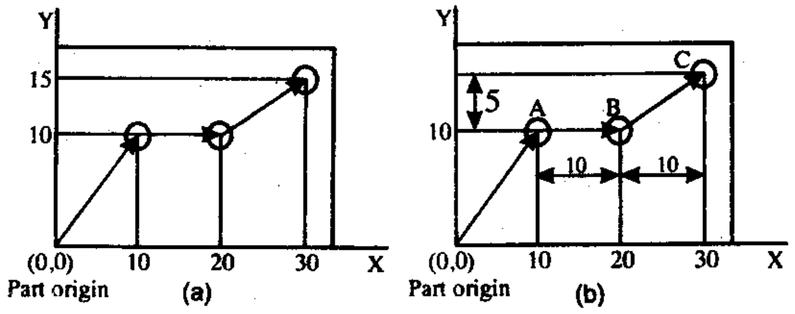


Figure 19.12 Example of part dimensioning
(a) absolute mode, (b) Incremental mode

Incremental system : An incremental system is one in which the reference point to the next instruction is the end point of the preceding operation. Each dimensional data is applied to the system as a distance-increment, measured from the preceding point at which the axis of motion was present. Notice that in the previous example in drilling two holes, the second movement would now be 10 in X direction and 0 for Y direction.

The incremental systems are not often used for controlling point-to-point machine tools. But incremental controls are generally cheaper to build.

One drawback of incremental systems is that if one incremental movement is in error, all other subsequent movements become erroneous. Figure 19.12 shows the example of the two systems.

19.8 NC PART PROGRAMMING

Part programming for NC comprises of the collection of all data required to produce the part, the calculation of a tool path along which the machine operation will be performed, and the arrangement of those given and calculated data in a standard format, which could be converted to an acceptable form for a particular machine control unit (MCU).

There are three types of programming techniques. They are :

1. Manual part programming
2. Computer - assisted part programming
3. Manual data input

19.9 MANUAL PART PROGRAMMING

In manual part programming, the data required for machining a part is written in a standard format on a special manuscript. The manuscript is a planning chart or list of instructions which describes the operations necessary to produce the part. The manuscript is typed with a Flexo-writer where typing causes the typed paper and the punched tape to be prepared simultaneously.

The manual programming is generally used for parts to be produced on a point-to-point machine, since in this case tool path calculations are simple. When the complete program is typed , all the instructions in the form of codes are checked for accuracy. This tape can be utilized to produce parts on the NC machine. Each set of instruction codes is called a NC block. A block is a complete line of information to the NC machine. It is composed of one word or an arrangement of words. Blocks may vary in length (i.e.. they may contain variable number of words). Characters are used to form words. Program words are composed of two main parts : an address followed by a number. Words are used to describe such important information as machine motions and dimensions in program. The block is marked by an end of block (eob) character which makes the data entry facility to start a new block. The eob character is automatically generated when the programmer enters a carriage return at computer, tape preparation machine or manual data entry.

The NC machine acts upon each block of instructions sequentially. The content of a typical block will have more than one instruction code. The explanation of words and code types are as follows.

Sequence number (N-code) identifies the block. It increases sequentially through the program.

Preparatory function (G-code) informs the controller what types of motion or action is to be carried out. The mode of movement is indicated by the numerical value following the 'G address. In general a G-code is typed at the beginning of the block after N-code so that it can set the control for a particular mode when acting on the other words in the same block or all other subsequent block including the block in which it contains. G-codes thus may be modal or nonmodal. For modal type, G-code specification will remain in effect for all subsequent block unless replaced by another modal G-code. For nonmodal type, G-code specification will only affect the block in which it contains. An example of G-code is GO2 which indicates that the next motion will be circular interpolation in a clockwise direction. GO2 is modal type. Co-ordinate data (X,Y,Z. . . . codes) are dimension words and they specify the co-ordinates for the tool to move. All machine tools have sliding and rotary motions. For example the single spindle NC drilling machine has three linear motion types; two horizontal table movements in X and Y direction and one tool movement in Z direction. For correct machining it is very important that these motions are defined accurately. Fig.19.11 shows the way, address and informations are stored in dimension words.

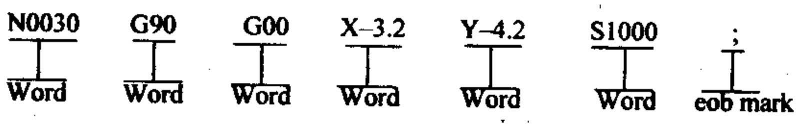


Figure 19.13 Way of machine axis addressing

The X,Y,Z codes indicate the conventional co-ordinates. In four – and higher axes machines, additional codes (A,B,C) may be used to indicate angular positions. U,V,W codes are axes parallel to X,Y,Z axes. I,J,K codes are used for circular interpolations to indicate the centre of the circular arc to be followed. (Refer Table 19.1)

Feed rate (F–code) indicates the rate at which the spindle moves along a programming axis. In English system the feed rate is expressed in inches per minute and in the metric system it is millimeters per minute. The feed rate is a modal code and thus unless a new F–code replaces the old one, it remains in effect in the subsequent block. For example F10 indicates a feed rate of 0.001 in/min. F10. specifies a feed rate of 10 in/min.

Spindle speed (S–code) specifies the spindle speed (r.p.m) at which the spindle rotates. A numerical value upto four digit maximum is entered following the address S. For example S1500 denotes that NC machine spindle is set at 1500 r.p.m. The S–code is modal and thus remains in effect for all subsequent blocks unless a new S–code is entered. However MO5 (spindle off command) cancels the S–code put before it.

Tool number (T–code) indicates which tool is being used.

Miscellaneous function (M–code) executes various NC machine functions not related to dimensional or axial movement. M–codes are classified in two broad categories. The first category consists of those which execute with the start of motion described in a block. The second category consists of those which execute with the completion of motion described in the block. Appendix lists the G-codes and M-codes.

Arrangement of addresses in a block : The order of putting the words (addresses) in a block may vary. Generally sequence number (N–code) is put in the first and G–code the next. The following sequence is a typical example.

1 → 2 → 3 → 4 →5 →6 →7 → 8 → 9 → 10 →11→ 12 →13 →14 →15
N..G..X..Y..Z..I..J..K..U..(V..W. .A. .B ..C)..P.

→ 16 → 17 → 8 →19 → 20 → 21 → 22
Q ..R.. F.. S .. T .. M .. H

N — Sequence number, indicates the sequence number of the block.

G — Preparatory function, specifies the mode of operation in which a command is to be executed.

X Y Z
I J K
U V W
A B C
P Q R

Dimension words, designate the amount of axis movement

TABLE 19.1 MOTION SPECIFICATION

Address	*Information stored*
X,Y,Z	Linear axes
A,B,C,	Rotary axes
U,V,W	Axes parallel to X,Y,Z axes
I,J,K	Axes used a auxiliary to Z axis
R,Q	Axes used as an auxiliary to Z axis

Table 19.1 indicates the specifications of dimension words.

F — Feed rate, designates the relative speed of the cutting tool with respect to the work.

S — Spindle function, designates the spindle speed in r.p.m.

T — Tool function designates the number of the tool to be used.

M — Miscellaneous function, designates a machine function such as spindle on/off, coolant on/off and so on.

H, D — Auxiliary input function, specifies the tool length offset number, number of repetitions of a fixed cycle etc.

Example 19.1

Tool moves to X.5Y.5

N0020 G00X.5Y.5

Sequence number

Move tool rapid speed

N0030 G90G01Z -.4F10

Absolute positioning

Tool moves to

N0040 X4.0

Tool moves to absolute X4.0 at feed rate of 10

N0050 Y3.5

Tool moves to absolute Y 3.5 at feed rate of 10

Subprogram / subroutine : A subprogram or a subroutine is a separate program meant for performing a specific machine task. The subprogram

subprogram becomes a powerful time saving device and can be separately developed and debugged. The subprogram is identified by a letter P followed by a number ranging from one to four digit, in the main program. The corresponding subprogram stored in the MCU's memory along with the main program is identified with the same number followed by 'O' in EIA format or ':' in ISO format.

The syntax of sub program is shown in Fig.19.14

O XXXX ← program number
Block.1
:
Block n
M 99 ← last statement of subprogram

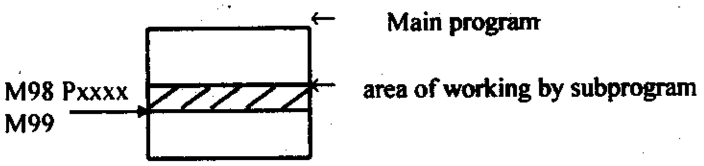


Figure 19.14 Example of a main program using a single subprogram

For example, repetitive work of machining slots as shown in Fig.19.15 can be performed using a subprogram.

Canned cycle : It is a preset sequence of events that is executed by issuing a single command. For example G84 code will initiate tapping autocycle. G81 to G89 are reserved for canned cycle. G80 is used to cancel the canned cycle.

Do loop : In any part program, do loops are used to perform any machining operations repetitively. For example in multiple turning, the same statements can be repeated a number of times using do loop.

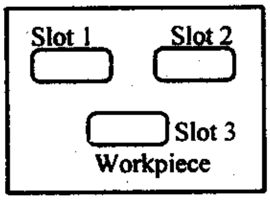


Figure 19.15 Part drawing to illustrate the use of subprogram

Decoding of block in a tape reader : Machine tools cannot understand commands given in the block. Tape readers read the blocks and decodes the information of the blocks (containing G.M. and other codes) and send it to MCU. Fig.19.16 shows how the tape reader decodes the tape and sends the information to the storage areas.

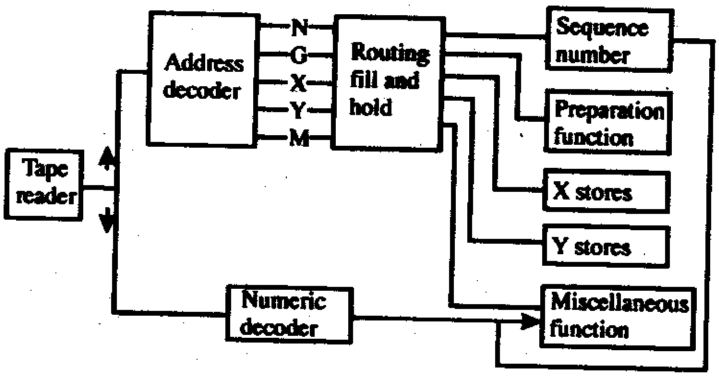


Figure 19.16 Decoding of block in a tape reader

19.10 COMPUTER AIDED NC LANGUAGE

In computer-aided part programming, much of the tedious computational work needed in manual programming is performed by the computer processor. In this programming type the programmer prepares the set of instructions in high level computer language. The high level computer languages use simple English words which can be converted to machine tool level program with the help of processors. Most of the programming language systems have been developed to perform computational work for tool movements accurately and thus the part programming becomes less time consuming and accurate

Apart from manual NC part programming, a number of NC programming languages are available for NC/CNC/DNC systems. Fig.19.17 shows some of the common NC programming languages. APT, a very useful language is described briefly in the subsequent paragraphs.

APT : Automatic Programming of Tools (APT) is initially developed by a group at MIT's at the Electronics Systems Laboratory. It has the largest vocabulary (more than 300 English words) of the general processing languages. Many of the modern processors and computer aided design packages have an APT–like processor that can accept cutter location (CL) data directly from data base. Fig.19.18 shows the basic computer-aided NC Program preparation.

The APT organization contains (1) Part definition, (2) Machining plan and (3) Machining specifications.

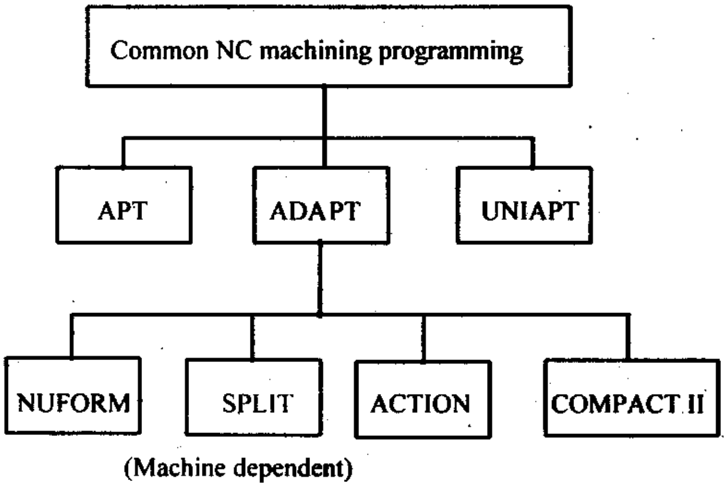


Figure 19.17 Common NC programming languages

Part definition (Geometry) : Part definition defines geometric points and surfaces on a part which represent the size and shape of the part. Part definition involves breaking the component shape into its primitive geometric elements. The geometric types in APT are POINT, LINE CIRCLE, PLANE, VECTOR, PATERN, SPHERE, GCONIC, TABCYL. The general format for geometric statement is

< Symbol > = geometric type / modifiers

Point : APT can define a point in a number of ways. For example a point at co-ordinate location x = 5, y =7, and z = 0 can be written

PT1 = POINT/5, 7, 0 (Fig.19.19(a))

If a point is the intersection of two lines (LIN1 and LIN2) then the point can be defined as

PT2 = POINT / INTOF, LIN1, LIN2 (Fig.19.19(b))

A linear pattern of equidistant (n – 2) points can be generated with the beginning point and end point.

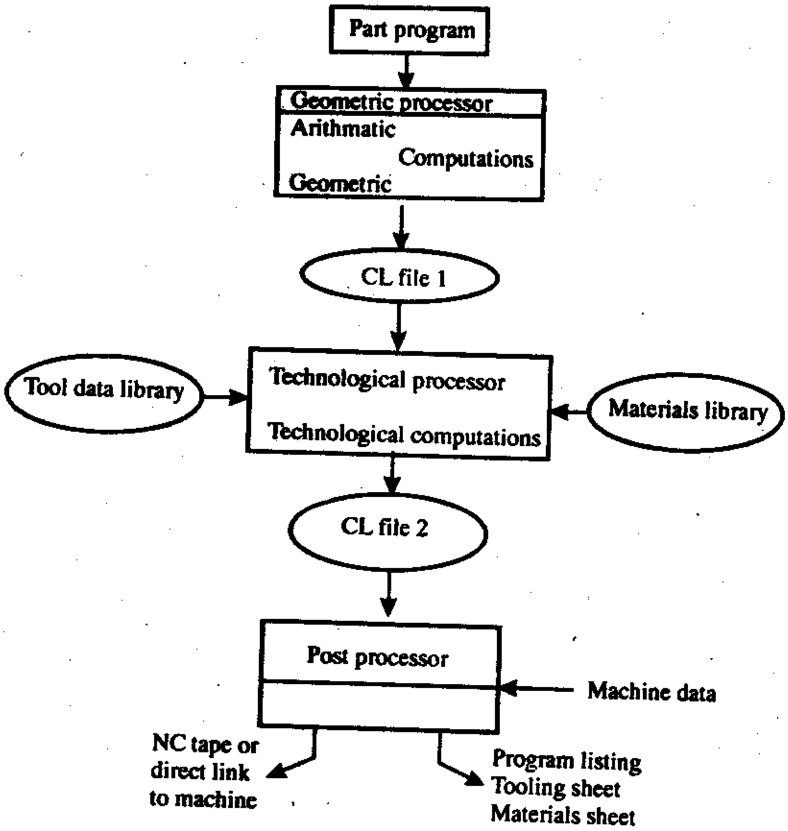


Figure 19.18 Basic computer - aided NC Program preparation

Source : Fundamentals of Machining and Machine Tools, Geoffrey Boothroyed and Knight W.A., Marcel Dekker, Inc

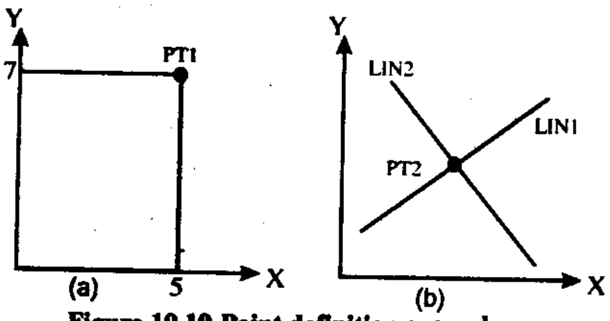


Figure 19.19 Point definition examples

< Symbol > PATTERN / LINEAR , < start >, < end >, < n >
PATA = PATTERN / LINEAR, P10, P15, 16

Using this command 15 more points will be generated between points P10 and P15

Line : APT can define a line in a number of ways. The general syntax of LINE is

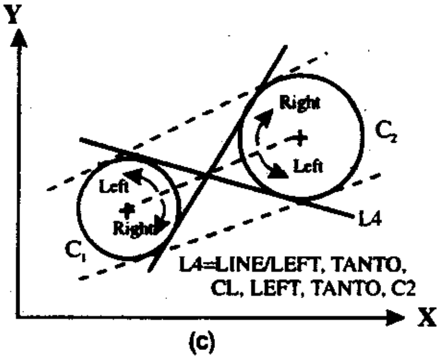
	< Symbol >	=	LINE / < Parametric string >	
Example	L1	=	LINE / PT1, PT2	Fig.19.20(a)
Example	L2	=	LINE / PT3, PERPTO, L1	Fig.19.20(b)

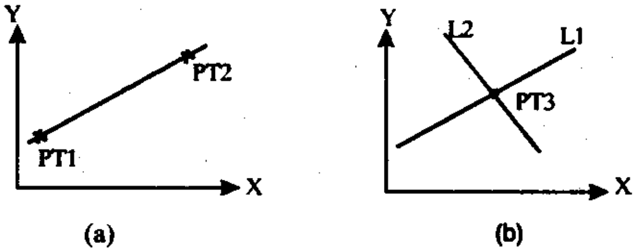
Line L2 passes through point PT3 and is perpendicular (PERPTO) to line L1.

Example

RIGHT
LINE / TANTO, C_1
LEFT

RIGHT
TANTO, C_2
LEFT





(a) (b)

Figure 19.20 (a), (b), (c) Line definition examples

Planes :

The general syntax of PLANE is :

< Symbol > = PLANE / < Parametric string >

Planes are surfaces of infinite area. An example is shown in Fig.19.21

Examples

PL 16 = PLANE / PT3, PT4 , PT6
PL 20 = PLANE / PT6, PARLEL, PT16

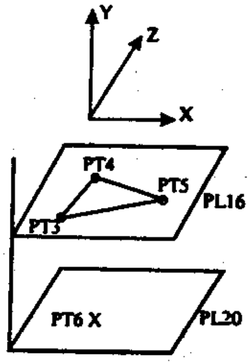


Figure 19.21 Plane definition example

Circle : The general syntax of circle is :

< Symbol > = CIRCLE / < Parametric string >

An example is depicted in Fig.19.22.

Machining plan :

There are three categories as discussed in Section 19.5. The three commands in APT for point to point machining are :

FROM / < Point location >
GOTO / < Point location >
GODLTA / < Co-ordinate increment >

Fig.19.23 illustrates the drawing corresponding program is shown along with the figure.

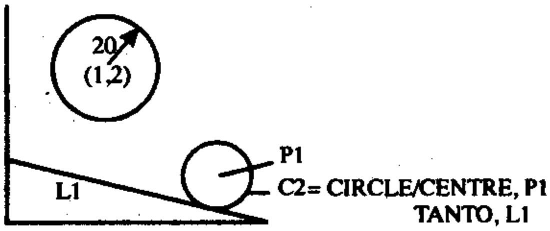


Figure 19.22 Example for circle

```
FROM / P0
GOTO / P1
GODLTA / 0,0, – 0.7
GODLTA / 0,0, + 0.7
GOTO / P2
GODLTA / 0,0, – 0.7
GODLTA / 0,0, + 0.7
GOTO / P0
```

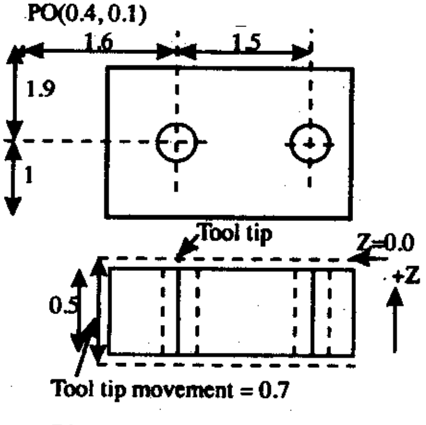


Figure 19.23 APT example

For contouring machining APT recognized three types of surfaces :

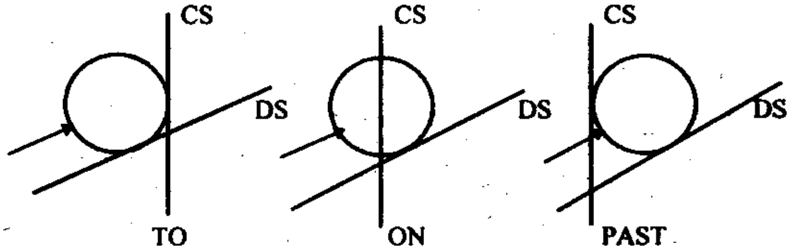
1. Drive surface against which the edge of the tool moves (the actual part edge being cut by milling tool)
2. Part surface on which the end of the tool rides
3. Check surface to which the current tool motion stops.

For positioning the cutting tool with respect to the surfaces, a GO surface command is needed. The syntax is

$$\text{GO/}\begin{bmatrix}\text{TO}\\ \text{PAST}\\ \text{ON}\end{bmatrix}\text{, DRIVE SURFACE, }\begin{bmatrix}\text{TO}\\ \text{PAST}\\ \text{ON}\end{bmatrix}\text{, PART SURFACE,}$$

$$\begin{bmatrix}\text{TO}\\ \text{PAST}\\ \text{ON}\\ \text{TANTO}\end{bmatrix}\text{, CHECK SURFACE}$$

TANTO modifiers are used only in conjunction with a check surface. The three possibilities of ending location of tool movement are shown in Fig.19.24.



DS = drive surface CS = check surface

Figure 19.24 Use of TO, ON, and PAST modifiers

Machining specifications : This organization contains (1) Post processor statement and (2) Auxiliary statement.

Post processor statement : Post processor uses the English-like statement to generate the data required to instruct the CNC machine. Post processor directly accept the statement without getting it processed by tape reader unit. They are used to specify speeds, feed, and other features to actuate the machine. Some of the common post processor statement are :

COOLNT / , END, FEDRAT /, MACHIN / RAPID, SPINDL /, TURRET

Auxiliary statements : These statements are the miscellaneous statements used to identify the part, tool, tolerances etc.

Some of them are, CLPRNT, INTOL / , CUTTER / , FINI, OUTTOL / , PARTNO etc.

For example : CUTTER/0.800 specifies the cutter diameter equal to 0.800 inch. Thus the tool path must be offset from the part outline by 0.400 inch.

19.11 MANUAL DATA INPUT

It is a procedure in which the part programmer directly keys in the program into the MCU of the machine tool. Most of the modern CNC machine is having this facility. This facility helps the programmer to change any existing program before the machine operations. However, the main limitation is that the data entry time is high and thus this on-line system may be useful for small change in the main program and for testing of machine parameters.

19.12 PREPARATION OF PROCESSING INSTRUCTIONS

In numerical control machine tools, the full instructions and informations, both dimensional and managerial, are keyed in to the control of the machine in a suitable code expressed by different numbers expressed in 0 and 1 only. Various coding systems use in different ways to represent or indicate the same instructions.

The binary system : In conventional decimal system of numbering, altogether 10 digits are used to express any number. Base is 10, smallest digit is 0 and the highest digit is 9. But to make it convenient to convert the numbers representing informations, into electric pulses for the controller and computer, a suitable system of numbering called binary code has been evolved, In this binary system, smallest digit is 0, highest digit is 1 and the base is 2, so that any binary number can never have more than two types of digits, i.e. 0 and 1. Either a hole on a tape allows electrical contact to be made ; ON, or the absence of a hole in the tape does not allow electrical contact to be made ; OFF. Therefore, a hole can represent 1, and no hole can represent 0. Hence, a tape can be used to transmit any required set of numbers in binary form.

When using 2 as the base, the values of the powers of 2 are as follows :

$$2^0 = 1, 2^1 = 2, 2^2 = 4, 2^3 = 8, \text{etc.}$$

Any decimal number can be represented in binary. This is explained in Table 19.2.

TABLE 19.2 BINARY EQUIVALENT OF DECIMAL NUMBERS

Decimal number	Binary number	Derivation
0	1	(0×2^0)
1	1	(1×2^0)
2	10	$(1\times2^1)+(0\times2^0)$
3	11	$(1\times2^1)+(1\times2^0)$
4	100	$(1\times2^2)+(0\times2^1)+(0\times2^0)$
5	101	$(1\times2^2)+(0\times2^1)+(1\times2^0)$
6	110	$(1\times2^2)+(1\times2^1)+(0\times2^0)$
7	111	$(1\times2^2)+(1\times2^1)+(1\times2^0)$
8	1000	$(1\times2^3)+(0\times2^2)+(0\times2^1)+(9\times2^0)$
9	1001	$(1\times2^3)+(0\times2^2)+(0\times2^1)+(0\times2^0)$

Each numerical in a binary number is referred to as a *bit* or *binary digit*. The binary number, 101 $[=(5)_{10}]$ is a 3-bit number. Computers are rated by the number of bits that can be stored in their memory sections and the capacity of bit-stórage is directly related to the computer precision and ability to handle complex operations.

The number of the bits in a binary system is large compared to that in decimal system, such as $(16)_{10}$ requires five bits (10000), $(32)_{10}$ requires six bits (100000) and so on. Therefore, it becomes inconvenient to read and express very large numbers in binary system. To overcome this inconvenience, a *binary coded decimal* (*b.c.d.*) is used, where each decimal digit is separately converted into the binary code instead of converting the whole decimal number into binary number; and a block of four binary digit is used to represent each character in a decimal number. For example,

Decimal		Binary		Decimal – binary
69	=	10001 101	=	0110 1001
569			=	0101, 0110, 1001

Other often usable codes are ternary code, octal code, and Gray code (Cyclic or Reflected Binary code) which are rearrangements of the binary digits to represent decimal numbers. Though Gray code has a few advantages over ordinary binary system, it has no mathematical basis. In this code, only one binary digit is required to change when the equivalent decimal number increases or decreases by unity. The Gray code is shown in Table 19.2 where this characteristic will be observed. It is found from the examples that in Gray code only the first digit is changed and thus ambiguous signals are avoided during the change-over period.

TABLE 19.3 COMPARISON OF CODES

Decimal	*Natural binary*	*Gray code*	*Binary decimal*	
1	0001	0001	0000	0001
2	0010	0011	0000	0010
3	0011	0010	0000	0011
4	0100	0110	0000	0100
10	1010	1111	0001	0000
11	1011	1110	0001	0001
12	1100	1010	0001	0010

Digitizer or encoder : The planning of a binary code digitizer or encoder to convert analogue quantity into numerical during control is illustrated Fig.19.25. The disc has transparent /opaque segments for use with photoelectric cell scanning head. The segments are coded in concentric tracks. If the tracks are 'straightened out', i.e. developed, the relationship of the segments to the binary code of holes punched in tape can be recognized—dark areas correspond to the *no hole* condition in punched tape.

The disc is mounted on the rotating shaft of the machine tool, usually at the free end. A fixed source of light is provided on the side of the disc and a photoelectric cell on one other side of the disc. As the disc rotates, light is periodically permitted to fall on the photoelectric cell through a lens or radial slit placed in between them, and the tracks are illuminated to allow the photocell to be activated by the pulses of light energy.

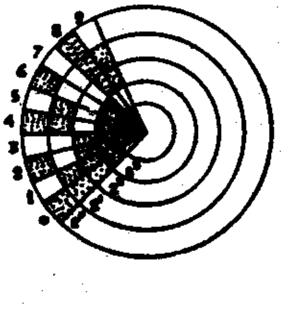


Figure 19.25 Plan of a digitizer

The pulses picked up by the photocell scanning head are decoded and fed back in the system. The feed-back signal indicates the *actual* slide position, which is compared with the signal corresponding to the *desired* slide position.

Punched tape : The informations and instructions are coded in a suitable system and then stored in punch cards or tapes. Generally, five-hole or eight-hole tapes made of paper, terylene laminates, mylar papers, vinyl or similar plastics are used to store the codes in hole and no-hole forms. The tape is prepared on a punching machine called 'flexo-writer'. The most commonly used punched tape is 25 mm (1 inch) wide, 8-track, i.e. eight punched holes can be accommodated in one line across the width of the tape. Besides the eight channels, there is one channel of smaller holes running the whole length of the tape for the sprocket. This ensures positive drive for the tape. These holes are termed feed or transport holes and are different from other code holes.

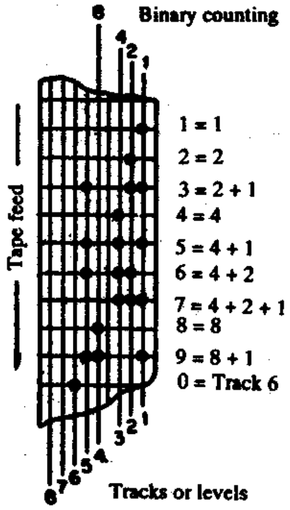


Figure 19.26 Coding for numbers (Small dots are sprocket feed holes)

The EIA (Electronic Industries Association) format was widely used in earlier NC machines. In more recent years, the ISO (International Standard Organization) format, illustrated in Fig.19.26, has gained wide acceptance. Format means the presentation that a particular numerical control system understands and acts upon it.

In the binary-coded decimal system tracks or channels 1, 2, 3 and 4 are used to represent the powers of 2. Thus track 1 is the number 1, track 2 is the number 2, track 3 is number 4, and track 4 is the number 8 from

$$2^0 = 1, \quad 2^1 = 2, \qquad 2^2 = 4, \quad 2^3 = 8,$$

These tracks are also used to record commands for feed and speed, etc.. The binary coding for numbers is illustrated in Fig.19.26 to show how easily numbers can be read from a punched tape.

According to standard specifications, the total number of holes across the width of the tape must be odd parity. When the numeric code is even, a hole is punched in track 5. This is called 'parity check'. For example, when the number 6 is punched, holes should appear in tracks 2 and 3. A hole is also punched in track 5 to achieve an odd number of holes in that row (see Fig.19.27). Parity check will signal an error if a ragged or torn hole appear, or if there has been a coding error by the punch, such as an even number of holes for any character. It is really a safety device to help reduce the chance for error.

Track 6 is reserved for zero commands. Track 7 and 8 are miscellaneous tracks for items such as tape start, coolant on and off, machine start and tape return. Track 8 is termed as EOB or End of Block and it represents end of the operation. It is punched at every line of punched information. The first four tracks for numeric characters in the two formats, EIA and ISO formats, are identical but differences occur in other tracks as seen from Fig.19.26. Another difference lies in the choice of track for the parity hole. Track number 5 is used in the EIA format and track number 8 in the ISO format. In the ISO system, *even* parity is employed, a hole being included in track 8 when it is required to bring the holes in the row to an even number.

19.13 NC/CNC/DNC SYSTEM

In the original NC systems the physical components are hard–wired i.e. the circuitry and components can perform their respective functions only and are not flexible to adopt changes. In CNC system the physical components are software units. In soft-wired units the loaded program in computer makes the control unit operate to suit the need of machinist. The MCU, the heart of the NC system underwent a great development with the introduction of very large scale integrated circuits. The new features not available in pre – 1970 hardwired control units are :

1. Cathode-ray tube which is capable to simulate cutting parameters and show the positions of machine table and cutting tool before the part is actually loaded on machine tool. Actual cutting position may also be shown when the part is being machined. The entire program also can be listed in the screen.
2. Provisions of absolute and incremental programming which are incorporated by G90 (absolute) and G91 (incremental) codes.
3. Provision of inch or metric data input through G70 (inch) and G71 (metric) address.
4. Adaptable to both EIA or ASCII tape formats.
5. Availability of manual data input (MDI) to incorporate changes in part programming as well as editing program / data can be made available as and when necessary.

EIA					*CODE*				
Character	**8**	**7**	**6**	**5**	**4**	**•**	**3**	**2**	**1**
0			o			•			
1						•			o
2						•		o	
3				o		•		o	o
4						•	o		
5				o		•	o		o
6				o		•	o	o	
7						•	o	o	o
8					o	•			
9				o	o	•			o
a		o	o			•			o
b		o	o			•		o	
c		o	o	o		•		o	o
d		o	o			•	o		
e		o	o	o		•	o		o
f		o	o	o		•	o	o	
g		o	o			•	o	o	o
h		o	o		o	•			
i		o	o	o	o	•			o
j		o		o		•			o
k		o		o		•		o	
l		o				•		o	o
m		o		o		•	o		
n		o				•	o		o
o		o				•	o	o	
p		o		o		•	o	o	o
q		o		o	o	•			
r		o			o	•			o
s			o	o		•		o	
t			o			•		o	o
u			o	o		•	o		
v			o			•	o		o
w			o			•	o	o	
x			o	o		•	o	o	o
y			o	o	o	•			
z			o		o	•			o
Del		o	o	o	o	•	o	o	o
Blank						•			
BS			o		o	•		o	
Tab			o	o	o	•	o	o	
CR/EOB		o				•			
SP				o		•			
ER					o	•		o	o
(2-4-5)				o	o	•		o	
(2-4-7)		o			o	•		o	
+		o	o	o		•			
−		o				•			
/			o	o		•			o
.		o	o		o	•		o	o
&					o	•	o	o	
,			o	o	o	•		o	o

2-4-5 — Begining of statement.
2-4-7 — End of statement.

Direction of Tape movement

ISO					*CODE*				
Character	**8**	**7**	**6**	**5**	**4**	**•**	**3**	**2**	**1**
0			o	o		•			
1	o		o	o		•			o
2	o		o	o		•		o	
3			o	o		•		o	o
4	o		o	o		•	o		
5			o	o		•	o		o
6			o	o		•	o	o	
7	o		o	o		•	o	o	o
8	o		o	o	o	•			
9			o	o	o	•			o
A		o				•			o
B		o				•		o	
C	o	o				•		o	o
D		o				•		o	
E	o	o				•	o		o
F	o	o				•	o	o	
G		o				•	o	o	o
H		o			o	•			
I	o	o			o	•			o
J	o	o			o	•		o	
K		o			o	•		o	o
L	o	o			o	•	o		
M		o			o	•	o		o
N		o			o	•	o	o	
O	o	o			o	•	o	o	o
P		o		o		•			
Q	o	o		o		•			o
R	o	o		o		•		o	
S		o		o		•		o	o
T	o	o		o		•	o		
U		o		o		•	o		o
V		o		o		•	o	o	
W	o	o		o		•	o	o	o
X	o	o		o	o	•			
Y		o		o	o	•			o
Z		o		o	o	•		o	
Del	o	o	o	o	o	•	o	o	o
NUL						•			
BS	o				o	•			
HT					o	•			o
LF/ML					o	•		o	
CR	o				o	•	o		o
SP	o		o			•			
%	o		o			•	o		
(			o		o	•			
)	o		o		o	•			o
+			o		o	•		o	o
−			o		o	•	o		o
/	o		o		o	•	o	o	o
.			o		o	•	o	o	
&	o		o			•	o	o	
,	o		o		o	•	o		

(— Begining of statement.
) — End of statement.

Figure 19.27 Code sets for punched tape :
(a) EIA format, (b) ISO format

6. Advanced interpolation methods like helical and cubic make it more versatile. In previous available NC systems only linear, curricular and parabolic interpolators are available.
7. Point-to-point and continuous-path positioning are both available in CNC system.
8. Cutter diameter and length compensation calculations are incorporated.
9. Provision of high volume program and data storage area for future storage and use are incorporated with hard disks.
10. Use of canned or fixed cycle programming to reduce complexity in programming.
11. Incorporation of provision of subroutine/subprogramming and macros.
12. Capability to create axes inversion (mirror image) to produce right or left hand or left hand part from the same program.
13. Digitizing to make a part programming directly from the existing part.

CNC denotes a numerical control system that uses a dedicated micro processes as an integrated part in its MCU to execute the basic NC control function.

A program can be loaded in MCU and for this reason dependency on the tape reader is eliminated. Motion interpolation is transferred to MCU with its soft-wired control capability. Fig.19.28 shows the CNC control unit features.

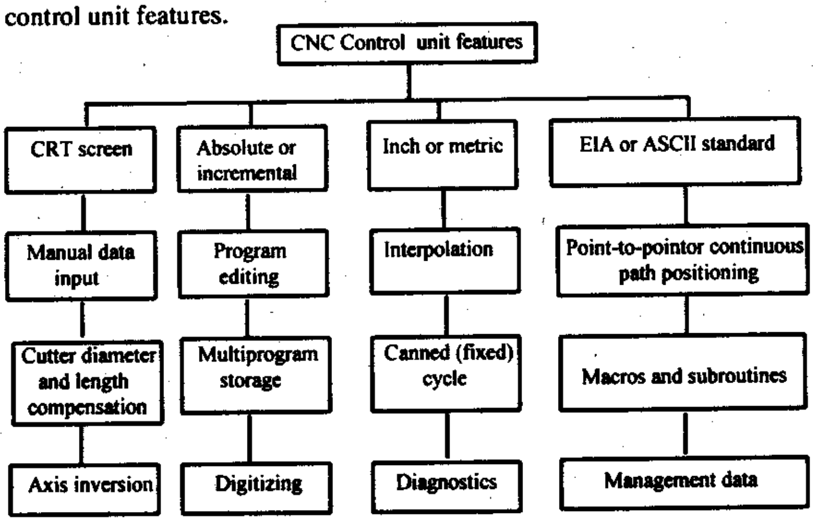


Figure 19.28 CNC control unit features

DNC system : Direct numerical control makes use of a large (mainframe) computer to manipulate operations of a number of NC machines. Development of local area networking with high processing power of computer system facilitated the development of DNC system.

Difference between CNC and DNC system : The difference between CNC and DNC system are :

1. CNC computers control only one machine whereas DNC computers manipulate more than one machine using local networking.
2. CNC computer is an integrated part of the machine whereas DNC computer is located at a distance from the machine.
3. DNC computers are having higher processing power than CNC computers (micro processors).
4. DNC software considers management of information flow to a group of machines apart from transferring machining instructions.

The main components of CNC and DNC system are shown in Fig.19.29.

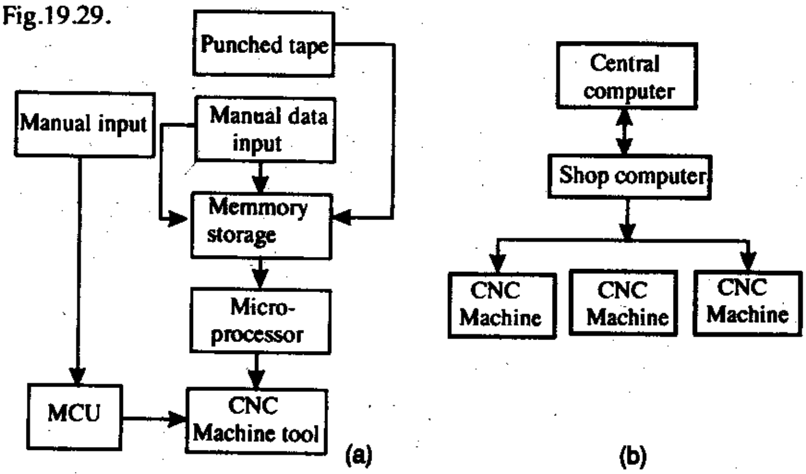


Figure 19.29 The main components of (a) CNC and (b) DNC system

19.14 NC MACHINES

1. Single spindle drilling machine : It is the most simple numerically controlled machine. Most drilling machines are programmed on three axes

: X axis controls the table movement to the right and left of the column, Y-axis controls the table movement towards or away from the column and Z axis controls the up and down movement of the spindle.

2. Lathe: Lathe is the most productive machine tool to manufacture round parts. Lathes are programmed on two axes : X axis controls the cross motion of the cutting tool and Z axis controls the carriage travel towards and away from the head stock.

3. Milling machine : Milling machine has been accepted as one of the most versatile machine tools used in manufacturing industry. Milling machines are programmed on three axes : X axis controls the table movement left or right, Y axis controls the table movement towards and away from the column and Z axis controls the vertical movement of the knee or spindle.

4. Turning centres : Turning centres are more accurate and productive than engine lathes and has a higher spindle rate. The turret is of disc type and can accommodate 12 tools and as such can produce a wide range of components without tool change. Programming is for two axes : X axis for movement of cross slide and Z axis for saddle movement towards or away from headstock. Turning centres with increased capacity tool changers are also making a strong appearance in modern production shapes.

5. Machining centres : Machining centres are of two types ; horizontal and vertical spindle types. They are operated on three axes.

Horizontal machining centre has X axis control for table movement left or right, Y axis control for the vertical movement of the spindle and Z axis control for the horizontal movement of the spindle. Specifications of a machine is furnished in table 19.4.

Vertical machining centre has X axis control for table movement left or right, Y axis control for the table movement towards or away from the column and Z axis control for the vertical movement of the spindle.

Machining centres are capable of a variety of machining operations. For this reason a variety of tools are required in a machining centre. Thus a machining centre to be efficient must have automatic tool changing, work part positioning and pallet shuttling apart from other CNC functions.

Most of the machining centres have automatic tool changers in angled double gripping form with retractable gripping fingers for simultaneous insertion and removal of tools in the spindle and tool magazine. A tool magazine can be of different types. However, most common type is the chain type tool magazine containing 30 to 60 tools.

Tool changing follows similar pattern as given in the following sequence :

TABLE 19.4 SPECIFICATIONS OF A TYPICAL HORIZONTAL MACHINING CENTRE

		MC 1000
Spindle		
Drive motor (44% ED)	kW	32
Speed	rpm	20-3600
Max spindle torque	Nm	1150
Tool shank taper (DIN 69871)		A50
Front bearing dia	mm	100
Traverse		
Table (X-axis)	mm	1600
Spindle (Y-axis)	mm	1250
Column (Z-axis)	mm	1100
Axis drive		
Feed rate	mm/min	1-10000
Rapid traverse X,Y/Z	m/min	15
Index table (NC rotary table)		
Pallet table size	mm × mm	1000 × 1000
Load capacity	kg	2000
Max. job swing	mm	1600
Index increments	deg	1 (0.001)
Automatic tool changer		
No of tools		60 (72)
Max tool dia	mm	120
Max tool dia with adjacent pockets empty	mm	315
Max tool length	mm	550
Max tool weight	kg	25 (35)
Accuracy		
Positioning accuracy as per VDI/DGQ 3441	mm	0.015
Installation data		
Machine weight	kg	24500
Total connected load	kVA	60
(Values given brackets are optional features)		

Manufacturer : Bharat Fritz Werner limited.

1. Tool in spindle is oriented in position.
2. Tool in magazine is ready.
3. Gripping fingers of tool changer gripped both the tools (new tools from tool magazine and old tool from the spindle).
4. Tools are removed by gripper arm.
5. Charge over procedure effected by gripper arm swinging through 180°.

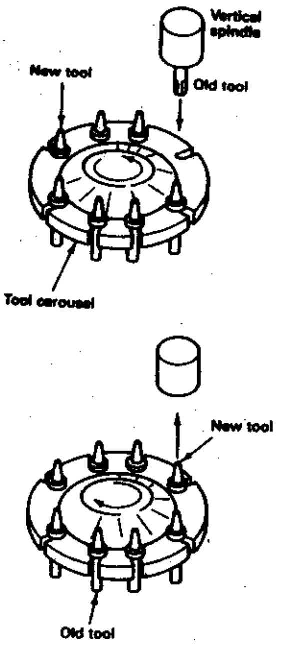


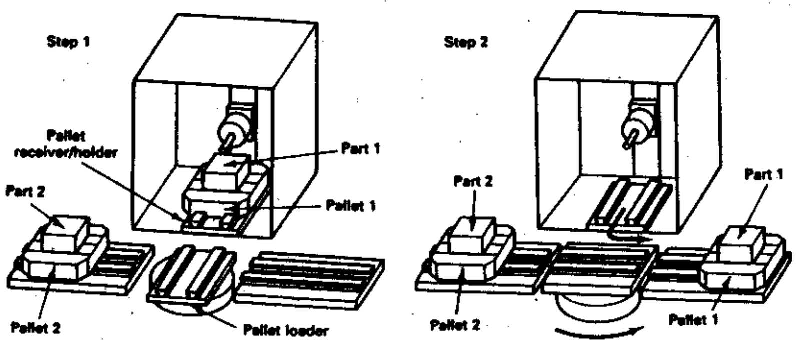
Figure 19.30 A simple automatic tool changing mechanism

6. New tool is inserted in the spindle and old tool goes to tool magazine.
7. Gripping fingers are retracted.
8. Tool magazine starts rotating to make the next required available at the tool change position.

Fig.19.30 shows a simple automatic tool changer. Fig.19.31 shows a pallet changing mechanism.

6. **CNC cylindrical grinding machine** : In CNC cylindrical grinding machine, control is on longitudinal traverse of table (Z-axis) and wheel head traverse (X – axis). The machine can be employed and programmed for external plunge grinding, traverse grinding, taper grinding and profile grinding. All these can be done in one set up if required. The machine is suitable for external grinding of low and medium batch size. The machine contains wheel head spindle, wheel head slide workhead, tailstock and table along with its drive system.

7. **CNC Trainers** : Presently many machine tool manufacturers are supplying CNC trainers to industries and training centres where operators, technicians, programmers and engineers can be trained on CNC working through these trainers. These are small, low cost machines with low power requirement and can be easily installed in class rooms. These trainers have alphanumeric key board for MDI programming, G code, absolute / incremental programming, inch/metric programming, F–code availability, position presets, linear/circular interpolation and other facilities. CNC train master lathe and CNC train master machining centres are two popular CNC trainer types



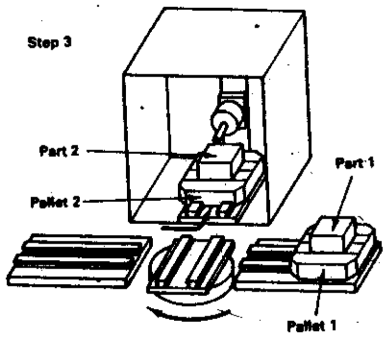


Figure 19.31 A pallet changing mechanism

8. Wire cutting EDM machine :

Wire cutting EDM machines utilize a very thin wire (0.02 mm to 0.3 mm) made of brass or molybdenum as an electrode. The wire is stretched between two rollers and the part is eroded by spark from the wire. Thus the wire cuts the part like a band saw to the required profile. CNC is used to control horizontal table movement. Here wire is the tool and workpiece moves in X and Y axis simultaneously. Auxiliary co-ordinate table for top wire guide block provides movement in U and V axes. The system is having wire drive system. Dielectric fluid used is deionised water. Fig.19.32 shows the principle of a wire cutting EDM.

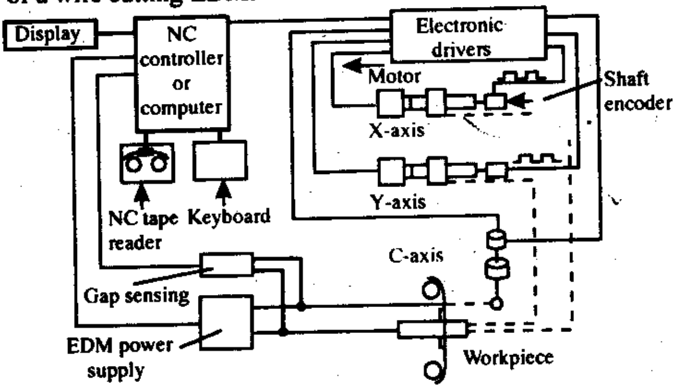


Figure 19.32 Principle of wire cutting EDM

REVIEW QUESTIONS

1. Define Numerical Control. State the advantages of numerical control machine tools over conventional machine tools.
2. What are the important components of a NC systems ? Describe.
3. Explain point - to - point positioning control system and straight - cut positioning system.
4. What is meant in NC coding by character, word, block ?
5. How do you classify NC systems ? Explain.
6. What are the tool positioning modes in NC programming ? Identify the advantages and disadvantages of them.
7. If you are to drill 3 holes (A, B, and C) of equal diameter in a plate, show the difference of part dimensioning in absolute and incremental systems. The centre of holes are ; a(3,5) B(15, 20), C(20,20).
8. Write the limitations of Manual part programming. In what type of NC machines, it is applicable ? In NC machine how the machine axes are addressed ? Explain with a neat diagram.
9. Define X, Y, and Z axes on a NC drill machine.
10. Where might rotational axes be used ? Explain.
11. Define F-code, S-code and M-code of manual part programming.
12. How different NC codes are written in a block ? Explain.
13. What is the function of a subprogram ? What is a canned cycle ? Do loop ?
14. What are the features of APT ? Why it is accepted as one of the most efficient part programming language.
15. Name of the common NC machining programming languages.
16. Explain in which situations MDI is preferred ?
17. What do you understand by post processor statement and auxiliary statements ?
18. Explain the working of a digitizer.
19. Differentiate between NC, CNC, and DNC systems.
20. Explain how the NC instructions are punched in tapes. Describe EIA or ISO format in brief.
21. Describe any two NC machines briefly.

20

NON-TRADITIONAL MACHINING

20.1 INTRODUCTION

From some time past engineering industries have witnessed a rapid growth in the development of harder and difficult-to-machine materials such as hastalloy, nitralloy, waspalloy, nimonics, carbides, stainless steel, heat-resisting steels, and many other high-strength-temperature-resistant (HSTR) alloys. These materials find wide application in aerospace, nuclear engineering, and other industries owing to their high strength-to-weight ratio, hardness, and heat-resisting qualities. For such materials the conventional edged tool machining, in spite of recent technological advancement, is highly uneconomical and the degree of accuracy and surface finish attainable are poor. Besides, machining of these materials into complex shapes is difficult, time-consuming and sometimes impossible.

Considering the seriousness of the problem, Merchant in 1960's emphasized the need for the development of newer concepts in metal machining. Consequently, non-traditional machining processes have emerged to overcome these difficulties. These processes are non-traditional or unconventional in the sense that they do not employ a conventional or traditional tool for metal removal, instead, they directly utilize some form of energy for metal machining.

20.2 CLASSIFICATION OF THE MACHINING PROCESSES

Non-traditional machining processes can be classified into various groups according to type of fundamental machining they employ, namely, mechanical, electrical, chemical, electro-chemical, thermo-electric, etc. The classification of the machining processes, based upon the type of energy used, the mechanism of metal removal in the process, the source of the immediate energy required for material removal, and the medium for transfer of those energies, etc. is shown in Table 20.1 and listed as follows :

TABLE 20.1 CLASSIFICATION OF NON-TRADITIONAL MACHINING PROCESSES

Type of energy	*Basic mechanism of metal removal*	*Transfer media*	*Energy source*	*Processes*
Mechanical	Erosion shear	High velocity particles. Physical contact	Pneumatic/hydraulic pressure Cutting tool	AJM, USM Conv. machining
Chemical	Chemical ablation	Reactive environment	Corrosive agent	CHM
Electro-chemical	Ion displacement	Electrolyte	High current	ECM; ECG
Thermo-electric	Fusion Vaporization	Hot gases Electron Radiation	Ionized material High Voltage Amplified light	IBM PAM EBM EDM LBM

1. Mechanical
   (a) Abrasive Jet Machining (AJM)
   (b) Ultrasonic Machining (USM)
2. Chemical
   (a) Chemical Machining (CHM)
3. Electro-Chemical
   (a) Electro-Chemical Matching (ECM)
   (b) Electro-Chemical Grinding (ECG)
4. Thermo-electric.
   (a) Ion-Beam Machining (IBM)
   (b) Plasma Arc Machining (PAM)
   (c) Electrical Discharge Machining (EDM)
   (d) Electron-Beam Machining (EDM)
   (e) Laser-Beam Machining (LBM)

Process selection : In order to make use of the non-traditional machining processes efficiently, it is necessary that the exact nature of the machining problem must be known. The points which should be looked into before the selection of these processes are :

1. Physical parameters.
2. Properties of the work material and the shape to be machined.
3. Process capability or machining characteristics.
4. Economic consideration.

The non-traditional machining processes have relatively good application to cover all metals and alloys. This is in contrast to the conventional machining processes which vary in their application, depending upon the strength and hardness of the material. However, materials applications of the various methods are summarized in Table 20.2.

TABLE 20.2 MATERIAL APPLICATION OF NON-TRADITIONAL MACHINING

Process	*Aluminium*	*Steel*	*Super alloy*	*Titanium*	*Refrac -tories*	*Ceramics*	*Plastic*	*Glass*
USM	P	F	P	F	G	G	F	G
AJM	F	F	G	F	G	G	F	G
ECM	F	G	G	F	F	N	N	N
CHM	G	G	F	F	P	P	P	F
EDM	F	G	G	G	G	N	N	N
EBM	F	F	F	F	G	G	F	F
LBM	F	F	F	F	P	G	F	F
PAM	G	G	G	F	P	N	P	N

G = Good, F = Fair, P = Poor, N = Not applicable.

The applications of the non-traditional machining processes are also influenced by the workpiece shape and size to be produced, viz. holes, through holes, surfacing, through cutting, and special applications.

The process capability or machining characteristics can be analyzed with respect to :

1. Metal removal rate obtained.
2. Tolerance maintained.
3. Surface finish obtained
4. Depth of surface damage.
5. Power required for machining.

Table 20.3 shows the process capabilities of different processes.

The economics of the various processes are analyzed by considering

1. Capital cost.
2. Tooling cost.
3. Consumed power cost.
4. Metal removal rate efficiency.
5. Wear of tooling.

TABLE 20.3 PROCESS CAPABILITIES

Process	*MRR, mm^3/min*	*Tolerance, micron*	*Surface finish micron CLA*	*Depth of surface damage (micron)*	*Power (watts)*
USM	300	7.5	0.2-0.5	25	2,400
AJM	0.8	50	0.5-1.2	2.5	250
ECM	15,000	50	0.1-2.5	5	100,000
CHM	15	50	0.5-2.5	5	–
EDM	800	15	0.2-1.2	125	2,700
EBM	1.6	25	0.5-2.5	250	150(Average) 200 (peak)
LBM	0.1	25	0.5-1.2	125	2 (Average) 2000 (peak)
PAM	75.0	125	Rough	500	50,000
Conventional machining	50,000	50	0.5-5	25	3,000

20.3 ABRASIVE JET MACHINING (AJM)

The fundamental principle of Abrasive jet machining involves the use of a high-speed stream of abrasive particles carried by a high pressure gas or air on the work surface through a nozzle. The metal removal occurs due to erosion caused by the abrasive particles impacting the work surface at high speed. With repeated impacts, small bits of material get loosened and a fresh surface is exposed to the jet.

Fig.20.1 shows a schematic diagram of working of the process. The filtered gas, supplied under a pressure of 2 to 8 kgf/cm^2 to the mixing chamber containing the abrasive powder and vibrating at 50 Hz entrains the abrasive particles and is then passed into a connecting hose. This abrasive and gas mixture emerge from a small nozzle mounted on a fixture at high velocity ranging from 150 to 300 m/min. The abrasive powder feed rate is controlled by the amplitude of vibration of the mixing chamber. A pressure regulator controls the gas flow and pressure. To control the size and shape of the cut either the workpiece or the nozzle is moved by cams, pantographs or other suitable mechanisms. The carrier gas should be cheap, non-toxic and easily available. Air and nitrogen are two of the most widely used gas in AJM.

The abrasives generally employed are aluminium oxide, silicon carbide, glass powder or specially prepared sodium bicarbonate. The average particle sizes vary from 10 to 50 microns. Larger sizes are used for rapid removal rate while smaller sizes are used for good surface finish and precision work. In addition to the above abrasives, dolomite (calcium magnesium carbonate) of 200 grit size is found suitable for light cleaning and etching. Glass beeds of diameter 0.30 to 0.60 mm are light polishing and deburring.

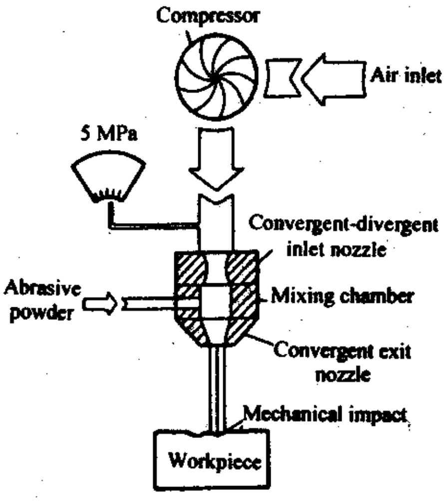


Figure 20.1 Abrasive jet machining

Since nozzles are subjected to a great degree of abrasion wear, they are made of hard materials such as tungsten carbide or synthetic sapphire (ceramic) to reduce the wear rate. Nozzles made of tungsten carbide have an average life of 10 to 20 hours while nozzles of sapphire last for about 300 hour of operation when used with 27μ abrasive powder. The gases used are nitrogen, carbon dioxide or clean air.

The metal removal rate depends upon the diameter of nozzle, composition of abrasive-gas mixture, jet pressure, hardness of abrasive particles and that of work material, particle size, velocity of jet and distance of workpiece from the jet. A typical material removal rate for abrasive jet machining is 16 mm^3/min in cutting glass. Fig.20.2 shows the effect of abrasive jet pressure and grain size on the material removal rate.

Accuracy : With close control of the various parameters a dimensional tolerance of ± 0.05 mm can be obtained. On normal production work an accuracy of ± 0.1 mm is easily held.

Applications : The process finds application in cutting slots, thin sections, contouring, drilling, for producing shallow crevices, deburring, and for producing intricate shapes in hard and brittle materials. It is often used for cleaning and polishing of plastics, nylon and teflon components, frosting of the interior surface of the glass tubes, etching of markings on glass cylinders, etc.

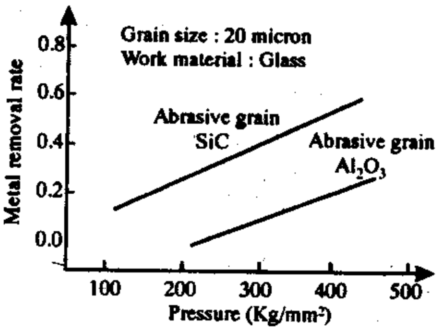


Figure 20.2 Effect of jet pressure for AJM

Advantages : The advantages of AJM are :

1. Ability to cut intricate hole shapes in materials of any hardness and brittleness.
2. Ability to cut fragile and heat-sensitive materials without damage as no heat is generated due to the passing of gas or air.
3. Low capital cost.

Disadvantages : The disadvantages of the process lie in the following :

1. Material removal rate is slow and its application is therefore limited.
2. The machining accuracy is poor and the nozzle wear rate is high.
3. Additional cleaning of the work surface may occur as there is a possibility of sticking abrasive grains in softer materials.

Water jet machining is another variation where a high pressure jet of water is directed on a surface to remove material.

20.4 ULTRASONIC MACHINING (USM)

The term ultrasonic is used to describe a vibratory wave of frequency above that of the upper frequency limit of the human ear, i.e., generally above 16 kHz. The device for converting any type of energy into ultrasonic waves is ultrasonic transducer. This electrical energy is converted into mechanical vibrations, and for this piezo-electric effect in natural or synthetic crystals or magne-tostriction effect exhibited by some metals is utilized. 'Magne-tostriction' means a change in the dimension occurring in ferromagnetic materials subjected to an alternating magnetic field.

In ultrasonic machining, a tool vibrating longitudinally at 20 to 30 kHz with amplitude between 0.01 to 0.06 mm is pressed on to the work surface with a light force. As the tool vibrates with a specific frequency, an abrasive slurry, usually a mixture of abrasive grains and water of definite proportion (20-30 per cent), is made to flow under pressure through the tool-workpiece interface. The impact force arising out of the vibration of the tool end and the flow of slurry through the work-tool interface actually causes thousands of microscopic grains to remove the work material by abrasion. The tool has the same shape as the cavity to be machined. The method is chiefly employed to machine hard and brittle materials (which are either electrically conducting or non-conducting). Analysis of the mechanism of material removal by USM process indicates that it may sometimes be called *Ultrasonic grinding* (USG).

The ultrasonic machining operation is shown schematically in Fig.20.3. The electronic oscillator and amplifier, also known as the generator, converts the available electrical energy of low frequency to high frequency power of the order of 20 kHz which is supplied to the transducer. The transducer operates by magnetostriction. The high-frequency power supply activates the stack of the magnetostrictive material which produces longitudinal vibratory motion of the tool. The amplitude of this vibration is inadequate for cutting purposes. This is, therefore, transmitted to the penetrating tool through a mechanical focusing device which provides an intense vibration of the desired amplitude at the tool end. The mechanical focusing device is sometimes called a *velocity transformer*. This is virtually a tapered shank or so called 'horn', its upper end being rigidly clamped or brazed to the lower face of the magnetostrictive material, and its lower end is provided with means for securing the tool. All these parts, including the tool made of low-carbon or stainless steel to the shape of the desired cavity, act as one elastic body transmitting the vibrations to the tip of the tool.

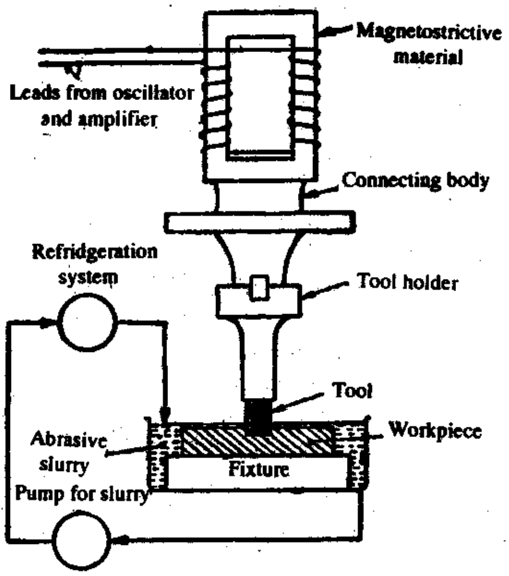


Figure 20.3 Schematic diagram of ultrasonic machining

The commonly used abrasives are : aluminium oxide (alumina), boron carbide, silicon carbide, and diamond dust. Boron is the most expensive abrasive material and is best suited to cutting of tungsten carbide, tool steel and gems. Silicon finds most application. For cutting glass and ceramics, alumina is found as the best. The abrasive slurry is circulated to the work-tool interface by pumping. A refrigerated cooling system is used to cool the abrasive slurry to a temperature of 5 to 6° C. A good method is to keep the slurry in a bath in the cutting zone. The liquid to produce abrasive slurry should have the following characteristics :

1. Good wetting characteristic.
2. Low viscosity.
3. High thermal conductivity.
4. Anti corrosive property.
5. Approximately having equal density with abrasive.
6. Low cost.

The size of abrasive varies between 200 and 2000 grit. Coarse grades are good for roughing, whereas finer grades, say 1000 grit, are used for finishing. Fresh abrasives cut better and the slurry therefore be replaced periodically.

Cutting rate : Cutting rate by using USM varies on certain factors. These are :

1. Grain size of abrasive.
2. Abrasive materials.
3. Concentration of slurry.
4. Amplitude of vibration.
5. Frequency.

Fig.20.4 shows the effect of various cutting parameters.

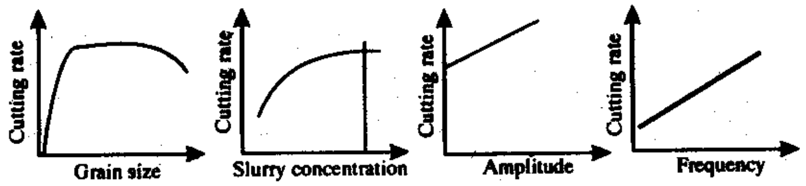


Figure 20.4 Effect of cutting parameters in USM

Accuracy : The maximum speed of penetration in soft and brittle materials such as soft ceramics are of the order of 20 mm/min, but for hard and tough materials, the penetration rate is lower. Dimensional accuracy upto ± 0.005 mm is possible and surface finishes down to an R_a value of 0.1-0.125μ can be obtained. A minimum corner radius of 0.10 mm is possible in finish machining. The range of sizes of USM machines varies from a light portable type having an input of about 20W to heavy machines taking an input of upto 2kW.

Application : The simplicity of the process makes it economical for a wide range of applications such as :

1. Introducing round holes and holes of any shape for which a tool can be made. The range of obtainable shapes can be increased by moving the workpiece during cutting.
2. In performing/machining operations likes drilling, grinding, profiling and milling operations on all materials both conducting and non-conducting.
3. In machining glass, ceramic, tungsten and other hard carbides, gem, stones such as synthetic ruby.
4. In cutting threads in components made of hard metals and alloys by approximately rotating and translating either the workpiece or the tool.
5. In making tungsten carbide and diamond wire drawing dies and dies for forging and extrusion processes.
6. Enabling a dentist to drill a hole of any shape on teeth without creating any pain.

Limitations of the process : The major limitation of the process is its comparatively low metal cutting rates. The maximum metal removal rate is 3 mm^3/s and the power consumption is high. The depth of cylindrical holes is presently limited to 2.5 times the diameter of the tool. Wear of the tool increases the angle of hole, while sharp corners become rounded. This implies that tool replacement is essential in the production of accurate blind holes. Also, the process is limited, in its present form to machine on surfaces of comparatively small size.

The tool material employed in USM should be tough and ductile. The difficulties with very ductile metals like Aluminium can be traced due to its short tool life. This difficulty can be eliminated by using low carbon steel and stainless steel as tool materials. Experimental verification has shown that Metal Removal Rate decreases with the ratio of workpiece hardness and tool hardness. Thus if the workpiece hardness increases, it is expected that the tool hardness is also increased. The choice of tool metal is one of the most important decision making for optimization of metal removing and tool cost. The mass length of the tool also pose difficulty as the tool materials absorbs much of the ultrasonic energy, reducing the efficiency. Longer tool causes overstressing. The grains size and abrasive slurry also of the correct dimension. It has been observed that if grain size is more or less than the amplitude of the vibration, machining rate decreases. Choosing a grain for finish machining should not overlap with the specified grains of rough machining while cutting deep holes special techniques are needed for supplying the slurry through the tool holder else accumulation of grain particles, inside the hole will abstract further machining. Forced circulation, mixing alternatively higher and lower sized grains, suctioning are some of the many effective methods followed to remove this deep hole machining problem.

Recent development : Recently a new development in ultrasonic machining has taken place in which a tool impregnated with diamond dust is used and no slurry is used. The tool is oscillated at ultrasonic frequencies as well as rotated. If it is not possible to rotate the tool the workpiece may be rotated.

This innovation has removed some of the drawbacks of conventional process in drilling deep holes. For instance the hole dimensions can be kept within ± 0.125 mm. Holes upto 75 mm, depth have been drilled in ceramics without any fall in the rate of machining as is experienced in the conventional process.

20.5 CHEMICAL MACHINING (CHM)

Chemical machining is the stock removal process for the production of desired shapes and dimensions through selective or overall removal of material by controlled chemical attack with acids or alkalis (etchant solution). The metal is gradually transformed into metallic salt by chemical reaction and is ultimately removed in this form. Areas from where material is not to be removed are protected by an etchant resistant material, known as 'maskant' or 'resist'. Nearly all the materials, from metals to ceramics, can be chemically machined.

The component to be machined is first cleaned in trichlorethylene vapour or in a solution of mild alkaline solution at 80 to 90° C, followed by washing in clean water. One of the roughest methods is to coat the component all over by spraying or dipping. This removes dust and oil. The cleaning ensures a good adhesion of the coating or masking agent which is applied to protect the portions which are not to be machined. After cleaning the component is dried and coated with the maskant material which must be cut and peel, photoresist or screen-print, type. Finally, the metal is removed by etching.

The process can be suitably applied to different types of operations such as milling, blanking, and engraving. The different chemical machining processes can thus be classified as :

1. Chemical milling.
2. Chemical blanking.
3. Chemical engraving.

Chemical machining for some special purposes can also be accomplished by using a jet of reactive gas, e.g., chlorine on the machining zone. This is known as *Gaseous Chemical Machining* or *Hot Chlorine Machining*, and can be employed for deburring of metal parts.

Chemical milling : Chemical milling, sometimes called *Chemilling* or *contour machining* or *etching* is used mainly to produce shapes by selective or overall removal of metal parts from relatively large surface areas. The main purpose is to achieve shallow but complex profiles, reduction in weight by removing unwanted material from the surface as in the skin of an aircraft.

Chemical milling entails four steps :

1. Cleaning.
2. Masking.
3. Etching.
4. De-masking

The components are thoroughly cleaned and degreased by immersion in trichlorethylene vapour or some alternative chemical cleaner followed by washing in clean water. The component is then coated with a cut and peel maskant by brushing, dipping or spraying (upto 0.2 mm). This can be a suitable fluid with a neoprene base or some alternative plastics solution impervious to the action of the etching agent (permitting etching depths upto 10 mm). When this has dried, by mild heating or otherwise, the desired shape to be processed on the work material is cut on the maskant with a scribe knife and the unmachined portions of the maskant are peeled away. Usually, a template is used to portray the desired machining shape within tolerance. The parts are then dipped completely into a tank of chemicals which will dissolve (etch) away the exposed metal. After etching to the required depth, and washing to remove all traces of the etchant, the entire masking is stripped from the component and their surfaces are anodized or treated with a temporary protective agent as necessary. Table 20.4 shows typical masking materials for different metals.

TABLE 20.4 MASKANT MATERIALS FOR DIFFERENT METALS

Metal	*Etchant*	*Temperature °C*	*Maskants*
Aluminium	Alkaline	90	Acrylonitrile rubber, butyl rubber, neoprene rubber
Ferrous metals	Acid	54	Polyvinyl chloride; polyethelene butyl rubber
Magnesium	Acid	< 38	Polymers
Titanium	Acid	20 - 35	Translucent chlorinated polymers
Beryllium	Acid	20 - 54	Vinyl, neoprene, butyl based materials
Nickel	Acid	45 - 50	Neoprene

With optimum time, temperature and solution control, accuracies of the range of ± 0.01 mm can be achieved on relatively shallow depths of cut. The surface finish obtained may be around 5 microns. Aluminium alloys show better surface finish of the order of 1.6 microns. The metal removal rate on an aluminium components is reported to be about 140 cm^3/min. The size of the workpiece that can be treated is limited only by the size of the tank in which the component is dipped for etching.

Chemical blanking : Chemical blanking, chem-blanking, photoforming, photofabrication or photoetching is a variation of chemical milling. In this process, the metal is totally removed from certain areas by chemical action. The process is used chiefly on their sheets and foils. Almost any metal can be worked by this process, however, it is not recommended for material thinner than 2 mm.

The workpiece is cleaned, degreased and pickled by acid or alkalis. The cleaned metal is dried and photoresist material is applied to the workpiece by dipping, whirl coating or spraying. It is then dried and cured. The technique of photography has been suitably employed to produce etchant resistant images in photoresist materials. This type of maskant is sensitive to light of a particular frequency, usually ultraviolet light, and not to room light. This surface is now exposed to the light through the negative, i.e., a photographic plate of the required design, just as in developing pictures. After exposure, the image is developed. The unexposed portions are dissolved out during the developing process exposing the bare metal. The treated metal is next put into a machine which sprays it with a chemical etchant, or it may be dipped into the solution. The etching solution may be hydrofluoric acid (for titanium), or one of several other chemicals. After 1 to 15 min, the unwanted metal has been eaten away, and the finished part is ready for immediate rising to remove the etchant. The cutting action is illustrated in Fig.20.5.

Printed circuit cards, other *engraving operations* and blanking of intricate designs can be suitably made by chemical blanking by using photoresist maskants.

The *advantages* of this process can be summarized as follows :

1. Very thin material (0.005 mm) can be suitably etched.
2. High accuracy of the order of ± 0.015 mm can be maintained.
3. High production rate can be met by using automatic photographic technique.

Application of CHM : Chemical machining has been applied successfully in a great number of usages where the depth of material removal is critical to a few microns, and the tolerances are close. The surface finish obtained in the process is in the range 0.5 to 2 microns. Besides, it removes metal from a portion or the entire surface of formed or irregularly shaped parts such as forgings, castings, extrusions or formed wrought stock. One of the major applications of chemical machining is in the manufacture of burr free, intricate stampings.

Advantages of CHM : The advantages of CHM are ;

1. Components are produced burr-free.
2. Several components can be produced simultaneously.
3. The process does not distort the machined components.
4. Most difficult-to-machine materials can be processed.
5. High surface finishing is possible.

Disadvantages of CHM : the disadvantages of CHM are ;

1. Metal removal rate is slow.
2. Metal thicker than 2 mm can not be usually machined.
3. Higher operator skill is required.
4. Corrosive etchant damages the equipment.

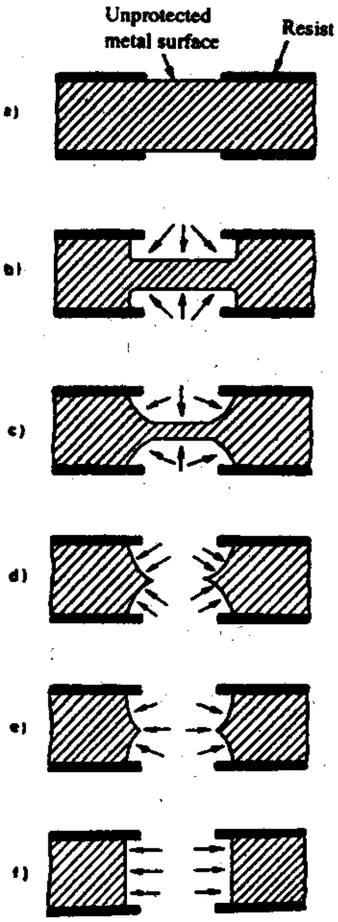


Figure 20.5 Chemical blanking

20.6 ELECTRO-CHEMICAL MACHINING (ECM)

Electro-chemical machining is one of the newest and most useful machining process of metal removal by the controlled dissolution of the anode of an electrolytic cell. The process is particularly suited to metal and alloys which are difficult or impossible to machine by mechanical machining processes. This is based on Michael Faraday's classical laws of electrolysis, requiring basically the two-electrodes, an electrolytes, a gap and a source of D.C power of sufficient capacity.

In the actual process, the cathode is tool-shaped, more or less like the mirror image of the finished workpiece. The workpiece is connected to the positive supply. The tool or cathode, connected to the negative terminal, is advanced towards the anode (workpiece) through the electrolyte that completes the electrical circuit between the anode and cathode. Metal is then removed from the workpiece through electrical action, and the cathode (tool) shape is reproduced on the workpiece. The electrolyte bath is pumped at high pressure through the gap between the workpiece and tool and must be circulated at a rate sufficiently high to conduct current between them and to carry heat. The electrolysis process that takes places at the cathode liberates hydroxyl ions (negatively charged) and free hydrogen. The hydroxyl ions combine with the metal ions of the anode to form insoluble metal hydroxides and the material is thus removed from the anode. This process continues and the cathode (tool) reproduces its shape in the workpiece (anode). The tool does not contact the workpiece producing no direct friction and, therefore, does not wear and no heat build-up occurs.

Figure 20.6 shows a typical set-up of electro-chemical machining. The electric current is of the order of 50 to 40,000 A at 5 to 30 V D.C for a current density of 20 to 300 A/cm^2, across a gap of 0.05 to 0.7 mm between the tool and the workpiece. The electrolyte flows through this gap at a velocity of 30 to 60 m/s forced by an inlet pressure of about 20 kgf/cm^2. Suspended solids are removed from the electrolytes by setting, centrifuging, or filtering, and the filtered electrolyte is recirculated for use.

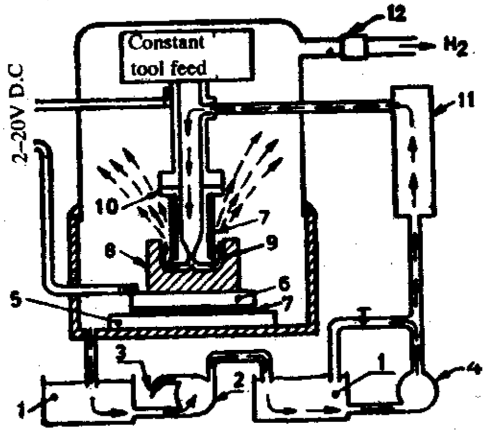


Figure 20.6 Scheme of electro-chemical machining

The electrolysis process : In the electrolytic circuit shown in Fig.20.6 the electron-flow is from, the workpiece, through the power supply to the tool. Many chemical reactions occur at the cathode, the anode, and in the electrolyte.

At the cathode the following reactions are possible :

1. $M^+ + e^- \rightarrow M$ (M denotes any metal)
2. $2H^+ + 2e^- \rightarrow H_2$ (Hydrogen evolution)

The following reactions occur at the anode with a halogen electrolyte :

1. $M \rightarrow M^+ + e^-$ (Metal dissolution)
2. $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ (Oxygen evolution)
3. $2Cl^- \rightarrow Cl_2 + 2e^-$ (Halogen gas evolution)

It has been established that the metal dissolution reaction is main or the only reaction that occurs. As an example, let the machining of iron in an NaCl electrolyte can be considered.

$$Fe \rightarrow Fe^{++} + 2e^-$$
$$NaCl \Leftrightarrow Na^+ + Cl^-$$
$$2H_2O + 2e \Leftrightarrow 2(OH)^- + H_2 \uparrow$$
$$Fe^{++} + 2(OH)^- \rightarrow Fe(OH)_2$$
$$Fe(OH)_2 + Air \rightarrow Fe(OH)_3 \downarrow sludge$$
$$2Fe + 4H_2O + O_2 \rightarrow 2Fe(OH)_3 + H_2$$

At the anode, the reaction products are $FeCl_2$, $Fe(OH)_2$, $FeCl(OH)$, $Fe(OH)_3$ which form a layer. Thus, it is seen how iron is removed by electrolytic action. It is interesting to note that the salt is not being consumed and the metal is being machined at the expense of electrical energy and a little of water. The electrolyte acts only as a carrier of current. From this it can further be seen that current of 1000 A would dissolve iron at the rate of about 15 g/min, and generate hydrogen at the rate of about 300 cm^3/min.

Elements of ECM : Important elements of ECM are :

1. Electrolyte.
2. Cathode tool.
3. Anode workpiece.
4. D.C power supply.

Electrolytes : The common electrolytes used are sodium chloride, sodium nitrate potassium chloride, sodium hydroxide, sodium fluoride, sulfuric acid and sodium chlorate. These solutions on reaction produce an insoluble compound in the form of sludge. The main functions of an electrolyte in ECM are :

1. It carries the current between the tool and the workpiece.
2. It removes products of machining and other insoluble products from the cutting region.
3. It dissipates heat produced in the operation.

The essential characteristics of electrolyte includes :

1. Good electrical conductivity.
2. Non-toxicity and chemical stability.
3. Non-corrosive property.
4. Low viscosity and high specific heat.

The most commonly used electrolyte is the solution of sodium chloride in concentration varying from 0.1 to 0.25 kg/litre of water. An advantage of using sodium chloride solution is that its electrical conductivity is fairly constant from PH value 0 to 13. It is inexpensive and non-poisonous. However, the disadvantage is that it is corrosive and it produces a large amount of sludge. The suspension of a large amount of sludge makes the electrolyte more viscous though the conductivity of the solution is little changed. Consequently, greater power is required to make it flow through the thin gap.

Table 20.5 shows characteristics and applications of various electrolytes.

The electrolyte in flowing through the machining gap creates a thin boundary layer of slowly moving fluid next to the anode. Ions of work material leaving the metal surface must traverse this slowly moving boundary layer primarily by a process of diffusion. The rate at which ion can move through the boundary layer influences the rate of metal removal. The ideal electrolyte would provide a uniformly thin boundary layer over the entire surface of the workpiece, irrespective of pressure and fluid velocity variations.

High velocity flow (30-60 m/s) over the electrode surface is one of the key factors in ECM. This is necessary in order to prevent crowding of hydrogen gas and debris of machining. If this is not fulfilled, bubbles of hydrogen gas will fill the machining gap and machining will stop in that area. It also flushes the metallic particles suspended in the electrolyte, leading to local heating or arcing, and ultimately damage of the tooling and the workpiece.

TABLE 20.5 ELECTROLYTE SOLUTIONS : CHARACTERISTICS AND APPLICATIONS

Type	*Concentration (weight % in aqueous solution)*	*Application*	*Characteristics*
Neutral Salts Common salt (NaCl)	5 – 20	Alloyed and unalloyed steel	Inexpensive, non-poisonous, pitting, corrosive moderate m.r.r.
Sodium chlorate ($NaClO_3$)	20 – 45	Steel	High m.r.r., inflamable
Sodium nitrite ($NaNO_2$)	up to 12	Copper alloys	Poisonous, moderate to low m.r.r.
Acid Sulphuric acid (H_2SO_4)	up to	Nickel, chromium, cobalt alloys	Highly corrosive, poisonous
Alkalies Sodium hydrate (NaOH)	up to 10	Tungsten and molybdenum	Corrosive

The permissible electrolyte *flow velocity, U,* in case of rectangular electrode is given by

$$U = \frac{V^2 l}{4.187 r h^2 \rho_e C_e (\theta_B - \theta_0)} \quad \text{m/s} \qquad (20.1)$$

where, V = voltage applied, V
l = length of the electrode, m
r = specific resistance, ohm-m
h = gap length, m
ρ_e = density of electrolyte, kg/m^3
C_e = specific heat of electrolyte, cal/kg K
θ_0 = ambient temperature, K
θ_B = boiling temperature of electrolyte, K

The quantity of electrolyte q, flowing per unit time, through the gap is given as by :

$$q = Ubh \qquad 20.2$$

where, U = flow velocity
b = width of rectangular anode or workpiece.
h = gap length, m

Tool material for ECM : The general requirements on the tool material in ECM are :

1. It should be conductor of electricity.
2. It should be rigid enough to take up the load due to fluid pressure.
3. It should be chemically inert to the electrolyte.
4. It should be easily machinable to make it in the desired shape.

Copper, brass, titanium, copper-tungsten and stainless steels are most commonly used electrode material when the electrolyte is made of salts of sodium or potassium. Where the electrolyte has the tendency to anodize the tool as in the case of sulfuric acid, titanium has been found to be most suitable. Table 20.6 shows the properties of some of the tool materials. The other materials which can be used as tool materials are aluminium, graphite, bronze, platinum and tungsten carbide. The cavity or hole that is made, exactly reproduces the tool shape. Thus the accuracy of the tool shape directly affects the workpiece accuracy. Electroforming and cold-forging are two methods of tool - shaping.

TABLE 20.6 ECM TOOL MATERIALS PROPERTIES (COMPARATIVE INDEX)

Properties	*Material*			
	Copper	Brass	Stainless steel	Copper-tungsten
Electrical resistivity	1.00	4.00	53.00	8.00
Stiffness	1.60	1.00	1.90	2.20
Machinability	6.00	8.00	2.50	1.80
Thermal conductivity	25.00	7.50	1.00	10.00

Metal removal rate : The overall machining rate is governed by Faraday's Laws of Electrolysis which state (1) that the amount of chemical change produced by current, *i.e.*, the amount of any substance deposited or dissolved is proportional to the quantity of electricity that is passed through the electrolyte, and 2) that the amount of metal from an electrode or deposited on to an electrode by flow of the same quantity of electricity, e.g., one *Faraday* is equal to one gram equivalent weight of the metal.

The quantitative unit of electricity called *Faraday* which is the amount of electricity that reduces one gram - equivalent weight of a substance at the cathode and oxidises one gram equivalent weight of a substance at the anode.

1 faraday = 6.02×10^{23} e^- = 96500 Coulombs

Combining these two laws,

$$W = \frac{EIt}{F} \qquad 20.3$$

where, W is the mass of ions dissolved in kg ion, E the equivalent weight of a substance dissolved or deposited and is equal to atomic weight (N)/valency (n), t, the time in sec, and F is equal to Faraday constant or 96,500 coulombs or 26.8 amp-hr.

Assuming that all the current flowing through the electrolytic cell is used in the desired metal removal process, *i.e.*, 100% current efficiency, in the steady state flow condition, the rate of metal removal, *expressed in terms of the height of the removed layer*, will be given by :

$$MRR = \frac{W}{A\rho t} m/s \qquad 20.4$$

where, A is the machined area in m^2, and ρ the density of the workpiece in kg/m^3.

Using equation (20.3), equation (20.4) can be written as :

$$MRR = \frac{EIt}{FA\rho t} = \frac{EI}{FA\rho} \qquad 20.5$$

Hence, $$MRR = \frac{EJ_c}{F\rho} m/s \qquad 20.6$$

where, J_c = current density $= I/A$
for 1 square unit area.

Also, $$MRR = \frac{EI}{F\rho} m^3/s \qquad 20.7$$

The feed rate of electrode(f) is given by :

$$f = \frac{V}{\rho_s h} \times \frac{E}{F\rho} m/s \qquad 20.8$$

where, V is the machining voltage (volt), ρ_s the specific resistance of electrolyte in ohm-m, and h the tool-work gap in *m*.

The *current efficiency* is given by :

$$\eta = \frac{\text{Actual metal removed/amp-min}}{\text{Theoretical metal removal/amp-min}} \times 100\% \qquad 20.9$$

Table 20.7 shows the material removal rates for various metals.

TABLE 20.7 ECM METAL REMOVAL RATES*

Material	*Density* (g/cm^3)	*Removal rate* (cm^3/min)
Aluminium	2.7	1.9
Cobalt	8.9	1.9
Copper	8.9	3.9
Iron	7.8	2.1
Lead	11.3	5.0
Molybdenum	10.1	1.8
Nickel	8.9	1.9
Titanium	4.5	1.9
Tungsten	19.3	0.8
Uranium	19.0	1.8
Zirconium	6.5	1.9

* Source : G.Benedict, Nontraditional manufacturing Processes, Marcel Dekker, NY, 1987.

Example 20.1 : Calculate the machining rate and the electrode feed rate when iron is electro-chemical machined using copper electrode and sodium chloride solution (specific resistant =5.0 ohm-cm). The power supply data of the ECM machine used were :

Supply voltage = 18V dc
Current = 5000 A

A 'tool-work' gap of 0.5 cm (constant) may be assumed.

The current efficient η can be taken as 100 per cent with sodium chloride electrolyte.

For iron (anode), atomic weight, N = 56
valency, n = 2
density, ρ = 7.87 g/cm^3

According to Eq. (20.7), $MRR = \frac{EI}{F\rho} m^3 / s$

$$MRR = \frac{1}{96{,}500} \times \frac{56}{2} \times \frac{1}{7.87} \times 5000$$

$$= 3.67 \times 10^{-5} \times 5000$$

$$= 0.1835 \text{ cm}^3/\text{s}$$

$$= \mathbf{1.835 \times 10^{-7} \ m^3/s}$$

Electrode feed rate,

$$f = \frac{V}{\rho_s \times h} \times \frac{E}{F\rho}$$

$$f = \frac{18 \times 3.67 \times 10^{-5}}{5 \times 0.05} cm / s$$

$$= \mathbf{1.58 \ mm/min.}$$

Example 20.2 : In a certain electro-chemical dissolution process of iron, a metal removal rate of 3 cm^3/min was desired. Determine the amount of current required for the process, assuming :

Atomic weight of iron, $N = 56$ g
valency, $n = 2$
Density of iron, $\rho = 7.8 \text{ g/cm}^3$

According to Eq. (20.7), $MRR = \frac{EI}{F\rho} cm^3 / s$

or, $$3 = \frac{56 \times I}{1{,}609 \times 2 \times 7.8}$$

where, $F = 1{,}609$ amp-min.

Therefore, $$I = \frac{3 \times 1609 \times 7.8}{28} = 1344.6 \text{ amp.}$$

Example 20.3 : During electro-chemical machining of iron with a copper tool working in a saturated solution of NaCl in water, the following properties of the electrolyte are observed :

Specific heat = 0.997 cal/g°C
Density = 1 g/cm^3
Specific resistance = 3 ohm-cm

The electrode area is given by 2.54 × 2.54 cm. The initial gap (h) for electrolyte to pass is equal to 0.0254 cm.

(a) Calculate the permissible fluid flow velocity if the maximum permissible temperature of electrolyte is the boiling point (95°C). The ambient temperature is 35°C and the applied voltage has been 12 V.

(*b*) Calculate also the maximum metal removal rate if the permissible current density has been 160 amp/cm^2.

(I.E., India : "New technology", Dr. A. Bhattacharyya)

According to Eq. (20.1), Flow velocity,

$$U = \frac{V^2 l}{4.187 r h^2 \rho_e C_e (\theta_B - \theta_o)}$$

As given in the problem,

$$U = \frac{(12)^2 \times 2.54}{4.187 \times 3 \times (0.0254)^2 \times 1 \times 0.997(95-35)}$$

$$= 765 \text{ cm/s} \qquad = \mathbf{459\ m/min.}$$

According to Eq. (20.6), metal remove rate is given by

$$MRR = \frac{EJ_c}{F\rho}$$

As given in the problem,

$$MRR = \frac{28 \times 160}{96{,}500 \times 7.86} = 0.0059 \text{ cm/s} \qquad = \mathbf{3.44\ mm/min.}$$

Accuracy of ECM : There are a number of factors which govern the accuracy of the parts produced by ECM. The major ones are:

1. Machining voltage.
2. Feed rate of electrode (tool).
3. Temperature of electrolyte.
4. Concentration of electrolyte.

Under ideal conditions with properly designed tooling ECM is capable of holding tolerances of the order of ± 0.02 mm and less. In general, tolerance can be maintained on a production basis in the region of ± 0.02 to 0.04 mm. As a general rule, the more complex the shape of the work, the more difficulties to hold tight tolerances. ECM results in internal radii greater than 0.2 mm and external radii of the order of 0.05 mm. Taper is of the order of 0.010 mm for 10 mm depth and the side over- cut is about 0.1 to 0.2 mm. Surface finish in ECM is of the order of 0.2 to 0.8 micron (CLA) depending on the work material and the electrolyte used, and no burrs or sharp edges are left on the workpiece.

Application : The main applications of ECM process are in machining of hard-heat-resisting alloys, for cutting cavities in forging dies, for drilling holes, machining of complex external shapes like that of turbine blades, aerospace components, machining of tungsten carbide and that of nozzles in alloy steels. Almost any conducting material can be machined by this method.

Advantages : The advantages of the ECM process can be enumerated as follows :

1. The metal removal rate by this process is quite high for high-strength-temperature-resistant (HSTR) materials compared to conventional machining processes.
2. Residual stress is low ; depth of work-hardened layer is lower by one-hundredth compared to turning compressive stress is absent.
3. It can machine configurations which are beyond the capability of conventional machining processes.
4. Surface finish is in the order of 0.2 to 0.8 microns.
5. Tool wear is nearly absent.
6. Extremely thin metal sheets can be easily worked without distortion.

Disadvantages : The ECM process suffers from a number of disadvantages.

1. The specific power consumption in this process is nearly 100 times more than in turning or milling steel.
2. Nonconducting materials can not be machined.
3. Corrosion and rust of ECM machine can be a hazard. But preventive measures can help in this regard.

20.7 ELECTRO-CHEMICAL GRINDING

Electrolyte grinding is a modification of both the grinding and electro-chemical machining. In this process, machining is affected both by the grinding action and by the electro-chemical process. Hence, in the true sense, it may be called 'mechanically assisted electro-chemical machining'.

In ECG, the metal bonded grinding wheel impregnated with a *non-conductive* abrasive is made the cathode and the workpiece the anode as in ECM. The electrolyte, which is usually sodium nitrate, sodium chloride, sodium nitrite, potassium nitrite, with a concentration of 0.150 to 0.300 kg/litre of water, is passed through nozzle in the machining zone in order to complete the electrical bridge between the anode and the cathode. The work and wheel do not make contact with each other because they are kept apart by the insulating abrasive particles which protrude from the face of the grinding wheel. A constant gap of 0.025 mm is maintained into which a stream of electrolyte is directed. The electrolyte is carried past the work surface at high speed by the rotary action of the grinding wheel. With the rotation of the grinding wheel, metal is removed from the workpiece by the simultaneous electrolytic and abrasive action. Actually, abrasive grains on the surface of the wheel serve to act as a paddle which pick up the electrolyte and cause a pressure to a build-up at the work area. The phenomenon of metal removal is illustrated in Fig. 20.7.

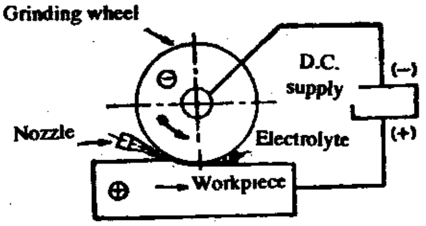
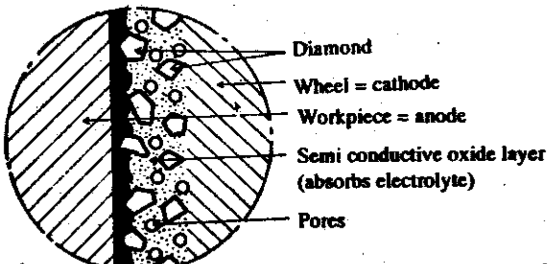


Figure 20.7 Electro-chemical grinding

The wheel and work conditions are shown in Fig. 20.8. The electrolyte is entrapped in small cavities of semiconductive oxide between projecting nonconductive abrasives forming electrolytic cell. When these cells come in contact with the work the current



Agathon Matchless Machines Ltd.

Figure 20.8 The wheel and work condition in electro-chemical grinding

flows the wheel to the work and this leads to the electrochemical decomposition of work. The short circuiting between the wheel and work is prevented due to point contact made by abrasion in order to make the surface more receptive.

It can be seen that the process is similar to conventional grinding in that an abrasive grinding wheel is used, and the work is fed against the rotating wheel. In fact, 10 per cent of the work metal is removed by abrasive cutting, and 90 per cent by electrolytic action.

The grinding wheels used are of conventional shape and structure Metal bond, diamond grit wheels are used for grinding tungsten carbide tips. Carbon bond wheels are used upon the hard alloy steels such as the stainless steels. Wheel wear is negligible because the greatest part of the cutting action is electrolytic, and little dressing of grinding wheel is necessary.

The wheel, with its spindle and bearings, must be insulated electrically from the machine frame and supplied with current through slip rings. The machine is similar in design to surfce grinder or tool and cutter-grinder, and the equipment includes a tank, filter and pump for the supply of electrolyte, and a power unit for delivering a heavy *D.C current*. The current applied is in the range of 50 to 3000 A at 4 to 10 V (250 A/cm^3).

Accuracy : Because there is very little abrasive action, ECG grinding does not leave fine scratches which may impair the finish and leave stress raisers. Tolerances of about ± 0.02 are held on rather complex grinding operations. For closer tolerances, the proportion of material removed by abrasive should be increased. The surface finish is held in the range of 0.2 to 0.4 micron on carbide and 0.4 to 0.8 micron on steel. Sharp corners are difficult to obtain and a minimum radius of 0.2 mm can not be avoided unless a final pass without electrolytic action is used.

Application of ECG : Any material which is electrically conductive may be ground by the electrolytic process, but its most useful application is concerned with hardened steel, cemented carbides, and similar materials. This is mainly applied to resharpening and reconditioning of carbide tools and other materials that are difficult to grind. As the grinding pressure is low, it is possible to grind and cut thin sections and thin-wall tubing of 'difficult' materials without distortion or burr.

Advantages and disadvantages : The greatest advantages are that all work is completely free of burrs ; no heat is generated, so no heat cracks or distortions are developed; and very little pressure is exerted on the work, and practically no wheel wear is found. Besides, higher metal removal rates are possible, particularly upon hard materials.

The major disadvantage is the cost of the ECG system. The metal removal rates are comparatively low being of the order of 15 mm^3/s and power consumption is high.

20.8 ELECTRIC DISCHARGE MACHINING

Electric discharge machining, also known as *spark erosion, electro-erosion* or *spark machining* is a process of metal removal based on the principle of erosion of metals by an interrupted electric spark discharge between the electrode tool (usually cathode) and the work (anode).

Fundamentally, the electric erosion effect is understood by the breakdown of electrode material accompanying any form of electric discharge. The discharge is usually through a gas, liquid or in some cases through solids. A necessary condition for producing a discharge is ionization of the dielectric, *i.e.*, splitting up of its molecules into ions and electrons.

Fig.20.9 illustrates the schematic layout of the electric discharge machining system. The main components are the electric power supply, the dielectric medium, the workpiece and the tool, and a servocontrol.

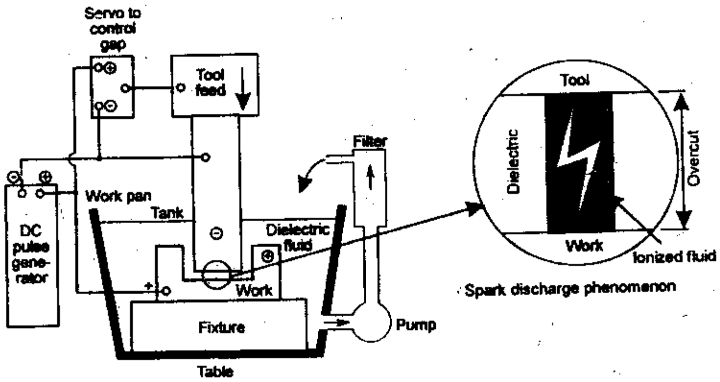


Figure 20.9 Basic scheme of electric discharge machining

The workpiece and the tool are electrically connected to a D.C electric power supply. The workpiece is connected to the positive terminal of the electric source, so that it becomes the anode. The tool is the cathode. A gap, known as the 'spark gap' in the ranges of 0.005 to 0.05 mm is maintained between the workpiece and the tool, and suitable dielectric slurry, which is non conductor of electricity is forced through this gap at pressure of 2 kgf/cm^2 or less. When a suitable voltage in the range of 50 to 450 V is applied, the dielectric breaks down and electrons are emitted from the cathode and the gap is ionized. In fact, a small ionized fluid column is formed owing to formation of an avalanche of electrons in the spark gap where the process of ionizational collision takes place. When more electrons collect in the gap the resistance drops causing electric spark to jump between the workpiece surface and the tool. Each electric discharge or spark causes a focused stream of electrons to move with a very high velocity and acceleration from the cathode towards the anode, and ultimately creates compression shock waves on both the electrode surface, particularly at high spots on the workpiece surface, which are closest to the tool. The generation of compression shock waves develops a local rise in temperature. The whole sequence of operation occurs within a few microseconds. However, the temperature of spot hit by the electrons is of the order of 10,000°C. This temperature is sufficient to melt a part of the metals. The forces of electric and magnetic fields caused by the spark produce a tensile force and tear off particles of molten and softened metal from this spot in the workpiece. A part of the metal may vaporize and fill up the gap. The metal is thus removed in this way from the workpiece. The electric and magnetic fields on the heated metal cause a compressive force to act on the cathodic tool so that metal removal from the tool is at a slower rate than that from the workpiece. Hence, the workpiece is connected to the positive terminal and tool to the negative terminal.

The current density in the discharge of channel is of the order of 10,000 A/cm^2 ; the power density, of the order of 500 MW/cm^2.

Electrohydraulic servo control is usually preferred. The servo gets its input signal from the difference between a selected reference voltage and the actual voltage across the gap. The signal is amplified and the tool, as it wears a little, is advanced by hydraulic control. A short circuit across the gap causes the servo to reverse the motion of the tool until the correct gap is established.

Spark generator : The spark generating circuit may be one of the following types : (1) relaxation, or (2) pulse-generator.

The spark generator supplies current to a condenser, the discharge from which produces the spark. The workpiece alternatively becomes a positive electrode (anode) or negative electrode (cathode) respectively. On each reversal of polarity the tool is eroded mire than the workpiece. Hence, the tool wear is greater with this type of arrangement.

The introduction of *pulse generators* has overcome the drawbacks of relaxation generators. Pulse generators are available, fitted with transistorized pulse-generator circuits in which reverse pulses are eliminated. These generators consist of electronic switching units which let the current pass periodically. Modern pulse generators possess the means of accurate control over discharge duration, pause time and the current. These factors determine the overcut and hence the accuracy and surface finish. The tool wear is also greatly reduced. While for finding work high frequency and low-amperage settings are used, in roughing work low frequency discharges with high amperage are applied.

Overcut : The shape of the area of the cavity produced in the workpiece should theoretically be the same as that of the tool. This, however, is not exactly true because of the overcut. Overcut is the distance, the spark will penetrate the workpiece from the tool and remove metal from the workpiece. Theoretically, it is slightly larger than the gap between the end of the tool and the workpiece. The overcut is generally 0.025 to 0.2 mm, on *all* surfaces. Overcut causes internal corners on the workpiece to have fillets with radii equal to the overcut. Another effect of overcut is to cause the radius of the cavity in the workpiece slightly larger than the corresponding radius of the tool nose and also to cause the radius of projection on the workpiece to be slightly lesser than the radius of the cavity of the tool.

This overcut is a function of the voltage of the spark. The overcut *increases* with higher current and *decreases* with higher frequency. Fig.20.10 shows the relationships.

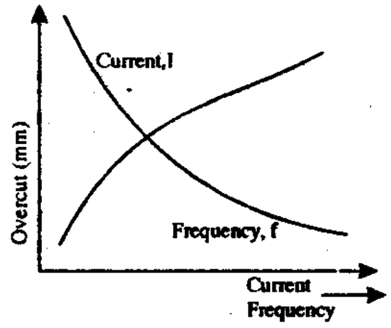


Figure 20.10 Variation of overcut with current and frequency

The electrode (tool) : The *shape of the tool* will be basically the same as that of the product desired except that an allowance is made for side clearance and overcut. For broaching small holes solid rods may be used but for larger ones, hollow tools are preferred. Dielectric may then be pumped through hollow tool. If an object is having a geometrical shape or is having symmetry about some axis, a tool equal to only a part of the object will be sufficient for complete machining the object. Such segmented tools are specially useful for machining complex shapes that do not require close accuracy. It may sometimes be convenient to use a series of simpler tool rather than a complex single tool, to produce a particular cavity.

The *material* used for the tool influences the tool wear and the side clearance and hence, in turn, it has considerable influence on the rate of metal removal, finish obtained, and the production rate. The electrode materials generally used can be classified as metallic materials (copper etc.), non-metallic materials (graphite), and combination of metallic and non-metallic materials (copper graphite). Copper, yellow brass, zinc, graphite and some other materials are used for tools. Low wearing tools include silver-tungsten, copper-tungsten, and metallized graphite. For commercial applications, copper is best suited for fine machining, aluminium is used for die-sinking, and cast iron for rough machining. One of the advantages of EDM is due to the fact that a tool made of a material softer than the workpiece material and which is a good conductor of electricity can be used to machine a material of any hardness.

The *wear of the tool* in the EDM process due to electron bombardment is inevitable. The tool wear rates determine the machining accuracy, tool movement, and the tool consumption. The tool wear is a function of the rate of metal removal, material of the workpiece, current setting, machining area, gap between the tool and the workpiece and the polarity of the tool. It has been found that the higher the tool material melting point, the less the tool wear. Wear is best defined as :

$$\text{Wear ratio} = \frac{\text{Volume of work material removed}}{\text{Volume of electrode consumed}}$$

This is often simplified to :

$$\text{Wear ratio} = \frac{\text{Depth of cut}}{\text{Decrease in usable length of electrode}}$$

The wear ratio for carbon electrodes is upto 100 : 1. Other wear ratios (for cutting steel) are copper, 2 : 1; brass, 1 : 1; and copper tungsten, 8 : 1. Thus, a piece of copper cutting 25mm deep into steel will wear 12.5 mm. These ratios are approximate and will vary considerably depending upon the situation.

Dielectric fluids : The essential requirements of a dielectric fluid to be used in EDM process are that they should :

1. Remain electrically nonconducting until the required breakdown voltage has been reached.
2. Breakdown electrically in the shortest possible time once the breakdown voltage has been reached.
3. Rapidly quench the spark or deionize the spark or spark gap after the discharges have occurred.
4. Provide an effective cooling medium.
5. Be capable of carrying away the swarf particles, in suspension away from the working gap.
6. Have a good degree of fluidity.
7. Be cheap and easily available.

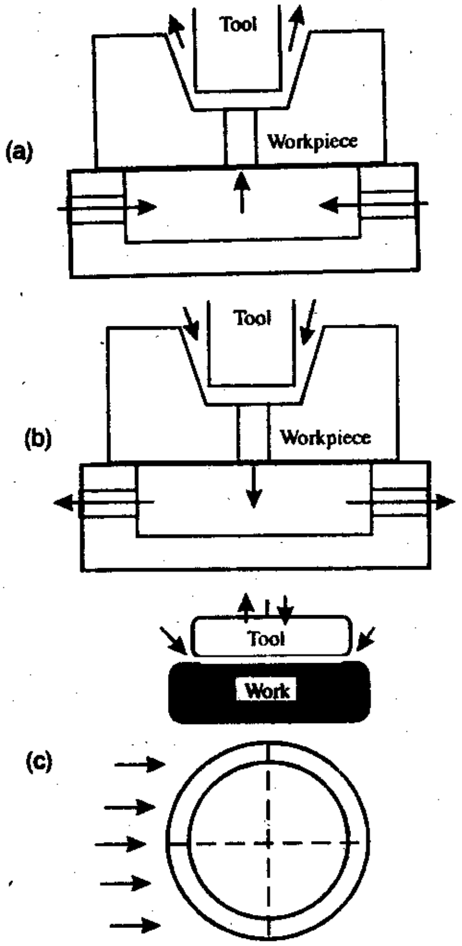


Figure 20.11 Flushing system in EDM
(a) Pressure flushing, (b) Suction flushing, (c) Side flushing

Light hydocarbon oils seem to satisfy these requirements best of all. The common dielectrics used are kerosene, paraffin, transformer oil tryethylene glycol (with water 40 % by volume) or their mixture and certain aqueous solutions. Water, being an electrical conductor, gives a metal removal rate of only about 40 per cent of that obtained when using paraffin as a dielectric.

The dielectric should be filtered before reuse so that chip contamination of the fluid will not affect machining accuracy. The dielectric fluid must circulate freely between the tool and workpiece. Flushing of eroded particle in correct manner makes the machining system efficient. Pressure flushing, suction flushing and side flushing are the three methods employed for the same. Fig.20.11 shows the three methods.

Metal removal rate (MRR) : The metal removal rate is generally described as the volume of metal removed per unit time. The machining rate during roughing of steel with a graphite electrode and 50A generator is about 400 mm^3/min and with a 400A generator it is about 4800 mm^3/min. For precision machining with low amperage and high frequency the material removal rate is as low as 2 mm^3/min. It is, therefore, evident that the MRR is proportional to the working current value.

The material being cut will affect the MRR. Experiments indicate that the MRR varies inversely as the melting point of the metal. The approximate value is :

$$\text{MRR} = \frac{2.4}{(\text{melting point, °C})^{1.25}} \qquad 20.10$$

Thus EDM will cut aluminium much faster than steel.

Accuracy : Tolerance value of ± 0.05 mm could be easily achieved by EDM in normal production. However, by close control of the several variables a tolerance of ± 0.003 mm could be achieved. A typical taper value is about 0.005 to 0.05 mm per 100 mm depth. The taper effect decreases substantially to zero after about 75 mm penetration. An overcut of 5 to 100 micron is produced, depending upon finishing or roughing. The best surface finish that can be economically achieved on steel is 0.4 micron. In 'no wear' machining, using graphite electrode a surface finish within 3.2 micron can be achieved.

Application of EDM : The electrical discharge machining is used for the manufacture of tools having complicated profiles and a number of other components. The decision to use EDM process for either of these broad applications is usually based on one or more of the basic characteristics inherent in the process.

The EDM provides economic advantage for making stamping tools, wire drawing and extrusion dies, header dies, forging dies, intricate mould cavities, etc. It has been extremely used for machining of exotic materials used in aerospace industries, refractory metals, hard carbides, and hardenable steels.

Typical EDM spplications include.

1. Fine cutting with thread shaped electrode (wire - cutting EDM).
2. Drilling of micro - holes.

3. Thread cutting.
4. Helical profile milling.
5. Rotary forming.
6. Curved hole drilling.

Delicate workpiece like copper parts for fitting into the vacuum tubes can be produced by this method. The workpiece in this case is fragile to withstand the cutting tool load during conventional machining.

Advantages : Extremely high popularity of the EDM process is due to the following advantages :

1. The process can be applied to all electrically conducting metals and alloys irrespective of their melting points, hardness, toughness or brittleness.
2. Any complicated shape that can be made on the tool can be reproduces on the workpiece.
3. Highly complicated shapes can be made by fabricating the tool with split sectioned shapes, by welding, brazing or by applying quick setting conductive epoxy adhesives.
4. Time of machining is less than conventional machining processes.
5. EDM can be employed for extremely hardened workpiece. Hence, the distortion of the workpiece arising out of the heat treatment process can be eliminated.
6. No mechanical stress is present in the process. It is due to the fact that the physical contact between the tool and the workpiece is eliminated. Thus, fragile and slender workplaces can be machined without distortion.
7. Cratering type of surface finish automatically creates accommodation for lubricants causing the die life to improve.
8. Hard and corrosion resistant surfaces, essentially needed for die making, can be developed.

Disadvantages : The following disadvantages of the process limit its application :

1. Profile machining of complex contours is not possible at required tolerances.
2. Machining times are too long.

3. Machining heats the workpiece considerably and hence causes change in surface and metallurgical properties.
4. Excessive tool wear.
5. High specific power consumption.

Fig.20.12 shows the basic features of a wire-cutting EDM. A brief outline of the wire-cutting EDM is given in section 19.13

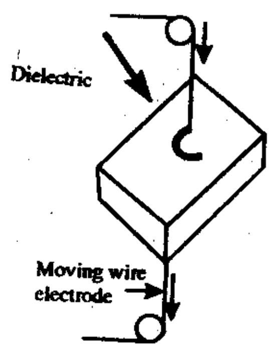


Figure 20.12 Basic features of wire - cutting EDM

20.9 ELECTRON-BEAM MACHINING (EBM)

Electron-beam machining is the metal removal process by a high velocity focused stream of electrons which heats, melts and vapourizes the work material at the point of bombardment. The production of free electrons is obtained from thermo-electronic cathodes wherein metal are heated to the temperature at which the electrons acquire sufficient speed for escaping to the space around the cathode. The acceleration of the electrons is carried by an electric field while the focusing and concentration are done by controlled magnetic fields. The kinetic energy of a beam of free electrons is transformed into heat energy as a result of the interaction of the electrons with the workpiece material. EBM is, therefore, a thermo-electric process.

Fig.20.13 shows the principle of operation of electron-beam machining. A beam of electrons is emitted from the electron gun which is basically a triode consisting of

1. A cathode which is a hot tungsten filament (2500°C) emitting high negative potential electrons.
2. A grid cup, negatively based with respect to the filament.
3. An anode which is heats at ground potential, and through which the high velocity electrons pass.

The gun is supplied with electric current from a high voltage D.C source. The flow of electrons is controlled by the negative bias applied to the grid cup. The electrons passing through the anode are accelerated to two-thirds of the velocity of light by applying 50 to 150 kV at the anode, and this speed is maintained till they strike the workpiece. Due to the pattern of the electrostatic field produced by the grid cup, the electrons are focused and made to flow in the form of a converging beam through a hole in the anode. A magnetic deflection coil is used to make the electron beam circular having a cross-sectional diameter of 0.01 to 0.02 mm and deflect it anywhere. A built-in microscope with a magnification of 40 on the workpiece enables the operator to accurately locate the beam impact and observe the actual machining operation.

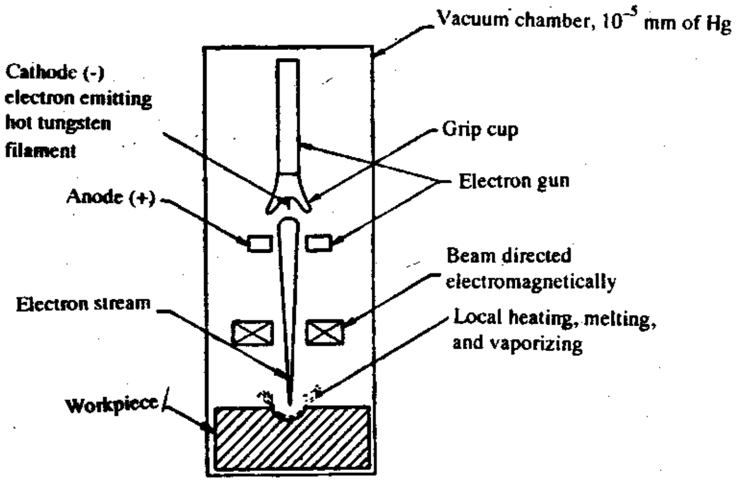


Figure 20.13 Electron-beam machining

As the beam impacts on the workpiece surface the kinetic energy of high velocity electrons is immediately converted into the thermal energy and it vaporized the material at the spot of its impact. The power density being very high (about 1.5 billion W/cm^3) it takes a few microseconds to melt and vaporize the material on impact. The process is carried out in repeated pulses of short duration. The pulse frequency may range from 1 to 16,000 Hz and duration may range from 4 to 64,000 micro-seconds.

The application of the above principle is also found in *electron-beam drilling* in which an organic or synthetic backing material is sandwitched on the other side of the component. The beam rapidly penetrates the workpiece, vapourizing it and reaches the backing material which in turn vapourizes rapidly with an explosive release of vapour at high pressure. The high vapour pressure of the backing material expells the original metal vapour generated at the initial stage, making a clean hole.

Accuracy : Typical tolerances are about 10 per cent of slot width or hole diameter. Taper of about 4° included angle is present in slots and holes and this limits the depth-to-width ratio. The depth-to diameter ratio can reach 20 : 1 with multiple pulses. Heat affected zones of up to 0.03 mm deep have been observed. The stock removal rate is generally in the region of 1.5 mm^3/s with a penetration rate of about 0.25 mm/s or faster.

Application of EBM : Some typical applications of the process are :

1. To drill fine gas orifices, less than 0.002 mm, in space nuclear reactors, turbine blades for supersonic aero-engines.
2. To produce metering holes in injector nozzles in diesel engines, etc.
3. To scribe thin films.
4. To remove small broken taps from holes.
5. To remove small broken taps from holes.

Advantages and limitations : EBM is an excellent method for micro-finishing. It can drill holes or cut slots which otherwise cannot be made. It is possible to cut any known material, metal or nonmetal that can exist in vacuum. Besides, there is no cutting tool pressure or wear. As a result, distortion-free machining having precise dimensions can be achieved.

The biggest disadvantage is the high equipment cost and employment of high skill operator. Besides, only small cuts are possible. Further, requirement of vacuum restricts the size of specimens that can be machined.

Analysis of EBM : The *velocity* of electron impingement,

$$V_s = 600\sqrt{E_s} \text{ km/s} \qquad 20.11$$

where E_s = voltage of the electric field, volt.

The *power* of electron beam,

$$P_b = E_s I_b \text{ W} \qquad 20.12$$

where I_b = beam current, amp.

The electron beam *pressure*

$$F_b = 0.34 \times I_b \sqrt{E_s} \text{ dyne/cm}^2 \qquad 20.13$$

The thermal velocity acquired by an electron,

$$V_a = \sqrt{\frac{2k\theta}{M_a}} \text{ m/s} \qquad 20.14$$

where k = Boltzman's constant = 1.38×10^{-23} J/K/atom

θ = temperature raised through electron bombardment, K

M_a = mass of one atom of the workpiece, kg

Example 20.4 : In an electric beam machine, calculate : (a) the velocity of the electron impingement, (b) power of the electron beam, (c) electron beam pressure, and (d) thermal velocity acquired.

Given : Voltage of the electric field = 2.0×10^5 V

Beam current = 2.5×10^{-5} A

Current density = 2×10^{-3} A/cm^2

Vaporization temptation = 3,600K

Mass of the electron = 9.1×10^{-28} g

(a) $V_s = 600\sqrt{2 \times 10^5}$ $= 2.7 \times 10^5$ km/s

(b) $P_b = 2 \times 10^5 \times 2.5 \times 10^{-5}$ $= 5$ W

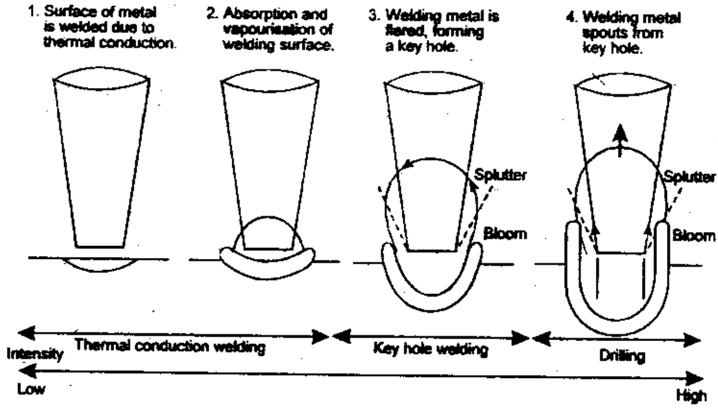
(c) $F_b = 0.34 \times 2 \times 10^{-3} \times \sqrt{2 \times 10^5}$ $= 0.30$ dynes/cm^2

(d) $V_a = \sqrt{\frac{2 \times 1.38 \times 10^{-23} \times 3600}{9.1 \times 10^{-28}}}$ $= 0.104 \times 10^5$ m/s

20.10 LASER BEAM MACHINING (LBM)

Laser is an electromagnetic radiation. It produces monochromatic light which is in the form of an almost collimated beam that can be focused optically on to very small sports of less than 0.002 mm dia. The word 'laser' stands for *L*ight *A*mplification by *S*timulated *E*mission of *R*adiation.

The principle of laser can be explained as follows : Let us consider that the atoms of a medium (for example, a ruby crystal rod) are at ground state. When a quantum of energy from a light source is made to fall on this medium, it causes absorption of radiation by the atoms of the medium. This results in electron of the atoms of the medium to jump to the upper energy level. The atoms in the upper energy level are then said to be in an excited state. The atom in an excited state immediately begins to drop spontaneously to the metastable (intermediate) state. From the metastable state the atom emits p*hoton* at random before it falls to the original energy level. This radiation of photons is known as spontaneous emission which is extremely rapid.



Laser beam absorption and welding mechanism on metal

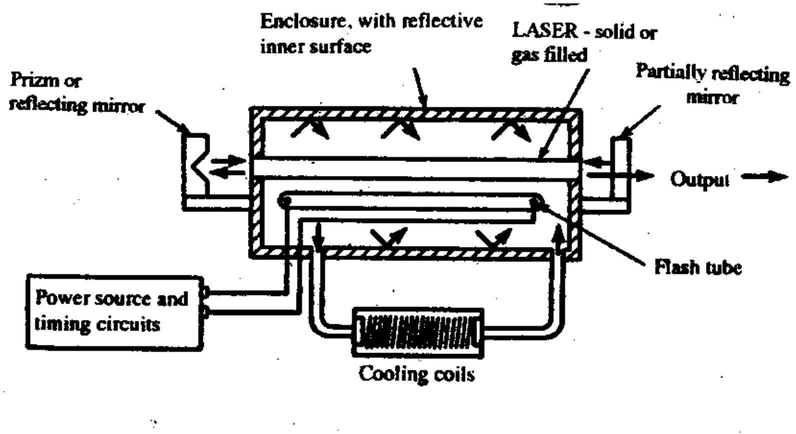


Figure 20.14 A basic LASER circuit

However, in the presence of light of the appropriate frequency stimulated emission will occur in the upper energy level when the atoms will begin to emit and chain reaction will occur by causing more to emit and the whole avalanche would dump down together. This is called *lasing action.*

A basic laser circuit, illustrated in Fig.20.14, consists of three parts : (1) a pair of mirrors, (2) a source of energy, and (3) an optical amplifier. This amplifier is popularly called the *laser.* To these basic parts must be added a control system and a cooling system.

The most important part of the laser apparatus is the laser crystal. The commonly used laser crystal is a man made ruby consisting of aluminium oxide into which 0.05 per cent chromium has been introduced. Another is calcium fluoride crystals doped with neodymium ($Ca+F_2+Nd$). The crystal rods are usually round and the end surfaces are made reflective by mirrors. The laser material needs a source of energy called a pump. This may be a flash lamp filled with xenon, argon, or krypton gas. The lamp is placed close to the amplifier of crystal rod inside a highly reflecting cylinder which directs the light from the flash lamp into the rod so that as much energy as possible can be absorbed by the laser material. The chromium atoms in the ruby are thus excited to high energy levels. The excited atom emits energy (photons) when they return to the normal state. In this way very high energy is obtained in short pulses. The ruby rod becomes less efficient at higher temperatures, it is thus continuously cooled with water, air or liquid nitrogen.

In operation, the workpiece to be cut is placed on the aluminium work table (which is resistant to being cut be laser beam). The laser head is traversed over the workpiece and an operator visually inspects the cut while manually adjusting the control panel. The actual profile is obtained from a linked mechanism, made to copy the master drawing or actual profile, placed on a near-by bench.

The laser in short pulses, has a power output of nearly 10 kW/cm^2 of the beam cross-section. By focusing a laser beam on a spot 1/100 of a square mm in size, the beam can be concentrated in a short flash to power density of 100,00 kW/cm^2 and an energy of several joules lasting for a minute fraction of a second. For machining, powerful short pulses of say 100 Joules energy are required. The laser can, therefore, provide enough heat of melt and vaporize any of the known materials.

The mechanism by which a laser beam removes material from the surface being worked involves a combination of melting and evaporation process. However, with some materials, mechanism is purely of evaporation.

Machining rate : Laser can be used for cutting as well as for drilling. The material removal rate in LBM is comparatively low and is of the order of the 4000 mm^3/hr. The cutting is found from the following relationship :

$$\text{Cutting rate (mm/min)}, \quad C = k\,\frac{P}{EAt_1} \qquad 20.15$$

where, P = laser power incident on surface, W
E = vaporization energy of material, W/mm^2
A = are of laser beam at focal point, mm^2
t_1 = thickness of material, mm
k = constant characteristic of the material and the conversion efficiency of laser energy to the material, mm/min.

The approximate energy, E needed to raise a volume of metal to its vaporization point is given by :

$$E = \rho_g v_g \frac{C_P(\theta_m - \theta_0) + C_v(\theta_B - \theta_m) + L_m + L_v}{\eta_P}\, J \qquad 20.16$$

where, ρ_g = density of material, kg/m^3
v_g = volume to be evaporate, m^3
C_P = specific heat cal/kg K,
θ_m = melting point, K
θ_B = boiling point, K
θ_0 = ambient temperature, K
L_m = latent heat of fusion, cal/kg
L_v = latent heat of vaporization cal/kg
η_P = efficiency of the process

Example 20.5 : Calculate the energy and power density required for laser drilling an 1.3 mm dia. hole in a 1 mm thick iron plate. Given :

Density of iron = 8 g/cm^3
Specific heat of iron = 0.11cal/gK
Melting point of iron = 1808 K
Boiling point of iron = 3000K
Ambient temperature = 20°C
Latent heat of fusion = 67 cal/g
Latent heat of vaporization = 1630 cal/g
Efficiency of lasing process = 70%