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New Scheme Based On AICTE Flexible Curricula

Mechanical Engineering, IV-Semester

ME405- MANUFACTURING TECHNOLOGY

[1] Analysis of Machining processes, introduction, tool geometry, tool materials, wear characteristics, cutting forces, , cutting fluids, failure of cutting tools, broaching operation, types of broaching machines, design of broaching tools, centre less grinding, thread chaser, thread grinding boring, super finishing processes like honing, lapping, electro polishing and buffing

[2] Gear machining, types of gears, elements of gears, different methods of gear production, gear cutting on milling machine, gear machining by generation method, principles of generation of surfaces – hobbing, shaping and basic rack cutting, gear finishing by shaving and gear grinding, tooth profile grinding, suitable gear treatments

[3 Plastics, composition of plastic materials, moulding method- injection moulding, compression moulding, transfer moulding, extrusion moulding, calendaring, blow moulding, laminating and reinforcing, welding of plastics.

[4] Unconventional machining processes, introduction, abrasive jet machining, ultrasonic machining, electrochemical machining, electro discharge machining, electron beam machining, laser beam machining, plasma arc machining, non destructive testing of machined surfaces and tools,

[5] Extrusion, principles, hot and cold extrusion processes, tube extrusion, sawing, power hacksaw, band saw, circular saw, Introduction to numerical control machining, NC Machine tools, NC tooling ,part programming, functions, coordinate systems

BOOKS:

[1] Ghosh A., Mallik A.K.,Manufacturing science,EWP Pvt Ltd, ISBN 81 85095 85 X
[2] R.K.Jain, Production Technology, Khanna Publishes, ISBN 81 7409 099 1
[3] Campbell J.S., Principles of Manufacturing Materials and Processes.
[4] CMTI Handbook
[5] Rao P.N., Manufacturing Technology, Tata McGraw Hill

UNIT - I

Analysis of machining processes

INTRODUCTION

In an industry, metal components are made into different shapes and dimensions by using various metal working processes.

Metal working processes are classified into two major groups. They are:

- Non-cutting shaping or chips less or metal forming process - forging, rolling, pressing, etc.
- Cutting shaping or metal cutting or chip forming process - turning, drilling, milling, etc.

MATERIAL REMOVAL PROCESSES

Definition of machining

Machining is an essential process of finishing by which work pieces are produced to the desired dimensions and surface finish by gradually removing the excess material from the preformed blank in the form of chips with the help of cutting tool(s) moved past the work surface(s).

Principle of machining

Fig. 1.1 typically illustrates the basic principle of machining. A metal rod of irregular shape, size and surface is converted into a finished product of desired dimension and surface finish by machining by proper relative motions of the tool-work pair.

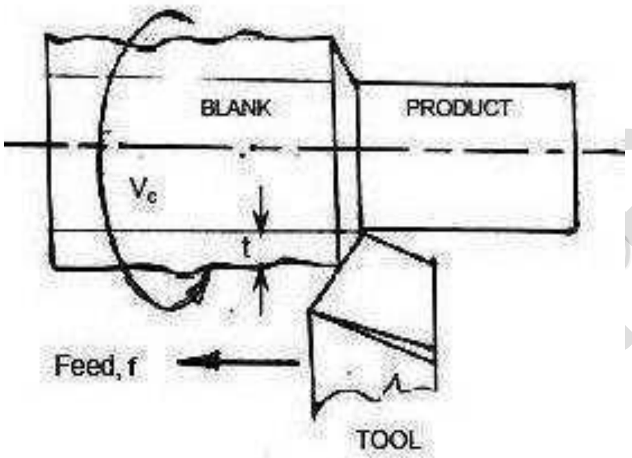


Fig. 1.1 Principle of machining (Turning)

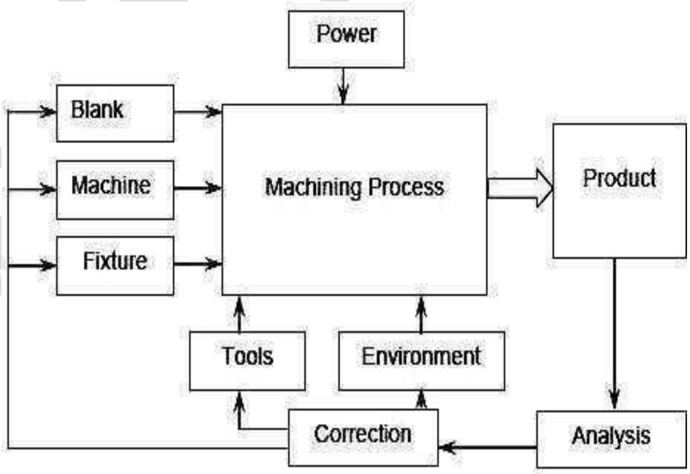


Fig. 1.2 Requirements for machining

Purpose of machining

Most of the engineering components such as gears, bearings, clutches, tools, screws and nuts etc. need dimensional and form accuracy and good surface finish for serving their purposes. Preforming like casting, forging etc. generally cannot provide the desired accuracy and finish. For that such preformed parts, called blanks, need semi-finishing and finishing and it is done by machining and grinding. Grinding is also basically a machining process.

Machining to high accuracy and finish essentially enables a product:

- Fulfill its functional requirements.
- Improve its performance.
- Prolong its service.

Requirements of machining

The essential basic requirements for machining a work are schematically illustrated in Fig. 1.2.

The blank and the cutting tool are properly mounted (in fixtures) and moved in a powerful device called machine tool enabling gradual removal of layer of material from the work surface resulting in its desired dimensions and surface finish. Additionally some environment called cutting fluid is generally used to ease machining by cooling and lubrication.

THEORY OF METAL CUTTING

Types of cutting tools

Cutting tools may be classified according to the number of major cutting edges (points) involved as follows:

- Single point: e.g., turning tools, shaping, planning and slotting tools and boring tools.
- Double (two) point: e.g., drills.
- Multipoint (more than two): e.g., milling cutters, broaching tools, hobs, gear shaping cutters etc.

Geometry of single point cutting (turning) tools

Both material and geometry of the cutting tools play very important roles on their performances in achieving effectiveness, efficiency and overall economy of machining.

Concept of rake and clearance angles of cutting tools

The word tool geometry is basically referred to some specific angles or slope of the salient faces and edges of the tools at their cutting point. Rake angle and clearance angle are the most significant for all the cutting tools. The concept of rake angle and clearance angle will be clear from some simple operations *shown in Fig. 1.3.*

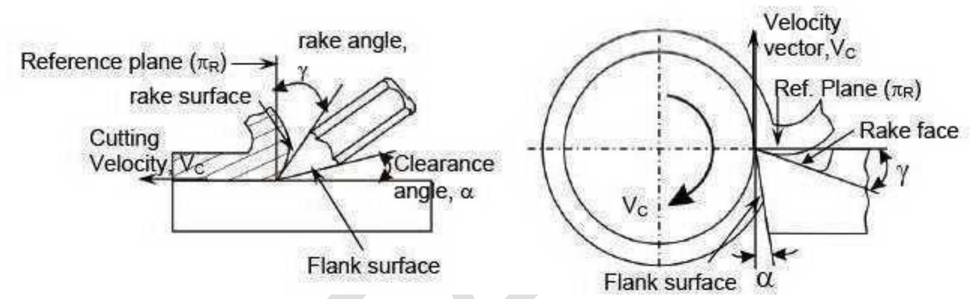
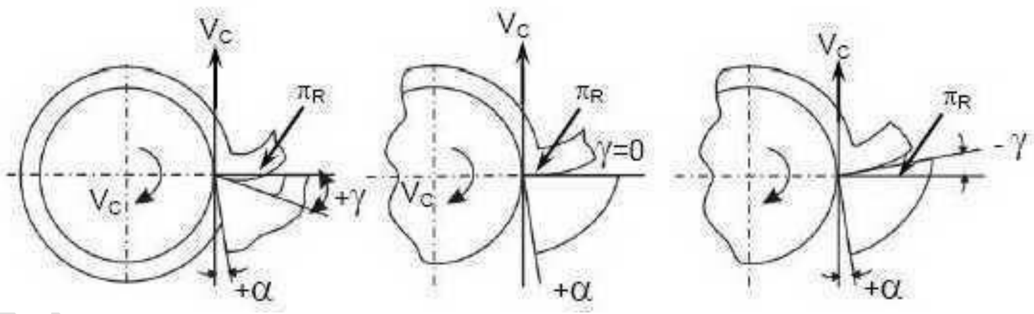


Fig. 1.3 Rake and clearance angles of cutting tools

Definition

- *Rake angle (γ):* Angle of inclination of rake surface from reference plane.
- *Clearance angle (α):* Angle of inclination of clearance or flank surface from the finished surface.

Rake angle is provided for ease of chip flow and overall machining. Rake angle may be positive, or negative or even zero *as shown in Fig. 1.4 (a, b and c).*



(a) Positive rake (b) Zero rake (c) Negative rake

Fig. 1.4 Three possible types of rake angles

Relative advantages of such rake angles are:

- Positive rake - helps reduce cutting force and thus cutting power requirement.
- Zero rake - to simplify design and manufacture of the form tools.
- Negative rake - to increase edge-strength and life of the tool.

Clearance angle is essentially provided to avoid rubbing of the tool (flank) with the machined surface which causes loss of energy and damages of both the tool and the job surface. Hence, clearance angle is a must and must be positive (3^0 ~ 15^0) depending upon tool-work materials and type of the machining operations like turning, drilling, boring etc.

Systems of description of tool geometry

- Tool-in-Hand System - where only the salient features of the cutting tool point are identified or visualized *as shown in Fig. 1.5 (a).* There is no quantitative information, i.e., value of the angles.
- Machine Reference System - ASA system.
- Tool Reference System - Orthogonal Rake System - ORS.
  - Normal Rake System - NRS.
- Work Reference System - WRS.

Description of tool geometry in Machine Reference System

This system is also called as ASA system; ASA stands for American Standards Association. Geometry of a cutting tool refers mainly to its several angles or slopes of its salient working surfaces and cutting edges. Those angles are expressed with respect to some planes of reference.

In Machine Reference System (ASA), the three planes of reference and the coordinates are chosen based on the configuration and axes of the machine tool concerned. The planes and axes used for expressing tool geometry in ASA system for turning operation *are shown in Fig. 1.5 (b).*

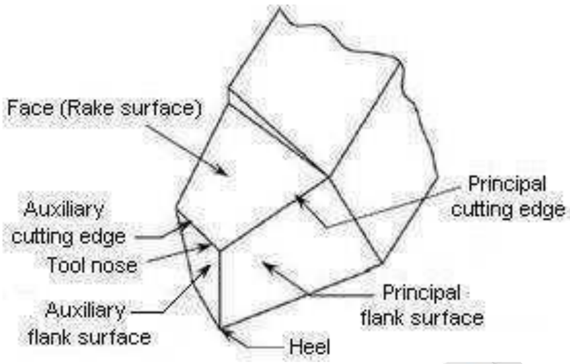


Fig 1.5 (a) Basic features of single point cutting (turning) tool

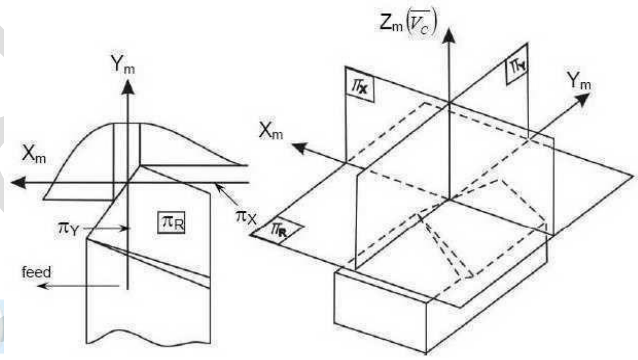


Fig. 1.5 (b) Planes and axes of reference in ASA system

The planes of reference and the coordinates used in ASA system for tool geometry are:

Π_R - Π_X - Π_Y and X_m - Y_m - Z_m; where,

Π_R = Reference plane; plane perpendicular to the velocity vector. Shown in Fig. 1.5 (b).

Π_X = Machine longitudinal plane; plane perpendicular to Π_R and taken in the direction of assumed longitudinal feed.

Π_Y = Machine transverse plane; plane perpendicular to both Π_R and Π_X. [This plane is taken in the direction of assumed cross feed]

The axes X_m, Y_m and Z_m are in the direction of longitudinal feed, cross feed and cutting velocity (vector) respectively. The main geometrical features and angles of single point tools in ASA systems and their definitions will be clear *from Fig. 1.6.*

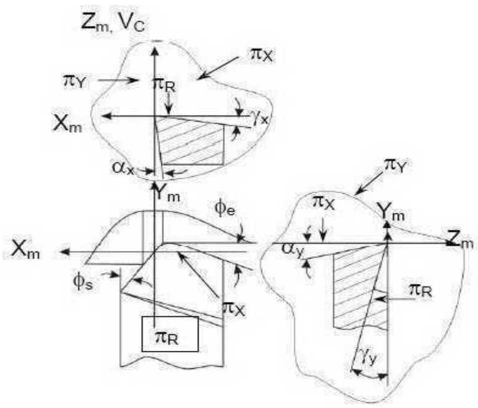


Fig. 1.6 Tool angles in ASA system

Definition of:

Shank: The portion of the tool bit which is not ground to form cutting edges and is rectangular in cross section. [Fig. 1.5 (a)]

Face: The surface against which the chip slides upward. [Fig. 1.5 (a)]

Flank: The surface which face the work piece. There are two flank surfaces in a single point cutting tool. One is principal flank and the other is auxiliary flank. [Fig. 1.5 (a)]

Heel: The lowest portion of the side cutting edges. [Fig. 1.5 (a)]

Nose radius: The conjunction of the side cutting edge and end cutting edge. It provides strengthening of the tool nose and better surface finish. [Fig. 1.5 (a)]

Base: The underside of the shank. [Fig. 1.5 (a)]

Rake angles: [Fig. 1.6]

γ_x = Side rake angle (axial rake): angle of inclination of the rake surface from the reference plane (Π_R) and measured on machine reference plane, Π_X.

γ_y = Back rake angle: angle of inclination of the rake surface from the reference plane and measured on machine transverse plane, Π_Y.

Clearance angles: [Fig. 1.6]

α_x = Side clearance angle (Side relief angle): angle of inclination of the principal flank from the machined surface (or CV) and measured on Π_X plane.

α_y = Back clearance angle (End relief angle): same as α_x but measured on Π_Y plane.

Cutting angles: [Fig. 1.6]

ϕ_s = Side cutting edge angle (Approach angle): angle between the principal cutting edge (its projection on Π_R) and Π_Y and measured on Π_R.

ϕ_e = End cutting edge angle: angle between the end cutting edge (its projection on Π_R) from Π_X and measured on Π_R.

Designation of tool geometry

The geometry of a single point tool is designated or specified by a series of values of the salient angles and nose radius arranged in a definite sequence as follows:

Designation (Signature) of tool geometry in ASA System - $\boldsymbol{\gamma_y, \gamma_x, \alpha_y, \alpha_x, \phi_e, \phi_s}$, **r** (in inch)

Example: A tool having 7, 8, 6, 7, 5, 6, 0.1 as designation (Signature) in ASA system will have the following angles and nose radius.

Back rack angle	=	7^0
Side rake angle	=	8^0
Back clearance angle	=	6^0
Side clearance angle	=	7^0
End cutting edge angle	=	5^0
Side cutting edge angle	=	6^0
Nose radius	=	0.1 inch

Types of metal cutting processes

The metal cutting process is mainly classified into two types. They are:

- ***Orthogonal cutting process*** (Two - dimensional cutting) - The cutting edge or face of the tool is 90^0 to the line of action or path of the tool or to the cutting velocity vector. This cutting involves only two forces and this makes the analysis simpler.
- ***Oblique cutting process*** (Three - dimensional cutting) - The cutting edge or face of the tool

is inclined at an angle less than 90^0 to the line of action or path of the tool or to the cutting

5

velocity vector. Its analysis is more difficult of its three dimensions.

Orthogonal and oblique cutting

It is appears from the diagram *shown in Fig. 1.7 (a and b)* that while turning ductile material by a sharp tool, the continuous chip would flow over the tool's rake surface and in the direction apparently perpendicular to the principal cutting edge, i.e., along orthogonal plane which is normal to the cutting plane containing the principal cutting edge. But practically, the chip may not flow along the orthogonal plane for several factors like presence of inclination angle, λ, etc.

The role of inclination angle, λ on the direction of chip flow is schematically shown in Fig. 1.8 which visualizes that:

- When $\lambda = 0^0$, the chip flows along orthogonal plane, i.e, $p_c = 0^0$.
- When $\lambda \neq 0^0$, the chip flow is deviated from u_o and $p_c = \lambda$ where p_c is chip flow deviation (from u_o) angle.

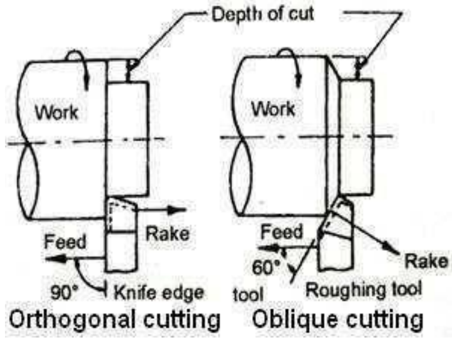


Fig. 1.7 (a) Setup of orthogonal and oblique cutting

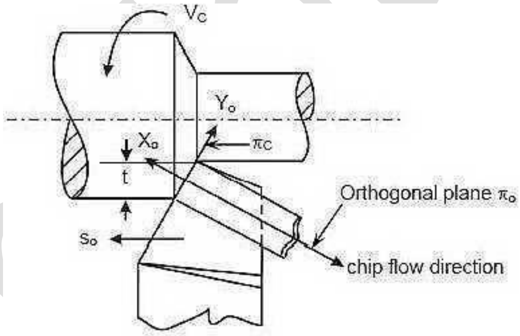


Fig. 1.7 (b) Ideal direction of chip flow in turning

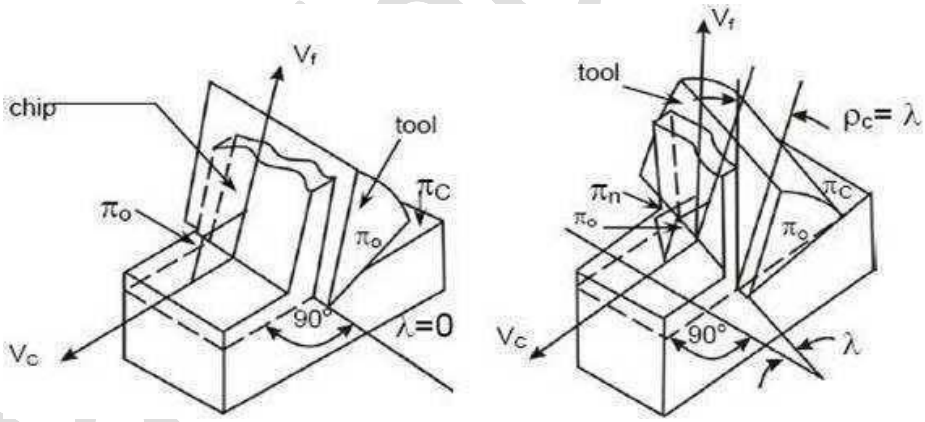


Fig. 1.8 Role of inclination angle, λ on chip flow direction

Orthogonal cutting: When chip flows along orthogonal plane, u_o, i.e., $p_c = 0^0$.

Oblique cutting: When chip flow deviates from orthogonal plane, i.e. $p_c \neq 0^0$.

But practically p_c may be zero even if $\lambda = 0^0$ and p_c may not be exactly equal to λ even if $\lambda \neq 0^0$. Because there is some other (than λ) factors also may cause chip flow deviation.

Pure orthogonal cutting

This refers to chip flow along u_o and $\phi = 90^0$ *as typically shown in Fig. 1.9.* Where a pipe like job of uniform thickness is turned (reduced in length) in a center lathe by a turning tool of geometry; $\lambda = 0^0$ and $\phi = 90^0$ resulting chip flow along u_o which is also u_x in this case.

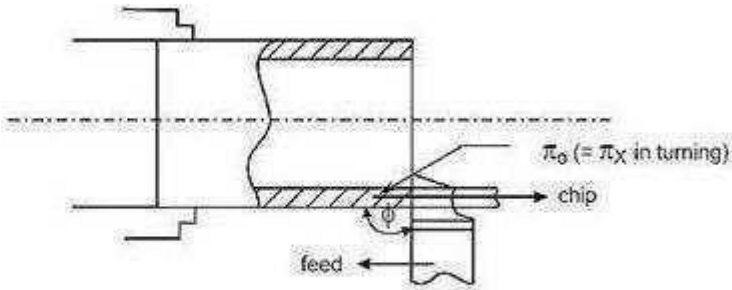


Fig. 1.9 Pure orthogonal cutting (pipe turning)

7

Types of chips

Different types of chips of various shape, size, colour etc. are produced by machining depending upon:

- Type of cut, i.e., continuous (turning, boring etc.) or intermittent cut (milling).
- Work material (brittle or ductile etc.).
- Cutting tool geometry (rake, cutting angles etc.).
- Levels of the cutting velocity and feed (low, medium or high).
- Cutting fluid (type of fluid and method of application).

The basic major types of chips and the conditions generally under which such types of chips form are given below:

Continuous chips without BUE

When the cutting tool moves towards the work piece, there occurs a plastic deformation of the work piece and the metal is separated without any discontinuity and it moves like a ribbon. The chip moves along the face of the tool. This mostly occurs while cutting a ductile material. It is desirable to have smaller chip thickness and higher cutting speed in order to get continuous chips. Lesser power is consumed while continuous chips are produced. Total life is also mortised in this process. *The formation of continuous chips is schematically shown in Fig. 1.10.*

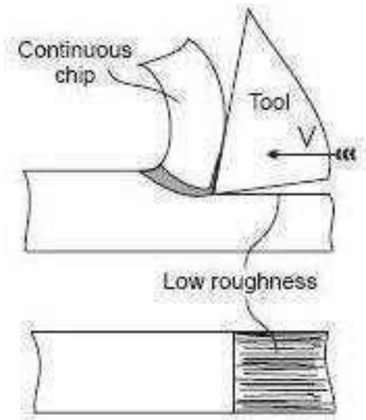


Fig. 1.10 Formation of continuous chips

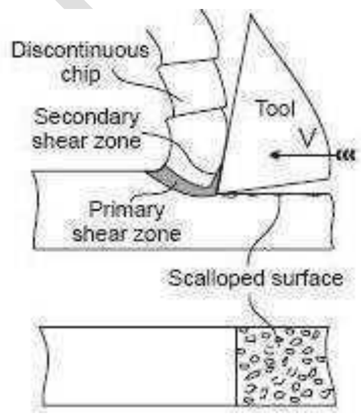


Fig. 1.11 Formation of discontinuous chips

The following condition favors the formation of continuous chips

- Work material - ductile.
- Cutting velocity - high.
- Feed - low.
- Rake angle - positive and large.
- Cutting fluid - both cooling and lubricating.

Discontinuous chips

This is also called as segmental chips. This mostly occurs while cutting brittle material such as cast iron or low ductile materials. Instead of shearing the metal as it happens in the previous process, the metal is being fractured like segments of fragments and they pass over the tool faces. Tool life can also be more in this process. Power consumption as in the previous case is also low. *The formation of continuous chips is schematically shown in Fig. 1.11.*

The following condition favors the formation of discontinuous chips:

- Of irregular size and shape: - work material - brittle like grey cast iron.
- Of regular size and shape: - work material ductile but hard and work hardenable.
- Feed rate - large.
- Tool rake - negative.
- Cutting fluid - absent or inadequate.

ORTHOGONAL METAL CUTTING

Benefit of knowing and purpose of determining cutting forces

The aspects of the cutting forces concerned:

- Magnitude of the cutting forces and their components.
- Directions and locations of action of those forces.
- Pattern of the forces: static and / or dynamic.

Knowing or determination of the cutting forces facilitate or are required for:

- Estimation of cutting power consumption, which also enables selection of the power source(s) during design of the machine tools.
- Structural design of the machine - fixture - tool system.
- Evaluation of role of the various machining parameters (process - V_C, f_o, t, tool - material and geometry, environment - cutting fluid) on cutting forces.
- Study of behavior and machinabilty characterization of the work materials.
- Condition monitoring of the cutting tools and machine tools.

Cutting force components and their significances

The single point cutting tools being used for turning, shaping, planing, slotting, boring etc. are characterized by having only one cutting force during machining. But that force is resolved into two or three components for ease of analysis and exploitation. Fig. 1.12 visualizes how the single cutting force in turning is resolved into three components along the three orthogonal directions; X, Y and Z.

The resolution of the force components in turning can be more conveniently understood from their display in 2-D as shown in Fig. 1.13.

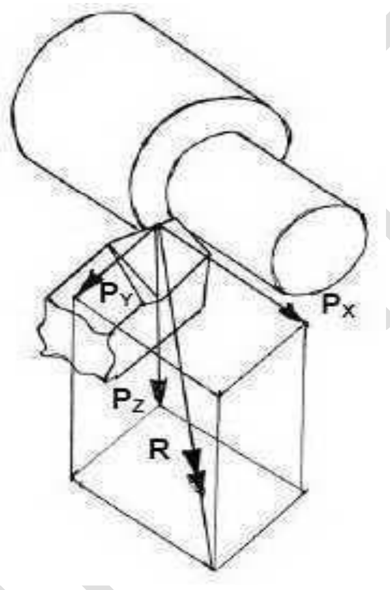


Fig. 1.12 Cutting force R resolved into P_X, P_Y and P_Z

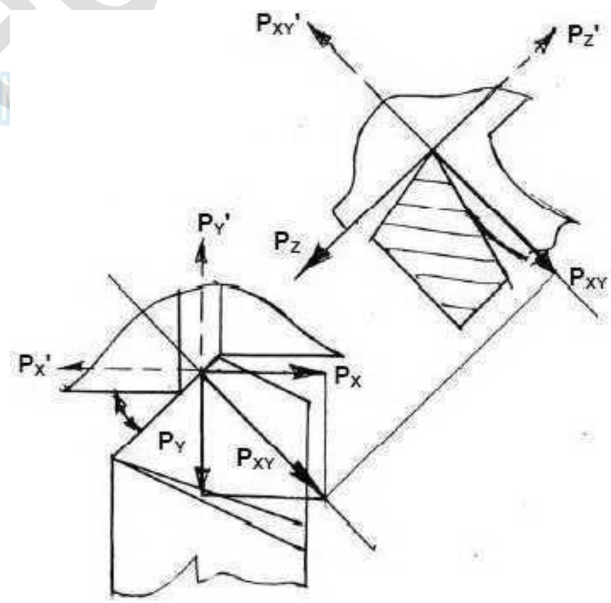


Fig. 1.13 turning force resolved into P_Z, P_X and P_Y

The resultant cutting force, R is resolved as,

$$\mathbf{R = P_Z + P_{XY}} \qquad 1.13$$

and $$\mathbf{P_{XY} = P_X + P_Y} \qquad 1.14$$

where, $$\mathbf{P_X = P_{XY} \sin\phi} \qquad 1.15$$

and $$\mathbf{P_Y = P_{XY} \cos\phi} \qquad 1.16$$

P_Z - Tangential component taken in the direction of Z_m axis.

P_X - Axial component taken in the direction of longitudinal feed or X_m axis.

P_Y - Radial or transverse component taken along Y_m axis.

In Fig. 1.12 and Fig. 1.13 the force components are shown to be acting on the tool. A similar set of forces also act on the job at the cutting point but in opposite directions *as indicated by P_Z', P_{XY}', P_X' and P_Y' in Fig.*

1.13.

Significance of P_Z, P_X and P_Y

- P_Z: Called the main or major component as it is the largest in magnitude. It is also called power component as it being acting along and being multiplied by V_C decides cutting power ($P_Z.V_C$) consumption.
- P_Y: May not be that large in magnitude but is responsible for causing dimensional inaccuracy and vibration.
- P_X: It, even if larger than PY, is least harmful and hence least significant.

Merchant's Circle Diagram and its use

In orthogonal cutting when the chip flows along the orthogonal plane, u_0, the cutting force (resultant) and its components P_Z and P_{XY} remain in the orthogonal plane. *Fig. 1.14 is schematically showing the forces acting on a piece of continuous chip coming out from the shear zone at a constant speed.* That chip is apparently in a state of equilibrium.

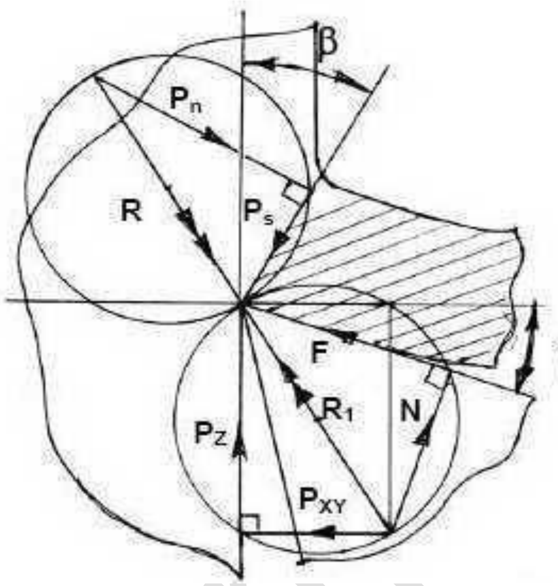


Fig 1.14 Development of Merchant's circle diagram

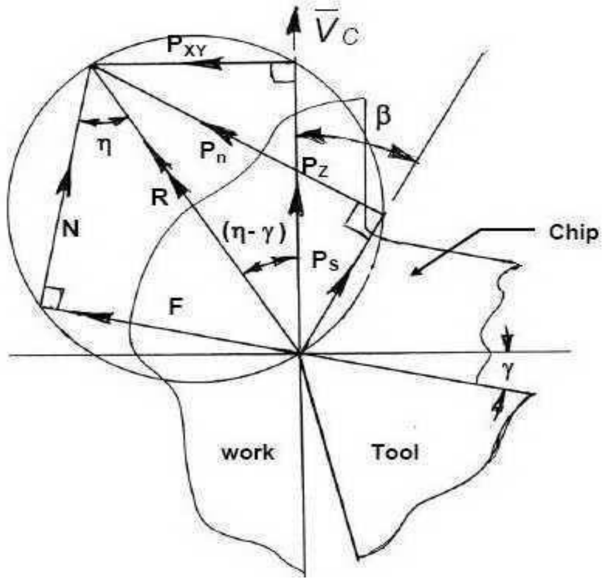


Fig. 1.15 Merchant's Circle Diagram with cutting forces

The forces in the chip segment are:

- From job-side:
  - P_s - Shear force.
  - P_n - force normal to the shear force.
- From the tool side:
  - R_1 = R (in state of equilibrium) where, $R_1 = F + N$

    N - Force normal to rake face.

    F - Friction force at chip tool interface.

The resulting cutting force R or R_1 can be resolved further as,

$R_1 = P_Z + P_{XY}$ where, P_Z - Force along the velocity vector.

P_{XY} - force along orthogonal plane.

The circle(s) drawn taking R or R_1 as diameter is called Merchant's circle which contains all the force components concerned as intercepts. The two circles with their forces are combined into one circle having all the forces contained in that *as shown by the diagram called Merchant's Circle Diagram (MCD) in Fig. 1.15.*

The significance of the forces displayed in the Merchant's Circle Diagram is:

P_s - The shear force essentially required to produce or separate the chip from the parent body by shear. P_n - Inherently exists along with P_s.

F - Friction force at the chip tool interface.

N - Force acting normal to the rake surface.

$P_Z = P_{XY} – P_X + P_Y$ = main force or power component acting in the direction of cutting velocity.

The magnitude of P_S provides the yield shear strength of the work material under the cutting action. The values of F and the ratio of F and N indicate the nature and degree of interaction like friction at the chip tool interface. The force components P_X, P_Y, P_Z are generally obtained by direct measurement. Again P_Z helps in determining cutting power and specific energy requirement. The force components are also required to design the cutting tool and the machine tool.

Advantageous use of Merchant's circle diagram

Proper use of MCD enables the followings:

- Easy, quick and reasonably accurate determination of several other forces from a few known forces involved in machining.
- Friction at chip tool interface and dynamic yield shear strength can be easily determined.
- Equations relating the different forces are easily developed.

Some limitations of use of MCD:

- Merchant's circle diagram (MCD) is only valid for orthogonal cutting.
- By the ratio, F/N, the MCD gives apparent (not actual) coefficient of friction.
- It is based on single shear plane theory.

Development of equations for estimation of cutting forces

The two basic methods of determination of cutting forces and their characteristics are:

(a) Analytical method: Enables estimation of cutting forces.

Characteristics:

- Easy, quick and inexpensive.
- Very approximate and average.
- Effect of several factors like cutting velocity, cutting fluid action etc. are not revealed.
- Unable to depict the dynamic characteristics of the forces.

(b) Experimental methods: Direct measurement.

Characteristics:

- Quite accurate and provides true picture.
- Can reveal effect of variation of any parameter on the forces.
- Depicts both static and dynamic parts of the forces.
- Needs measuring facilities, expertise and hence expensive.

The equations for analytical estimation of the salient cutting force components are conveniently developed using Merchant's Circle Diagram (MCD) when it is orthogonal cutting by any single point cutting tool like, in turning, shaping, planing, boring etc.

Development of mathematical expressions for cutting forces

Tangential or main component, P_Z

This can be very conveniently done by using Merchant's Circle Diagram, as shown in Fig. 1.15.

From the MCD shown in Fig. 1.15,

$P_Z = R\cos(\eta – \gamma)$ 1.17

$P_s = R\cos(\beta + \eta – \gamma)$ 1.18

Dividing Eqn. 1.17 by Eqn. 1.18,

$P_Z = P_s \cos(\eta – \gamma) / \cos(\beta + \eta – \gamma)$ 1.19

It was already shown that, $P_s = t.f.\tau_s / \sin\beta$ 1.20

where, τ_s - Dynamic yield shear strength of the work material.

Thus, $P_Z = t.f.\ \tau_s \cos(\eta - \gamma) / \sin\beta \cos(\beta + \eta - \gamma)$ 1.21

For brittle work materials, like grey cast iron, usually, $2\beta + \eta - \gamma = 90^0$ and τ_s remains almost unchanged. Then for turning brittle material,

$P_Z = t.f.\ \tau_s \cos(90^0 - 2\beta) / \sin\beta \cos(90^0 - \beta)$ 1.22

or $P_Z = 2\ t.f.\ \tau_s \cot\beta$ 1.23

Where, $\cot\beta = r_c -$

$\tan\gamma$ $r_c = a_2 / a_1 = a_2 / f$

$\sin\phi$

It is difficult to measure chip thickness and evaluate the values of ζ while machining brittle materials and the value of τ_s is roughly estimated from

$\tau_s = 0.175$ BHN 1.24

where, BHN - Brinnel's Hardness number.

But most of the engineering materials are ductile in nature and even some semi-brittle materials behave ductile under the cutting condition. The angle relationship reasonably accurately applicable for ductile metals is

$\beta + \eta - \gamma = 45^0$ 1.25

and the value of τ_s is obtained from,

$\tau_s = 0.186$ BHN (approximate) 1.26

or $\tau_s = 0.74\sigma_u \varepsilon^{0.6\Delta}$ (more suitable and accurate) 1.27

where, σ_u - Ultimate tensile strength of the work material

ε - Cutting strain, $\varepsilon \cong r_c - \tan\gamma$

Δ - % elongation

Substituting Eqn. 1.25 in Eqn. 1.21,

$P_Z = t.f.\ \tau_s(\cot\beta + 1)$ 1.28

Again $\cot\beta \cong r_c - \tan\gamma$

So, $\mathbf{P_Z = t.f.\tau_s(r_c - \tan\gamma + 1)}$ 1.29

Axial force, P_X and transverse force, P_Y

From the MCD shown in Fig. 1.40,

$P_{XY} = P_Z \tan(\eta - \gamma)$ 1.30

Combining Eqn. 1.21 and Eqn. 1.30,

$P_{XY} = t.f.\tau_s \sin(\eta - \gamma) / \sin\beta \cos(\beta + \eta - \gamma)$ 1.31

Again, using the angle relationship $\beta + \eta - \gamma = 45^0$, for ductile material

$P_{XY} = t.f.\tau_s(\cot\beta - 1)$ 1.32

or $\mathbf{P_{XY} = t.f.\tau_s(r_c - \tan\gamma - 1)}$ 1.33

where, $\tau_s = 0.74\sigma_u\varepsilon^{0.6\Delta}$ or $\tau_s = 0.186$ BHN

It is already known,

$P_X = P_{XY}\sin\phi$ and $P_Y = P_{XY}\cos\phi$

Therefore, $\mathbf{P_X = t.f.\tau_s(r_c - \tan\gamma - 1)\sin\phi}$ 1.34

and $\mathbf{P_Y = t.f.\tau_s(r_c - \tan\gamma - 1)\cos\phi}$ 1.35

Friction force, F, normal force, N and apparent coefficient of friction μ_a

From the MCD shown in Fig. 1.40,

$F = P_Z \sin\gamma + P_{XY} \cos\gamma$ 1.36

and $N = P_Z \cos\gamma - P_{XY} \sin\gamma$ 1.37

$\mu_a = F / N = P_Z \sin\gamma + P_{XY} \cos\gamma / P_Z \cos\gamma - P_{XY} \sin\gamma$ 1.38

or $\mathbf{\mu_a = P_Z \tan\gamma + P_{XY} / P_Z - P_{XY} \tan\gamma}$ 1.39

Therefore, if P_Z and P_{XY} are known or determined either analytically or experimentally the values of F, N and μ_a can be determined using equations only.

Shear force P_s and P_n

From the MCD shown in Fig. 1.40,

$$\mathbf{P_s = P_Z \cos\beta - P_{XY} \sin\beta} \quad 1.40$$

and $$\mathbf{P_n = P_Z \sin\beta + P_{XY} \cos\beta} \quad 1.41$$

From P_s, the dynamic yield shear strength of the work material, τ_s can be determined by using the relation,

$$\mathbf{P_s = A_s\tau_s}$$

where, $A_s = t.f / \sin\beta$ = Shear area

Therefore, $\tau_s = P_s \sin\beta / t.f$

$$\mathbf{\tau_s = (P_Z \cos\beta - P_{XY} \sin\beta)\sin\beta / t.f} \quad 1.42$$

Metal cutting theories

Earnst - Merchant theory

Earnst and Merchant have developed a relationship between the shear angle β, the cutting rake angle γ, and the angle of friction η as follows:

$$\mathbf{2\beta + \eta - \gamma = C}$$

where C is a *machining constant* for the work material dependent on the rate of change of the shear strength of the metal with applied compressive stress, besides taking the internal coefficient of friction into account.

Modified - Merchant theory

According to this theory the relation between the shear angle β, the cutting rake angle γ, and the angle of friction η as follows:

$$\beta = \frac{g}{4} - \frac{\gamma}{2} + \frac{\gamma}{2}$$

- Shear will take place in a direction in which energy required for shearing is minimum.
- Shear stress is maximum at the shear plane and it remains constant.

Lee and Shaffer's theory

This theory analysis the process of orthogonal metal cutting by applying the theory of plasticity for an ideal rigid plastic material. The principle assumptions are:

- The work piece material ahead of the cutting tool behaves like an ideal plastic material.
- The deformation of the metal occurs on a single shear plane.
- This is a stress field within the produced chip which transmits the cutting force from the shear plane to the tool face and therefore, the chip does not get hardened.
- The chip separates from the parent material at the shear plane.

Based on this, they developed a slip line field for stress zone, in which no deformation would occur even if it is stressed to its yield point. From this, they derived the following relationship.

$$\beta = \frac{g}{4} - \eta + \gamma$$

Velocity relationship

The velocity relationships for orthogonal cutting are illustrated, where V_C is the cutting velocity, V_s is the velocity of shear and V_f is the velocity of chip flow up the tool face.

$$V_s = V_C \cos\gamma / \cos(\beta - \gamma) \quad 1.43$$

and $$V_f = \sin\beta / \cos(\beta - \gamma) \quad 1.44$$

14

From equation $V_f = V_C / r_c$

It can be inferred from the principle of kinematics that the relative velocity of two bodies (here tool and the chip) is equal to the vector difference between their velocities relative to the reference body (the work piece). So, $\mathbf{V_C = V_s + V_f}$ 1.45

Metal removal rate

It is defined as the volume of metal removed in unit time. It is used to calculate the time required to remove specified quantity of material from the work piece.

Metal removal rate (**MRR**) $= t.\ f.V_C$ 1.46

where, t - Depth of cut (mm), f - Feed (mm / rev) and V_C - Cutting speed (mm / sec).

If the MRR is optimum, we can reduce the machining cost. To achieve this:

- The cutting tool material should be proper.
- Cutting tool should be properly ground.
- Tool should be supported rigidly and therefore, there should be any vibration.

For turning operation, **MRR** $= t.f.V_C$ 1.47

For facing and spot milling operation, **MRR = B.t.T** 1.48

where B - Width of cut (mm) and T- Table travel (mm /sec).

For planing and shaping, **MRR = t.f.L.S** 1.49

where L - length of workpiece (mm) and S - Strokes per minute.

Evaluation of cutting power consumption and specific energy requirement

Cutting power consumption is a quite important issue and it should always be tried to be reduced but without sacrificing MRR.

Cutting power consumption **(P_C)** can be determined from, $P_C = P_Z.V_C + P_X.V_f$ 1.50

where, V_f = feed velocity = **Nf / 1000** m/min [N = rpm]

Since both P_X and V_f, specially V_f are very small, $P_X.V_f$ can be neglected and then $P_C \cong P_Z.V_C$ 1.51

Specific energy requirement **(U_s)** which means amount of energy required to remove unit volume of material, is an important machinability characteristics of the work material. Specific energy requirement, U_s, which should be tried to be reduced as far as possible, depends not only on the work material but also the process of the machining, such as turning, drilling, grinding etc. and the machining condition, i.e., V_C, f, tool material and geometry and cutting fluid application.

Compared to turning, drilling requires higher specific energy for the same work-tool materials and grinding requires very large amount of specific energy for adverse cutting edge geometry (large negative rake). Specific energy, U_s, is determined from,

$U_s = P_Z.V_C / MRR = P_Z / t.f$ 1.52

CUTTING TOOL MATERIALS

Essential properties of cutting tool materials

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

- High mechanical strength; compressive, tensile, and TRA.
- Fracture toughness - high or at least adequate.
- High hardness for abrasion resistance.
- High hot hardness to resist plastic deformation and reduce wear rate at elevated temperature.
- Chemical stability or inertness against work material, atmospheric gases and cutting fluids.

- Resistance to adhesion and diffusion.

17

- Thermal conductivity - low at the surface to resist incoming of heat and high at the core to quickly dissipate the heat entered.
- High heat resistance and stiffness.
- Manufacturability, availability and low cost.

Characteristics and applications of cutting tool materials

a) High Speed Steel (HSS)

Advent of HSS in around 1905 made a break through at that time in the history of cutting tool materials though got later superseded by many other novel tool materials like cemented carbides and ceramics which could machine much faster than the HSS tools.

The basic composition of HSS is 18% W, 4% Cr, 1% V, 0.7% C and rest Fe. Such HSS tool could machine (turn) mild steel jobs at speed only up to 20 ~ 30 m/min (which was quite substantial those days)

However, HSS is still used as cutting tool material where:

- The tool geometry and mechanics of chip formation are complex, such as helical twist drills, reamers, gear shaping cutters, hobs, form tools, broaches etc.
- Brittle tools like carbides, ceramics etc. are not suitable under shock loading.
- The small scale industries cannot afford costlier tools.
- The old or low powered small machine tools cannot accept high speed and feed.
- The tool is to be used number of times by resharpening.

With time the effectiveness and efficiency of HSS (tools) and their application range were gradually enhanced by improving its properties and surface condition through:

- Refinement of microstructure.
- Addition of large amount of cobalt and Vanadium to increase hot hardness and wear resistance respectively.
- Manufacture by powder metallurgical process.
- Surface coating with heat and wear resistive materials like TiC, TiN, etc. by Chemical Vapour Deposition (CVD) or Physical Vapour Deposition (PVD).

The commonly used grades of HSS are given in Table 1.1.

Table 1.1 Compositions and types of popular high speed steels

Type	C	W	Mo	Cr	V	Co	RC
T - 1	0.70	18		4	1		
T - 4	0.75	18		4	1	5	
T - 6	0.80	20		4	2	12	
M - 2	0.80	6	5	4	2		64.7
M - 4	1.30	6	5	4	4		
M - 15	1.55	6	3	5	5	5	
M - 42	1.08	1.5	9.5	4	1.1	8	62.4

Addition of large amount of Co and V, refinement of microstructure and coating increased strength and wear resistance and thus enhanced productivity and life of the HSS tools remarkably.

b) Stellite

This is a cast alloy of Co (40 to 50%), Cr (27 to 32%), W (14 to 19%) and C (2%). Stellite is quite tough and more heat and wear resistive than the basic HSS (18 - 4 - 1) But such stellite as cutting tool material became obsolete for its poor grindability and especially after the arrival of cemented carbides.

c) Sintered Tungsten carbides

The advent of sintered carbides made another breakthrough in the history of cutting tool materials.

i) Straight or single carbide

First the straight or single carbide tools or inserts were powder metallurgically produced by mixing, compacting and sintering 90 to 95% WC powder with cobalt. The hot, hard and wear resistant WC grains are held by the binder Co which provides the necessary strength and toughness. Such tools are suitable for machining grey cast iron, brass, bronze etc. which produce short discontinuous chips and at cutting velocities two to three times of that possible for HSS tools.

ii) Composite carbides

The single carbide is not suitable for machining steels because of rapid growth of wear, particularly crater wear, by diffusion of Co and carbon from the tool to the chip under the high stress and temperature bulk (plastic) contact between the continuous chip and the tool surfaces.

For machining steels successfully, another type called composite carbide have been developed by adding (8 to 20%) a gamma phase to WC and Co mix. The gamma phase is a mix of TiC, TiN, TaC, NiC etc. which are more diffusion resistant than WC due to their more stability and less wettability by steel.

iii) Mixed carbides

Titanium carbide (TiC) is not only more stable but also much harder than WC. So for machining ferritic steels causing intensive diffusion and adhesion wear a large quantity (5 to 25%) of TiC is added with WC and Co to produce another grade called mixed carbide. But increase in TiC content reduces the toughness of the tools. Therefore, for finishing with light cut but high speed, the harder grades containing up to 25% TiC are used and for heavy roughing work at lower speeds lesser amount (5 to 10%) of TiC is suitable.

Gradation of cemented carbides and their applications

The standards developed by ISO for grouping of carbide tools and their application ranges are given in Table 1.2.

Table 1.2 Broad classifications of carbide tools

ISO Code	Colour Code	Application
P	Sky blue	For machining long chip forming common materials like plain carbon and low alloy steels.
M	Yellow	For machining long or short chip forming ferrous materials like Stainless steel.
K	Red	For machining short chipping, ferrous and non-ferrous material and non-metals like Cast Iron, Brass etc.

K-group is suitable for machining short chip producing ferrous and non-ferrous metals and also some non metals.

P-group is suitably used for machining long chipping ferrous metals i.e. plain carbon and low alloy steels.

M-group is generally recommended for machining more difficult-to-machine materials like strain hardening austenitic steel and manganese steel etc.

Each group again is divided into some subgroups like P10, P20 etc., as shown in Table 1.3 depending upon their properties and applications.

Table 1.3 Detail grouping of cemented carbide tools

ISO App. group	Material	Process
P01	Steel, Steel castings	Precision and finish machining, high speed
P10	Steel, steel castings	Turning, threading and milling high speed, small chips
P20	Steel, steel castings, malleable cast iron	Turning, milling, medium speed with small chip section
P30	Steel, steel castings, malleable cast iron forming long chips	Turning, milling, low cutting speed, large chip section
P40	Steel and steel casting with sand inclusions	Turning, planning, low cutting speed, large chip section
P50	Steel and steel castings of medium or low tensile strength	Operations requiring high toughness turning, planning, shaping at low cutting speeds
K01	Hard grey C.I., chilled casting, Al. alloys with high silicon	Turning, precision turning and boring, milling, scraping
K10	Grey C.I. hardness > 220 HB. Malleable C.I., Al. alloys containing Si	Turning, milling, boring, reaming, broaching, scraping
K20	Grey C.I. hardness up to 220 HB	Turning, milling, broaching, requiring high toughness
K30	Soft grey C.I. Low tensile strength steel	Turning, reaming under favourable conditions
K40	Soft non-ferrous metals	Turning milling etc.
M10	Steel, steel castings, manganese steel, grey C.I.	Turning at medium or high cutting speed, medium chip section
M20	Steel casting, austenitic steel, manganese steel, spherodized C.I., Malleable C.I.	Turning, milling, medium cutting speed and medium chip section
M30	Steel, austenitic steel, spherodized C.I. heat resisting alloys	Turning, milling, planning, medium cutting speed, medium or large chip section
M40	Free cutting steel, low tensile strength steel, brass and light alloy	Turning, profile turning, especially in automatic machines.

The smaller number refers to the operations which need more wear resistance and the larger numbers to those requiring higher toughness for the tool.

d) Plain ceramics

Inherently high compressive strength, chemical stability and hot hardness of the ceramics led to powder metallurgical production of indexable ceramic tool inserts since 1950. *Table 1.4 shows the advantages and limitations of alumina ceramics in contrast to sintered carbide.* Alumina (Al_2O_3) is preferred to silicon nitride (Si_3N_4) for higher hardness and chemical stability. Si_3N_4 is tougher but again more difficult to process. The plain ceramic tools are brittle in nature and hence had limited applications.

Table 1.4 Cutting tool properties of alumina ceramics

Advantages	**Shortcoming**
Very high hardness	Poor toughness
Very high hot hardness	Poor tensile strength
Chemical stability	Poor TRS
Antiwelding	Low thermal conductivity
Less diffusivity	Less density
High abrasion resistance	
High melting point	
Very low thermal conductivity*	
Very low thermal expansion coefficient	

**** Cutting tool should resist penetration of heat but should disperse the heat throughout the core.***

Basically three types of ceramic tool bits are available in the market:

- Plain alumina with traces of additives - these white or pink sintered inserts are cold pressed and are used mainly for machining cast iron and similar materials at speeds 200 to 250 m/min.
- Alumina; with or without additives - hot pressed, black colour, hard and strong - used for machining steels and cast iron at VC = 150 to 250 m/min.
- Carbide ceramic (Al_2O_3 + 30% TiC) cold or hot pressed, black colour, quite strong and enough tough - used for machining hard cast irons and plain and alloy steels at 150 to 200 m/min.

The plain ceramic outperformed the existing tool materials in some application areas like high speed machining of softer steels mainly for higher hot hardness as indicated in Fig. 1.16.

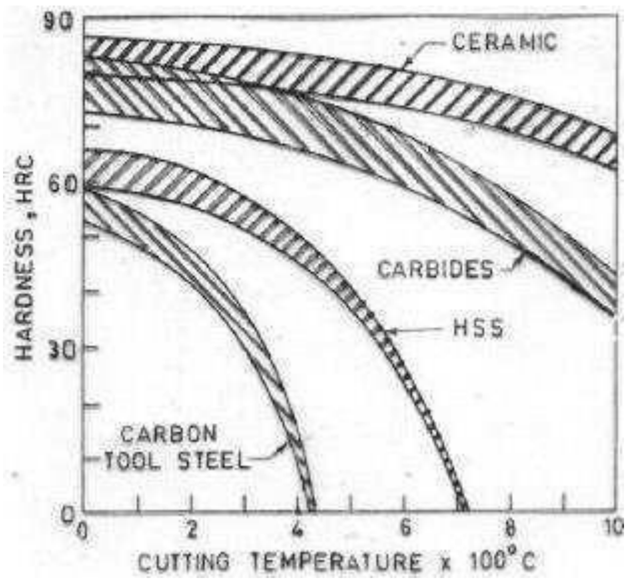


Fig. 1.16 Hot hardness of the different commonly used tool materials (Ref. Book by A. Bhattacharya)

However, the use of those brittle plain ceramic tools, until their strength and toughness could be substantially improved since 1970, gradually decreased for being restricted to:

- Uninterrupted machining of soft cast irons and steels only
- Relatively high cutting velocity but only in a narrow range (200 ~ 300 m/min)
- Requiring very rigid machine tools

Advent of coated carbide capable of machining cast iron and steels at high velocity made the ceramics almost obsolete.

Development and applications of advanced tool materials

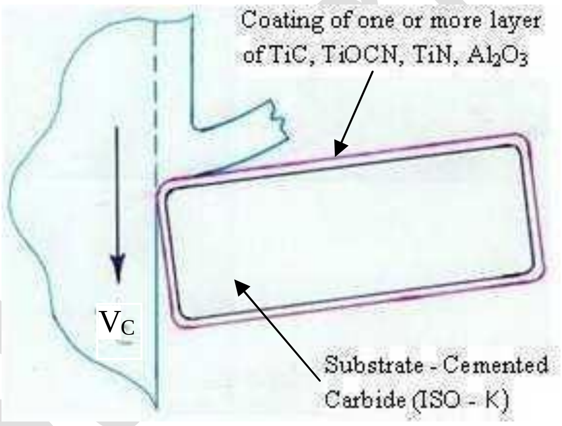
a) Coated carbides

The properties and performance of carbide tools could be substantially improved by:

- Refining microstructure.
- Manufacturing by casting - expensive and uncommon.
- Surface coating - made remarkable contribution.

Thin but hard coating of single or multilayer of more stable and heat and wear resistive materials like TiC, TiCN, TiOCN, TiN, Al_2O_3 etc on the tough carbide inserts (substrate) ***(Fig. 1.17)*** by processes like chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD) etc at controlled pressure and temperature enhanced MRR and overall machining economy remarkably enabling:

- Reduction of cutting forces and power consumption.
- Increase in tool life (by 200 to 500 %) for same V_C or increase in V_C (by 50 to 150 %) for same tool life.
- Improvement in product quality.
- Effective and efficient machining of wide range of work materials.
- Pollution control by less or no use of cutting fluid, *through* -
  - Reduction of abrasion, adhesion and diffusion wear.
  - Reduction of friction and BUE formation.
  - Heat resistance and reduction of thermal cracking and plastic deformation.



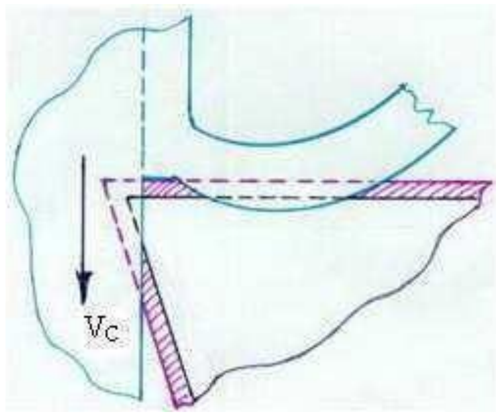


Fig. 1.17 Machining by coated carbide insert. Fig. 1.18 Role of coating even after its wear and rupture

The contribution of the coating continues even after rupture of the coating as indicated in Fig. 1.18.

The cutting velocity range in machining mild steel could be enhanced from 120 ~ 150 m/min to 300 ~ 350 m/min by properly coating the suitable carbide inserts.

About 50% of the carbide tools being used at present are coated carbides which are obviously to some extent costlier than the uncoated tools.

Different varieties of coated tools are available. The appropriate one is selected depending upon the type of the cutting tool, work material and the desired productivity and product quality.

The properties and performances of coated inserts and tools are getting further improved by:

- Refining the microstructure of the coating.

- Multilayering (already up to 13 layers within 12 ~ 16 μm).
- Direct coating by TiN instead of TiC, if feasible.
- Using better coating materials.

b) Cermets

These sintered hard inserts are made by combining 'cer' from ceramics like TiC, TiN or TiCN and 'met' from metal (binder) like Ni, Ni-Co, Fe etc. Since around 1980, the modern cermets providing much better performance are being made by TiCN which is consistently more wear resistant, less porous and easier to make.

The characteristic features of such cermets, in contrast to sintered tungsten carbides, are:

- The grains are made of TiCN (in place of WC) and Ni or Ni-Co and Fe as binder (in place of Co)
- Harder, more chemically stable and hence more wear resistant.
- More brittle and less thermal shock resistant.
- Wt% of binder metal varies from 10 to 20%.
- Cutting edge sharpness is retained unlike in coated carbide inserts.
- Can machine steels at higher cutting velocity than that used for tungsten carbide, even coated carbides in case of light cuts.

c) Coronite

It is already mentioned earlier that the properties and performance of HSS tools could have been sizably improved by refinement of microstructure, powder metallurgical process of making and surface coating. Recently a unique tool material, namely Coronite has been developed for making the tools like small and medium size drills and milling cutters etc. which were earlier essentially made of HSS.

Coronite is made basically by combining HSS for strength and toughness and tungsten carbides for heat and wear resistance. Micro fine TiCN particles are uniformly dispersed into the matrix.

Unlike solid carbide, the coronite based tool is made of three layers:

- The central HSS or spring steel core.
- A layer of coronite of thickness around 15% of the tool diameter.
- A thin (2 to 5 μm) PVD coating of TiCN.

Such tools are not only more productive but also provide better product quality. The coronite tools made by hot extrusion followed by PVD-coating of TiN or TiCN outperformed HSS tools in respect of cutting forces, tool life and surface finish.

d) High Performance ceramics (HPC)

Ceramic tools as such are much superior to sintered carbides in respect of hot hardness, chemical stability and resistance to heat and wear but lack in fracture toughness and strength *as indicated in Fig. 1.19.*

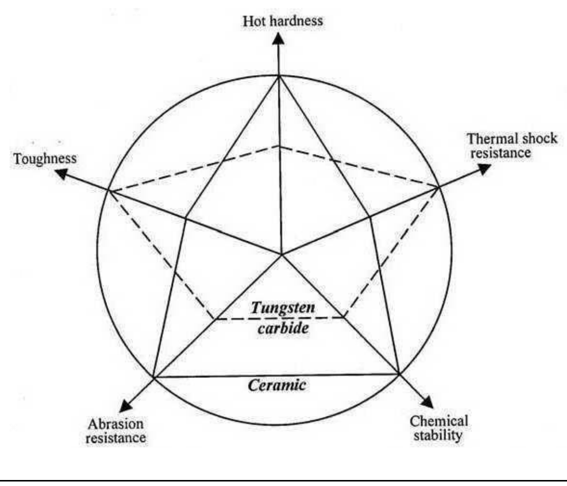


Fig. 1.19 Comparison of important properties of ceramic and tungsten carbide tools

Through last few years' remarkable improvements in strength and toughness and hence overall performance of ceramic tools could have been possible by several means which include:

- Sinterability, microstructure, strength and toughness of Al_2O_3 ceramics were improved to some extent by adding TiO_2 and MgO.
- Transformation toughening by adding appropriate amount of partially or fully stabilized zirconia in Al_2O_3 powder.
- Isostatic and hot isostatic pressing (HIP) - these are very effective but expensive route.
- Introducing nitride ceramic (Si3N4) with proper sintering technique - this material is very tough but prone to built-up-edge formation in machining steels.
- Developing SIALON - deriving beneficial effects of Al_2O_3 and Si_3N_4.
- Adding carbide like TiC (5 ~ 15%) in Al_2O_3 powder - to impart toughness and thermal conductivity.
- Reinforcing oxide or nitride ceramics by SiC whiskers, which enhanced strength, toughness and life of the tool and thus productivity spectacularly. But manufacture and use of this unique tool need especially careful handling.
- Toughening Al_2O_3 ceramic by adding suitable metal like silver which also impart thermal conductivity and self lubricating property; this novel and inexpensive tool is still in experimental stage.

The enhanced qualities of the unique high performance ceramic tools, specially the whisker and zirconia based types enabled them machine structural steels at speed even beyond 500 m/min and also intermittent cutting at reasonably high speeds, feeds and depth of cut. Such tools are also found to machine relatively harder and stronger steels quite effectively and economically.

The successful and commonly used high performance ceramic tools have been discussed here: The HPC tools can be broadly classified into two groups as:

HPC Tools

Nitride Ceramics	Oxide Ceramics
Silicon Nitride	Alumina toughened by
(i) Plain	(i) Zirconia
(ii) SIALON	(ii) SiC whiskers
(iii) Whisker toughened	(iii) Metal (Silver, etc.)

Nitride based ceramic tools

i) Plain nitride ceramics tools

Compared to plain alumina ceramics, Nitride (Si_3N_4) ceramic tools exhibit more resistance to fracturing by mechanical and thermal shocks due to higher bending strength, toughness and higher conductivity. Hence such tool seems to be more suitable for rough and interrupted cutting of various material excepting steels, which cause rapid diffusion wear and BUE formation. The fracture toughness and wear resistance of nitride ceramic tools could be further increased by adding zirconia and coating the finished tools with high hardness alumina and titanium compound.

Nitride ceramics cannot be easily compacted and sintered to high density. Sintering with the aid of 'reaction bonding' and 'hot pressing' may reduce this problem to some extent.

ii) SIALON tools

Hot pressing and sintering of an appropriate mix of Al_2O_3 and Si_3N_4 powders yielded an excellent composite ceramic tool called SIALON which are very hot hard, quite tough and wear resistant.

These tools can machine steel and cast irons at high speeds (250 - 300 m/min). But machining of steels by such tools at too high speeds reduces the tool life by rapid diffusion.

iii) SiC reinforced Nitride tools

The toughness, strength and thermal conductivity and hence the overall performance of nitride ceramics could be increased remarkably by adding SiC whiskers or fibers in 5 - 25 volume %. The SiC whiskers add fracture toughness mainly through crack bridging, crack deflection and fiber pull-out.

Such tools are very expensive but extremely suitable for high production machining of various soft and hard materials even under interrupted cutting.

iv) Zirconia (or partially stabilized Zirconia) toughened alumina (ZTA) ceramic

The enhanced strength, TRS and toughness have made these ZTAs more widely applicable and more productive than plain ceramics and cermets in machining steels and cast irons. Fine powder of partially stabilized zirconia (PSZ) is mixed in proportion of ten to twenty volume percentage with pure alumina, then either cold pressed and sintered at 1600^0 C - 1700^0 C or hot isostatically pressed (HIP) under suitable temperature and pressure. The phase transformation of metastable tetragonal zirconia (t-Z) to monoclinic zirconia (m-Z) during cooling of the composite (Al_2O_3 + ZrO_2) inserts after sintering or HIP and during polishing and machining imparts the desired strength and fracture toughness through volume expansion (3 - 5%) and induced shear strain (7%). The mechanisms of toughening effect of zirconia in the basic alumina matrix are stress induced transformation toughening *as indicated in Fig. 1.20* and micro crack nucleation toughening.

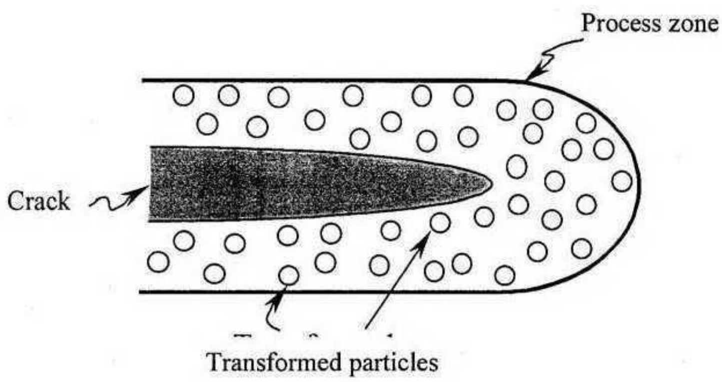


Fig. 1.20 The method of crack shielding by a transformation zone

Their hardness has been raised further by proper control of particle size and sintering process. Hot pressing and HIP raise the density, strength and hot hardness of ZTA tools but the process becomes expensive and the tool performance degrades at lower cutting speeds. However such ceramic tools can machine steel and cast iron at speed range of 150 - 500 m/min.

v) ***Alumina ceramic reinforced by SiC whiskers***

The properties, performances and application range of alumina based ceramic tools have been improved spectacularly through drastic increase in fracture toughness (2.5 times), TRS and bulk thermal conductivity, without sacrificing hardness and wear resistance by mechanically reinforcing the brittle alumina matrix with extremely strong and stiff silicon carbide whiskers. The randomly oriented, strong and thermally conductive whiskers enhance the strength and toughness mainly by crack deflection and crack-bridging and also by reducing the temperature gradient within the tool.

After optimization of the composition, processing and the tool geometry, such tools have been found too effectively and efficiently machine wide range of materials, over wide speed range (250 - 600 m/min) even under large chip loads. But manufacturing of whiskers need very careful handling and precise control and these tools are costlier than zirconia toughened ceramic tools.

vi) ***Silver toughened alumina ceramic***

Toughening of alumina with metal particle became an important topic since 1990 though its possibility was reported in 1950s. Alumina-metal composites have been studied primarily using addition of metals like aluminium, nickel, chromium, molybdenum, iron and silver. Compared to zirconia and carbides, metals were found to provide more toughness in alumina ceramics. Again compared to other metal-toughened ceramics, the silver-toughened ceramics can be manufactured by simpler and more economical process routes like pressureless sintering and without atmosphere control.

All such potential characteristics of silver-toughened alumina ceramic have already been exploited in making some salient parts of automobiles and similar items. Research is going on to develop and use silver-toughened alumina for making cutting tools like turning inserts.. *The toughening of the alumina matrix by the addition of metal occurs mainly by crack deflection and crack bridging by the metal grains as schematically shown in Fig. 1.21.*

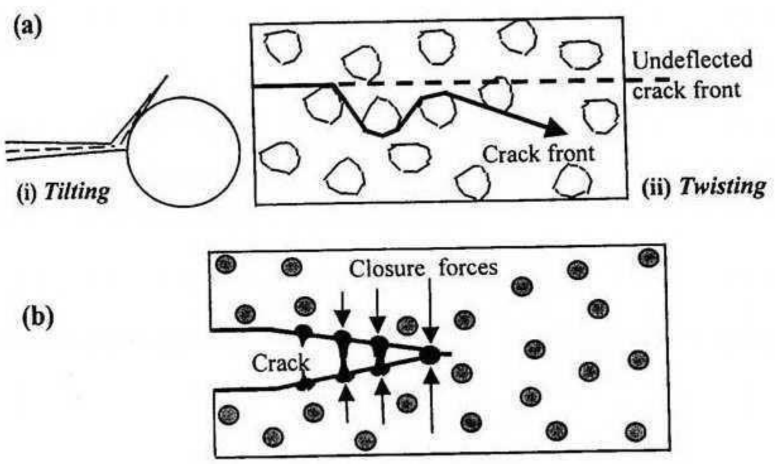


Fig. 1.21 Toughening mechanism of alumina by metal dispersion

Addition of silver further helps by increasing thermal conductivity of the tool and self lubrication by the traces of the silver that oozes out through the pores and reaches at the chip-tool interface. Such HPC tools can suitably machine with large MRR and V_C (250 - 400 m/min) and long tool life even under light interrupted cutting like milling. Such tools also can machine steels at speed from quite low to very high cutting velocities (200 to 500 m/min).

e) ***Cubic Boron Nitride***

Next to diamond, cubic boron nitride is the hardest material presently available. Only in 1970 and onward CBN in the form of compacts has been introduced as cutting tools. It is made by bonding a- 1 mm layer of polycrystalline cubic boron nitride to cobalt based carbide substrate at very high temperature and pressure. It remains inert and retains high hardness and fracture toughness at elevated machining speeds. It shows excellent performance in grinding any material of high hardness and strength. The extreme hardness, toughness, chemical and thermal stability and wear resistance led to the development of CBN cutting tool inserts for high material removal rate (MRR) as well as precision machining imparting excellent surface integrity of the products. Such unique tools effectively and beneficially used in machining wide range of work materials covering high carbon and alloy steels, non- ferrous metals and alloys, exotic metals like Ni-hard, Inconel, Nimonic etc and many non-metallic materials which are as such difficult to machine by conventional tools. It is firmly stable at temperatures up to 1400^0 C. The operative speed range for CBN when machining grey cast iron is 300 ~ 400 m/min. *Speed ranges for other materials are as follows:*

- Hard cast iron (> 400 BHN): 80 - 300 m/min.
- Superalloys (> 35 RC): 80 - 140 m/min.
- Hardened steels (> 45 RC): 100 - 300 m/min.

In addition to speed, the most important factor that affects performance of CBN inserts is the preparation of cutting edge. It is best to use CBN tools with a honed or chamfered edge preparation, especially for interrupted cuts. Like ceramics, CBN tools are also available only in the form of indexable inserts. The only limitation of it is its high cost.

(f) Diamond Tools

Single stone, natural or synthetic, diamond crystals are used as tips/edge of cutting tools. Owing to the extreme hardness and sharp edges, natural single crystal is used for many applications, particularly where high accuracy and precision are required. Their important uses are:

- Single point cutting tool tips and small drills for high speed machining of non-ferrous metals, ceramics, plastics, composites, etc. and effective machining of difficult-to-machine materials.
- Drill bits for mining, oil exploration, etc.
- Tool for cutting and drilling in glasses, stones, ceramics, FRPs etc.
- Wire drawing and extrusion dies.
- Superabrasive wheels for critical grinding.

Limited supply, increasing demand, high cost and easy cleavage of natural diamond demanded a more reliable source of diamond. It led to the invention and manufacture of artificial diamond grits by ultra-high temperature and pressure synthesis process, which enables large scale manufacture of diamond with some control over size, shape and friability of the diamond grits as desired for various applications.

i) Polycrystalline Diamond (PCD)

The polycrystalline diamond (PCD) tools consist of a layer (0.5 to 1.5 mm) of fine grain size, randomly oriented diamond particles sintered with a suitable binder (usually cobalt) and then metallurgically bonded to a suitable substrate like cemented carbide or Si_3N_4 inserts. PCD exhibits excellent wear resistance, hold sharp edge, generates little friction in the cut, provide high fracture strength, and had good thermal conductivity. These properties contribute to PCD tooling's long life in conventional and high speed machining of soft, non-ferrous materials (aluminium, magnesium, copper etc), advanced composites and metal-matrix composites, superalloys, and non-metallic materials.

PCD is particularly well suited for abrasive materials (i.e. drilling and reaming metal matrix composites) where it provides 100 times the life of carbides. PCD is not usually recommended for ferrous metals because of high solubility of diamond (carbon) in these materials at elevated temperature. However, they can be used to machine some of these materials under special conditions;

for example, light cuts are being successfully made in grey cast iron. The main advantage of such PCD tool is the greater toughness due to finer microstructure with random orientation of the grains and reduced cleavage.

But such unique PCD also suffers from some limitations like:

- High tool cost.
- Presence of binder, cobalt, which reduces wear resistance and thermal stability.
- Complex tool shapes like in-built chip breaker cannot be made.
- Size restriction, particularly in making very small diameter tools.

The above mentioned limitations of polycrystalline diamond tools have been almost overcome by developing Diamond coated tools.

ii) Diamond coated carbide tools

Since the invention of low pressure synthesis of diamond from gaseous phase, continuous effort has been made to use thin film diamond in cutting tool field. These are normally used as thin (<50 µm) or thick (> 200 µm) films of diamond synthesized by CVD method for cutting tools, dies, wear surfaces and even abrasives for Abrasive Jet Machining (AJM) and grinding.

Thin film is directly deposited on the tool surface. Thick film (> 500 µm) is grown on an easy substrate and later brazed to the actual tool substrate and the primary substrate is removed by dissolving it or by other means. Thick film diamond finds application in making inserts, drills, reamers, end mills, routers.

CVD coating has been more popular than single diamond crystal and PCD mainly for:

- Free from binder, higher hardness, resistance to heat and wear more than PCD and properties close to natural diamond.
- Highly pure, dense and free from single crystal cleavage.
- Permits wider range of size and shape of tools and can be deposited on any shape of the tool including rotary tools.
- Relatively less expensive.

However, achieving improved and reliable performance of thin film CVD diamond coated tools; (carbide, nitride, ceramic, SiC etc) in terms of longer tool life, dimensional accuracy and surface finish of jobs essentially need:

- Good bonding of the diamond layer.
- Adequate properties of the film, e.g. wear resistance, micro-hardness, edge coverage, edge sharpness and thickness uniformity.
- Ability to provide work surface finish required for specific applications.

While CBN tools are feasible and viable for high speed machining of hard and strong steels and similar materials, Diamond tools are extremely useful for machining stones, slates, glass, ceramics, composites, FRPs and non ferrous metals specially which are sticky and BUE former such as pure aluminium and its alloys. *CBN and Diamond tools are also essentially used for ultra precision as well as micro and nano machining.*

TOOL WEAR

Failure of cutting tools

Smooth, safe and economic machining necessitates:

- Prevention of premature and terrible failure of the cutting tools.
- Reduction of rate of wear of tool to prolong its life.

To accomplish the aforesaid objectives one should first know why and how the cutting tools fail.

Cutting tools generally fail by:

- Mechanical breakage due to excessive forces and shocks. Such kind of tool failure is random and catastrophic in nature and hence is extremely detrimental.
- Quick dulling by plastic deformation due to intensive stresses and temperature. This type of failure also occurs rapidly and is quite detrimental and unwanted.
- Gradual wear of the cutting tool at its flanks and rake surface.

The first two modes of tool failure are very harmful not only for the tool but also for the job and the machine tool. Hence these kinds of tool failure need to be prevented by using suitable tool materials and geometry depending upon the work material and cutting condition.

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

It is understood or considered that the tool has failed or about to fail by one or more of the following conditions:

(a) In R&D laboratories

- Total breakage of the tool or tool tip(s).
- Massive fracture at the cutting edge(s).
- Excessive increase in cutting forces and/or vibration.
- Average wear (flank or crater) reaches its specified limit(s).

(b) In machining industries

- Excessive (beyond limit) current or power consumption.
- Excessive vibration and/or abnormal sound (chatter).
- Total breakage of the tool.
- Dimensional deviation beyond tolerance.
- Rapid worsening of surface finish.
- Adverse chip formation.

Mechanisms and pattern (geometry) of cutting tool wear

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

The common mechanisms of cutting tool wear are:

(a) Mechanical wear

- Thermally insensitive type; like abrasion, chipping and de-lamination.
- Thermally sensitive type; like adhesion, fracturing, flaking etc.

Flank wear is a flat portion worn behind the cutting edge which eliminates some clearance or relief. It takes place when machining brittle materials. Wear at the tool-chip interface occurs in the form of a depression or crater. It is caused by the pressure of the chip as it slides up the face of the cutting tool. Both flank and crater wear take place when feed is greater than 0.15 mm/rev at low or moderate speeds.

(b) Thermo chemical wear

- Macro-diffusion by mass dissolution.
- Micro-diffusion by atomic migration.

In diffusion wear the material from the tool at its rubbing surfaces, particularly at the rake surface gradually diffuses into the flowing chips either in bulk or atom by atom when the tool material has chemical affinity or solid solubility towards the work material. The rate of such tool wears increases with the increase in temperature at the cutting zone. This wear becomes predominant when the cutting temperature becomes very high due to high cutting velocity and high strength of the work material.

(c) Chemical wear

Chemical wear, leading to damages like grooving wear may occur if the tool material is not enough chemically stable against the work material and/or the atmospheric gases.

(d) Galvanic wear

Galvanic wear, based on electrochemical dissolution, seldom occurs when the work and tool materials are electrically conductive, cutting zone temperature is high and the cutting fluid acts as an electrolyte.

The usual pattern or geometry of wear of face milling inserts, turning tools and turning inserts are typically shown in Fig. 1.22 (a, b, c and d).

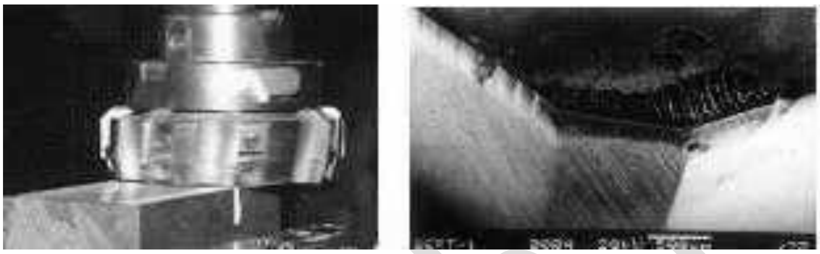


Fig. 1.22 (a) Schematic view of wear pattern of face milling insert

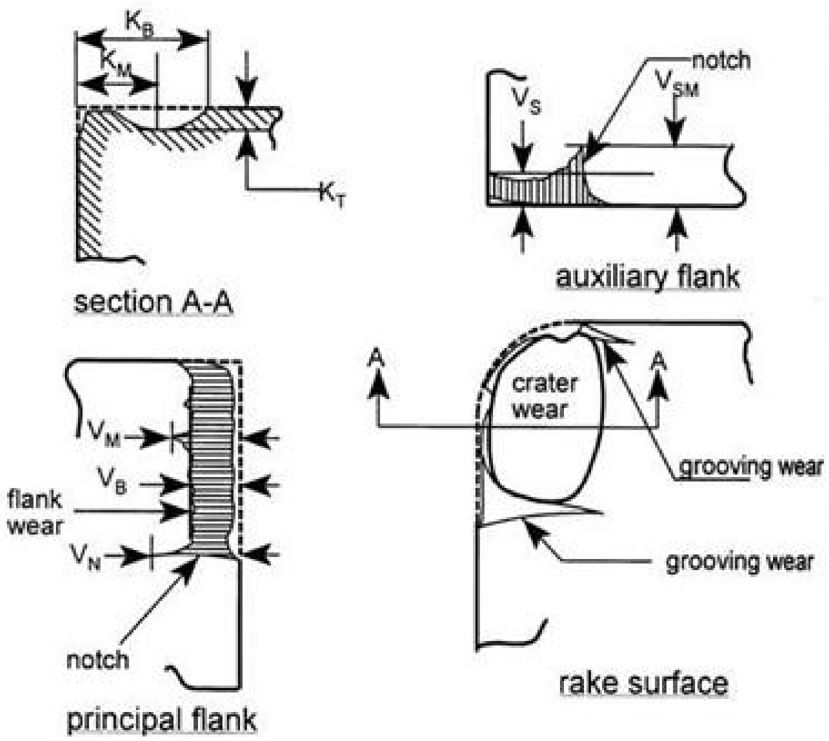


Fig. 1.22 (b) Geometry and major features of wear of turning tools

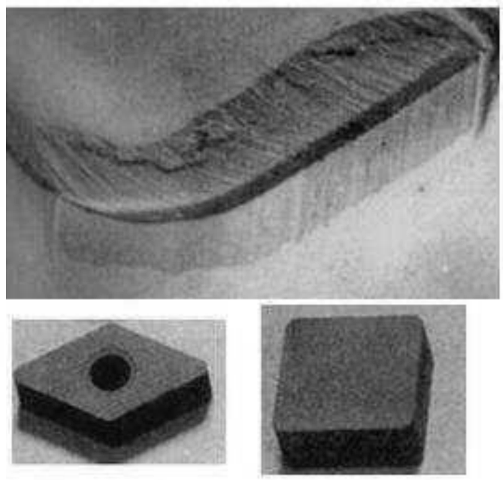


Fig. 1.22 (c) Photographic view of the wear pattern of a turning tool insert

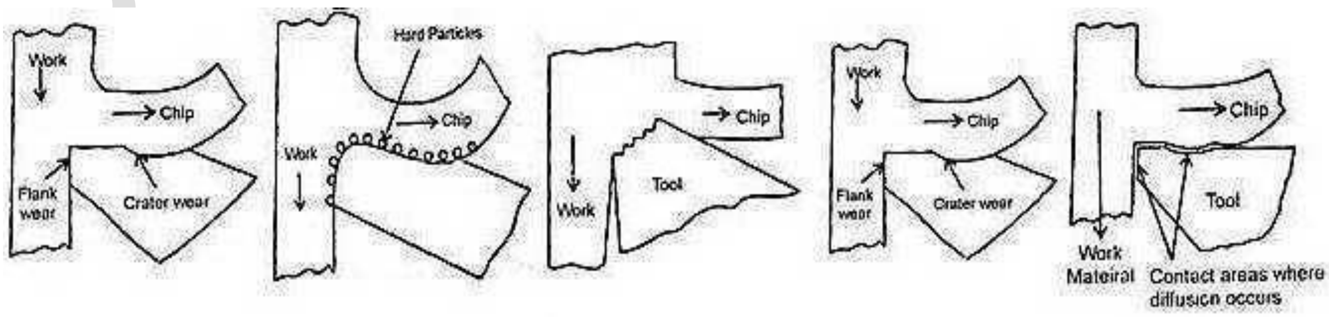


Fig. 1.22 (d) Different types of wears of turning tools

In addition to ultimate failure of the tool, the following effects are also caused by the growing tool-wear:

- Increase in cutting forces and power consumption mainly due to the principal flank wear.
- Increase in dimensional deviation and surface roughness mainly due to wear of the tool-tips and auxiliary flank wear (Vs).
- Odd sound and vibration.
- Worsening surface integrity.
- Mechanically weakening of the tool tip.

Measurement of tool wear

The various methods are:

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

TOOL LIFE

Definition:

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

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

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

Assessment of tool life

For R & D purposes, tool life is always assessed or expressed by span of machining time in minutes, whereas, in industries besides machining time in minutes some other means are also used to assess tool life, depending upon the situation, such as:

- Number of pieces of work machined.
- Total volume of material removed.
- Total length of cut.

Effect of side cutting edge angle on tool life

The side cutting edge angle (ϕ_s) may improve tool life under non-chatter conditions:

$$V_C T^{0.11} = 78(''_s + 15^0)^{0.264} \qquad 1.56$$

Tool life in terms of metal removal

38

The volume of metal removal from the work piece between tool sharpening for definite depth of cut, feed and cutting speed can be determined as follows. For example in case of turning:

Cutting speed $V_C = uDN / 1000$ m/min 1.57

where D - Diameter of work piece (mm).

N - Rotation speed of work piece (rpm).

Let t - Depth of cut (mm).

f - Feed rate (mm/min).

t_{tf} - Time of tool failure (min).

T - Tool life in 1 mm^3 of metal removal.

Volume of metal removed per revolution = u.D.t.f mm^3 1.58

Volume of metal removed per minute = u.D.t.f.N mm^3 1.59

Volume of metal removed in 't_{tf}' minute = u.D.t.f.N.t_{tf} mm^3 1.60

Therefore, Volume of metal removed between tool grinds = u.D.t.f.N.t_{tf} mm^3 1.61

$T = u.D.t.f.N.t_{tf}\ mm^3 = 1000.V_C.t.f.t_{tf}\ mm^3$ 1.62

$\mathbf{T = V_C.t.f.t_{tf}\ cm^3}$ 1.63

Factors affecting tool life

The life of the cutting tool is affected by the following factors:

- Cutting speed.
- Feed and depth of cut.
- Tool geometry.
- Tool material.
- Cutting fluid.
- Work piece material.
- Rigidity of work, tool and machine.

Machinabilty

Concept, definition and criteria of judgment of machinabilty

The term; 'Machinabilty' has been introduced for gradation of work materials with respect to machining characteristics. But truly speaking, there is no unique or clear meaning of the term machinabilty. *People tried to describe "Machinabilty" in several ways such as:*

- It is generally applied to the machining properties of work material.
- It refers to material (work) response to machining.
- It is the ability of the work material to be machined.
- It indicates how easily and fast a material can be machined.

But it has been agreed, in general, that it is difficult to clearly define and quantify Machinabilty. *For instance, saying 'material A is more machinable than material B' may mean that compared to 'B':*

- 'A' causes lesser tool wear or longer tool life.
- 'A' requires lesser cutting forces and power.
- 'A' provides better surface finish.

Attempts were made to measure or quantify machinabilty and it was done mostly in terms of:

- Tool life which substantially influences productivity and economy in machining.
- Magnitude of cutting forces which affects power consumption and dimensional accuracy.
- Surface finish which plays role on performance and service life of the product.

Often cutting temperature and chip form are also considered for assessing machinabilty.

$$\textbf{\textit{Machinability rating (MR)}} = \frac{\text{cpeed(fpm)ofmachining the work giving 60 minute tool life}}{\text{cpeed(fpm)ofmachining the ctandard metaS giving 60 minute tooS Sife}} \; x\ 100 \qquad 1.64$$

The free cutting steel, AISI - 1112, when machined (turned) at 100 fpm, provided 60 min of tool life. If the work material to be tested provides 60 min of tool life at cutting velocity of 60 fpm (say), under the same set of machining condition, then machinability (rating) of that material would be,

$MR = \frac{60}{100}$ x 100 = 60 % or simply 60 (based on 100% for the standard material) or, simply the value of the cutting velocity expressed in fpm at which a work material provides 60 min tool life was directly considered as the MR of that work material. In this way the MR of some materials, for instance, were evaluated as,

Metal	MR
Ni	200
Br	300
Al	200
CI	70
Inconel	30

CUTTING FLUIDS

Purposes and application of cutting fluid

The basic purposes of cutting fluid application are:

- Cooling of the job and the tool to reduce the detrimental effects of cutting temperature on the job and the tool.
- Lubrication at the chip - tool interface and the tool flanks to reduce cutting forces and friction and thus the amount of heat generation.
- Cleaning the machining zone by washing away the chip - particles and debris which, if present, spoils the finished surface and accelerates damage of the cutting edges.
- Protection of the nascent finished surface - a thin layer of the cutting fluid sticks to the machined surface and thus prevents its harmful contamination by the gases like SO_2, O_2, H_2S, and N_XO_Y present in the atmosphere.

However, the main aim of application of cutting fluid is to improve machinability through reduction of cutting forces and temperature, improvement by surface integrity and enhancement of tool life.

Essential properties of cutting fluids

To enable the cutting fluid fulfill its functional requirements without harming the Machine - Fixture - Tool - Work (M-F-T-W) system and the operators, the cutting fluid should possess the following properties:

- *For cooling:*
  - High specific heat, thermal conductivity and film coefficient for heat transfer.
  - Spreading and wetting ability.
- *For lubrication:*
  - High lubricity without gumming and foaming.
  - Wetting and spreading.
  - High film boiling point.
  - Friction reduction at extreme pressure (EP) and temperature.
- Chemical stability, non-corrosive to the materials of the M-F-T-W system.
- Less volatile and high flash point.
- High resistance to bacterial growth.
- Odourless and also preferably colourless.
- Non toxic in both liquid and gaseous stage.
- Easily available and low cost.

Principles of cutting fluid action

The chip-tool contact zone is usually comprised of two parts; *plastic or bulk contact zone and elastic contact zone as indicated in Fig. 1.23.*

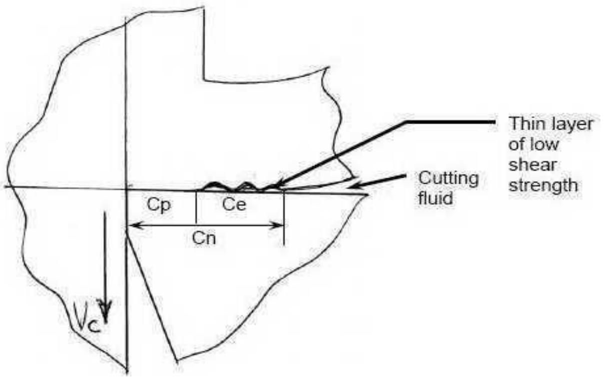


Fig. 1.23 Cutting fluid action in machining

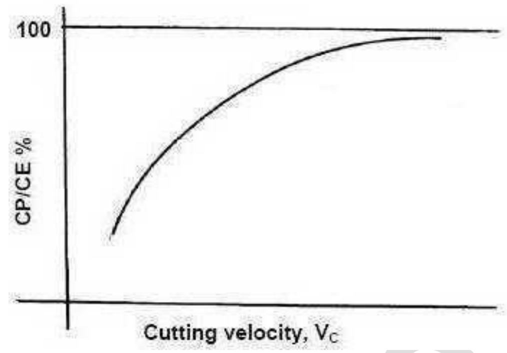


Fig. 1.24 Apportionment of plastic and elastic contact zone with increase in cutting velocity

The cutting fluid cannot penetrate or reach the plastic contact zone but enters in the elastic contact zone by capillary effect. With the increase in cutting velocity, the fraction of plastic contact zone gradually increases and covers almost the entire chip-tool contact zone *as indicated in Fig. 1.24.* Therefore, at high speed machining, the cutting fluid becomes unable to lubricate and cools the tool and the job only by bulk external cooling.

The chemicals like chloride, phosphate or sulphide present in the cutting fluid chemically reacts with the work material at the chip under surface under high pressure and temperature and forms a thin layer of the reaction product. The low shear strength of that reaction layer helps in reducing friction.

To form such solid lubricating layer under high pressure and temperature some extreme pressure additive (EPA) is deliberately added in reasonable amount in the mineral oil or soluble oil.

For extreme pressure, chloride, phosphate or sulphide type EPA is used depending upon the working temperature, i.e. moderate (200^0 C ~ 350^0 C), high (350^0 C ~ 500^0 C) and very high (500^0 C ~ 800^0 C) respectively.

Types of cutting fluids and their application

Generally, cutting fluids are employed in liquid form but occasionally also employed in gaseous form. Only for lubricating purpose, often solid lubricants are also employed in machining and grinding.

The cutting fluids, which are commonly used, are:

Air blast or compressed air only

Machining of some materials like grey cast iron become inconvenient or difficult if any cutting fluid is employed in liquid form. In such case only air blast is recommended for cooling and cleaning.

Solid or semi-solid lubricant

Paste, waxes, soaps, graphite, Moly-disulphide (MoS_2) may also often be used, either applied directly to the workpiece or as an impregnant in the tool to reduce friction and thus cutting forces, temperature and tool wear.

Water

For its good wetting and spreading properties and very high specific heat, water is considered as the best coolant and hence employed where cooling is most urgent.

Soluble oil

Water acts as the best coolant but does not lubricate. Besides, use of only water may impair the machine-fixture-tool-work system by rusting. So oil containing some emulsifying agent and additive like EPA, together called cutting compound, is mixed with water in a suitable ratio (1 ~ 2 in 20 ~ 50).

42

This milk like white emulsion, called soluble oil, is very common and widely used in machining and grinding.

Cutting oils

Cutting oils are generally compounds of mineral oil to which are added desired type and amount of vegetable, animal or marine oils for improving spreading, wetting and lubricating properties. As and when required some EP additive is also mixed to reduce friction, adhesion and BUE formation in heavy cuts.

Chemical fluids

These are occasionally used fluids which are water based where some organic and or inorganic materials are dissolved in water to enable desired cutting fluid action.

There are two types of such cutting fluid:

- *Chemically inactive type* - high cooling, anti-rusting and wetting but less lubricating.
- *Active (surface) type* - moderate cooling and lubricating.

Cryogenic cutting fluid

Extremely cold (cryogenic) fluids (often in the form of gases) like liquid CO_2 or N_2 are used in some special cases for effective cooling without creating much environmental pollution and health hazards.

Methods of application of cutting fluid

The effectiveness and expense of cutting fluid application significantly depend also on how it is applied in respect of flow rate and direction of application. *In machining, depending upon the requirement and facilities available, cutting fluids are generally employed in the following ways (flow):*

- Drop-by-drop under gravity.
- Flood under gravity.
- In the form of liquid jet(s).
- Mist (atomized oil) with compressed air.
- Z-Z method - centrifugal through the grinding wheels (pores) *as indicated in Fig. 1.25.*

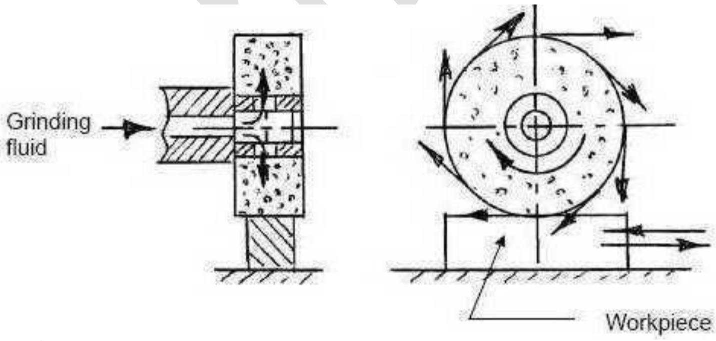


Fig 1.25 Z-Z method of cutting fluid application in grinding

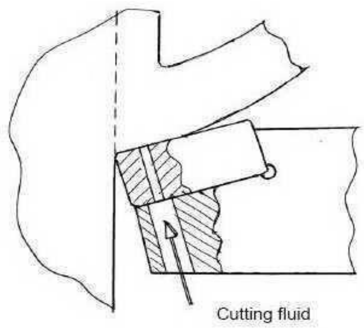


Fig. 1.26 Application of cutting fluid at high pressure through the hole in the tool

The direction of application also significantly governs the effectiveness of the cutting fluid in respect of reaching at or near the chip-tool and work-tool interfaces. Depending upon the requirement and accessibility the cutting fluid is applied from top or side(s). In operations like deep hole drilling the pressurized fluid is often sent through the axial or inner spiral hole(s) of the drill.

For effective cooling and lubrication in high speed machining of ductile metals having wide and plastic chip-tool contact, cutting fluid may be pushed at high pressure to the chip-tool interface through hole(s) in the cutting tool, *as schematically shown in Fig. 1.26.*

Selection of cutting fluid

The benefits of application of cutting fluid largely depend upon proper selection of the type of the cutting fluid depending upon the work material, tool material and the machining condition. As for example, for high speed machining of not-difficult-to-machine materials greater cooling type fluids are preferred and for low speed machining of both conventional and difficult-to-machine materials greater lubricating type fluid is preferred.

Selection of cutting fluids for machining some common engineering materials and operations are presented as follows:

Grey cast iron:

- Generally dry for its self lubricating property.
- Air blast for cooling and flushing chips.
- Soluble oil for cooling and flushing chips in high speed machining and grinding.

Steels:

- If machined by HSS tools, sol. Oil (1: 20 ~30) for low carbon and alloy steels and neat oil with EPA for heavy cuts.
- If machined by carbide tools thinner sol. Oil for low strength steel, thicker sol. Oil (1:10 ~ 20) for stronger steels and straight sulphurised oil for heavy and low speed cuts and EP cutting oil for high alloy steel.
- Often steels are machined dry by carbide tools for preventing thermal shocks.

Aluminium and its alloys:

- Preferably machined dry.
- Light but oily soluble oil.
- Straight neat oil or kerosene oil for stringent cuts.

Copper and its alloys:

- Water based fluids are generally used.
- Oil with or without inactive EPA for tougher grades of Cu-alloy.

Stainless steels and Heat resistant alloys:

- High performance soluble oil or neat oil with high concentration with chlorinated EP additive.

The brittle ceramics and cermets should be used either under dry condition or light neat oil in case of fine finishing.

Grinding at high speed needs cooling (1: 50 ~ 100) soluble oil. For finish grinding of metals and alloys low viscosity neat oil is also used.

Broaching operation

Like any other machining, broaching is also accomplished through a series of following sequential steps:

- Selection of broach and broaching machine.
- Mounting and clamping the broach in the broaching machine.
- Fixing work piece in the machine.
- Planning tool - work motions.
- Selection of the levels of the process parameters and their setting.
- Conducting machining by the broach.

Selection of broach and broaching machine

There are various types of broaches available. The appropriate one has to be selected based on:

- Type of the job; size, shape and material.
- Geometry and volume of work material to be removed from the job.
- Desired length of stroke and the broach.
- Type of the broaching machines available or to be used.

Broaching machine has to be selected based on:

- The type, size and method of clamping of the broach to be used.
- Size, shape and material of the work piece.
- Strength, power and rigidity required for the broaching machine to provide the desired productivity and process capability.

Function of broaching machines

The basic function of a broaching machine is to provide a precise linear motion of the tool past a stationary work position. There are two principal modifications of the broaching machines, horizontal, and vertical. The former are suitable for broaching of relatively long and small diameter holes, while the later are used for short lengths and large diameters.

The unique characteristics of broaching operation are:

- For producing any surface, the form of the tool (broach) always provides the Generatrix and the cutting motion (of the broach relative to the job surface) provides the Directrix.
- So far as tool – work motions, broaching needs only one motion and that is the cutting motion (velocity) preferably being imparted to the broach.

Hence design, construction and operation of broaching machines, requiring only one such linear motion, are very simple. Only alignments, rigidity and reduction of friction and wear of slides and guides are to be additionally considered for higher productivity, accuracy and surface finish.

Specification of broaching machines

Broaching machines are generally specified by:

- Type; horizontal, vertical etc.
- Maximum stroke length.
- Maximum working forces (pull or push).
- Maximum cutting velocity possible.
- Type of drive - Electro-Mechanical, Hydraulic etc.
- Power rating of electrical motor.
- Floor space required.

Most of the broaching machines have hydraulic drive for the cutting motion. Electro-mechanical drives are also used preferably for high speed of work but light cuts.

Classification of broaching machines

There are different types of broaching machines which are broadly classified as:

47

According to purpose of use

- General purpose.
- Single purpose.
- Special purpose.

According to nature of work

- Internal broaching.
- External (surface) broaching.

According to configuration

- Horizontal.
- Vertical.

According to number of slides or stations

- Single station type.
- Multiple station type.
- Indexing type.

According to tool / work motion

- Intermittent (one job at a time) type.
- Continuous type.

According to the type of drive

- Mechanical drive.
- Hydraulic drive.

PUSH BROACHING MACHINES

In these machines the broach movement is guided by a ram. These machines are simple, since the broach only needs to be pushed through the component for cutting and then retracted. The work piece is fixed into a boring fixture on the table. Even simple arbor presses can be used for push broaching.

Push down type vertical surface broaching machine

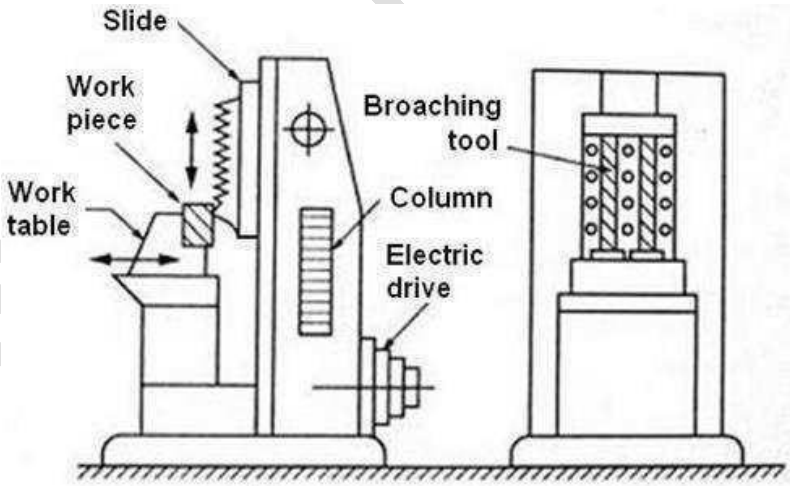


Fig. 1.27 Push down type vertical surface broaching machine

Fig. 1.27 shows the push down type vertical surface broaching machine. It consists of a box shape column, slide and drive mechanism. Broach is mounted on the slide which is hydraulically operated and accurately guided on the column ways. Slide with the broach travels at various speeds. The slide is provided with quick return mechanism. The worktable is mounted on the base in front of the column. The fixture is clamped to the table. The work piece is held in the fixture.

After advancing the table to the broaching position, it is clamped and the slide with the broach travel downwards for machining the workpiece. Then the table recedes to load a new work piece and the slide returns to its upper position. The same cycle is then repeated.

Vertical broaching machines occupy less floor space and are more rigid as the ram is supported by the base. They are mostly used for external or surface broaching though internal broaching is also possible and occasionally done.

PULL BROACHING MACHINES

These machines consist of a work holding mechanism, and a broach pulling mechanism along with a broach elevator to help in the removal and threading of the broach through the work piece. The work piece is mounted in the broaching fixture and the broach is inserted through the hole present in the work piece.

Then the broach is pulled through the work piece completely and the work piece is then removed from the table. Afterwards the broach is brought back to the starting point before a new work piece is located on the table. The same cycle is then repeated.

Pull type horizontal internal broaching machine

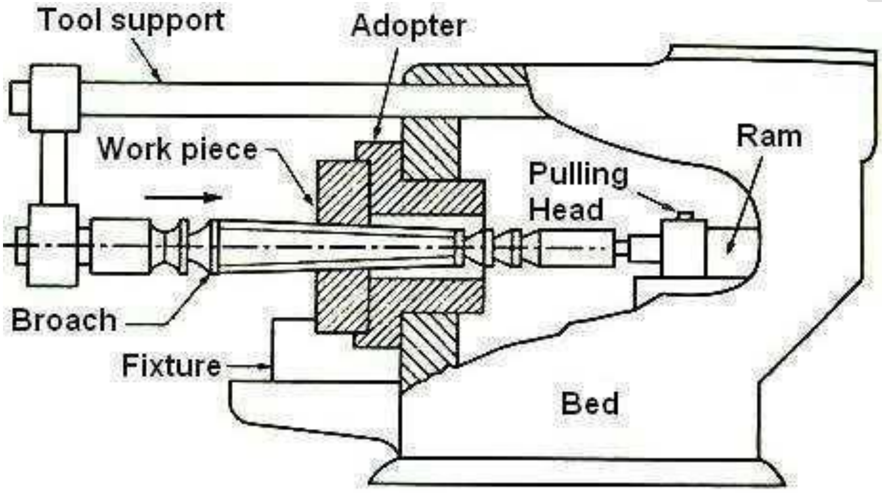


Fig. 1.28 Pull type horizontal internal broaching machine

Fig. 1.28 shows the pull type horizontal internal broaching machine. This machine has a box type bed. The length of bed is twice the length of stroke. Most of the modern horizontal broaching machines are provided with hydraulic or electric drive. It is housed in the bed. The job is located in the adopter. The adopter is fitted in the front vertical face of the machine. The small end of the broach is inserted through the hole of the job and connected to the pulling head.

The pulling head is mounted in the front end of the ram. The ram is connected to the hydraulic drive mechanism. The rear end of the broach is supported by a guide. The broach is moved along the guide ways. It is used for small and medium sized works. It is used for machining keyways, splines, serrations, internal gears, etc.

Horizontal broaching machines are the most versatile in application and performance and hence are most widely employed for various types of production. These are used for internal broaching but external broaching work is also possible. The horizontal broaching machines are usually hydraulically driven and occupy large floor space.

Pull down type vertical internal broaching machine

This machine has an elevator at the top. The pulling mechanism is enclosed in the base of the machine. The work piece is mounted on the table by means of fixture. The tail end of the broach is gripped in the elevator. The broach is lowered through the work piece.

The broach is automatically engaged by the pulling mechanism and is pulled down through the job. After the operation is completed, the broach is raised and gripped by the elevator. The elevator returns to its initial position. *This is illustrated in Fig. 1.29 (a).*

Pull up type vertical internal broaching machine

50

In this type, the ram slides on the vertical column of the machine. The ram carries the pulling head at its bottom. The pulling mechanism is above the worktable and the broach is in the base of the machine. The broach enters the job held against the underside of the table and is pulled upward. At the end of the operation, the work is free and falls down into a container. *This is illustrated in Fig. 1.29 (b).*

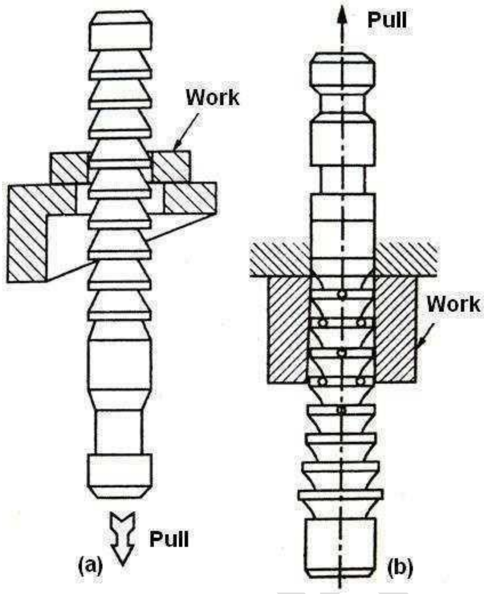


Fig. 1.29 Vertical internal broaching operation (a) pull down type (b) pull up type

SURFACE BROACHING MACHINES

In horizontal surface broaching machines, the broach is pulled over the top surface of the work piece held in the fixture on the worktable as shown in Fig. 1.30. The cutting speed ranges from 3 to 12 *mpm* with a return speed up to 30 *mpm*. The construction and working principle of horizontal surface broaching machine is similar to that of pull type horizontal internal broaching machine.

In vertical surface broaching machines, the work piece is held in the fixture while the surface broach is reciprocated with the ram on the vertical guide ways on the column as shown in Fig. 1.31. Surface broaching is relatively simple since the broach can be continuously held and then it will carry out only a reciprocating action.

Instead of using simple broach some times the progressive cut type broach with the teeth segments distributed into the three areas as shown in Fig. 1.56 (b) is used in surface broaching. The progressive action reduces the maximum broaching force, but results in a longer broach.

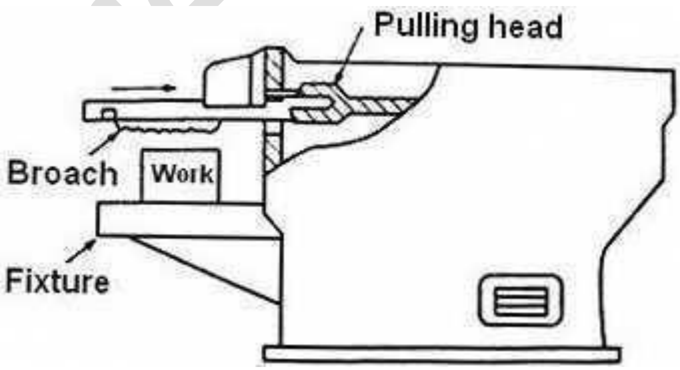


Fig. 1.30 Horizontal surface broaching machine

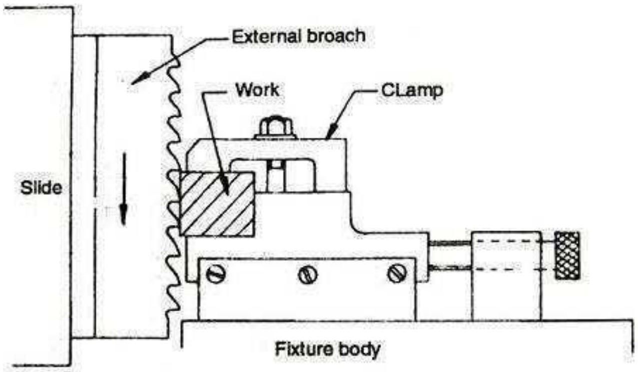


Fig. 1.31 Vertical surface broaching machine

CONTINUOUS BROACHING MACHINES

These broaching machines are also known as high production broaching machines. The reciprocation of the broach always involves an unproductive return stroke, which is eliminated in a continuous surface broaching machine. These machines are used for fast production of large number of pieces by surface broaching.

Horizontal continuous broaching machine

In this the small work pieces are mounted on the broaching fixtures which are in turn fixed to an endless chain continuously moving in between two sprockets. Broaches which are normally stationary are kept above the work pieces. The work pieces are pushed past the stationary broaches by means of the conveyor for cutting. The work pieces are loaded and unloaded onto the conveyor manually or automatically. *This is illustrated in Fig. 1.32 (a).*

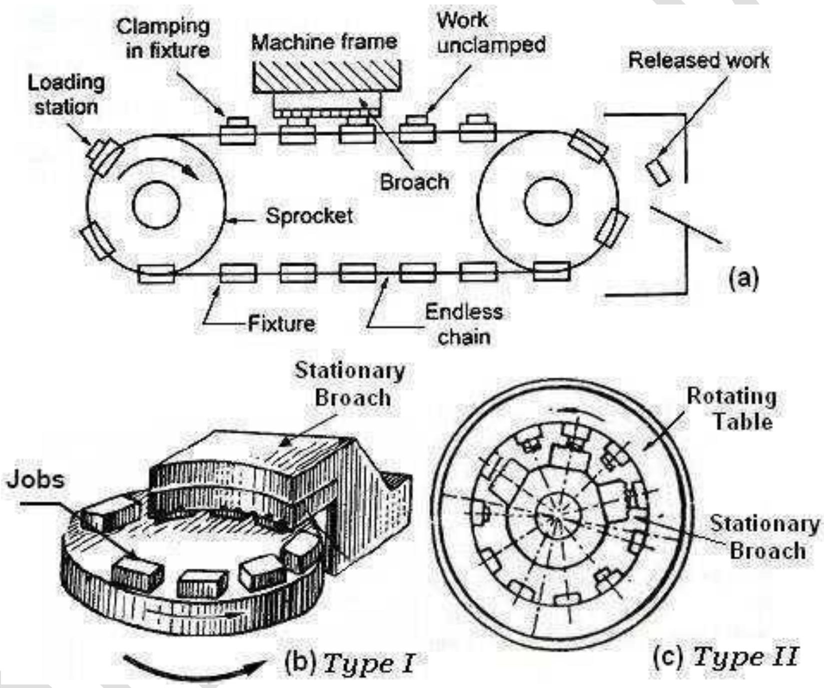


Fig. 1.32 Continuous broaching machine (a) Horizontal type (b) and (c) Rotary type

Rotary continuous broaching machine

Type I: This machine has a rotary table and a vertical column. The vertical column has a guide way. An arm is fixed in the vertical column and it moves up and down in the guide way. Work pieces are clamped in the fixtures horizontally above the work table. The broach is fixed underside of the arm. Now the work table is rotated and the broaching operation is carried out. Depth of cut is given by moving the work table in upward direction. *This is illustrated in Fig. 1.32 (b).*

Type II: This machine has a ring shaped rotating work table. Work pieces are clamped in the fixtures in the inner periphery of the work table. The stationary broaches are fixed in the outer periphery of the vertical column located inside the work table. Now the table is rotated and the broaching operation is carried out. *This is illustrated in Fig. 1.32 (c).*

Broaching operation and broaching machines are as such high productive but its speed of production is further enhanced by:

- Incorporating automation in tool – job mounting and releasing.
- Increasing number of workstations or slides for simultaneous multiple production.

- Quick changing the broach by turret indexing.
- Continuity of working

Thread chaser

A chaser is a multipoint threading tool having the same form and pitch of the thread to be chased. *An external thread chaser is shown in Fig. 1.33 (a).* A chaser is used to finish a partly cut thread to the size and shape required. *Fig. 1.33 (b) shows finishing of a partly cut thread by a thread chaser.* Thread chasing is done at about ½ of the speed of turning.

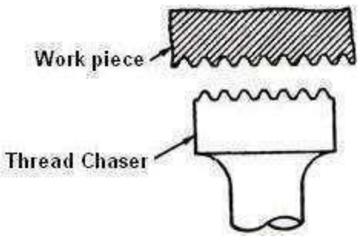


Fig. 1.33 (a) External thread chaser

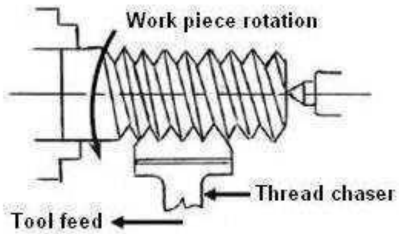


Fig. 1.33 (b) Finishing of a partly cut thread

HONING

Honing is a low abrading process which uses bonded abrasive sticks for removing stock from metallic and non-metallic surfaces. This process is used primarily to remove the grinding or the tool marks left on the surface by previous operations. However, it can be used for external cylindrical surfaces as well as flat surfaces. It is most commonly used for internal surfaces.

The advantages of honing are:

- Correction of geometrical accuracy.
- Dimensional accuracy.

Honing is a finishing process performed by a honing tool called as hone [shown in Fig. 1.34], which contains a set of three to a dozen and more bonded abrasive sticks. The sticks are equally spaced about the periphery of the honing tool. The sticks are held against the work surface with controlled light pressure, usually exercised by small springs.

The honing tool is given a complex rotational and oscillatory axial motion, which combine to produce a crosshatched lay pattern [shown in Fig. 1.35] of very low surface roughness. In addition to the surface finish of about 0.1 µm, honing produces a characteristic crosshatched surface that tends to retain lubrication during operation of the component, thus contributing to its function and service life.

A cutting fluid must be used in honing to cool and lubricate the tool and to help remove the chips. A common application of honing is to finish the holes. Typical examples include bores of internal combustion engines, bearings, hydraulic cylinders, and gun barrels.

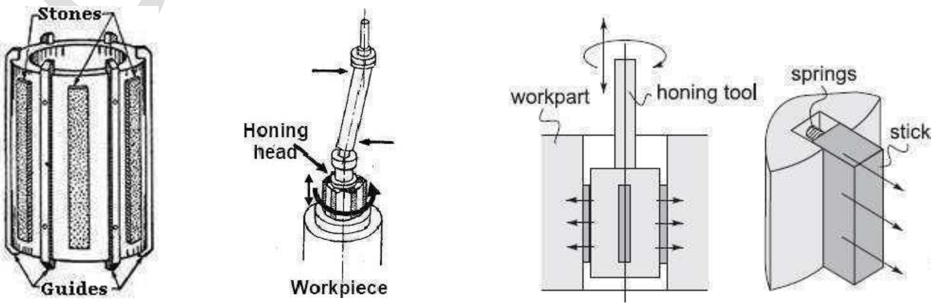


Fig. 1.34 Honing tool

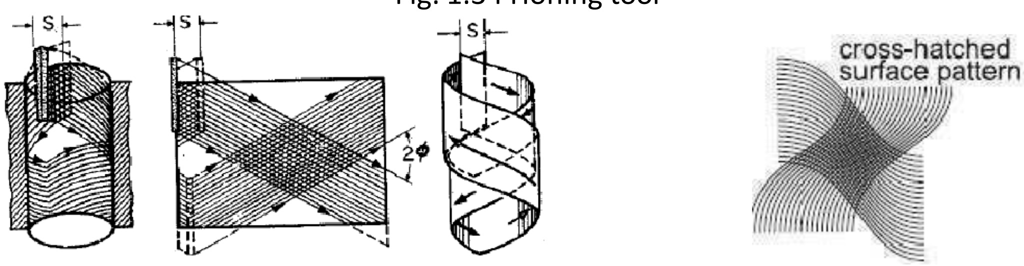


Fig. 1.35 Lay pattern produced by combination of rotary and oscillatory motion

54

The honing stones are given a complex motion so as to prevent every single grit from repeating its path over the work surface. *The critical process parameters are:*

- Rotation speed.
- Oscillation speed.
- Length and position of the stroke.
- Honing stick pressure.

With conventional abrasive honing stick, several strokes are necessary to obtain the desired finish on the work piece. However, with introduction of high performance diamond and CBN grits it is now possible to perform the honing operation in just one complete stroke. Advent of precisely engineered microcrystalline CBN grit has enhanced the capability further.

Honing stick with microcrystalline CBN grit can maintain sharp cutting condition with consistent results over long duration. Super abrasive honing stick with monolayer configuration, where a layer of CBN grits are attached to stick by a galvanically deposited metal layer [shown in Fig. 1.36], is typically found in single stroke honing application.

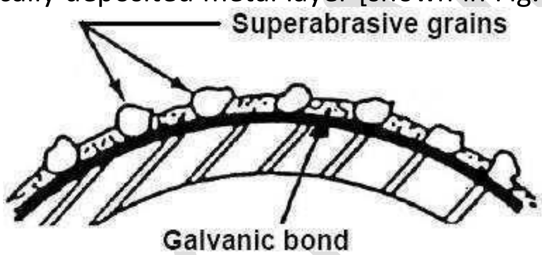


Fig. 1.36 Super abrasive honing stick with single layer configuration

With the advent of precision brazing technique, efforts can be made to manufacture honing stick with single layer configuration with a brazed metal bond. Like brazed grinding wheel such single layer brazed honing stick are expected to provide controlled grit density, larger grit protrusion leading to higher material removal rate and longer life compared to what can be obtained with a galvanically bonded counterpart.

LAPPING

Lapping is a surface finishing process used on flat or cylindrical surfaces. Lapping is the abrading of a surface by means of a lap (which is made of a material softer than the material to be lapped), which has been charged with the fine abrasive particles. *The process is employed toget:*

- Geometrically true surface.
- Extreme accuracy of dimension.
- Correction of minor imperfections in shape.
- Refinement of the surface finish, and
- Close fit between mating surfaces.

Lapping methods:

- Hand lapping for flat work.
- Hand lapping for external cylindrical work, (Ring lapping).
- Machine lapping.

In *lapping*, instead of a bonded abrasive tool, oil-based fluid suspension of very small free abrasive grains (aluminum oxide and silicon carbide, with typical grit sizes between 300 and 600) called a *lapping compound* is applied between the work piece and the lapping tool.

The lapping tool is called a *lap*, which is made of soft materials like copper, lead or wood. The lap has the reverse of the desired shape of the work part. To accomplish the process, the lap is pressed against the work and moved back and forth over the surface in a figure-eight or other motion pattern, subjecting all portions of the surface to the same action. Lapping is sometimes performed by hand, but *lapping machines* accomplish the process with greater consistency and efficiency.

The cutting mechanism in lapping is that the abrasives become embedded in the lap surface, and the cutting action is very similar to grinding, but a concurrent cutting action of the free abrasive particles in the fluid cannot be excluded. Lapping is used to produce optical lenses, metallic bearing surfaces, gauges, and other parts requiring very good finishes and extreme accuracy. Fig. 1.37 schematically represents the lapping process. Material removal in lapping usually ranges from .003 to .03 mm but many reach 0.08 to 0.1mm in certain cases.

Characteristics of lapping process:

- Use of loose abrasive between lap and the work piece.
- Usually lap and work piece are not positively driven but are guided in contact with each other.
- Relative motion between the lap and the work should change continuously so that path of the abrasive grains of the lap is not repeated on the work piece.

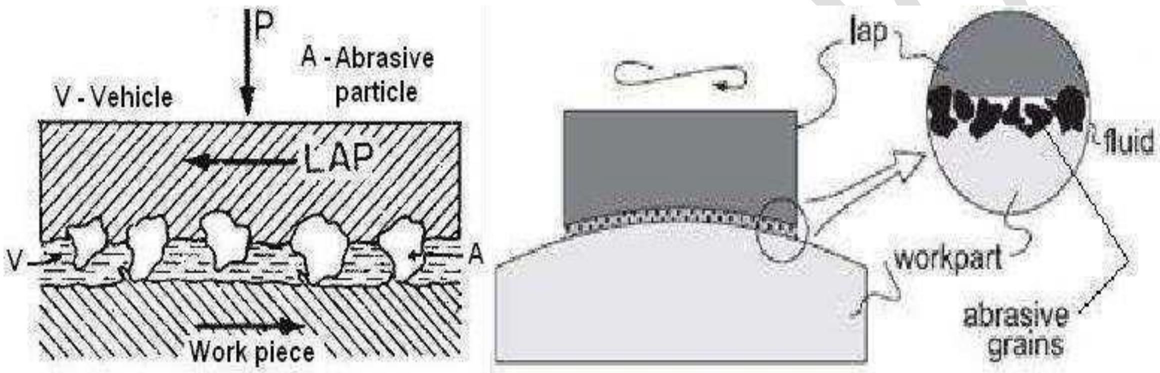


Fig. 1.37 Schematics of lapping process showing the lap and the cutting action of suspended abrasive particles.

Cast iron is the mostly used lap material. However, soft steel, copper, brass, hardwood as well as hardened steel and glass are also used.

Abrasives of lapping:

- Al_2O_3 and SiC, grain size 5~100μm.
- Cr_2O_3, grain size 1~2 μm.
- B_4C_3, grain size 5-60 μm.
- Diamond, grain size 0.5~5 V.

Vehicle materials for lapping:

- Machine oil.
- Rape oil.
- Grease.

Technical parameters affecting lapping processes are:

- Unit pressure.
- The grain size of abrasive.
- Concentration of abrasive in the vehicle.
- Lapping speed.

Lapping is performed either manually or by machine. Hand lapping is done with abrasive powder as lapping medium, whereas machine lapping is done either with abrasive powder or with bonded abrasive wheel.

Electro polishing

Electro polishing is the reverse of electroplating. Here, the work piece acts as anode and the material is removed from the work piece by electrochemical dissolution. The process is particularly

57

suitable for polishing irregular surface since there is no mechanical contact between work piece and

58

polishing medium. The electrolyte electrochemically etches projections on the work piece surface at a faster rate than the rest, thus producing a smooth surface. This process is also suitable for deburring operation.

BUFFING

Buffing is a finishing operation similar to polishing, in which the abrasive grains in a suitable carrying medium such as grease are applied at suitable intervals to the buffing wheel. Negligible amount of material is removed in buffing while a very high luster is generated on the buffed surface. Fig. 1.38 schematically shows the buffing process.

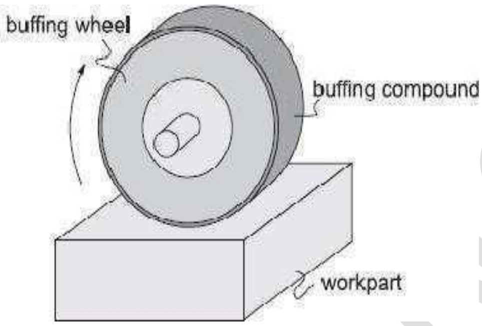


Fig. 1.38 Schematics of the buffing operation

As in polishing, the abrasive particles must be periodically replenished. As in polishing, buffing is usually done manually, although machines have been designed to perform the process automatically.

Polishing is used to remove scratches and burrs and to smooth rough surfaces while buffing is used to provide attractive surfaces with high luster. The dimensional accuracy of the parts is not affected by polishing and buffing operations.

External centreless grinder

This grinding machine is a production machine in which out side diameter of the workpiece is ground. The workpiece is not held between centres but by a work support blade. It is rotated by means of a regulating wheel and ground by the grinding wheel. In through-feed centreless grinding, the regulating wheel revolving at a much lower surface speed than grinding wheel controls the rotation and longitudinal motion of the workpiece. The regulating wheel is kept slightly inclined to the axis of the grinding wheel and the workpiece is fed longitudinally as shown in Fig. 1.39. C B A A

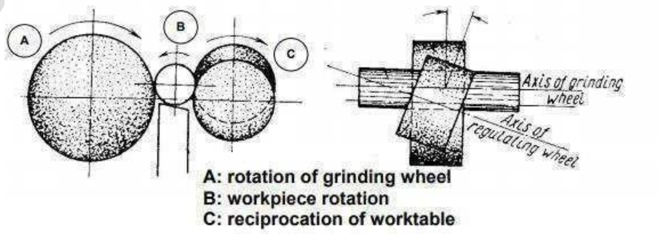


Fig 1.39 Centreless through feed grinding

Parts with variable diameter can be ground by Centreless infeed grinding as shown in Fig. 1.40(a). The operation is similar to plunge grinding with cylindrical grinder. End feed grinding shown in Fig. 1.40 (b) is used for workpiece with tapered surface.

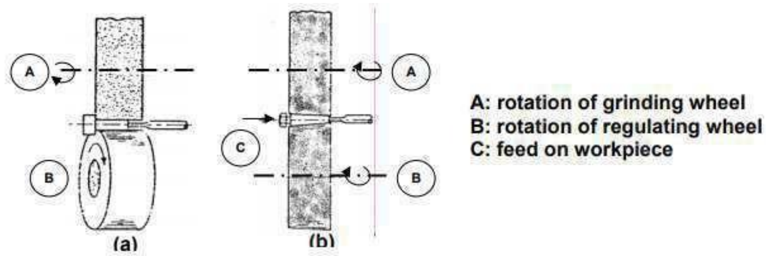


Fig. 1.40 Centreless (a) infeed and (b) end feed grinding

The grinding wheel or the regulating wheel or both require to be correctly profiled to get the required taper on the workpiece.

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Unit-2

GEAR MACHINING

Gears are important machine elements and widely used in various mechanisms and devices to transmit power and motion positively (without slip) between parallel, intersecting (axis) and non-intersecting non parallel shafts:

- Without change in the direction of rotation
- With change in the direction of rotation
- Without change of speed (of rotation)
- With change in speed at any desired ratio

Often some gearing system (rack – and – pinion) is also used to transform rotary motion into linear motion and vice-versa. There are large varieties of gears used in industrial equipments as well as a variety of other applications.

Special attention is paid to gear manufacturing because of the specific requirements to the gears. The gear tooth flanks have a complex and precise shape with high requirements to the surface finish. Gears can be manufactured by most of manufacturing processes. (casting, forging, extrusion, powder metallurgy, blanking, etc.)

But machining is applied to achieve the final dimensions, shape and surface finish in the gear. The initial operations that produce a semi finishing part ready for gear machining as referred to as blanking operations; the starting product in gear machining is called a gear blank.

Two principal methods of gear manufacturing include:

- **Gear forming** - where the profile of the teeth are obtained as the replica of the form of the cutting tool (edge); e.g., milling, broaching etc.
- **Gear generation** - where the complicated tooth profile are provided by much simpler form cutting tool (edges) through rolling type, tool – work motions, e.g., hobbing, gear shaping etc.

Each method includes a number of machining processes, the major of them discussed in this section.

Manufacture of gears needs several processing operations in sequential stages depending upon the material and type of the gears and quality desired. *Those stages generally are:*

- Preforming the blank without or with teeth.
- Annealing of the blank, if required, as in case of forged or cast steels.
- Preparation of the gear blank to the required dimensions by machining.
- Producing teeth or finishing the preformed teeth by machining.
- Full or surface hardening of the machined gear (teeth), if required.
- Finishing teeth, if required, by shaving, grinding etc.
- Inspection of the finished gears.

TYPES OF GEARS

Spur Gear

Gears having cylindrical pitch surfaces are called cylindrical gears. Spur gears belong to the parallel shaft gear group and are cylindrical gears with a tooth line which is straight and parallel to the shaft. Spur gears are the most widely used gears that can achieve high accuracy with relatively easy production processes. They have the characteristic of having no load in the axial direction (thrust load). The larger of the meshing pair is called the gear and smaller is called the pinion.

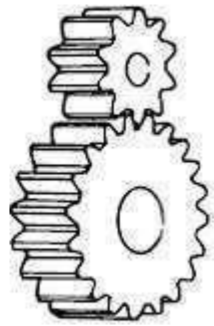


Fig.-2.1 Spur Gear

Helical Gear

Helical gears are used with parallel shafts similar to spur gears and are cylindrical gears with winding tooth lines. They have better teeth meshing than spur gears and have superior quietness and can transmit higher loads, making them suitable for high speed applications. When using helical gears, they create thrust force in the axial direction, necessitating the use of thrust bearings. Helical gears come with right hand and left hand twist requiring opposite hand gears for a meshing pair.

Fig.-2.2 Helical Gear

Gear Rack

Same sized and shaped teeth cut at equal distances along a flat surface or a straight rod is called a gear rack. A gear rack is a cylindrical gear with the radius of the pitch cylinder being infinite. By meshing with a cylindrical gear pinion, it converts rotational motion into linear motion. Gear racks can be broadly divided into straight tooth racks and helical tooth racks, but both have straight tooth lines. By machining the ends of gear racks, it is possible to connect gear racks end to end.

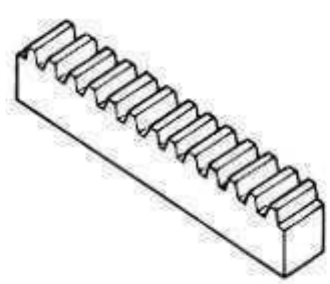


Fig.-2.3 Gear Rack

Bevel Gear

Bevel gears have a cone shaped appearance and are used to transmit force between two shafts which intersect at one point (intersecting shafts). A bevel gear has a cone as its pitch surface and its teeth are cut along the cone. Kinds of bevel gears include straight bevel gears, helical bevel gears, spiral bevel gears, miter gears, angular bevel gears, crown gears, zerol bevel gears and hypoid gears.

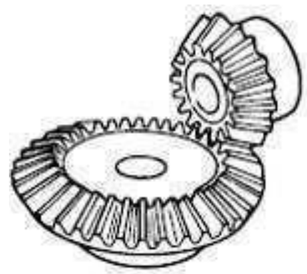


Fig.-2.4 Bevel Gear

Spiral Bevel Gear

Spiral bevel gears are bevel gears with curved tooth lines. Due to higher tooth contact ratio, they are superior to straight bevel gears in efficiency, strength, vibration and noise. On the other hand, they are more difficult to produce. Also, because the teeth are curved, they cause thrust forces in the axial direction. Within the spiral bevel gears, the one with the zero twisting angle is called zerol bevel gear.

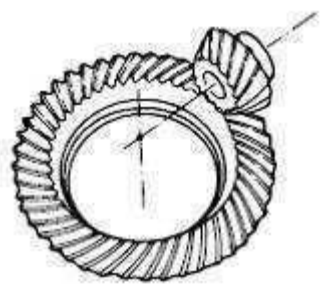


Fig.-2.5 Spiral Bevel Gear

Screw Gear

Screw gears are a pair of same hand helical gears with the twist angle of 45° on non-parallel, non-intersecting shafts. Because the tooth contact is a point, their load carrying capacity is low and they are not suitable for large power transmission. Since power is transmitted by the sliding of the tooth surfaces, it is necessary to pay attention to lubrication when using screw gears. There are no restrictions as far as the combinations of number of teeth.

Fig.-2.6 Screw Gear

Miter Gear

Miter gears are bevel gears with a speed ratio of 1. They are used to change the direction of power transmission without changing speed. There are straight miter and spiral miter gears. When using the spiral miter gears it becomes necessary to consider using thrust bearings since they produce thrust force in the axial direction. Besides the usual miter gears with 90° shaft angles, miter gears with any other shaft angles are called angular miter gears.

Fig.-2.7 Miter Gear

Worm Gear

A screw shape cut on a shaft is the worm, the mating gear is the worm wheel, and together on non-intersecting shafts is called a worm gear. Worms and worm wheels are not limited to cylindrical shapes. There is the hour-glass type which can increase the contact ratio, but production becomes more difficult. Due to the sliding contact of the gear surfaces, it is necessary to reduce friction. For this reason, generally a hard material is used for the worm, and a soft material is used for worm wheel. Even though the efficiency is low due to the sliding contact, the rotation is smooth and quiet. When the lead angle of the worm is small, it creates a self-locking feature.

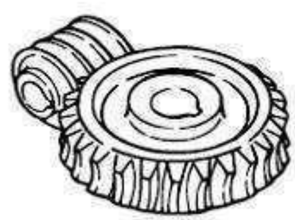


Fig.-2.8 Worm Gear

Internal gear

Internal gears have teeth cut on the inside of cylinders or cones and are paired with external gears. The main use of internal gears are for planetary gear drives and gear type shaft couplings. There are limitations in the number of teeth differences between internal and external gears due to involute interference, trochoid interference and trimming problems. The rotational directions of the internal and external gears in mesh are the same while they are opposite when two external gears are in mesh.

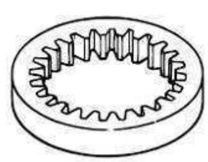


Fig.-2.9 Internal Gear

GEAR FORMING

Production of gears by gear forming method uses a single point cutting tool or a milling cutter having the same form of cutting edge as the space between the gear teeth being cut. This method uses simple and cheap tools in conventional machines and the setup required is also simple. *The principle of gear forming is shown in Fig. 2.10.*

Shaping, planning and slotting

Fig. 2.11 schematically shows how teeth of straight toothed spur gear can be produced in shaping machine. Both productivity and product quality are very low in this process. So this process is used only for making one or few teeth on one or two pieces of gears as and when required for repair and maintenance purpose. The planning and slotting machines work on the same principle. Planning machine is used for making teeth of large gears whereas slotting, generally, for internal gears.

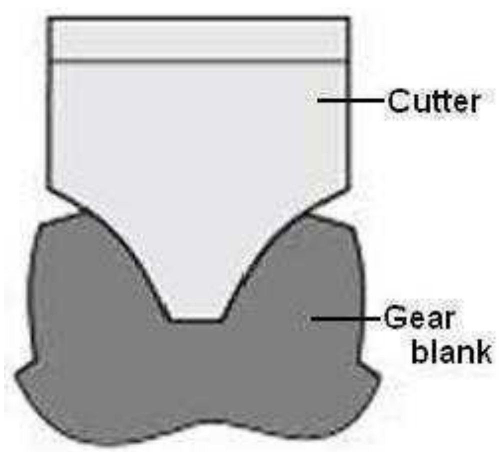


Fig. 2.10 Principle of gear forming

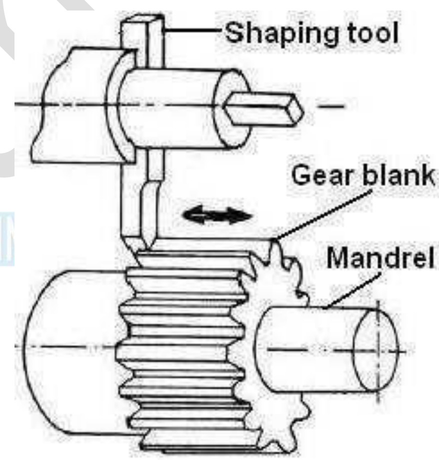


Fig. 2.11 Gear teeth cutting in ordinary shaping machine

Milling

Gear teeth can be produced by both disc type and end mill type form milling cutters in a milling machine. Fig. 2.12 illustrates the production of external spur gear teeth by using disc type and end mill type cutters. Fig. 2.13 shows the form cutters used for finishing cuts and for rough cuts. Fig. 2.14 illustrates the production of external helical gear teeth by using form milling cutter. Fig. 2.15 shows the dividing head and foot stock used to index the gear blank in form milling.

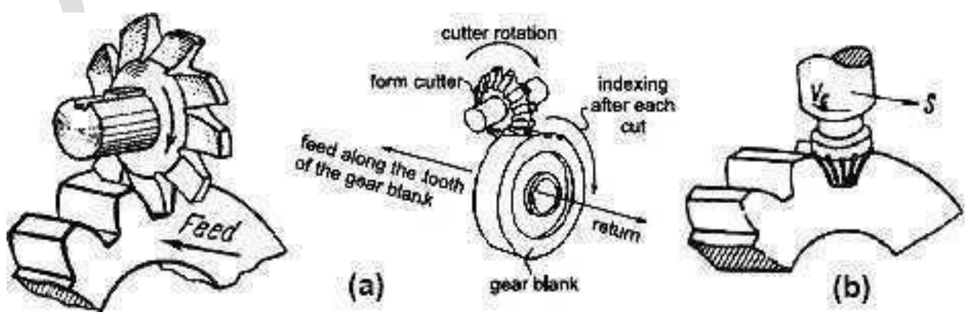


Fig. 2.12 Producing external teeth by form milling cutters

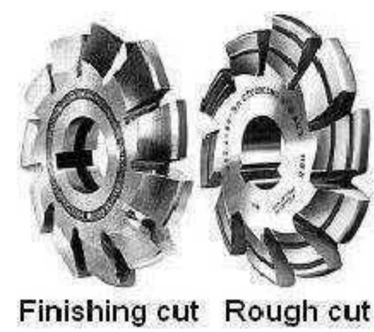
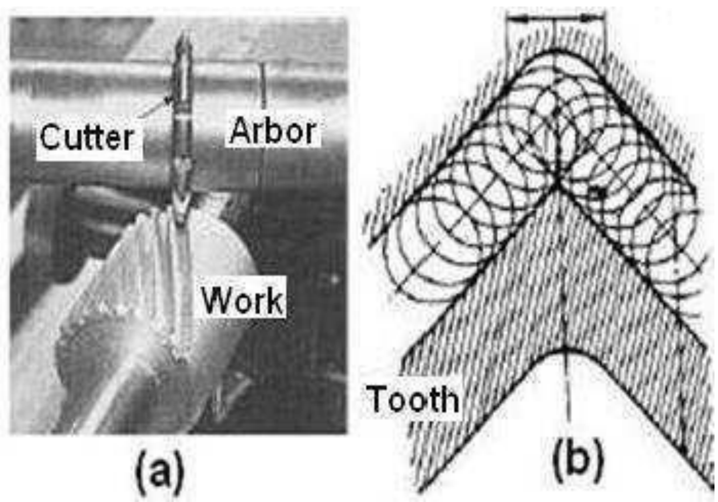


Fig. 2.13 Form milling cutters

(a) disc type and (b) end mill type



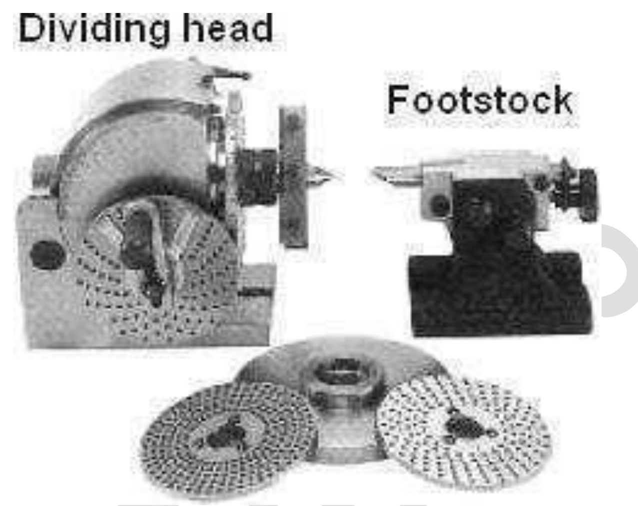


Fig. 2.14 Producing external teeth by form milling used cutters (a) single helical and (b) double helical teeth milling

Fig. 2.15 Dividing head and footstock to index the gear blank in form milling

The form milling cutter called DP (Diametral Pitch, used in inch systems which is equivalent to the inverse of a module) cutter have the shape of the teeth similar to the tooth space with the involute form of the corresponding size gear. These can be used on either horizontal axis or vertical axis milling machines, through horizontal axis is more common.

The cutting tool is fed radially into the work piece till the full depth is reached. Then the work piece is fed past the cutter to complete the machining of one tooth space. Milling of gears is relatively common process in machine shops; it is suitable for small volume production.

The work piece is actually mounted in the dividing head. In form milling, indexing of the gear blank is required to cut all the teeth. Indexing is the process of evenly dividing the circumference of a gear blank into equally spaced divisions. The index head of the indexing fixture is used for this purpose.

The index fixture consists of an index head (also dividing head, gear cutting attachment) and footstock, which is similar to the tailstock of a lathe. The index head and footstock attach to the worktable of the milling machine. An index plate containing graduations is used to control the rotation of the index head spindle. Gear blanks are held between centers by the index head spindle and footstock. Workpieces may also be held in a chuck mounted to the index head spindle or may be fitted directly into the taper spindle recess of some indexing fixtures.

Production of gear teeth by form milling are characterized by:

- Use of HSS form milling cutters.
- Use of ordinary milling cutters.
- Low production rate:
  - Need of indexing after machining each tooth gap.
  - Slow speed and feed.
- Low accuracy and surface finish.
- Inventory problem – due to need of a set of eight cutters for each module – pressure

angle combination.

- End mill type cutters are used for teeth of large gears and / or module.

Fast production of teeth of spur gears by parallel multiple teeth shaping

In principle, it is similar to ordinary shaping but all the tooth gaps are made simultaneously, without requiring indexing, by a set of radially in feeding single point form tools as indicated in Fig. 2.16. This old process was highly productive but became almost obsolete for very high initial and running costs.

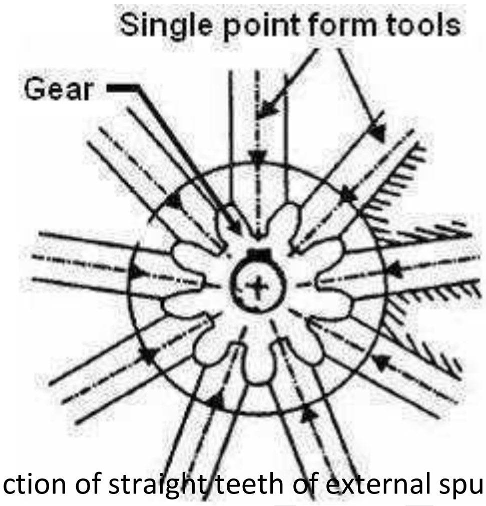
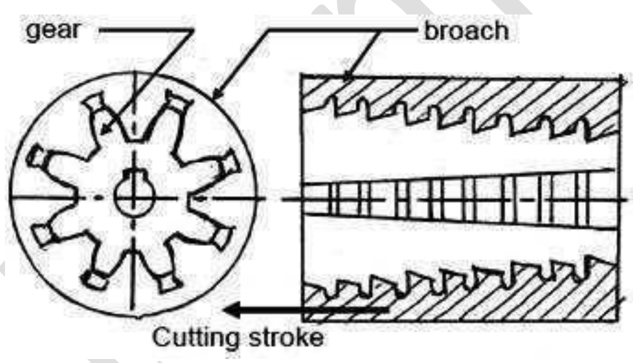


Fig. 2.16 High production of straight teeth of external spur gears by parallel shaping

Fast production of teeth of spur gears by Broaching

Teeth of small internal and external spur gears; straight or single helical, of relatively softer materials are produced in large quantity by this process. Fig. 2.17 (a and b) schematically shows how external teeth are produced by a broaching in one pass. The process is rapid and produces fine surface finish with high dimensional accuracy. However, because broaches are expensive and a separate broach is required for each size of gear, this method is suitable mainly for high-quantity production.



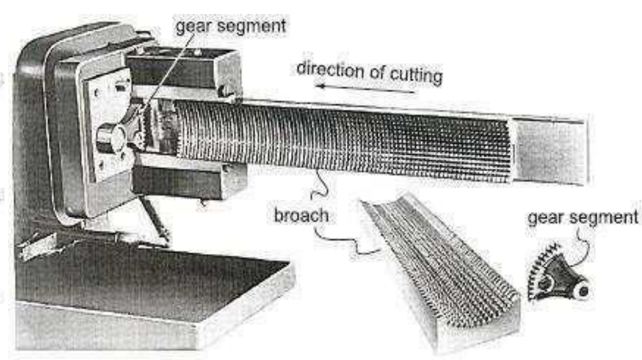


Fig. 2.17 (a) High production of straight teeth segment of external spur gears by broaching

Fig. 2.17 (b) Broaching the teeth of a gear by horizontal external broaching in one pass

GEAR GENERATION

To obtain more accurate gears, the gear is generally generated using a cutter, which is similar to the gear with which it meshes by following the general gear theory. The gears produced by generation are more accurate and the manufacturing process is also fast.

Generation method is characterized by automatic indexing and ability of a single cutter to cover the entire range of number of teeth for a given combination of module and pressure angle and hence provides high productivity and economy. These are used for large volume production.

In gear generating, the tooth flanks are obtained (generated) as an outline of the subsequent positions of the cutter, which resembles in shape the mating gear in the gear pair. In gear generating, two machining processes are employed, shaping and milling. There are several modifications of these processes for different cutting tool used:

- Milling with a hob (gear hobbing).
- Gear shaping with a pinion-shaped cutter.
- Gear shaping with a rack-shaped cutter.

Cutters and blanks rotate in a timed relationship: a proportional feed rate between them is maintained. Gear generating is used for high production runs and for finishing cuts.

Sunderland method using rack type cutter

Fig. 2.18 schematically shows the principle of this generation process where the rack type HSS cutter (having rake and clearance angles) reciprocates to accomplish the machining (cutting) action while rolling type interaction with the gear blank like a pair of rack and pinion.

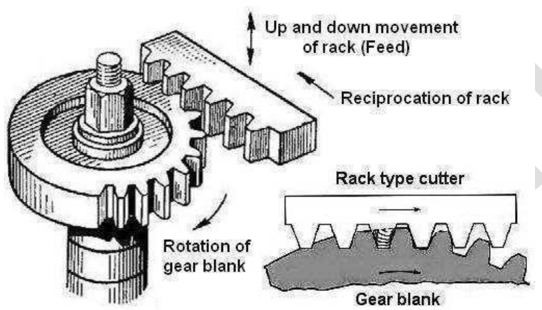


Fig. 2.18 External gear teeth generation by rack type cutter

The favorable and essential applications of this method (and machine) include:

- Moderate size straight and helical toothed external spur gears with high accuracy and finish.
- Cutting the teeth of double helical or herringbone gears with a central recess (groove).
- Cutting teeth of straight or helical fluted cluster gears.

However this method needs, though automatic, few indexing operations. Advantages of this method involve a very high dimensional accuracy and cheap cutting tool (the rack type cutter's teeth blanks are straight, which makes sharpening of the tool easy). The process can be used for low-quantity as well as high-quantity production of spur and helical external gears.

Gear shaping

In principle, gear shaping is similar to the rack type cutting process, except that, the linear type rack cutter is replaced by a circular cutter as indicated in Fig. 2.19, where both the cutter and the blank rotate as a pair of spur gears in addition to the reciprocation of the cutter. Fig. 2.20 schematically shows the generating action of a gear-shaper cutter.

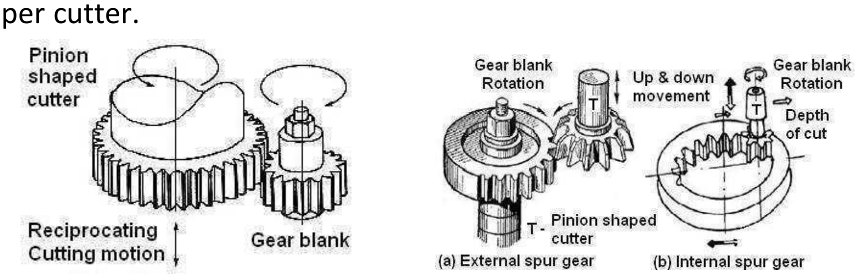


Fig. 2.19 Setup of gear teeth generation by gear shaping operation with a pinion-shaped cutter

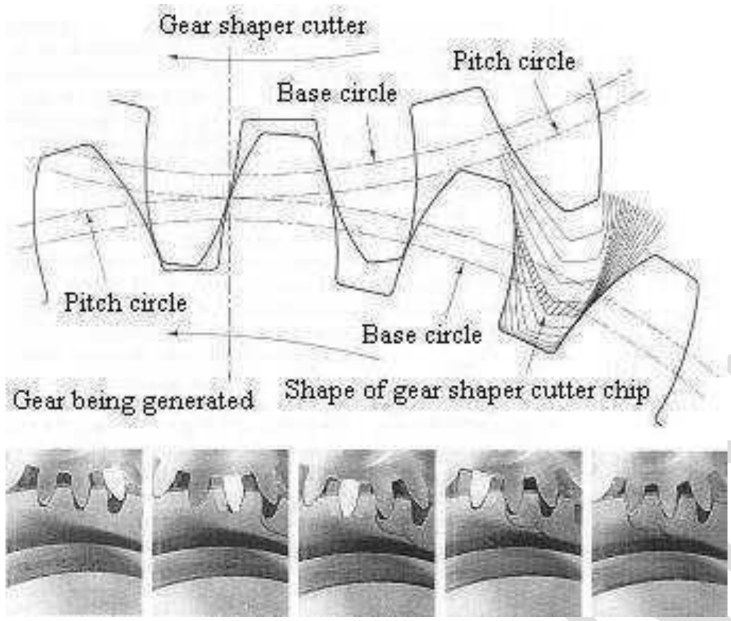


Fig. 2.20 Generating action of a gear-shaper cutter; (Bottom) series of photographs showing various stages in generating one tooth in a gear by means of a gear-shaper cutter, action taking place from right to left. One tooth of the cutter was painted white.

The gear shaper cutter is mounted on a vertical ram and is rotated about its axis as it performs the reciprocating action. The work piece is also mounted on a vertical spindle and rotates in mesh with the shaping cutter during the cutting operation. The relative rotary motions of the shaping cutter and the gear blank are calculated as per the requirement and incorporated with the change gears.

The cutter slowly moves into the gear blank surface with incremental depths of cut, till it reaches the full depth. The cutter and gear blank are separated during the return (up) stroke and come to the correct position during the cutting (down) stroke. Gear shaping can cut internal gears, splines and continuous herringbone gears that cannot be cut by other processes. The gear type cutter is made of HSS and possesses proper rake and clearance angles.

The additional advantages of gear shaping over rack type cutting are:

- Separate indexing is not required at all.
- Straight or helical teeth of both external and internal spur gears can be produced with high accuracy and finish.
- Productivity is also higher.

Gear hobbing

Gear hobbing is a machining process in which gear teeth are progressively generated by a series of cuts with a helical cutting tool (hob). The gear hob is a formed tooth milling cutter with helical teeth arranged like the thread on a screw. These teeth are fluted to produce the required cutting edges. All motions in hobbing are rotary, and the hob and gear blank rotate continuously as in two gears meshing until all teeth are cut. This process eliminates the unproductive return motion of the gear shaping operation. The work piece is mounted on a vertical axis and rotates about its axis.

The hob is mounted on an inclined axis whose inclination is equal to the helix angle of the hob. The hob is rotated in synchronization with the rotation of the blank and is slowly moved into the gear blank till the required tooth depth is reached in a plane above the gear blank.

The tool-work configuration and motions in hobbing are shown in Fig. 2.21, where the HSS or carbide cutter having teeth like gear milling cutter and the gear blank apparently interact like a pair of worm and worm wheel. The hob (cutter) looks and behaves like a single or multiple start worms. Having lesser number (only three) of tool – work motions, hobbing machines are much more rigid, strong and productive than gear shaping machine. But hobbing provides lesser accuracy and finish and is used only for cutting straight or helical teeth (single) of external spur gears and worm wheels.

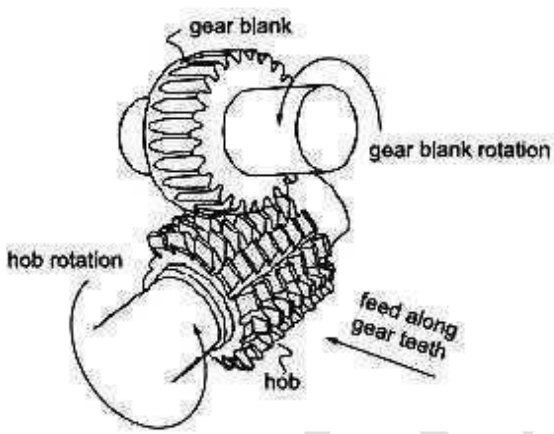


Fig. 2.21 Setup of gear hobbing operation

Fig. 2.22 shows the generation of different types of gears by gear hobbing.

When bobbing a spur gear, the angle between the hob and gear blank axes is 90° minus the lead angle at the hob threads. For helical gears, the hob is set so that the helix angle of the hob is parallel with the tooth direction of the gear being cut. Additional movement along the tooth length is necessary in order to cut the whole tooth length. Machines for cutting precise gears are generally CNC type and often are housed in temperature controlled rooms to avoid dimensional deformations.

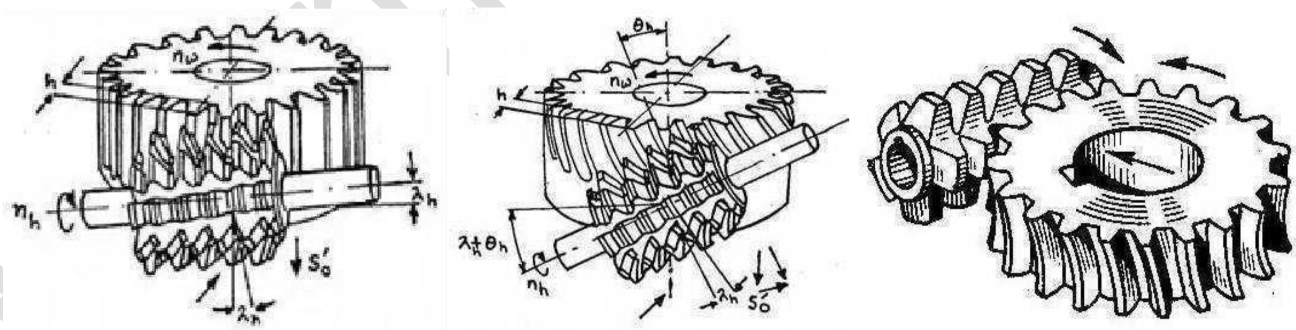


Fig. 2.22 Generation of external gear teeth by hobbing (a) spur gear (b) helical gear and (c) worm wheel

Unit-III
Plastics & Manufacturing of Plastics

Introduction

Plastics are commonly known as synthetic resins or polymers. In Greek terminology, the term polymer comprises 'poly' means 'many' and 'mers' means 'parts'. Thus, the term, polymer represents a substance built up of several repeating units, each unit being known as a monomer. Thousands of such units or monomers join together in a polymerization reaction to form a 'polymer'. Some natural polymers like starch, resins, shellac, cellulose, proteins, etc are vary common in today's use. Synthetic polymers possess a number of large applications in engineering work. Therefore plastic materials are fairly hard and rigid and can be readily molded into different shapes by heating or pressure or both. Various useful articles can be produced from them rapidly, accurately and with very good surface quality. They can be easily produced in different colors or as transparent. They are recognized by their extreme lightness, good corrosion resistance and high dielectric strength. Plastics are synthetic resins characterized as a group by plastic deformation under stress. These materials generally are organic high polymers (i.e. consisting of large chain like molecules containing carbon) which are formed in a plastic state either during or after their transition from a low molecular weight chemical to a high molecular weight solid material. These materials are very attractive organic engineering materials and find extensive applications in industrial and commercial work such as electrical appliances, automotive parts, communication products bodies (Telephone, Radio, TV), and those making household goods. They possess a combination of properties which make them preferable to other materials existing in universe.

Properties of plastics

The properties of plastics are given as under.

1. Plastics are light in weight and at the same time they possess good toughness strength and rigidity.
2. They are less brittle than glass, yet they can be made equally transparent and smooth.
3. Their high dielectric strength makes them suitable for electric insulation.
4. They resist corrosion and the action of chemicals.
5. The ease with which they can be mass-produced contributes greatly to their popularity as wrappers and bags.
6. They possess the property of low moisture absorption.
7. They can be easily molded to desired shapes.
8. They can easily be made colored.
9. They are bad conductance of heat.
10. They are hard, rigid and heat resistance.
11. They possess good deformability, good resistance against weather conditions, good color ability, good damping characteristics and good resistance to peeling.

Plastics are broadly classified into thermo plastics and thermo-setting plastics.

Thermo Plastics

Those plastics which can be easily softened again and again by heating are called thermoplastic. They can be reprocessed safely. They retain their plasticity at high temperature, i.e. they preserve an ability to be repeatedly formed by heat and pressure. Therefore, they can be heated and reshaped by pressing many times. On cooling they become hard. They are sometimes also called as cold-setting plastics. They can be very easily shaped into tubes, sheets, films, and many other shapes as per the need.

Types of Thermo Plastics

(A) Amorphous

1 Polystyrene
2 Acrylonitrite-butadiene-styrene
3 Mrthacrylate
4 P.V.C (Polyvinyl chloride)
5 Polychloroacetal
6 Auorinated polymers,
7 Polycarbonate etc.

(B) Crystalline

1 Polyethylene
2 Polyamides
3 Polyacetal

4 Polypropylene

The reason for the re-softening of thermoplastic resins with heat is that they are composed of linear or long chain molecules. Application of heat weakens the intermolecular bonds by increasing thermal agitation of the molecules, and the material softens and thus plastic can be easily molded and remolded without damage.

Thermo-Setting Plastics

Those plastics which are hardened by heat, effecting a non-reversible chemical change, are called thermo-setting. Alternatively these plastics materials acquire a permanent shape when heated and pressed and thus cannot be easily softened by reheating. They are commonly known as heat-setting or thermosets.

Thermosetting resins

(i) Phenol-formaldehyde resins
(ii) Urea-formaldehyde resins
(iii) Melamine-formaldehyde resins
(iv) Polyester resins
(v) Epoxy resins
(vi) Silicone resins

Comparison between Thermo Plastic and Thermosetting Plastic

S.No	Thermo Plastic	Thermosetting Plastic
1	They can be repeatedly softened by heat and hardened by cooling.	Once hardened and set, they do not soften with the application of heat.
2	They are comparatively softer and less strong.	They are more stronger and harder than thermoplastic resins
3	Objects made by thermoplastic resins cannot be used at comparatively higher temperature as they will tend to soften under heat.	Objects made by thermosetting resins can be used at comparatively higher temperature without damage
4	They are usually supplied as granular material	They are usually supplied in monomeric or partially polymerized material form in which they are either liquids or partially thermoplastic solids.
5	Applications. Toys, combs, toilet goods, photographic films, insulating tapes, hoses, electric insulation, etc.	Applications. Telephone receivers, electric plugs, radio and T.V. cabinets, camera bodies automobile parts, tapes, hoses, circuit breaker switch panels, etc.

Fabricating of Plastics

(a) Themo-plastics can be formed by

(i) Injection molding.
(ii) Extrusion.
(iii) Blow molding.
(iv) Calendaring
(v) Thermo-forming.
(vi) Casting.

(b) Thermosetting plastics can be formed by

(i) Compression or transfer molding.
(ii) Casting

Thermoplastics can be joined with the help of

(i) Solvent cements.
(ii) Adhesive bonding
(iii) Welding
(iv) Mechanical fasteners

Thermosetting plastics can be joined with the help of

(i) Adhesive bonding
(ii) Mechanical fasteners.

Composition and Structure of Plastics

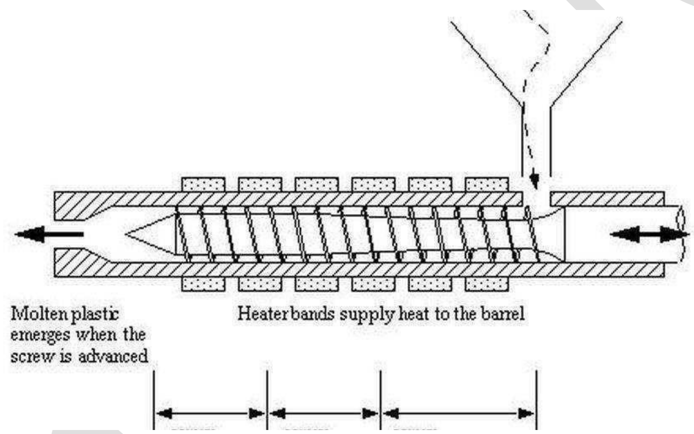
Plastics are mostly carbon-based atoms. Silicones are an exception since they based on the silicon atom. The carbon atom is capable of linking to other atoms with up to four chemical bonds. In plastics, the carbon atoms also link to hydrogen, oxygen, nitrogen, chlorine, or sulfur. When the linking of these atoms results in long chains, like pearls on a string of pearls, the polymer is termed as 'Thermoplastic'. Thermoplastics are meltable. All thermoplastics have repeating units, i.e. the smallest identical section of the chain. About vast majority of plastics are 92% thermoplastics.

To make unit cells a group of atoms is used called 'Monomers'. Upon the combination of monomers, we get polymers or plastics. All the monomers contain double bonds between carbon atoms such that the carbon atoms can subsequently react to form polymers.

The plastic behavior of polymers is influenced by their arrangement of molecules on a large scale. In other words, polymers are either amorphous or crystalline. The arrangement of molecules in the amorphous state is random and are intertwined. In crystalline state, the arrangement of molecules is in a closely identifiable manner. On the other hand, semicrystalline materials exhibit crystalline regions, called crystallites, within an amorphous matrix.

The chemical structure of the plastics can change, with the use of copolymers, and the chemical binding of different elements and compounds and on the other hand, the use of crystallizability can change the processing, aesthetic, and performance properties of plastics. Alteration of plastics can also happen by adding additives.

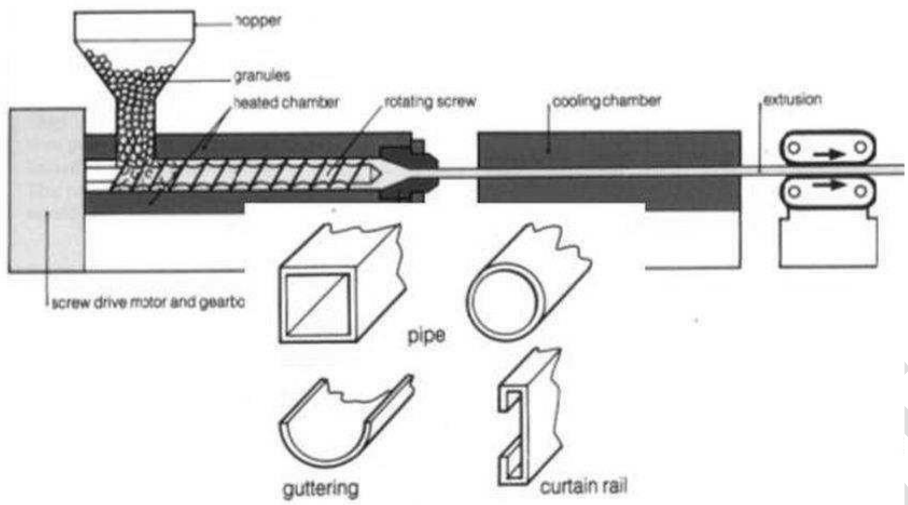
Plastic Injection Molding Process



Injection molding is one of the main methods by which parts are manufactured from plastic. The first step in the injection molding process is to feed plastic pellets into the hopper, which then feeds the pellets into the barrel. The barrel is heated and contains a reciprocating screw or a ram injector. A reciprocating screw is typically found in machines that produce smaller parts. The reciprocating screw crushes the pellets, making it easier for the plastic to be liquefied. Toward the front of the barrel, the reciprocating screw propels the liquefied plastic forward, thereby injecting the plastic through a nozzle and into the empty mold. Unlike the barrel, the mold is kept cool to harden the plastic into the correct shape. The mold plates are held closed by a large plate (referred to as a movable platen). The movable platen is attached to a hydraulic piston, which puts pressure on the mold. Clamping the mold shut prevents plastic from leaking out, which would create deformities in the finished pieces.

Plastic Extrusion Molding Process

Extrusion molding is another method of manufacturing plastic components. Extrusion molding is very similar to injection molding and is used to make pipes, tubes, straws, hoses and other hollow pieces. Plastic resin is fed into a barrel where it is liquefied. A rotating screw propels the liquefied plastic into a mold, which contains a tube-shaped orifice. The size and shape of the tube determines the size and shape of the plastic piece. The liquefied plastic then cools and is fed through an extruder, which flattens the plastic and forms the piece into its final shape.



Some common extrusions

Transfer Molding

Transfer molding process combines the principle of compression and transfer of the polymer charge. In the transfer molding, polymer charge is transferred from the transfer pot to the mold. The mold is cooled and molded part is ejected. The schematic of transfer molding process is shown in figure1.

In this process, the required amount of polymer charge is weighted and inserted into the transfer pot before the molding process. The transfer pot is heated by the heating element above the melting temperature of the polymer charge. The liquid charge is gravity filled through the sprue to the mold cavity. A “piston and cylinder” arrangement is built in the transfer pot so that the resin is squirted into the mold cavity through a sprue. The plunger is also preheated in the transfer pot. The plunger is used to push the liquid polymer charge from the transfer pot into the mold cavity under pressure. The mold cavity remains closed as the polymer charge is inserted. The mold cavity is held closed until the resin gets cured. The mold cavity is opened and the molded part can be removed once it has hardened with the help of ejector pin. The sprue and gate attached to the molded part have to be trimmed after the process has been completed.

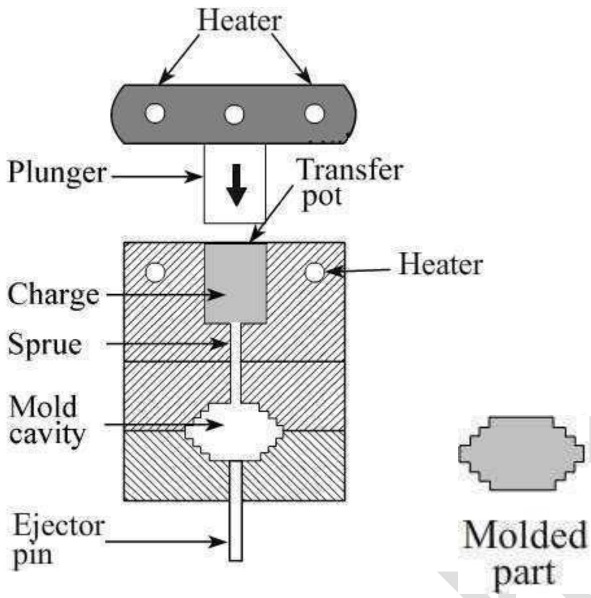


Figure Transfer molding process

This is used for mass production. It has short production cycle and smaller tolerances and more intricate parts can be achieved. It produces more waste material; therefore it is the more expensive process. The mold cavity can be made from metals such as aluminum or steel for larger production.

Process Parameters

- Heating time
- Melting temperature of the charge
- Applied pressure
- Cooling time

Materials Used

Generally, thermoset plastics (such as epoxy, polyester, phenol-formaldehyde, vinyl ester, silicone) are processed by transfer molding process, but certain thermoplastic materials can also be processed.

Applications

This process is widely used to encapsulate items such as integrated circuits, plugs, connectors, pins, coils, and studs. It is suitable for molding with ceramic or metallic inserts which are placed in the mold cavity. When the heated polymer fills the mold it forms bonding with the insert surface. Transfer molding is also used for manufacturing radio and television cabinets and car body shells.

Advantages

- Fast setup time and lower setup costs
- Low maintenance cost
- Plastic parts with metal inserts can be made
- Design flexibility
- Dimensionally stable
- Uniform thickness of parts
- Large production rate

Disadvantage:

- Wastage of material
- Production rate lower than injection molding
- Air can be trapped in the mold

Compression Molding

Compression molding process is one of the low cost molding methods as compared to injection molding and transfer molding. It is a high pressure forming process in which the molten plastic material is squeezed directly into a mould cavity by the application of heat and pressure to conform to the shape of the mold. The schematic of compression molding process is shown in figure.

Working Principle

In this process, the predetermined amount of charge of plastic material is placed in the lower half of a heated mold cavity. The plastic material is preheated before inserting into the mold cavity to reduce the temperature difference between the material and the mold cavity. The mold cavity is closed with upper movable half mold and pressure is applied to compress the material in to the mold cavity. This causes the raw material to be squeezed out to take the shape of the mold cavity. The application of the heat and pressure increases the polymerization process. Hence, plastic material is cured. The temperature of the mold cavity is usually in the range of 130- 200°C. Generally, the hydraulic pressure is required in the range of 7-25 MPa to squeeze the plastic material. The mold cavity is then cooled for sometimes so that molded plastic part gets solidified. The mould cavity is then opened and the final product is taken out with the help of ejector pin. The molded part may require the finishing operation.

In compression molding, the charge of plastic material may be inserted into the mold cavity either as a powder, granules or as a preformed. The manufacturing cycle time (heating, cooling, and part ejection) may be long (about 1-6 minutes). For high production rate, it is desirable to have multi cavity molds. Compression mold cavity can also be available in a wide variety of shapes and sizes; therefore plastic products can be manufactured into different shapes and sizes. There are four important factors to be considered before compression molding process:

- Amount of plastic material (charge)
- Heating time and melting temperature of plastic material
- Pressure required to squeeze the material in to the mold cavity
- Cooling time

Two different types of molding compounds i.e. bulk molding compound (BMC) and sheet molding compound (SMC) are commonly used in compression molding process.
In bulk molding compound, the plastic materials are blended with fillers and short fibers and placed into the mold cavity. In SMC, the long fiber sheet is usually cut according to the mold cavity and placed into the mold surface. The resin is placed on the fiber sheet. It is a layer by layer making process. The process is completed until desired thickness is obtained. The long fiber sheet results in better mechanical properties as compared with the bulk molding compound products. In both the molding compounds (BMC and SMC), the plastic materials are conformed to the mold cavity, with the application of heat and pressure.

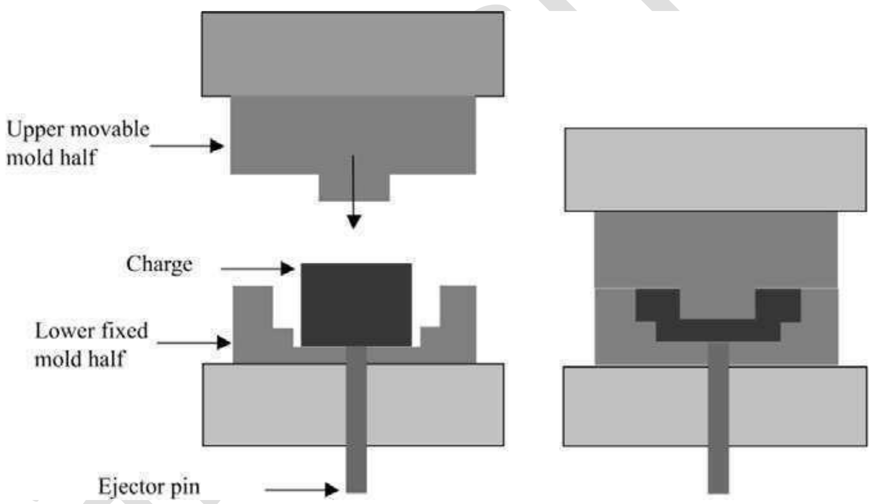


Figure Compression molding setup

Materials Used

Different types of thermosets and thermoplastics materials can be used for compression molding process. For example: Epoxies, Urea formaldehyde (UF), Melamine formaldehyde (MF), Phenolics (PF), Polyester, Polyamide (PI), Polyamide-imide (PAI), Polyphenylene sulfide (PPS), Polyetheretherketone (PEEK), Torlon, and Vespel.

Applications

Compression molding process is used for manufacturing electrical and electronic equipments (electrical wall receptacles, circuit breakers, television cabinets, radio cases, electric plugs and sockets, electrical switch, fuse box, electricity meter housing), brush and mirror handles, trays, cookware knobs, clothes dryer blower fan blade, cooking utensils, milling machine adjustment wheel, water testing equipment buttons, dinnerware, appliance housings, aircraft main power terminal housing, pot handles, dinnerware plates, automotive parts (such as hoods, fenders, scoops, spoilers, gears), flatware, buttons, buckles, and large container. Compression molding is also suitable for heavy molding applications.

Advantages

The advantages of the compression molding process are as following:

- Low initial setup costs and fast setup time
- Heavy plastic parts can be molded
- Complex intricate parts can be made
- Good surface finish of the molded parts
- Wastes relatively little material as compared with other methods
- The molding process is cheaper as compared to injection molding

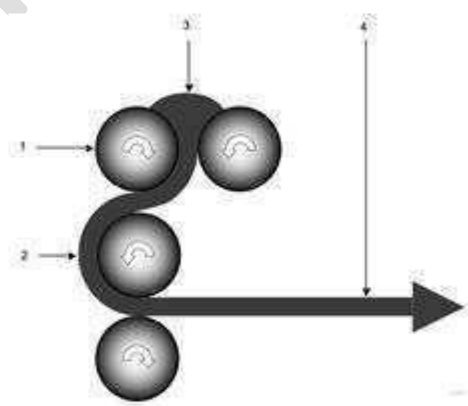
Disadvantages

The disadvantages of the compression molding process are as following:

- Low production rate
- Limited largely to flat or moderately curved parts with no undercuts

Calendering Process

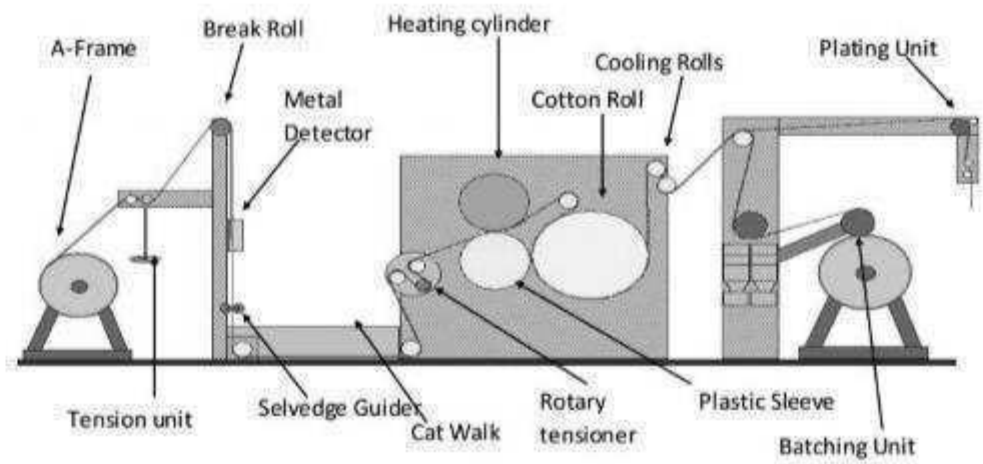
Calendering is a finishing process applied to textiles and plastic. During Calendering rolls of the material are passed between several pairs of heated rollers, to give a shiny surface. Extruded PVC sheeting is produced in this manner as well other plastics. Calendering is a final process in which heat and pressure are applied to a fabric by passing it between heated rollers, imparting a flat, glossy, smooth surface. Luster increases when the degree of heat and pressure is increased. Calendering is applied to fabrics in which a smooth, flat surface is desirable, such as most cotton, many linens and silks, and various man-made fabrics.



The molten material is fed to the calender rolls from a Banbury mixer and two-roll mill system, or from a large extruder. The major plastic material that is calendered is PVC. Products range from wall covering and upholstery fabrics to reservoir linings and agricultural mulching materials. Owing to the large separating forces developed in the calender gap, the rolls tend to bend. This may result in undesirable thickness variations in the finished product. Compensations for roll deflections are provided by using crowned rolls having a larger diameter in the middle than at the ends or by roll bending or roll skewing.

Calender installations require large initial capital investment. Film and sheet extrusion are competitive processes because the capital investment for an extruder is only a fraction of the cost of a calender. However, the high quality and volume capabilities of Calendering lines make them far superior for many products. Calendering in principle is similar to the hot rolling of steel into sheets. It is interesting to note that strip casting of semi-solid alloys can be modeled with the help of the hydrodynamic lubrication approximation for a power-law viscosity model, just like plastics calendering. The process of Calendering is also used extensively in the paper industry.

Passage of a Modern calendar machine:



Inlet unit: it contains tension device and break roll for even and proper feeding of fabric to the machine.
Metal detector: to detect metal particles in the fabric for avoiding damage to calenders rolls and fabric.
Cat walk: to avoid dust and dirt particle coming in contact with the fabric.
Calendering unit: this contains one steel roll, plastic coated roll and one cotton roll. Steel roll is heated with thermic fluid. Hydraulic oil is supplied in the plastic roll to give enough pressure on the steel roll. Cotton roll is used to increase the weight of the fabric.
Cooling rollers: are used to cool fabric after passing from calendar unit.
Batching / Plaiting device: is used to wind fabric or plaiting of the fabric in the trolley.

Advantages

- Improved appearance – Luster, Whiteness etc.,
- Improved Feel which depends on the handle of the fabric and its Softness, Suppleness, Fullness etc.,
- It improves the wearing qualities – Nonsoiling, Anti-crease.
- It gives special properties required for particular uses – Water proofing, Flame proofing etc.,
- It covers the faults of the original cloth.
- It increases the weight of the fabric.
- It increases the sale value of the material.
- It improves the natural attractiveness of the fabric.
- It improves the serviceability of the fabric.

Applications

Calendering is used for manufacturing sheet rubber in various thicknesses, for plasticizing and heating rubber stock, and for rubberizing fabric.

In textile manufacturing, Calendering is used for packing cotton, linen, and jute fabrics, adding luster to them, and applying embossed patterns.

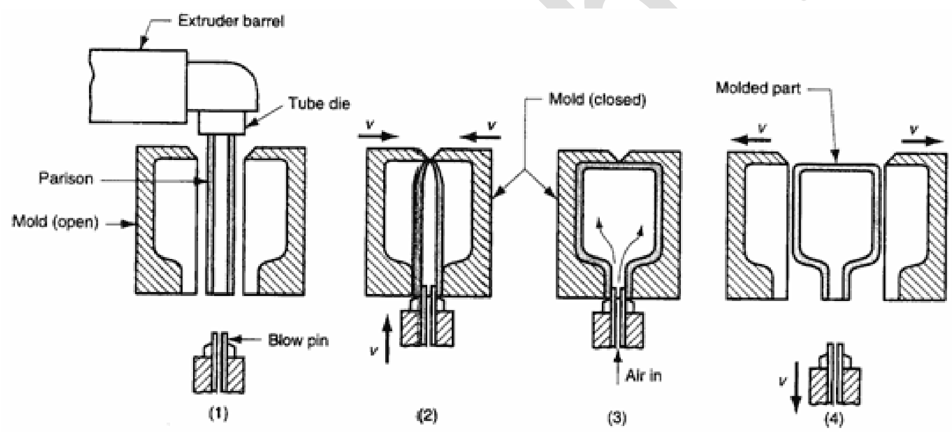
Blow Molding

Blow molding is a process in which manufacturers use air pressure to inflate soft plastic into a mold cavity. It’s a critical industrial process for making one-piece hollow plastic parts with thin walls, such as bottles and containers. Because

many blow molded items are used for mass marketed consumer beverages, blow molding manufacturers typically organize production with high quantities in mind. Manufacturers borrowed the molding technique from the glass industry, making them a competitor in the disposable and recyclable bottle market.
Blow molding consists of two steps:
Step 1: Fabricating a starting tube made of molten plastic called a parison (the same term used in glass blowing)
Step 2: Inflating the parison into the desired final shape

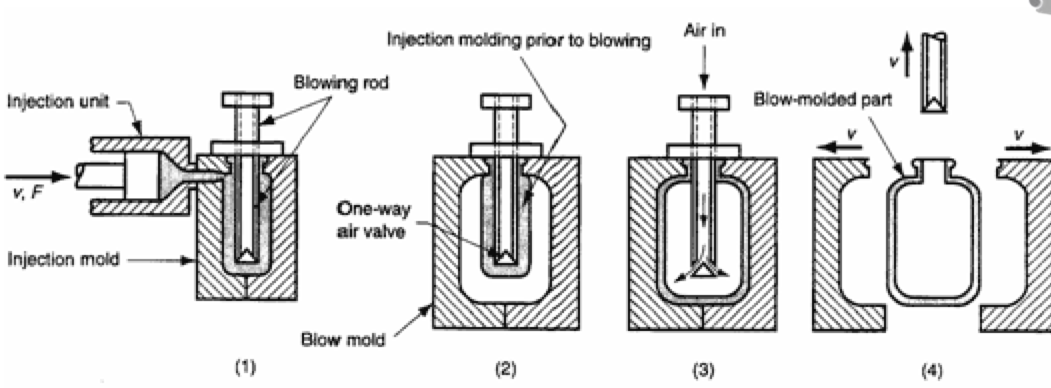
Extrusion Blow Molding
Custom injection molding companies use extrusion blow molding in high-production operations for making plastic bottles. The sequence is automated and is usually integrated with downstream operations, such as bottle filling and labeling. In general, blown containers must be rigid. A container's rigidity depends on several factors, such as wall thickness.
The extrusion blow molding cycle illustration below outlines the steps blow molding manufacturers take during the molding process:

- Extrude the parison
- Pinch the parison at the top and seal it at the bottom around a metal blow pin as the two halves of the mold come together
- Inflate the plastic tube so it takes the mold cavity's shape
- Open the mold and remove the solidified part



Injection Blow Molding
In the injection blow molding process, custom mold and design manufacturers inject-mold the starting parison instead of extrude it. Compared to its extrusion-based counterpart, the injection blow molding process has a lower production rate. Therefore, it isn't as widely used.
The injection blow molding process involves:

- Injection-mold the parison around a blowing rod
- Open the injection mold and transfer the parison to a blow mold
- Inflate a soft polymer to conform to a blow mold
- Open the blow mold and remove the blown product



Injection blow molding: (1) parison is injection molded around a blowing rod; (2) injection mold is opened and parison is transferred to a blow mold; (3) soft polymer is inflated to conform to a blow mold; and (4) blow mold is opened and blown product is removed.

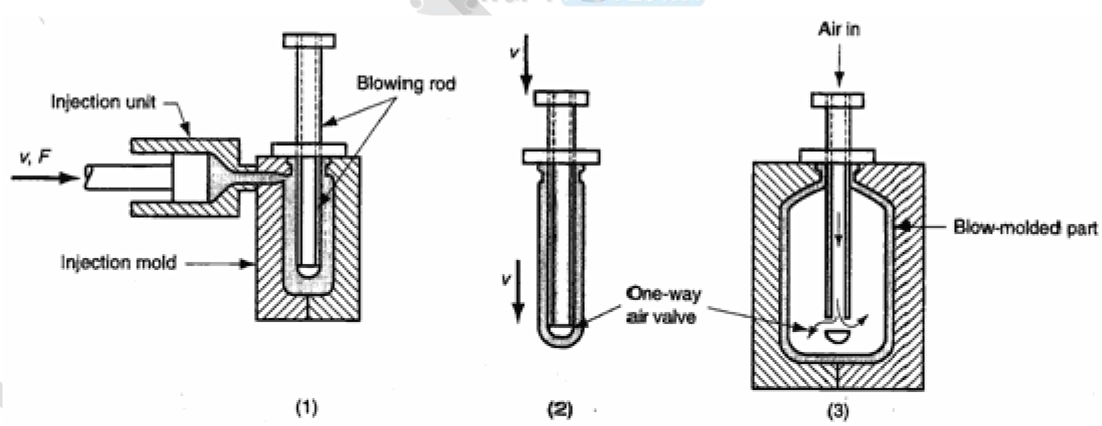
Stretch Blow Molding

Custom injection molding companies use a variation of injection blow molding called stretch blow molding. The technique involves extending a blowing rod downward into the injection molded parison (see step 2). This stretches the soft plastic and creates a more favorable stressing of the polymer than conventional injection blow molding or extrusion blow molding. As a result, the structure is more rigid, has higher transparency, and is more impact-resistant.

For this type of custom plastic injection molding, polyethylene terephthalate (PET) is the most popular material used. PET is polyester with low permeability. The stretch-blow-molding process strengthens it. The combination of PET's properties makes it ideal for making containers for carbonated beverages.

Stretch blow molding steps include:

- Injection molding the parison
- Stretching
- Blowing



Stretch blow molding: (1) injection molding of the parison; (2) stretching; and (3) blowing.

Blow Molding Materials and Products

Blow molding manufacturers are limited to thermoplastics. Polyethylene (PE) is the polymer of choice for blow molding because of its high density (HDPE) and high molecular weight polyethylene (HMWPE).

When comparing the properties of HDPE and HMWPE with a more affordable low-density PE in regard to the stiffness-related requirements of the final product, it's more economical to use the more expensive materials because it's possible to make a container's walls thinner.

Other materials used for blow molding include:

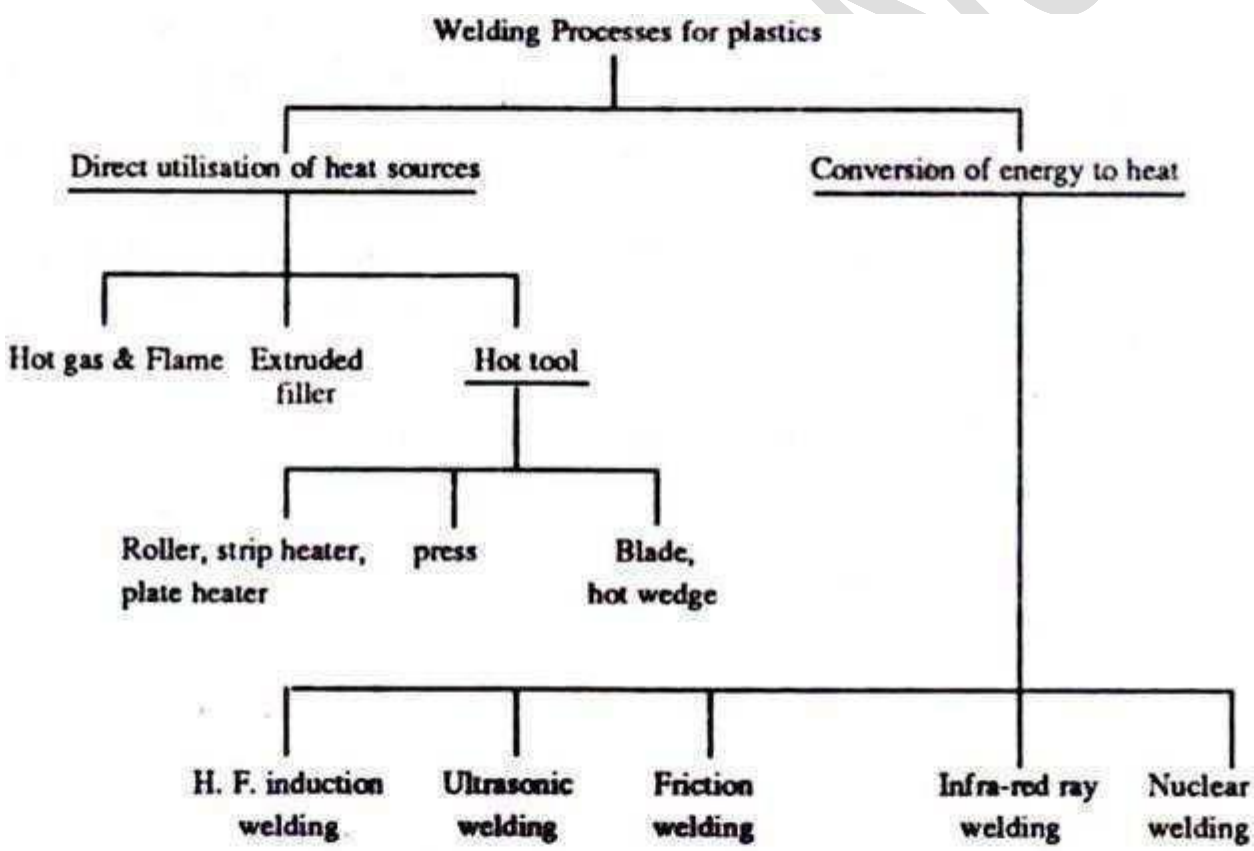
- Polypropylene (PP)
- Polyvinylchloride (PVC)
- Polyethylene terephthalate

Disposable containers for packaging liquid consumer goods make up the bulk of products made using blow molding. Custom injection molding companies use the technique to make other products, too, such as:

- 55-gallon shipping drums for liquids and powders
- 2,000-gallon storage tanks
- Automotive gasoline tanks
- Toys
- Sailboard and small boat hulls
- Small boat hulls are made using a single blow molding and cutting the finished product into two open hulls

Welding Process for Plastics

Welding of plastics is widely used in a number of industries particularly for joining of thermoplastic films and sheets. All welding processes employed at present involve the application of heat to the area of contact. According to the source of heat employed the welding process for plastics may be divided into two broad classes as shown in Fig.



A. Direct Utilisation of Heat Sources:

One class of welding processes utilises heat from an extraneous source such as a stream of hot gas, a hot extruded filler material, or a hot tool. In all these processes heat is transferred to the surfaces being welded by conduction, convection, and radiation.

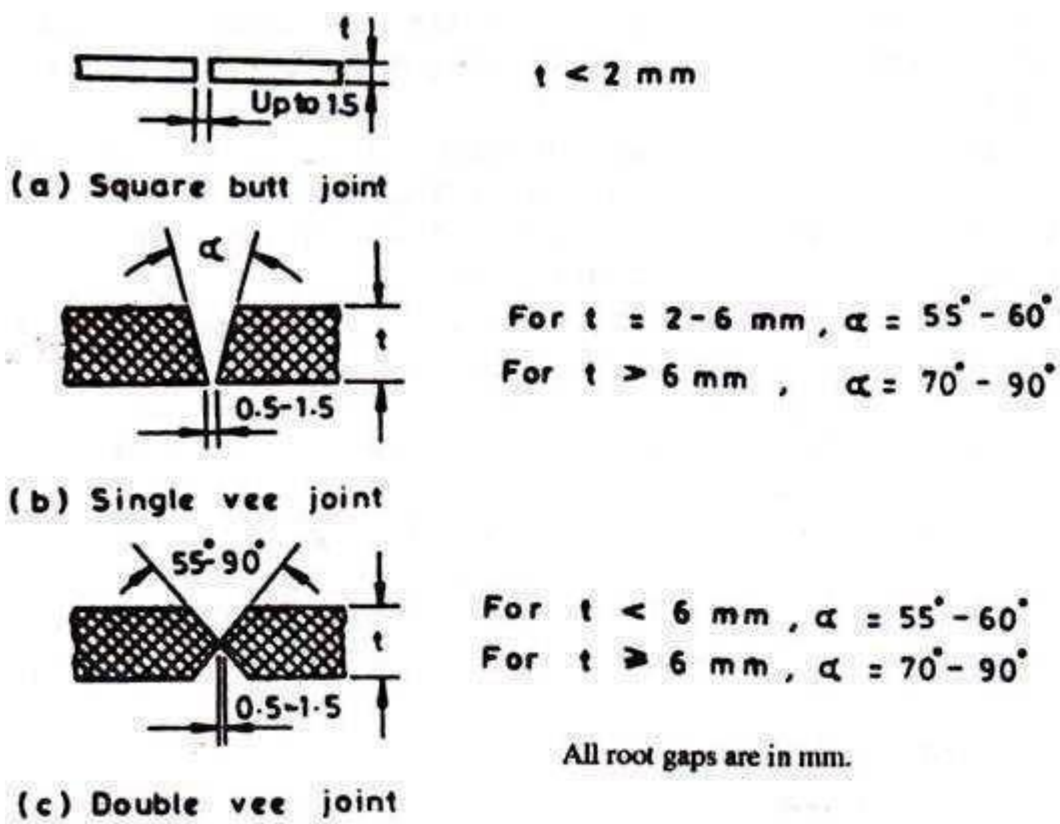
The second group includes processes in which heat is generated within the workpiece through conversion of some other form of energy such as high frequency current, ultrasonic waves, friction, infra-red light, chemical reactions, or neutron irradiation.

The mechanism of welding of plastics is considered to be the phenomenon of auto-cohesion by which welding is accomplished by the diffusion of some molecular chains from one piece into another to form a strong macro-molecular bond between the two pieces.

Welding of plastics is done in the viscous fluidic state under the application of pressure. Better weld ability is shown by thermoplastics which have a wider softening range rather than a sharp melting point. Because the coefficient of thermal

expansion of plastics is several times that of metals, residual stresses may develop in the weldment resulting in reduced joint strength.
The factors affecting process selection for welding of plastics include workpiece thickness, physio-chemical properties of the plastic, design of the article, and the number of components to be produced. The filler material used in welding plastics should be as close in mechanical properties to the parent material as possible.

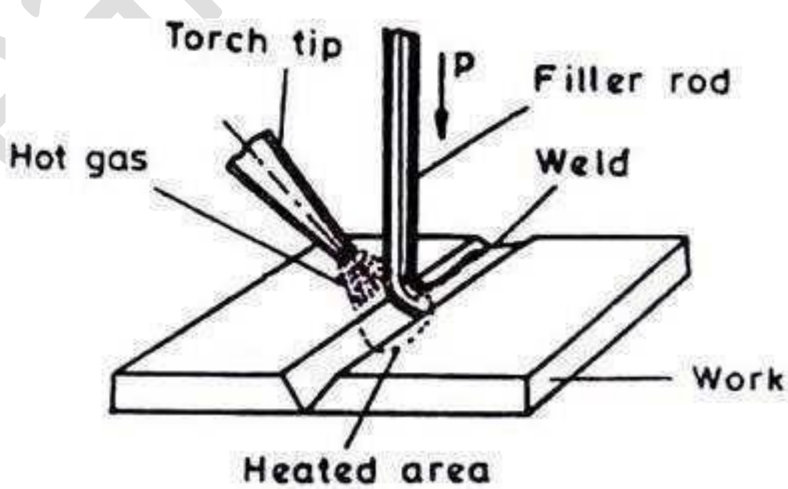
1. Hot Gas Welding:
In this process a jet of hot gas which may be air, nitrogen, argon, products of combustion of some fuel gas (for example, acetylene, hydrogen, LPG) is played on the edges to be joined as shown in Fig. Fuel gas cannot be used directly to weld plastics because the flame has a very high temperature.
That is why special torches have been developed for the hot gas welding of plastics. The welding gas may be heated by electricity or by flame. Air temperature can be adjusted by varying its flow rate and the resistance of the electric element.
The flow rate is set anywhere between 25 and 30 m/sec with a valve, and the resistance of the circuit with a rheostat. Air temperature can be checked by placing the tip of the torch within 5 mm of the bulb of a mercury thermometer. If the thermometer reads the required temperature in 10 to 15 second the operator may proceed with welding.
For operator safety, electrically heated torches operate on voltage not exceeding 36 volt. The efficiency of electrically heated torches is 60 percent. Such torches are simple to make and there is no open flame therefore these may be used in room holding inflammable materials. However, these torches are heavy and, thus, rather unwieldy for use in places difficult of access or in awkward positions.
Gas torches may be either directly or indirectly heated. In directly heated gas torches the welding gas is mixed with the products of combustion of fuel gas while in indirectly heated gas torches the products of combustion transfer their heat to the welding gas through the wall. The fuel gas (C_2H_2, H_2 LPG, etc.) is used under a pressure of 0.5 to 10 N/cm^2.
In comparison with electrically heated torches gas torches can weld at a higher rate, are lighter in weight and more durable. When used eight hours a day, the service life of a gas torch is 1.5 to 2 years. A major drawback of gas torches is that the gases used are inflammable and explosive.



All root gaps are in mm.

Usually butt joints are preferred because lap, tee, and fillet joints are more difficult to make. Depending upon the work thickness, square edge, single vee, and double vee edge preparations are employed for butt joint preparation as shown in Fig. 22.16. The standard edge preparation for butt welds requires a root gap but no root face.
Double vee joints are usually stronger than single vee joints and the groove angle has a decisive effect on joint strength. As a rule joint strength increases as the groove angle is increased because better penetration is obtained at the root; however the production rate is lowered.

Welding Procedure:
The fusion faces are carefully cleaned and de- greased,-say with acetone; the glossy spots are removed with emery paper or scraper. Before welding torch is switched on or fired the welding gas is turned on and its flow rate adjusted. The gas is then fired in case of a gas torch or electric current switched on for an electric torch.
Filler rods used come in diameters of 2, 3, 4, ± 0.5 mm and other shapes like triangular and trapzoidal of different sizes. The filler rods are fabricated from the same material as the work material but may be of different colour and usually contain higher percentage of plasticizer to lower down its softening point.
The filler rods may either be cut to lengths of at least 0.5 m and tied up in bundles or uncut and supplied in coils of 3 to 4 kg. The size of filler rod is chosen to suit the work thickness, type of edge preparation and the strength desired. Thicker rods usually result in reduced joint strength.
The torch tip size is selected depending upon work thickness, and edge preparation. Tips with orifice diameter of 1-5 – 2 mm are used to weld sheets 3 to 5 mm thick while tips with diameter of 3-5 – 4 mm are used for sheets 16 to 20 mm thick. As a rule the orifice diameter of a tip should be equal to the diameter of filler rod used. Otherwise the rod will not be heated adequately and the strength of the joint will be impaired.
The torch-to-work angle is chosen in relation to material thickness. For sheet under 5 mm this angle should preferably be 20°-25° and for sheets in the range of 10—20 mm, it should be 30°- 45°. The torch tip-to-work distance should be kept constant between 5-8 mm. To produce a good bond between the filler and the work the rod should be heated and fused at the start of the weld so that its end extends 3—5 mm beyond the end of the work.
The hot gas stream must not be directed in any one position, instead it should be moved continuously over a short length of the welding rod and the surface being welded so as to heat both uniformly. The joint edges and the filler rod are rapidly heated at the surface because plastics are poor conductors of heat.
However, it is essential to heat the rod throughout its bulk so that it can be thoroughly softened at the center and properly placed in the groove. That is why thicker rods cannot be used and welding is slow by hot gas process particularly with filler rod technique. If the pressure is not applied properly the softened rod is compressed in the direction opposite to its motion which produces waviness in it.
The filler rod should be fed square to the weld so as to exert proper control of pressure. As the filler rod is forced down by hand it welds to the softened edges and forms a weld, as shown in Fig.



Hot gas welding without filler rod accelerates the process and enhances the mechanical properties of the joint. A simple setup for this technique is shown is Fig. (c). In this method the sheet edges are scarfed and fitted before being uniformly heated by hot gas.

The hot gas jet is followed by cold rollers which exert the required pressure to complete the weld. Welding rate with this technique may be 12 to 20 m per hour, depending upon sheet thickness. The strength of the joint is 80 to 90 percent that of the parent material and the impact strength remains the same. Hot gas welding without filler material is most often applied to make lap joints in films.

For critical joints it is better to seal the weld root to improve the joint strength and quality.

After welding the joint is allowed to cool. Artificial cooling particularly in material thicker than 10 mm may lead to cracking.

The strength of butt welds in plastics is 65% that of the parent material in shear, 75% in tension, 85% in compression, and 65% in bending while that of fillet weld is 65% in tension. The impact strength of the weld material is usually very low.

Apart from low strength of the joint hot gas welding also results in reduced plasticity in the weld and near-weld area, low production rate especially in thick sheets, danger of overheating and dependence on the operator skill. Inspite of these limitations hot gas welding is widely used for welding PVC, polyethylene, acrylics, and polyamide.

For welding PVC, hot gas welding process is most often used. PVC has no sharp melting point. At a temperature of over 80°C it softens. At 180°C it begins to flow, and at 200 – 220°C it passes into viscous fluidic state; if pressure is then applied it will weld. The welding temperature must be kept below the critical point at which the material begins to decompose.

To obtain an optimal temperature of 200 – 220 °C for hot air in the welding zone, it should be heated to 230 – 270°C in the torch. The effect of air temperature on welding rate and joint strength are presented in table.

Air temperature (°C)	Welding rate for single run (m/h)	U.T.S. for double vee joint (N/mm²)	Joint efficiency (%)	Remarks
210	4.8	14	25	Indirectly heated gas torch.
230	8.4	34	25	Air pressure 0.6 atmosphere.
250	11.4	32	58	Tip diameter, 2.5 mm.
270	13.8	35	63	Rod diameter, 2.5mm.
300	15.0	17	30	
320	Material decomposes.			

If a correct welding temperature has been chosen, a dull spot appears on the PVC sheet 2 or 3 seconds after the jet of hot air has been played on it.

Weld quality in PVC depends upon the rate at which the filler rod is fed into the joint, the angle at which it is fed into the joint, the force applied to press the heated rod into the joint, the distance of the torch tip from the work surface, the position and direction of the torch during welding. A filler rod 3 mm in diameter should be fed to the joint at a rate of 12 to 15 m per hour.

Welds made in PVC by hot gas filler rod technique show a low impact strength. PVC is sensitive to stress concentration to such an extent that even when a rod is welded to a tube the impact strength of the joint is just about 10% of the impact strength of the parent material.

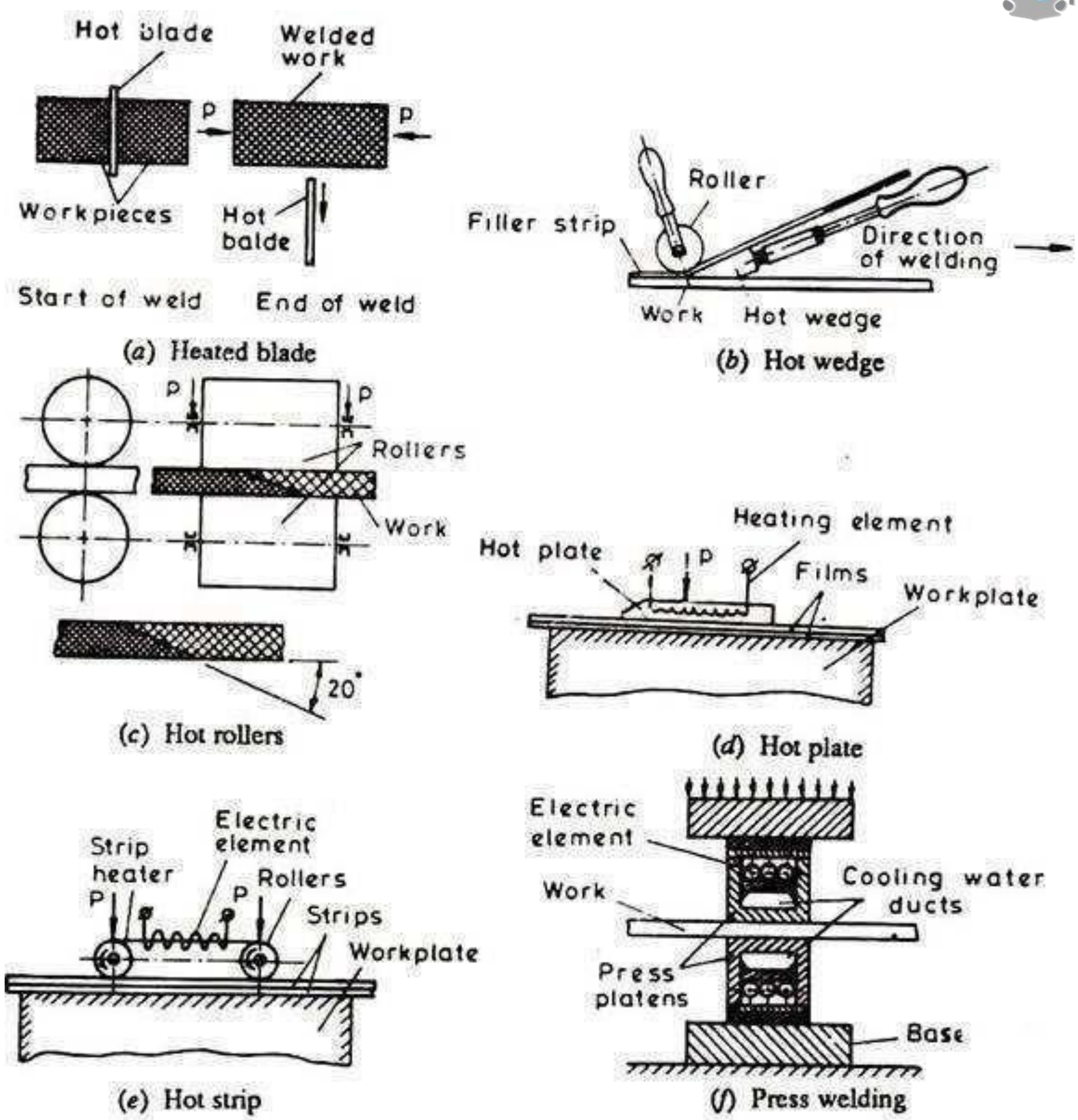
The welding of PVC by hot gas welding is a slow process. For example to weld one metre of PVC, 18—20 mm thick, with V edge preparation it is necessary to lay 30 to 35 rods, 3 mm in diameter, requiring about 2 hours to accomplish the job. The welding speed can be increased by raising the gas temperature to 300°C and by preheating the filler rod but this requires careful monitoring of the process otherwise the higher temperature may lead to the decomposition of the material.

Acrylics are welded with a jet of air of 200 – 220 °C. Time taken for welding acrylic sheet is almost double that required for PVC sheet of the same thickness, and the welding rate is therefore nearly halved. The filler rods used are cut from acrylic sheet and have a cross-sectional area of 7—12 mm^2. Acrylics can also be welded satisfactorily by using PVC filler

rods. To achieve quality welds in acrylics it is best to degrease the surfaces to be welded with acetone or dichloromethane prior to welding. The tensile strength of welded joints in acrylics is generally 3P – 45 % that of the parent material.
Polyethylene should preferably be welded with N_2 or CO_2 gas heated to 200— 220 °C, although gas flame torches may also be used.
Hot gas welding is also frequently used to weld vynil plastics, polystyrene, and some other plastic materials.
The major use of hot gas welding is in the production of very large fabrications made from sheet materials, for example, ducting, pipe work and ventilator hoods for chemical plant installations. This method is normally not used for joining small parts.

2. Extruded-Filler Welding:
In this method the filler in a viscous fluidic state is fed into the joint. The hot filler material melts the edges of the plastic being joined and a strong bond is formed between the filler and the parent material. In a way this process resembles the hot gas process with filler rod technique. Satisfactory welds can be accomplished by this process both in films and heavy gauge sheets.

3. Hot Tool Welding:
This process can be performed by several techniques depending upon the type of tool employed which may include hot blade, hot wedge, hot plate, strip heater or a press.
In hot blade welding, the heated blade is placed between the surfaces to be joined as shown in Fig. (a). After the hot blade has softened the surfaces it is rapidly withdrawn and the surfaces are brought in contact under pressure to accomplish the weld. This process can be used to make butt and lap joints over the entire surface of contact at the same time.



(a) Heated blade (b) Hot wedge (c) Hot rollers (d) Hot plate (e) Hot strip (f) Press welding

In hot wedge welding shown in Fig. (b) the heated wedge is place between the surfaces to be joined and is moved along the line of welding as the edges are softened. Pressure is applied through a roller to the top strip to weld it to the bottom sheet.

This process is used to weld elastic materials but can also be used to weld thin rigid sheets or straps upto 5 mm to thicker sheets. Precautions are, however, needed in this process to avoid sticking of work material to the hot wedge. Best of all this process can be used for welding films by using pressure rollers arranged above and below the films being joined together as shown in Fig. (c).

Apart from hot wedge method films can also be welded by hot plate, hot strip and thermal impulse methods.

In hot plate welding, resistance heated plate is moved over the films to be lap welded. When the desired welding temperature is reached, pressure is applied to accomplish the weld. The films to be welded are laid out on a work plate as shown in Fig. (d).

In hot strip welding the strip heater, heated by an electric element, is advanced by rollers and is simultaneously forced by pressure P against the films to be lap welded which are laid out on a workplate as shown in Fig. (e). The films can be advanced under the pressure rollers by moving either the welding head or the workplate.

In thermal-impulse process the material (films) is raised to the welding temperature almost instantaneously as a strong current pulse is passed through an electric heater. The heater may be of point, strip, or even an odd shaped type. Because the heat can be accurately metered, overheating at the joint is avoided.

In press welding heat is transferred to the area to be welded by the hot platen of the welding press. The plastic pieces with their edges scarfed are clamped between the resistance heated press platens as shown in Fig. (f). After the workpieces have been raised to the welding temperature, they are kept under the required pressure as the platens are cooled by the water circulated through the ducts.

Presses usually make butt welds. A typical plastics welding press for butt joints develops fairly high pressures, heats the work locally, and compresses the softened zone from all sides. That is why this technique is also referred to as static-jig welding. This technique can butt weld sheets, bars, strips and plates.

Stresses may be developed in welding of plastic especially if the sheets to be welded are large in thickness. To relieve these stresses it is a good practice to anneal the welded articles from a temperature 25 to 30°C below the softening point of the material.

Hot tool welding produces strong welds at a high production rate. This process is applicable to plastics which cannot be joined by high frequency induction welding, for example PTFE (polytetrafluorethylene), polyethylene, and polystyrene. Butt, fillet and T-joints can be made by this process. Acrylics joined by hot tool welding retain transparency and clarity at and around the joint it can also be used for welding films for seams of considerable length. When large quantities of welds are required, the hot tool welding method can be easily mechanized.

B. Conversion of Energy into Heat:

1. High Frequency Induction Welding:

In H.F. induction welding the workpiece is placed in a high frequency field set up between two metal electrodes as shown for roller seam welding in Fig. 22.18 (c). Only those plastics which are imperfect dielectric can be welded by this process.

The few free electrons existing in such plastics give rise to conduction current when the material is placed in the H.F. field. The work done to displace the charged particles is converted into heat. Some heat is also generated when the field alternates. To increase the amount of heat generated use is made of very high frequency current in the range of 30 to 40 MHz or even higher. Generally no filler material is used. As all the heat is generated directly in the body of the workpiece being welded, welding speed is high and the electrodes are not overheated.

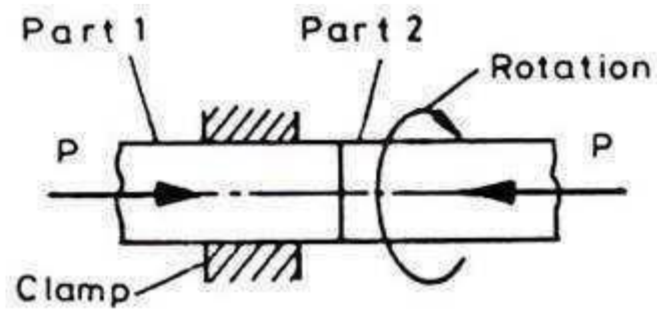
H.F. induction process is used to make spot, static-jig, and scam welds; however butt, fillet, and tee joints are difficult to make. The welds produced are tight and strong. The process can be easily automated to weld films, sheets, and tubes. Lap welds by seam welding machines can be carried out at speeds as high as 27 to 65 m/hr.

Among the merits of high frequency welding are high production rate, economy, and satisfactory joints. It can weld materials upto 5mm thick. However, materials with low dielectric dissipation factor like PTFE, polyethylene, and polystyrene are not possible to weld by H.F. induction welding.

But polyethylene can be welded by this process by placing a strip of PVC in the joint. PVC being an imperfect dielectric gets heated up under the action of H.F. current and transfers the heat to polyethylene to accomplish the weld.

2. Friction Welding:

Plastics are friction welded the same way as metals, though normal setup consists of rotating one piece and keeping the other stationary, as shown in Fig, but large pieces can be welded by keeping them stationary and rotating a short insert between them. The quality of the weld depends upon the speed of rotation, the axial force applied, and the amount of plastic deformation involved.



Because the heat is generated at the interface the properties of the adjoining material are not affected and the joint has good mechanical properties. Due to heat produced directly on the surfaces being joined this process has the advantage of high welding rate, adaptability to automatic control and usability under field conditions. However, the process can be used only if one of the components is cylindrical so that it can be rotated. Also flash formed at the joint means not only the wastage of material but also the additional cost in machining to remove it.

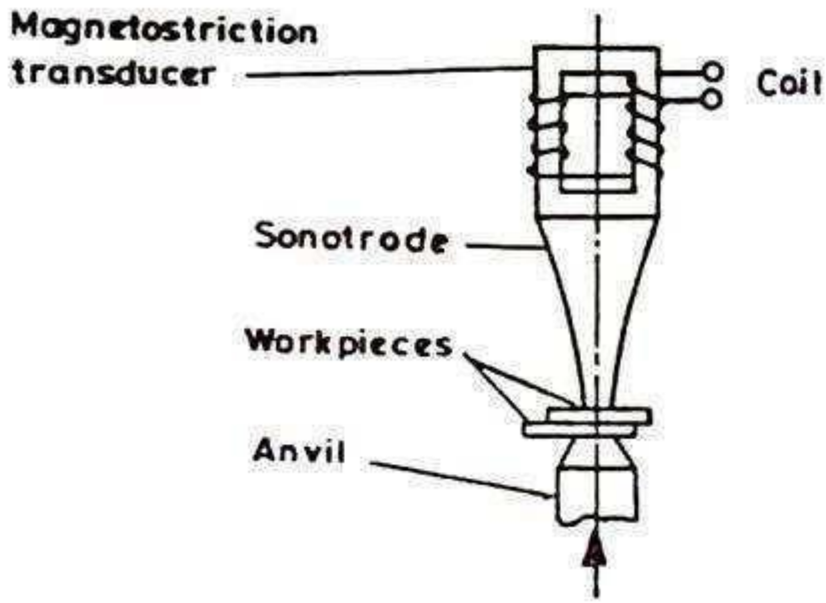
Friction welding of PVC tubes and pipes is well developed. Prior to welding the ends of the tubes are sized by heating the tube ends in oil to 100 °C for 3 toV4 minutes and then clamping the tubes in gauge for 3 minutes followed by water cooling to room temperature. The welding is accomplished by rotating one of the tubes in a chuck.

The speed of rotation depends on tube diameter, for example, 50 mm diameter tube is rotated at 800 rpm while 80 mm diameter tube is rotated at 600 rpm and the spinning time is 1 ± 0.5 minutes. After the desired viscous fluidic temperature of 140 – 160°C is reached the rotation is stopped and a pressure of 20 to 40 N/cm^2 is applied till the weld is cooled to room temperature in about 7 to 10 minutes.

Friction welds in PVC compare in quality with the parent material. Typical joint strength on like materials is about 90 % that of the parent material.

3. Ultrasonic Welding:

For ultrasonic welding of plastics the welding machine has the same features as the one for metals. The main element of the welding machine is a transducer, which converts the H.F. energy supplied by ultrasonic oscillator into vibrations. The vibrations are applied to the work through a sonotrode which is set up on an anvil as shown in Fig.



The mechanical vibrations applied to the work cause the generation of heat in the plastic material. Pressure is applied to the softened material to complete the joint. Welding takes place the same instant as the H.F. voltage is applied to the transducer coil. The frequency used is upto about 20 KHz.

4. Infra-Red Ray (IR) Welding:

In this process welding heat supplied by an infra-red light source such as sylite glower, a chrome-steel resistance element, a quartz rod lamp, etc. To speed up the process, welding is carried out on a black backing plate from a foamed plastic, sponge rubber or thick rubberized fabric. Welding pressure is supplied by the resilience of the backup plate which is held firmly against the workpiece.

Polyethylene film can be joined satisfactorily by IR welding. Work thickness which can be welded depends upon the power of the IR source. For example, a sylite glower with a temperature of 1200°C kept at a distance of 12 to 14 mm off the workpiece with sponge rubber backing can weld a maximum thickness of upto 2 mm. Any plastic film which can pass into viscous fluidic state and requires a low welding pressure can be welded by IR welding process. The welds produced by this process are usually free from undercuts and have high joint strength. Infra-red light can also weld sheets stacked up in a pile.

5. Nuclear Welding:

In this process the workpieces to be welded are irradiated with a stream of neutrons. The surfaces to be welded are given a coat of lithium or boron compound before welding. When such a coated surface is bombarded by neutrons, nuclear reaction takes place resulting in the generation of heat. The heat so produced raises the surfaces to the viscous fluidic state and therefore they can be welded. This process can be used to weld PTFE to polyethylene, polystyrene, quartz, and aluminium.

Nuclear welding has a limitation in that it cannot be applied to materials which become strongly radio-active when irradiated with neutrons.

Unit-5
Extrusion & numerical control machining

Introduction to Metal Extrusion

Metal extrusion is a metal forming process in which a material, of a certain length and cross section, is forced to flow through a die of a smaller cross sectional area, thus forming the work to the new cross section. The length of the extruded part will vary, dependent upon the amount of material in the work piece and the profile extruded. Numerous cross sections are manufactured by this method. The cross section produced will be uniform over the entire length of the metal extrusion. Starting work is usually a round billet, which may be formed into a round part of smaller diameter, a hollow tube, or some other profile. Extrusion is capable of creating tremendous amounts of geometric change and deformation of the work piece, more than other metal forming processes. Metal extrusion tends to produce an elongated grain structure, usually considered favorable, in the part's material in the direction that the work is extruded. Extrusion, in many instances, can be considered a semi continuous manufacturing operation. Continuous because the process will manufacture a continuous length of the same cross section. From this length, individual discrete parts can be cut. It is semi continuous and not completely continuous, (such as continuous casting), because the length of extruded product is still limited by the amount of material in the work piece. The work piece must be reloaded at the end of every cycle. Metal extrusion can also be a discrete manufacturing process, producing a single part with every cycle. As in other metal forming operations, the forces involved and the material flow patterns that occur during extrusion are of primary concern in the analysis and development of this manufacturing process. The many factors that affect metal flow will be discussed.

Features of Extrusion Process:

- Cost effective: Minimizes the need for secondary machining process.
- Surface finish: For steel is 3 µm; (125 µ in), for Aluminum and Magnesium -0.8 µm (30 µ in).
- Cross-section: Wide variety of cross-sections can be made.
- Minimum thickness: For steel 3 mm (0.120 in), for Aluminum and Magnesium 1mm (0.040 in).
- Minimum cross section: For steel 250 mm (0.4 in) for steel.
- Corner and fillet radii: 0.4 mm (0.015 in) for Aluminum and Magnesium, for steel the minimum corner radius is 0.8mm (0.030 in) and 4 mm (0.120 in) fillet radius.

Principle

The basic principle of metal extrusion is illustrated in figure.

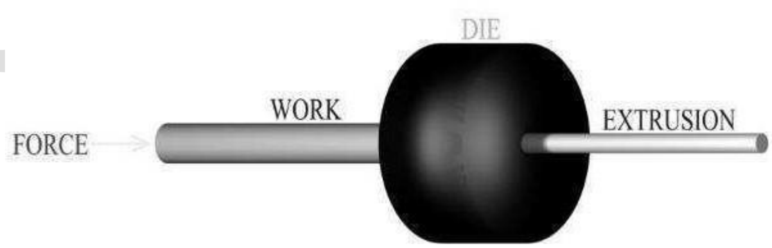


Figure: Principle of Metal Extrusion

Extrusion is a simple compressive metal forming process. In this process, piston or plunger is used to apply compressive force at work piece. This process can be summarized as follow.

- First billet or ingot (metal work piece of standard size) is produced.
- This billet is heated in hot extrusion or remains at room temperature and placed into a extrusion press (Extrusion press is like a piston cylinder device in which metal is placed in cylinder and pushed by a piston. The upper portion of cylinder is fitted with die).

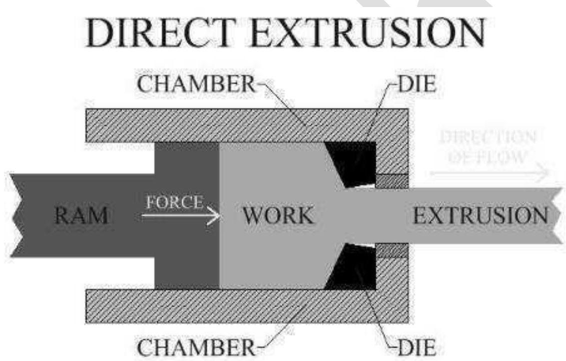
- Now a compressive force is applied to this part by a plunger fitted into the press which pushes the billet towards die.
- The die is small opening of required cross section. This high compressive force allow the work metal to flow through die and convert into desire shape.
- Now the extruded part is removed from press and is heat treated for better mechanical properties.

Types of Extrusion:

Extrusion process can be classified into following types-

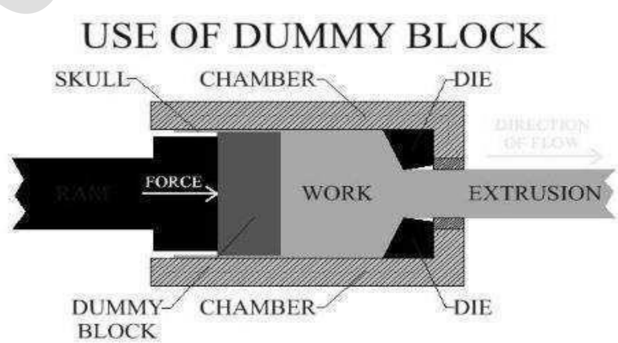
- According to the direction of flow of metal
    - Direct Extrusion
    - Indirect Extrusion
- According to the working temperature
    - Hot Extrusion
    - Cold Extrusion

Direct Extrusion



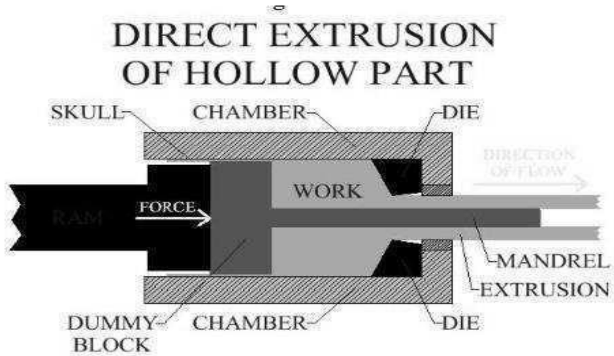
- In direct, or forward extrusion, the work billet is contained in a chamber.
- The ram exerts force on one side of the work piece, while the forming die, through which the material is extruded, is located on the opposite side of the chamber.
- The length of extruded metal product flows in the same direction that the force is applied.

Use of Dummy Block in Direct Extrusion



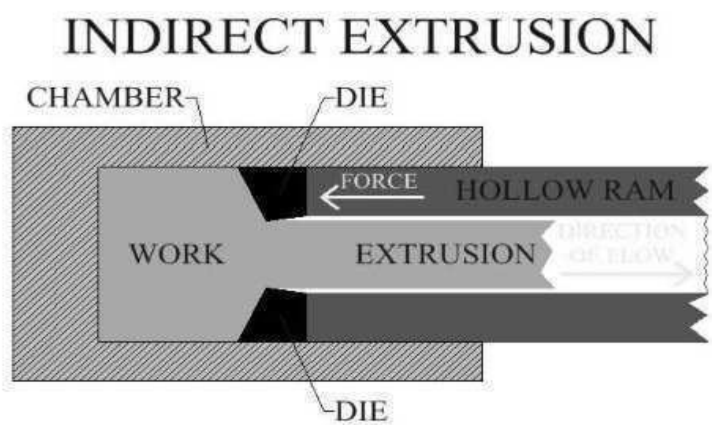
During direct extrusion, metal flow and forces required are affected by the friction between the work piece and the chamber walls. Particularly in hot working, oxide scale build up on the outer surfaces of the work piece can negatively influence the operation. For these reasons, it is common manufacturing practice to place a dummy block ahead of the ram. The dummy block is of slightly smaller diameter than the chamber and work piece. As the metal extrusion proceeds, the outermost surface of the work is not extruded and remains in the chamber. This material will form a thin shell, (called skull), that will later be removed. Much of the skull will be comprised of the surface layer of oxidized scale from the work metal.

Direct Extrusion of Hollow Parts



Hollow, or semi hollow, parts can be directly extruded with the use of a mandrel attached to the dummy block. A hole is created through the work, parallel to the axis over which the ram applies the force to form the extrusion. The mandrel is fitted within this hole. Once the operation begins, the ram is forced forward. The extruded metal flows between the mandrel and the die surfaces, forming the part. The interior profile of the metal extrusion is formed by the mandrel, while the exterior profile is formed by the extruding die.

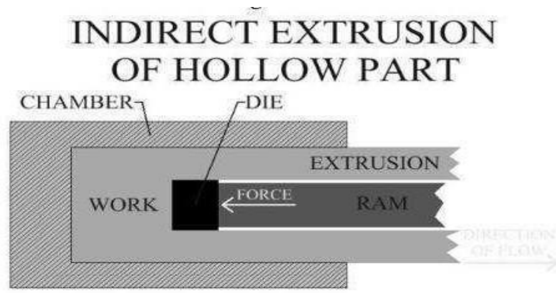
Indirect Extrusion



- Indirect extrusion is a particular type of metal extrusion process in which the work piece is located in a chamber that is completely closed off at one side.
- The metal extrusion die are located on the ram, which exerts force from the open end of the chamber.
- As the manufacturing process proceeds, the extruded product flows in the opposite direction that the ram is moving.
- For this purpose the ram is made hollow, so that the extruded section travels through the ram itself.
- This manufacturing process is advantageous in that there are no frictional forces between the work piece and the chamber walls.
- Indirect extrusion does present limitations.
- Tooling and machine set up are more complicated, hollow rams are not as strong and less ridged and support of the length of the metal extrusion's profile, as it travels out of the mold, is more difficult.

Indirect Extrusion of Hollow Parts

Indirect extrusion can also be used to produce hollow parts. In this process, a ram is forced into the work material. The ram gives the internal geometry to the tubular part, while the material is formed around it. Difficulties in supporting the ram limit this process and the length of tubular metal extrusions that may be manufactured.



Hot Extrusion

If the extrusion process takes place above recrystallisation temperature which is about 50-60% of its melting temperature, the process is known as hot extrusion.

Advantages:

- Low force required compare to cold working.
- Easy to work in hot form.
- The product is free from stain hardening.

Disadvantages:

- Low surface finish due to scale formation on extruded part.
- Increased die wear.
- High maintenance required.

Cold Extrusion

If the extrusion process takes place below crystallization temperature or room temperature, the process is known as cold extrusion. Aluminum cans, cylinder, collapsible tubes etc. are example of this process.

Advantages:

- High mechanical properties.
- High surface finish
- No oxidation at metal surface.

Disadvantages:

- High force required.
- Product is accomplished with strain hardening.

Tube Extrusion

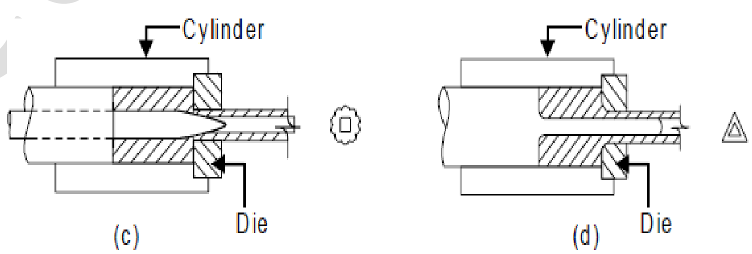


Figure: Tube Extrusion

This process is an extension of direct extrusion process where additional mandrel is needed to restrict flow of metal for production of seamless tubes. Aluminium based toothpaste and medicated tubes are produced using this process.

Applications of Metal Extrusion:

- Extrusion is widely used in production of tubes and hollow pipes.
- Aluminum extrusion is used in structure work in many industries.

- This process is used to produce frames, doors, window etc. in automotive industries.
- Extrusion is widely used to produce plastic objects.

Advantages of Metal Extrusion:

- High extrusion ratio (It is the ratio of billet cross section area to extruded part cross section area).
- It can easily create complex cross section.
- This working can be done with both brittle and ductile materials.
- High mechanical properties can be achieved by cold extrusion.

Disadvantages of Metal Extrusion:

- High initial or setup cost.
- High compressive force required.

Numeric Control Machining

Introduction

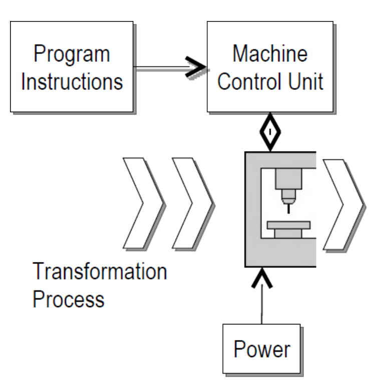
Numerical control, popularly known as the NC is very commonly used in the machine tools. Numerical control is defined as the form of programmable automation, in which the process is controlled by the number, letters, and symbols. In case of the machine tools this programmable automation is used for the operation of the machines. In other words, the numerical control machine is defined as the machined that is controlled by the set of instructions called as the program. In numerical control method the numbers form the basic program instructions for different types of jobs; hence the name numerical control is given to this type of programming. When the type of job changes, the program instructions of the job also change. It is easier to write the new instructions for each job, hence NC provides lots of flexibility in its use. The NC technology can be applied to wide variety of operations like drafting, assembly, inspection, sheet metal working, etc. But it is more prominently used for various metal machining processes like turning, drilling, milling, shaping etc. Due to NC all the machining operations can be performed at the fast rate resulting in bulk manufacturing becoming quite cheaper.

Principle of Numeric Control

"a system in which actions are controlled by direct insertion of numerical data at some point. The system must automatically interpret this data."

Numerical control, popularly known as the NC is very commonly used in the machine tools. Numerical control is defined as the form of programmable automation, in which the process is controlled by the number, letters, and symbols. In case of the machine tools this programmable automation is used for the operation of the machines. In numerical control method the numbers form the basic program instructions for different types of jobs; hence the name numerical control is given to this type of programming. When the type of job changes, the program instructions of the job also change. It is easier to write the new instructions for each job, hence NC provides lots of flexibility in its use.

Components of the Numerical Control System:



BASIC BLOCK DIAGRAM

There are three important components of the numerical control or NC system. These are:
1) Program of instructions
2) Controller unit, also called as the machine control unit (MCU) and
3) Machine tool

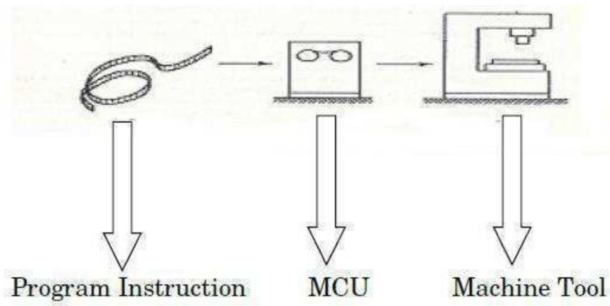


Figure: Components of NC System

1) Program of instructions

The typical desktop program gives the instructions to the computers to perform certain functions. The program of instructions of the NC machine is the step by step set of instructions that tells the machines what it has to do. One can also input the instructions directly into the controller unit manually, this method is called as manual data input (MDI), which is used for very simple jobs. Then there is direct numerical control method (DNC) in which the machines are controlled by the computers by direct link omitting the tape reader.

2) Controller Unit or Machine Controller Unit (MCU)

The controller unit is most vital parts part of the NC and CNC machines. The controller unit is made of the electronics components. It reads and interprets the program of instructions and converts them in the mechanical actions of the machine tool. Thus the controller unit forms an important link between the program and the machine tool. The control unit operates the machines as per the set of instructions given to it. The typical control unit comprises of tape reader, a date buffer, signal output channels to the machine tools, feedback channel from the machine tool, and the sequence control to coordinate the overall machining operation. Initially, the set of instructions from the punched tape are read by the tape reader, which is sort of the electromechanical devise. The data from the tape is stored into the data buffer in form of logical blocks of instructions with each block resulting in certain sequence of operations. The controller sends the instructions to the machine tool via signal output channels that are connected to the servomotors and other controls of the machines. The feedback channels ensure that the instructions have been executed by the machine correctly. The sequence control part of the controller unit ensures that all the operations are executed in the proper sequence. One important thing to note about the controller unit here is that all the modern NC machines are equipped with the microcomputer that acts as the controller unit. The program is fed into the computer directly and the computer controls the working the machine tool. Such machines are called as Computer Controller Machines (CNC) machines.

3) Machine Tools

It is the machine tool that performs the actual machining operations. The machine tool can be any machine like lathe, drilling machine, milling machine etc. The machine tool is the controlled part of the NC system. In case of the CNC machines, the microcomputer operates the machine as per the set of instructions or the program. The NC machine also have the control panel or control console that contains the dials and switches using which the operator runs the NC machine.

Computer Numerical Control

Computer numerical control (CNC) is the numerical control system in which a dedicated computer is built into the control to perform basic and advanced NC functions. CNC controls are also referred to as soft-wired NC systems because most of their control functions are implemented by the control software programs. CNC is a computer assisted process to control general purpose machines from instructions generated by a processor and stored in a memory system. It is a specific form of control system where position is the principal controlled variable. All numerical control machines manufactured since the seventies are of CNC type. The computer allows for the following: storage of additional programs, program editing, running of program from memory, machine and control diagnostics, special routines, inch/metric, incremental/absolute switchability.

CNC machines can be used as standalone units or in a network of machines such as flexible machine centres. The controller uses a permanent resident program called an executive program to process the codes into the electrical pulses that control the machine. In any CNC machine, executive program resides in ROM and all the NC codes in RAM. The information in ROM is written into the electronic chips and cannot be erased and they become active whenever the machine is on. The contents in RAM are lost when the controller is turned off. Some use special type of RAM called CMOS memory, which retains its contents even when the power is turned off.

Figure: CNC Milling Machine

Direct Numerical Control

In a Direct Numerical Control system (DNC), a mainframe computer is used to coordinate the simultaneous operations of a number NC machines as shown in the figures. The main tasks performed by the computer are to program and edit part programs as well as download part programs to NC machines. Machine tool controllers have limited memory and a part program may contain few thousands of blocks. So the program is stored in a separate computer and sent directly to the machine, one block at a time.

First DNC system developed was Molins System 24 in 1967 by Cincinnati Milacron and General Electric. They are now referred to as flexible manufacturing systems (FMS). The computers that were used at those times were quite expensive.

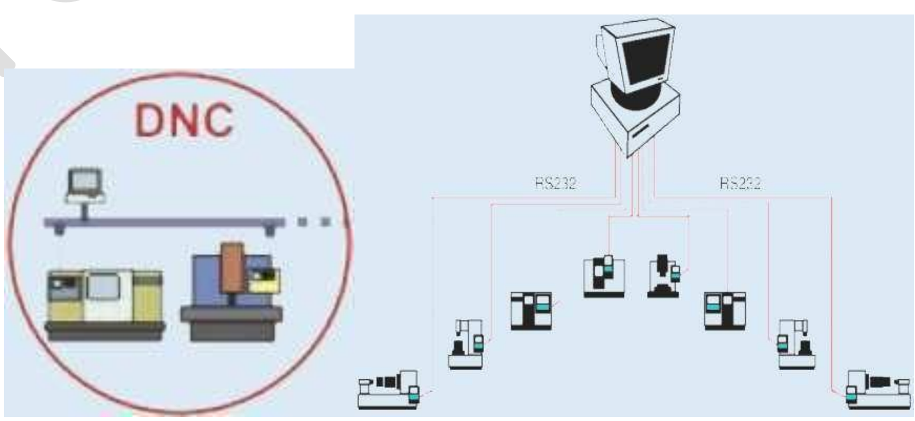


Figure: DNC System

Advantages of the CNC machines are:

- CNC machines can be used continuously and only need to be switched off for occasional maintenance.
- These machines require less skilled people to operate unlike manual lathes / milling machines etc.
- CNC machines can be updated by improving the software used to drive the machines.
- Training for the use of CNC machines can be done through the use of 'virtual software'.
- The manufacturing process can be simulated virtually and no need to make a prototype or a model. This saves time and money.
- Once programmed, these machines can be left and do not require any human intervention, except for work loading and unloading.
- These machines can manufacture several components to the required accuracy without any fatigue as in the case of manually operated machines.
- Savings in time that could be achieved with the CNC machines are quite significant.

Disadvantages of the CNC machines are:

- CNC machines are generally more expensive than manually operated machines.
- The CNC machine operator only needs basic training and skills, enough to supervise several machines.
- Increase in electrical maintenance, high initial investment and high per hour operating costs than the traditional systems.
- Fewer workers are required to operate CNC machines compared to manually operated machines. Investment in CNC machines can lead to unemployment.

Applications of NC/CNC machine tools

CNC was initially applied to metal working machinery: Mills, Drills, boring machines, punch presses etc and now expanded to robotics, grinders, welding machinery, EDM's, flame cutters and also for inspection equipment etc. The machines controlled by CNC can be classified into the following categories: CNC mills and machining centres.

- CNC lathes and turning centers
- CNC EDM
- CNC grinding machines
- CNC cutting machines (laser, plasma, electron, or flame)
- CNC fabrication machines (sheet metal punch press, bending machine, or press brake)
- CNC welding machines
- CNC coordinate measuring machines

CNC Coordinate Measuring Machines:

A coordinate measuring machine is a dimensional measuring device, designed to move the measuring probe to determine the coordinates along the surface of the work piece. Apart from dimensional measurement, these machines are also used for profile measurement, angularity, digitizing or imaging.

A CMM consists of four main components: the machine, measuring probe, control system and the measuring software. The control system in a CMM performs the function of a live interaction between various machine drives, displacement transducers, probing systems and the peripheral devices. Control systems can be classified according to the following groups of CMMs.

1. Manually driven CMMs
2. Motorized CMMs with automatic probing systems
3. Direct computer controlled (DCC) CMMs
4. CMMs linked with CAD, CAM and FMS etc.

The first two methods are very common and self explanatory. In the case of DCC CMMs, the computer control is responsible for the movement of the slides, readout from displacement transducers and data communication. CMM are of different configurations-fixed bridge, moving bridge, cantilever arm figure (a), horizontal arm and gantry type CMM as shown in figure (b).

(a) (b)

CLASSIFICATION OF CNC MACHINE TOOLS

(1) Based on the motion type ' Point-to-point & Contouring systems

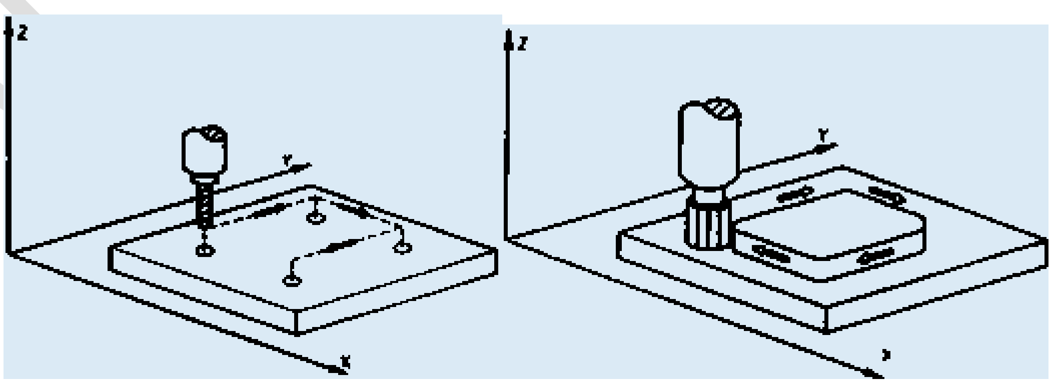
There are two main types of machine tools and the control systems required for use with them differ because of the basic differences in the functions of the machines to be controlled. They are known as point-to-point and contouring controls.

(1.1) Point-to-point systems

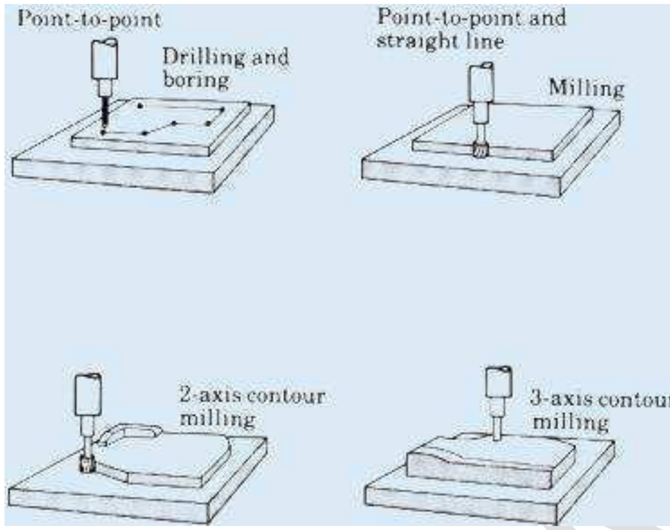
Some machine tools for example drilling, boring and tapping machines etc, require the cutter and the work piece to be placed at a certain fixed relative positions at which they must remain while the cutter does its work. These machines are known as point-to-point machines as shown in figure (a) and the control equipment for use with them are known as point-to-point control equipment. Feed rates need not to be programmed. In theses machine tools, each axis is driven separately. In a point-to-point control system, the dimensional information that must be given to the machine tool will be a series of required position of the two slides. Servo systems can be used to move the slides and no attempt is made to move the slide until the cutter has been retracted back.

(1.2) Contouring systems (Continuous path systems)

Other type of machine tools involves motion of work piece with respect to the cutter while cutting operation is taking place. These machine tools include milling, routing machines etc. and are known as contouring machines as shown in figure (b) and the controls required for their control are known as contouring control. Contouring machines can also be used as point-to-point machines, but it will be uneconomical to use them unless the work piece also requires having a contouring operation to be performed on it. These machines require simultaneous control of axes. In contouring machines, relative positions of the work piece and the tool should be continuously controlled. The control system must be able to accept information regarding velocities and positions of the machines slides. Feed rates should be programmed.



(a) Point-to-point system **(b) Contouring system**

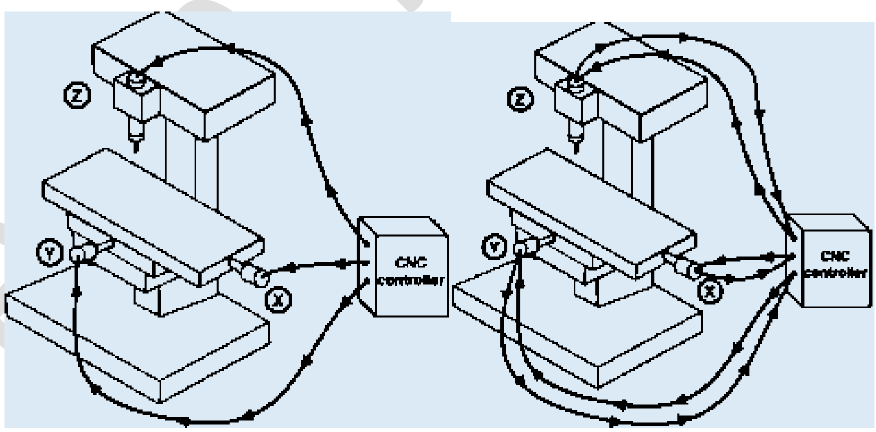


(b) Contouring systems

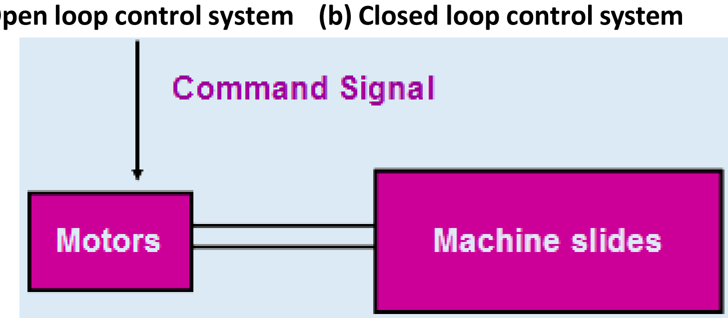
2 Based on the control loops ' Open loop & Closed loop systems

2.1 Open loop systems:

Programmed instructions are fed into the controller through an input device. These instructions are then converted to electrical pulses (signals) by the controller and sent to the servo amplifier to energize the servo motors. The primary drawback of the open-loop system is that there is no feedback system to check whether the program position and velocity has been achieved. If the system performance is affected by load, temperature, humidity, or lubrication then the actual output could deviate from the desired output. For these reasons the open -loop system is generally used in point-to-point systems where the accuracy requirements are not critical. Very few continuous-path systems utilize open-loop control.



(a) Open loop control system (b) Closed loop control system

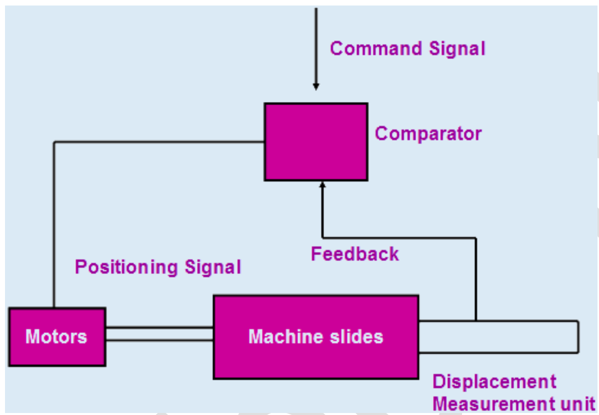


(c) Open loop system

2.2 Closed loop systems:

The closed-loop system has a feedback subsystem to monitor the actual output and correct any discrepancy from the programmed input. These systems use position and velocity feed back. The feedback system could be either analog or digital. The analog systems measure the variation of physical variables such as position and velocity in terms of voltage levels. Digital systems monitor output variations by means of electrical pulses. To control the dynamic behavior and the final position of the machine slides, a variety of position transducers are employed. Majority of CNC systems operate on servo mechanism, a closed loop principle. If a discrepancy is revealed between where the machine element should be and where it actually is, the sensing device signals the driving unit to make an adjustment, bringing the movable component to the required location.

Closed-loop systems are very powerful and accurate because they are capable of monitoring operating conditions through feedback subsystems and automatically compensating for any variations in real-time.



(d) Closed loop system

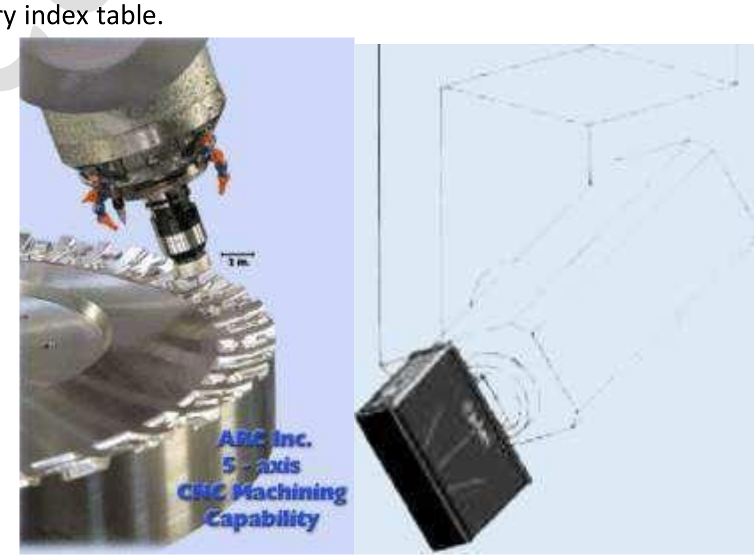
(3) Based on the number of axes ' 2, 3, 4 & 5 axes CNC machines.

(3.1) 2& 3 axes CNC machines:

CNC lathes will be coming under 2 axes machines. There will be two axes along which motion takes place. The saddle will be moving longitudinally on the bed (Z-axis) and the cross slide moves transversely on the saddle (along X-axis). In 3-axes machines, there will be one more axis, perpendicular to the above two axes. By the simultaneous control of all the 3 axes, complex surfaces can be machined.

(3.2) 4 & 5 axes CNC machines:

4 and 5 axes CNC machines provide multi-axis machining capabilities beyond the standard 3-axis CNC tool path movements. A 5-axis milling centre includes the three X, Y, Z axes, the A axis which is rotary tilting of the spindle and the B-axis, which can be a rotary index table.



Five axes CNC machine

Importance of higher axes machining :

Reduced cycle time by machining complex components using a single setup. In addition to time savings, improved accuracy can also be achieved as positioning errors between setups are eliminated.

Improved surface finish and tool life by tilting the tool to maintain optimum tool to part contact all the times.

Improved access to under cuts and deep pockets. By tilting the tool, the tool can be made normal to the work surface and the errors may be reduced as the major component of cutting force will be along the tool axis.

Higher axes machining has been widely used for machining sculptures surfaces in aerospace and automobile industry.

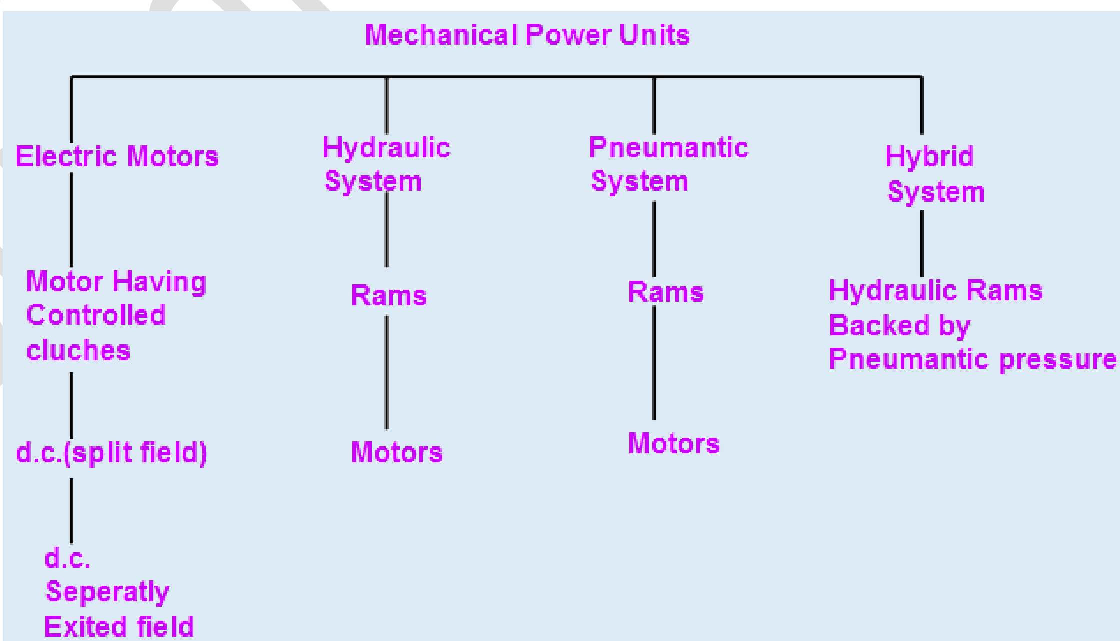
(3.3) Turning centre:

Traditional centre lathes have horizontal beds. The saddle moves longitudinally and the cross slide moves transversely. Although the tools can be clearly seen, the operator must lean over the tool post to position them accurately. Concentration of chips may be creating a heat source and there may be temperature gradients in the machine tool. Keeping the above points in view, developments in the structure of the turning centres lead to the positioning the saddle and the cross slide behind the spindle on a slant bed as shown in the figure . Chips fall freely because of slant bed configuration which is more ergonomically acceptable from operator's point of view.

Slant bed turning centre

4 Based on the power supply ' Electric, Hydraulic & Pneumatic systems

Mechanical power unit refers to a device which transforms some form of energy to mechanical power which may be used for driving slides, saddles or gantries forming a part of machine tool. The input power may be of electrical, hydraulic or pneumatic.



CNC TOOLING

(1) Tool changing arrangements

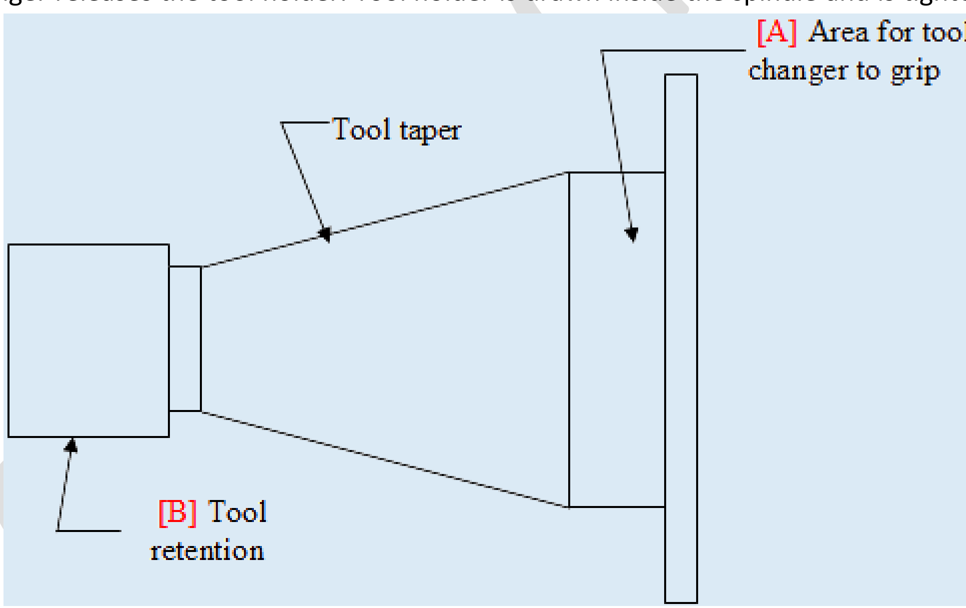
There are two types of tool changing arrangements: manual and automatic. Machining centres incorporate automatic tool changer (ATC). It is the automatic tool changing capability that distinguishes CNC machining centres from CNC milling machines.

(1.1) Manual tool changing arrangement:

Tool changing time belongs to non-productive time. So, it should be kept as minimum as possible. Also the tool must be located rigidly and accurately in the spindle to assure proper machining and should maintain the same relation with the work piece each time. This is known as the repeatability of the tool. CNC milling machines have some type of quick tool changing systems, which generally comprises of a quick release chuck. The chuck is a different tool holding mechanism that will be inside the spindle and is operated either hydraulically or pneumatically. The tool holder which fits into the chuck can be released by pressing a button which releases the hydraulically operated chuck. The advantage of manual tool changing is that each tool can be checked manually before loading the tools and there will be no limitation on the number of tools from which selection can be made.

(1.2) Automatic tool changing arrangement

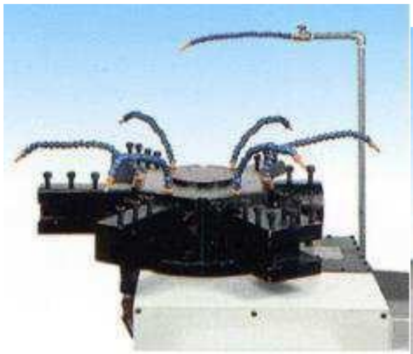
Tooling used with an automatic tool changer should be easy to center in the spindle, each for the tool changer to grab the tool holder and the tool changer should safely disengage the tool holder after it is secured properly. Figure 27.1 shows a tool holder used with ATC. The tool changer grips the tool at point A and places it in a position aligned with the spindle. The tool changer will then insert the tool holder into the spindle. A split bushing in the spindle will enclose the portion B. Tool changer releases the tool holder. Tool holder is drawn inside the spindle and is tightened.



Tool holder

(2) Tool turrets

An advantage of using tool turrets is that the time taken for tool changing will be only the time taken for indexing the turret. Only limited number of tools can be held in the turret. Tool turrets shown in figure a, b & c are generally used in lathes. The entire turret can be removed from the machine for setting up of tools.



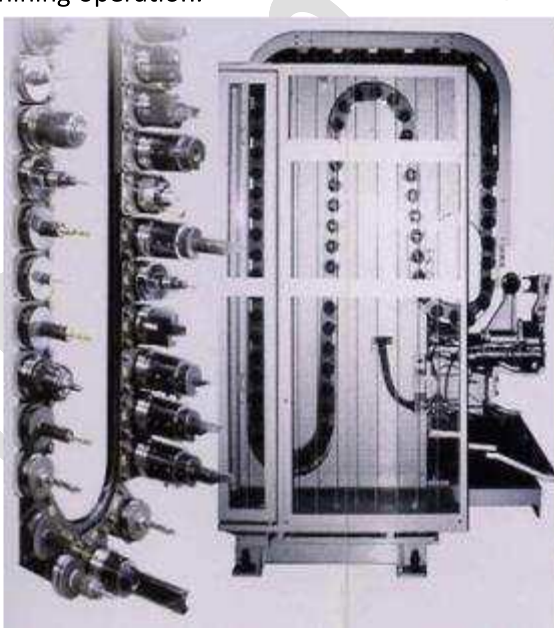
(a): Six station tool turret **(b): Eight station tool turret** **(c): Twelve station tool turret**

(3) Tool magazines

Tool magazines are generally found on drilling and milling machines. When compared to tool turrets, tool magazines can hold more number of tools and also more problems regarding the tool management. Duplication of the tools is possible and a new tool of same type may be selected whenever a particular tool has been worn off. Though a larger tool magazine can accommodate more number of tools, but the power required to move the tool magazine will be more. Hence, a magazine with optimum number of tool holders must be used. The following types of tool magazines exist: circular, chain and box type.

(3.1) Chain magazine:

These magazines can hold large number of tools and may hold even up to 100 tools. Figures a & b show chain magazines holding 80 and 120 tools respectively. In these chain magazines, tools will be identified either by their location in the tool holder or by means of some coding on the tool holder. In the former it is followed for identifying the tool and then the tool must be exactly placed in its location. The positioning of the magazine for the next tool transfer will take place during the machining operation.



(a) 80-tool chain magazine **(b) 120-tool chain magazine**

(3.2) Circular magazine:

Circular magazines shown in figure will be similar to tool turrets, but in the former the tools will be transferred from the magazine to the spindle nose. Generally these will be holding about 30 tools. The identification of the tool will be made either by its location in the tool magazine or by means of some code on the tool holder. The most common type of circular magazine is known as carousel, which is similar to a flat disc holding one row of tools around the periphery. Geneva mechanism is used for changing the tools.

Circular magazine

(3.3) Box magazine:

In these magazines, the tools are stored in open ended compartments. The tool holder must be removed from the spindle before loading the new tool holder. Also the spindle should move to the tool storage location rather than the tool to the spindle. Hence, more time will be consumed in tool changing. Box magazines are of limited use as compared to circular and chain type of tool magazines.

(4) Automatic tool changers:

Whenever controller encounters a tool change code, a signal will be sent to the control unit so that the appropriate tool holder in the magazine comes to the transfer position. The tool holder will then be transferred from the tool magazine to the spindle nose. This can be done by various mechanisms. One such mechanism is a rotating arm mechanism.

(5) Tool wear monitoring :

Most of the modern CNC machines now incorporate the facility of on-line tool wear monitoring systems, whose purpose is to keep a continuous track of the amount of tool wear in real time. These systems may reduce the tool replacement costs and the production delays. It is based on the principle that the power required for machining increases as the cutting edge gets worn off. Extreme limits for the spindle can be set up and whenever it is reached, a sub-program can be called to change the tool. Following figures show some typical tool wear monitoring systems.

CNC Part Programming fundamentals-I

Machining involves an important aspect of relative movement between cutting tool and workpiece. In machine tools this is accomplished by either moving the tool with respect to workpiece or vice versa. In order to define relative motion of two objects, reference directions are required to be defined. These reference directions depend on type of machine tool and are defined by considering an imaginary coordinate system on the machine tool. A program defining motion of tool / workpiece in this coordinate system is known as a part program. Lathe and Milling machines are taken for case study but other machine tools like CNC grinding, CNC Hobbing, CNC filament winding machine, etc. can also be dealt with in the same manner.

(1.1) Reference Points

Part programming requires establishment of some reference points. Three reference points are either set by manufacturer or user.

a) Machine Origin

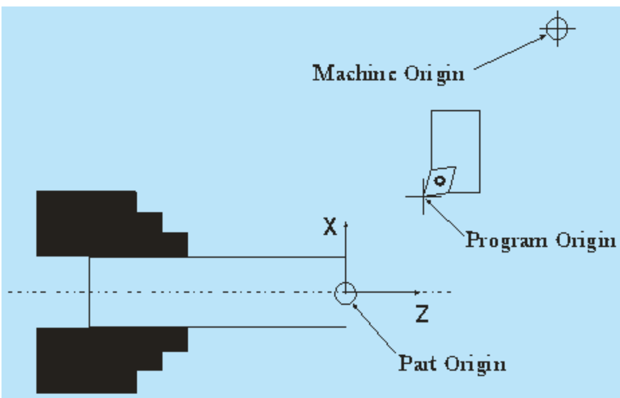
The machine origin is a fixed point set by the machine tool builder. Usually it cannot be changed. Any tool movement is measured from this point. The controller always remembers tool distance from the machine origin.

b) Program Origin

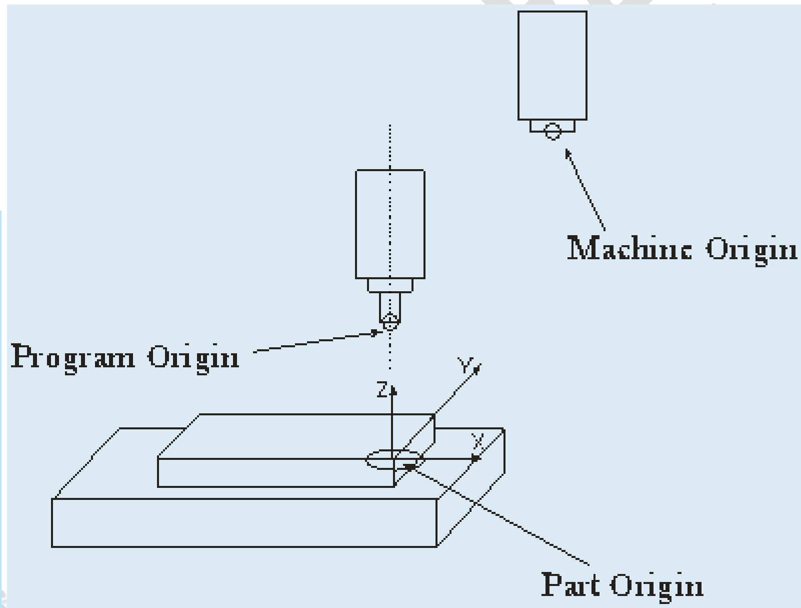
It is also called home position of the tool. Program origin is point from where the tool starts for its motion while executing a program and returns back at the end of the cycle. This can be any point within the workspace of the tool which is sufficiently away from the part. In case of CNC lathe it is a point where tool change is carried out.

c) Part Origin

The part origin can be set at any point inside the machine's electronic grid system. Establishing the part origin is also known as zero shift, work shift, floating zero or datum. Usually part origin needs to be defined for each new setup. Zero shifting allows the relocation of the part. Sometimes the part accuracy is affected by the location of the part origin. Figure 1 and 2 shows the reference points on a lathe and milling machine.



1. Reference points and axis on a lathe



2. Reference points and axis on a Milling Machine

(1.2) Axis Designation

An object in space can have six degrees of freedom with respect to an imaginary Cartesian coordinate system. Three of them are liner movements and other three are rotary. Machining of simple part does not require all degrees of freedom. With the increase in degrees of freedom, complexity of hardware and programming increases. Number of degree of freedom defines axis of machine.

Axes interpolation means simultaneous movement of two or more different axes to generate required contour. For typical lathe machine degree of freedom is 2 and so it called 2 axis machines. For typical milling machine degree of freedom is $2^1/_2$, which means that two axes can be interpolated at a time and third remains independent.

(1.3) Setting up of Origin

In case of CNC machine tool rotation of the reference axis is not possible. Origin can set by selecting three reference planes X, Y and Z. Planes can be set by touching tool on the surfaces of the workpiece and setting that surfaces as X=x, Y=y and Z=z.

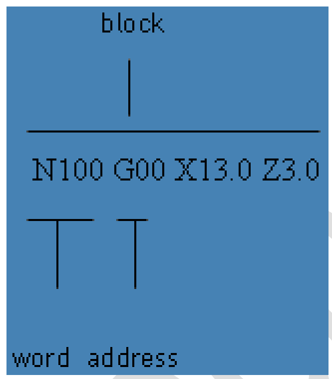
(1.4) Coding Systems

The programmer and the operator must use a coding system to represent information, which the controller can interpret and execute. A frequently used coding system is the Binary-Coded Decimal or BCD system. This system is also known as the EIA Code set because it was developed by Electronics Industries Association. The newer coding system is ASCII and it has become the ISO code set because of its wide acceptance.

(2) CNC Code Syntax

The CNC machine uses a set of rules to enter, edit, receive and output data. These rules are known as CNC Syntax, Programming format, or tape format. The format specifies the order and arrangement of information entered. This is an area where controls differ widely. There are rules for the maximum and minimum numerical values and word lengths and can be entered, and the arrangement of the characters and word is important. The most common CNC format is the word address format and the other two formats are fixed sequential block address format and tab sequential format, which are obsolete. The instruction block consists of one or more words. A word consists of an address followed by numerals. For the address, one of the letters from A to Z is used. The address defines the meaning of the number that follows. In other words, the address determines what the number stands for. For example it may be an instruction to move the tool along the X axis, or to select a particular tool.

Most controllers allow suppressing the leading zeros when entering data. This is known as leading zero suppression. When this method is used, the machine control reads the numbers from right to left, allowing the zeros to the left of the significant digit to be omitted. Some controls allow entering data without using the trailing zeros. Consequently it is called trailing zero suppression. The machine control reads from left to right, and zeros to the right of the significant digit may be omitted.



(3) Types of CNC codes

(3.1) Preparatory codes

The term "preparatory" in NC means that it "prepares" the control system to be ready for implementing the information that follows in the next block of instructions. A preparatory function is designated in a program by the word address G followed by two digits. Preparatory functions are also called G-codes and they specify the control mode of the operation.

(3.2) Miscellaneous codes

Miscellaneous functions use the address letter M followed by two digits. They perform a group of instructions such as coolant on/off, spindle on/off, tool change, program stop, or program end. They are often referred to as machine functions or M-functions. Some of the M codes are given below.

M00 Unconditional stop

M02 End of program

M03 Spindle clockwise

M04 Spindle counterclockwise

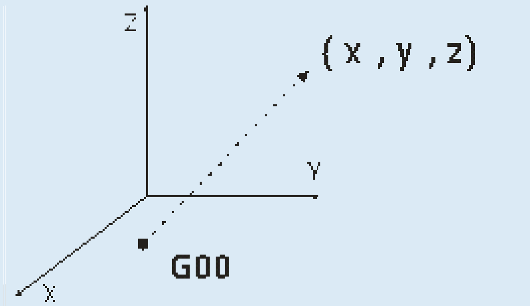
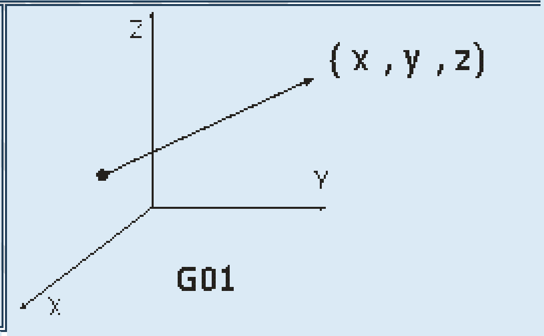
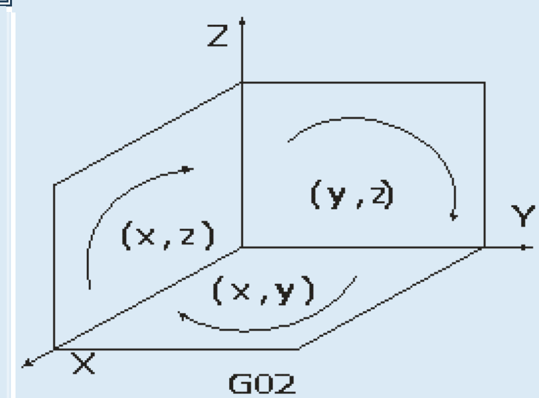
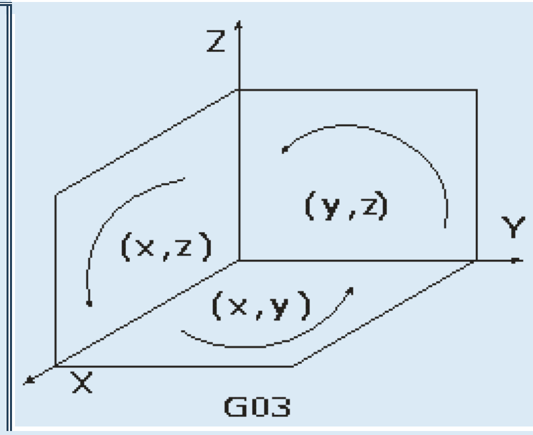
M05 Spindle stop

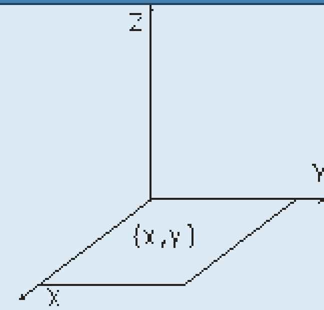
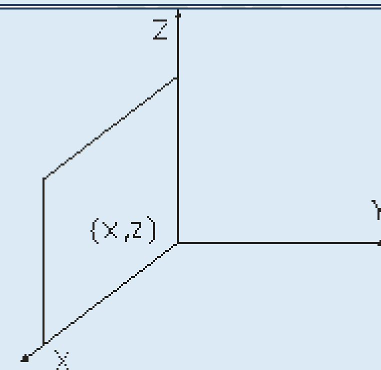
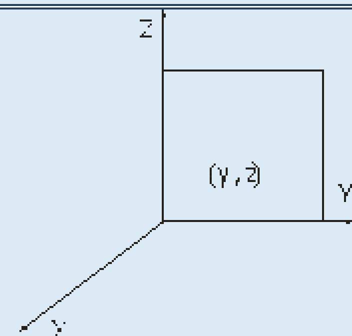
M06 Tool change (see Note below)

M30 End of program

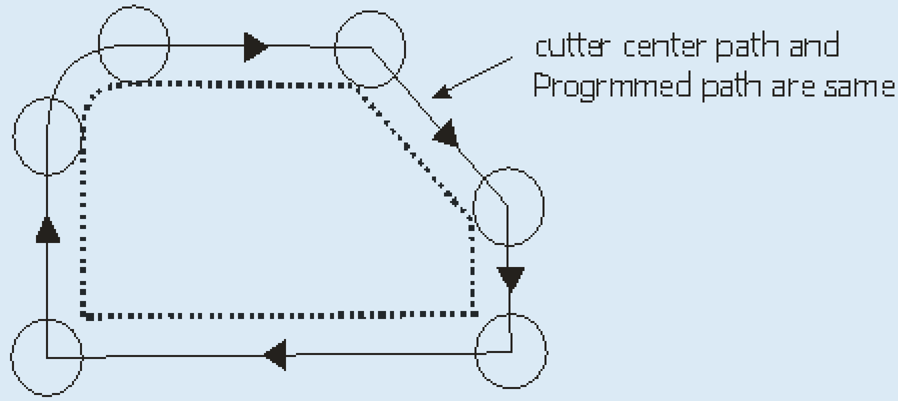
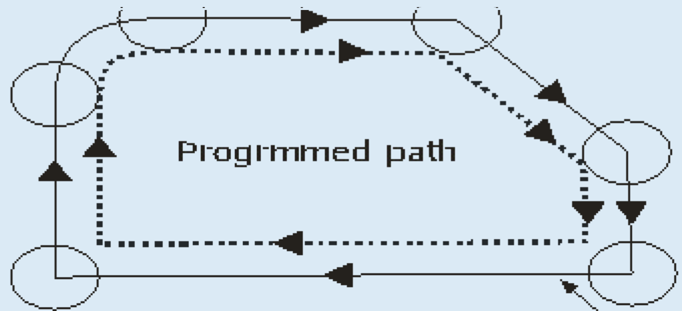
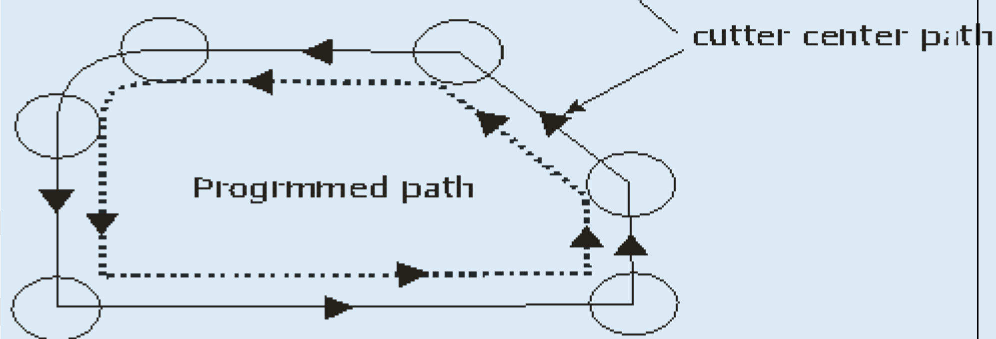
In principle, all codes are either modal or non-modal. Modal code stays in effect until cancelled by another code in the same group. The control remembers modal codes. This gives the programmer an opportunity to save programming time. Non-modal code stays in effect only for the block in which it is programmed. Afterwards, its function is turned off automatically. For instance G04 is a non-modal code to program a dwell. After one second, which is say, the programmed dwell time in one particular case, this function is cancelled. To perform dwell in the next blocks, this code has to be reprogrammed. The control does not memorize the non-modal code, so it is called as one shot codes. One-shot commands are non-modal. Commands known as "canned cycles" (a controller's internal set of preprogrammed subroutines for generating commonly machined features such as internal pockets and drilled holes) are non-modal and only function during the call.

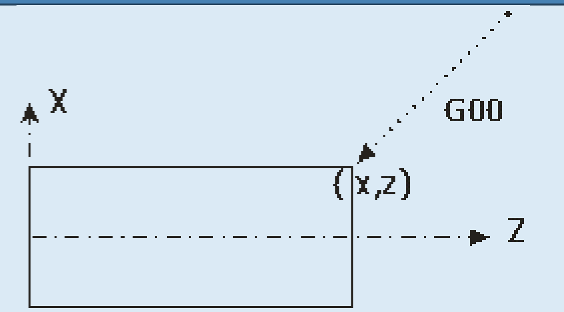
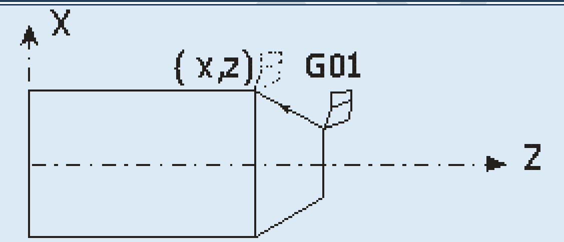
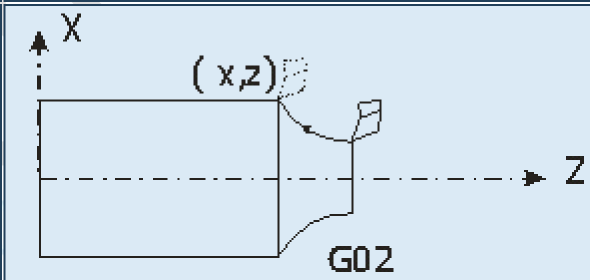
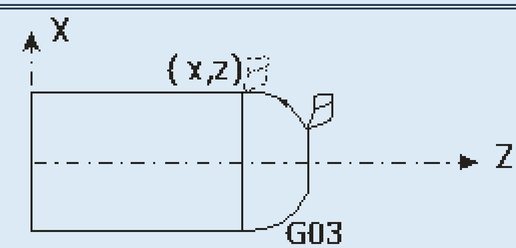
On some older controllers, cutter positioning (axis) commands (e.g., G00, G01, G02, G03, & G04) are non-modal requiring a new positioning command to be entered each time the cutter (or axis) is moved to another location.

Command group	G-code	Function and Command Statement	Illustration
Tool motion	G00	Rapid traverse G00 Xx Yy Zz	
	G01	Linear interpolation G01 Xx Yy Zz Ff	
	G02	Circular Interpolation in clock-wise direction G02 Xx Yy Ii Jj G02 Xx Zz Ii Kk G02 Yy Zz Jj Kk	
	G03	Circular interpolation in counter-clockwise direction G03 Xx Yy Ii Jj G03 Xx Zz Ii Kk G03 Yy Zz Jj Kk	

Command group	G-code	Function and Command Statement	Illustration
Plane Selection	G17	XY - Plane selection	
	G18	ZX - Plane selection	
	G19	YZ - plane selection	

Command group	G-code	Function and Command Statement	Illustration
Unit Selection	G20 or G70	Inch unit selection	
	G21 or G71	Metric unit selection	

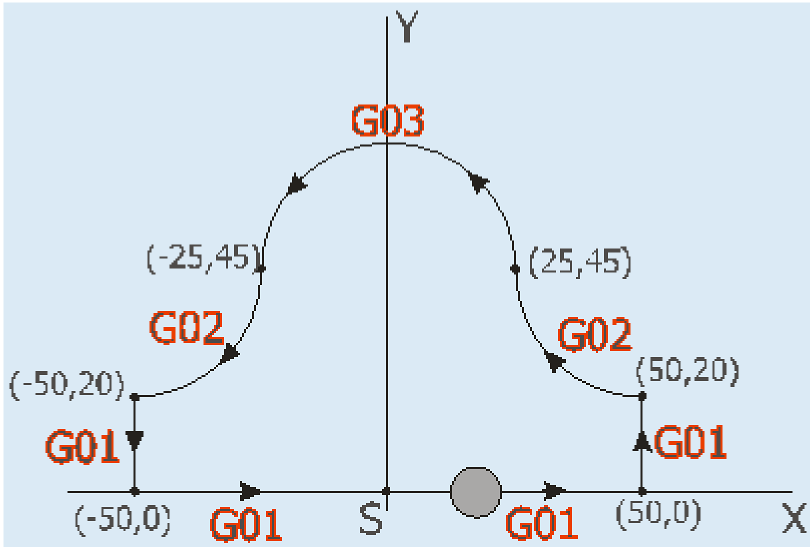
Command group	G-code	Function and Command Statement	Illustration
Offset and compensation	G40	Cutter diameter compensation cancel	
	G41	Cutter diameter cancellation left	
	G42	Cutter diameter compensation righ	

Command group	G-code	Function and Command Statement	Illustration
Tool motion	G00	Rapid traverse G00 Xx Zz	
	G01	Linear interpolation G01 Xx Zz	
	G02	Circular Interpolation in clock-wise direction G02 Xx Zz Ii Kk (or) G02 Xx Zz Rr	
	G03	Circular interpolation in counter- clockwise direction G03 Xx Zz Ii Kk (or) G03 Yy Zz Rr	

Ilustrative Example Program

A contour illustrated in figure 29.3 is to be machined using a CNC milling machine. The details of the codes and programs used are given below.

Example:



An illustrative example

O5678	Program number
N02 G21	Metric programming
N03 M03 S1000	Spindle start clockwise with 1000rpm
N04 G00 X0 Y0	Rapid motion towards (0,0)
N05 G00 Z-10.0	Rapid motion towards Z=-10 plane
N06 G01 X50.0	Linear interpolation
N07 G01 Y20.0	Linear interpolation
N08 G02 X25.0 Y45.0 R25.0	Circular interpolation clockwise(cw)
N09 G03 X-25.0 Y45.0 R25.0	Circular interpolation counter clockwise(ccw)
N10 G02 X-50.0 Y20.0 R25.0	Circular interpolation clockwise(cw)
N11 G01 Y0.0	Linear interpolation
N12 G01 X0.0	Linear interpolation
N13 G00 Z10.0	Rapid motion towards Z=10 plane
N14 M05 M09	Spindle stop and program end

CNC Part Programming fundamentals-II

In the previous section, fundamentals of programming as well basic motion commands for milling and turning have been discussed. This section gives an overview of G codes used for changing the programming mode, applying transformations etc.

1 Programming modes

Programming mode should be specified when it needs to be changed from absolute to incremental and vice versa. There are two programming modes, absolute and incremental and is discussed below.

1.1 Absolute programming (G90)

In absolute programming, all measurements are made from the part origin established by the programmer and set up by the operator. Any programmed coordinate has the absolute value in respect to the absolute coordinate system zero point. The machine control uses the part origin as the reference point in order to position the tool during program execution (Figure 30.1).

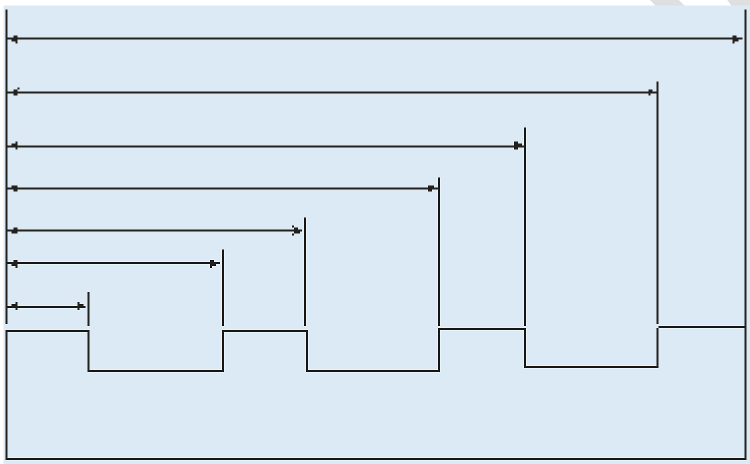


Figure 30.1. Absolute distances measured from reference zero

1.2 Relative programming (G91)

In incremental programming, the tool movement is measured from the last tool position. The programmed movement is based on the change in position between two successive points. The coordinate value is always incremented according to the preceding tool location. The programmer enters the relative distance between current location and the next point (Figure 30.2).

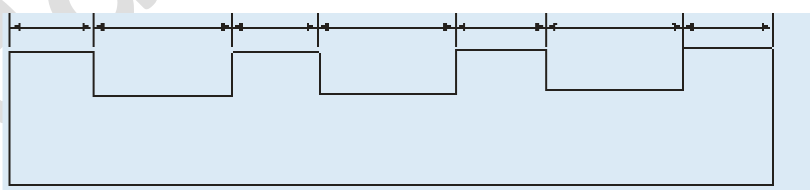


Figure 30.2. Incremental distances measured from previous locations

2 Spindle control

The spindle speed is programmed by the letter 'S' followed by four digit number, such as S1000. There are two ways to define speed.

1. Revolutions per minute (RPM)
2. Constant surface speed

The spindle speed in revolutions per minute is also known as constant rpm or direct rpm. The change in tool position does not affect the rpm commanded. It means that the spindle RPM will remain constant until another RPM is programmed. Constant surface speed is almost exclusively used on lathes. The RPM changes according to diameter being cut. The smaller the diameter, the more RPM is achieved; the bigger the diameter, the less RPM is commanded. This is changed automatically by the machine speed control unit while the tool is changing positions. This is the reason that, this spindle speed mode is known as diameter speed.

3 Loops and Unconditional jump (G25)

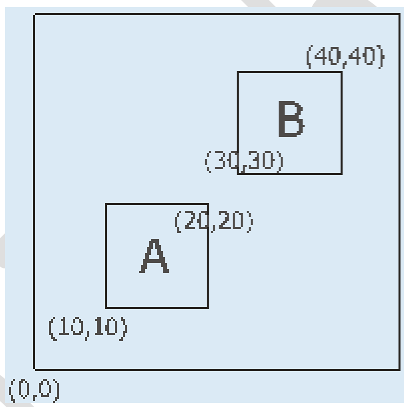
The unconditional jump is used to repeat a set of statements a number of times.

Example: N10

```
....
N70
N80
N90
N100
....
N160 G25 N70.100
```

In the above example, the program statements from N70 to N100 are repeated once when the statement N160 is executed. Usually the G25 is used after a mirror statement. Illustrative example geometry and its program are given below (Figure).

Example:



Illustrative example for programming loops

00001	Program number
N02 G21	Metric programming
N03 M03 S1000	Spindle start clockwise with 1000rpm
N04 G00 X0 Y0	Rapid motion towards (0,0)
N05 G00 Z0.0	Rapid motion towards Z=0 plane
N06 G91 G00 X10.0 Y10.0	Incremental programming starts
N07 G01 X10.0	Machining path A
N08 G01 Y10.0	
N09 G01 X-10.0	
N10 G01 Y-10.0	
N11 G00 Z10.0	
N12 G00 X20.0 Y20.0	
N13 G00 Z-10.0	
N14 G25 N07.10	Repeat lines 7 to 10 (machining of path B)
N15 G00 Z10.0	
N16 M05 M09	Spindle stop and program end

4 Mirroring

The mirroring command is used when features of components shares symmetry about one or more axes and are also dimensionally identical. By using this code components can be machined using a single set of data and length of programs can be reduced.

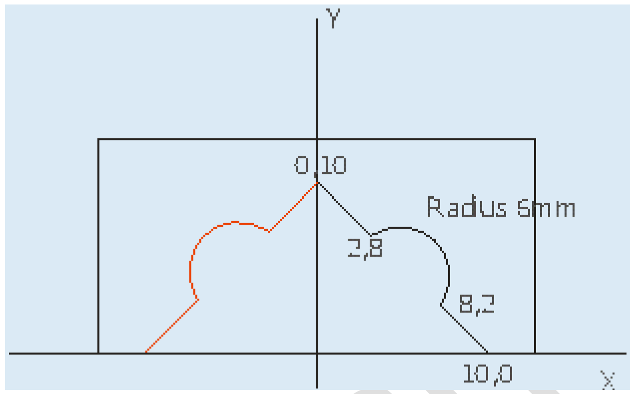
G10 cancellation of mirroring image

G11 Mirror image on X axis

G12 Mirror image on Y axis

G13 Mirror image on Z axis

Example:

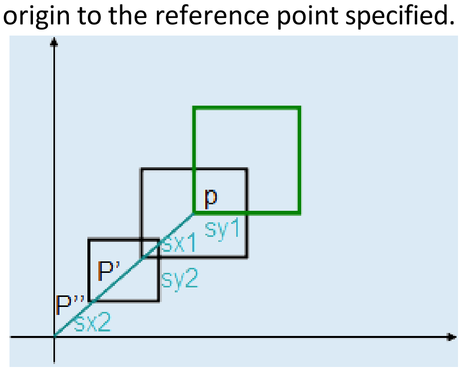


Illustrative Example for mirroring

00002	Program number
N02 G21	Metric programming
N03 M03 S1000	Spindle start clockwise with 1000rpm
N04 G00 X0.0 Y0.0	Rapid motion towards (0,0)
N05 G00 Z10.0	Rapid motion towards Z=10 plane
N06 G00 X10.0	Machining positive X side
N07 G00 Z0.0	
N08 G01 X8.0 Y2.0	
N09 G03 X2.0 Y8.0 R6.0	
N10 G01 X0.0 Y10.0	
N11 G00 Z10.0	
N12 G00 X0.0 Y0.0	
N13 G11	Mirror image on X axis
N14 G25 N06.12	Repeat lines 6 to 12 (machining of negative X side)
N15 G10	Cancellation of mirror image
N16 M05 M09	Spindle stop and program end

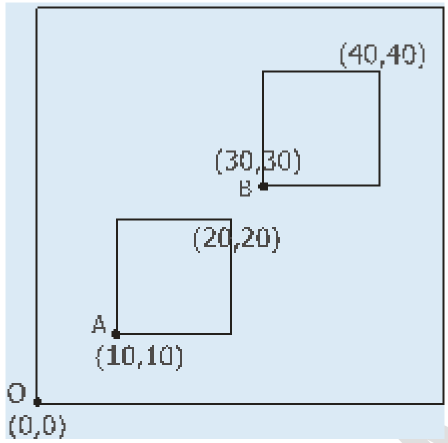
5 Shifting origin

G92 code is used to temporarily shift the origin to the reference point specified.



Example: G92 X-100 Y-80

In the above statement the x and y values gives the present values of original origin after shifting it. This is illustrated through an example (Figure 5).



5 Illustrative Example for shifting origin

00003	Program number
N02 G21	Metric programming
N03 M03 S1000	Spindle start clockwise with 1000rpm
N04 G00 X0 Y0	Rapid motion towards (0,0)
N05 G00 Z0.0	Rapid motion towards Z=0 plane
N06 G92 X-10.0 Y-10.0	Point A become new origin
N07 G00 X0.0 Y0.0	Tool movement to point A
N08 G01 X10.0	Machining path A
N09 G01 Y10.0	
N10 G01 X0.0	
N11 G01 Y0.0	
N12 G00 Z10.0	
N13 G92 X-20.0 Y-20.0	Point B become new origin
N14 G00 X0.0 Y0.0	
N15 G00 Z0.0	
N16 G25 N08.11	Repeat lines 8 to 11 (machining of path B)
N17 G00 Z10.0	
N18 M05 M09	Spindle stop and program end

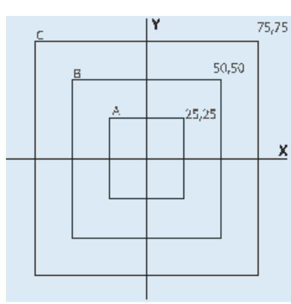
6 Scaling

Scaling function is used to program geometrically similar components with varying sizes.

Syntax: G72 Kk, where k is the scaling factor.

The scaling command can be cancelled by using the statement G72 K1.0.

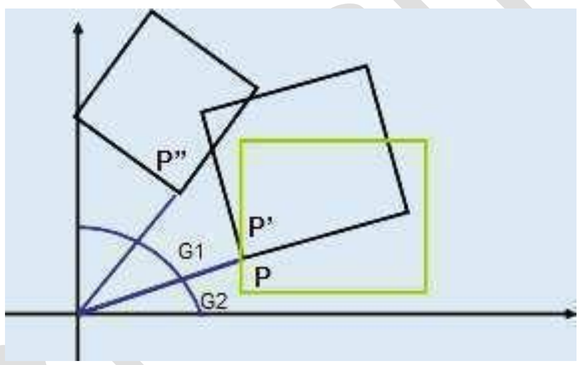
Example:



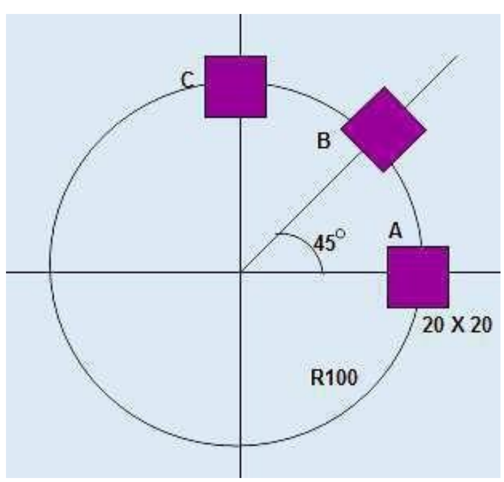
Illustrative Example for scaling

	Program number
N02 G21	Metric programming
N03 M03 S1000	Spindle start clockwise with 1000rpm
N04 G00 X0 Y0	Rapid motion towards (0,0)
N05 G00 Y25.0	
N06 G00 Z-10.0	
N07 G01 X-25.0	Machining path A
N08 G01 Y-25.0	
N09 G01 X25.0	
N10 G01 Y25.0	
N11 G01 X0.0	
N12 G00 Z10.0	
N13 G00 X0.0 Y0.0	
N14 G72 K2.0	Scaling using factor 2.0
N15 G25 N05.11	Repeat lines 5 to 11 (machining of path B)
N16 G00 Z10.0	
N17 G00 X0.0 Y0.0	
N18 G72 K3.0	Scaling using factor 3.0
N19 G25 N05.11	Repeat lines 5 to 11 (machining of path B)
N20 G00 Z10.0	
N21 G00 X0.0 Y0.0	
N22 M05 M09	Spindle stop and program end

7 Pattern rotation



Pattern rotation is used to obtain a pattern of similar features. G73 code is used to rotate the feature to form a pattern. Syntax G73 Aa, where 'a' is the angle of rotation. This command is cumulative, and the angle gets added up on time the program is executed. So all the rotational angle parameters should be cancelled using the code G73.
The unconditional jump code G25 is used in conjunction with this code to achieve the desired rotation.
The following example (Figure 30.7) depicts the case of a pattern which needs to be programmed through G73.
Example:



Illustrative Example for Pattern rotation

00001	Program number
N02 G21	Metric programming
N03 M03 S1000	Spindle start clockwise with 1000rpm
N04 G00 X0 Y0	Rapid motion towards (0,0)
N05 G00 X90.0	
N06 G00 Z-10.0	
N07 G01 Y10.0	Machining path A
N08 G01 X110.0	
N09 G01 Y-10.0	
N10 G01 X90.0	
N11 G01 Y0.0	
N12 G00 Z10.0	
N13 G00 X0.0 Y0.0	
N14 G73 A45.0	Rotation of axis 45 degree in ccw direction
N15 G25 N05.13	Repeat lines 5 to 13 (machining of path B)
N16 G73 A45.0	Rotation of axis 45 degree in ccw direction
N17 G25 N05.13	Repeat lines 5 to 13 (machining of path B)
N18 G73	All the rotation cancelled
N19 M05 M09	Spindle stop and program end

8 Tool selection

Tool selection is accomplished using 'T' function followed by a four digit number where, first two digits are used to call the particular tool and last two digits are used to represent tool offset in the program. The tool offset is used to correct the values entered in the coordinate system preset block. This can be done quickly on the machine without actually changing the values in the program.

Using the tool offsets, it is easy to set up the tools and to make adjustments

Feed rate control

Cutting operations may be programmed using two basic feed rate modes:

1. Feed rate per spindle revolution
2. Feed rate per time

The feed rate per spindle revolution depends on the RPM programmed.

Unit-IV
Unconventional Machining Processes

Introduction:

Machining is one of the most important process of metal forming and shaping. Mostly, it is used in all manufacturing processes. In the convention machining processes, **tool** is in direct contact with work piece. There are many disadvantages and limitations of conventional machining like tool wear, cannot machine complex surface efficiently, gives lower surface finish etc. Conventional machining processes are limited due to hardness of work piece. For machining hard surface through conventional machining, we require a harder tool material which is sometime uneconomical and sometimes unavailable. These limitations of traditional machining can be eliminated by non-traditional machining process. In these machining processes some other unconventional energy sources are used like laser, chemical, electron, hydraulic energy etc. An unconventional machining process (or non-traditional machining process) is a special type of machining process in which there is no direct contact between the tool and the workpiece. In unconventional machining, a form of energy is used to remove unwanted material from a given workpiece.

Why unconventional machining processes are used?

The answer is simple. In several industries, hard and brittle materials like tungsten carbide, high speed steels, stainless steels, ceramics etc. find a variety of applications. For example, tungsten carbide is used for making cutting tools while high speed steel is used for making gear cutters, drills, taps, milling cutters etc. If such materials are machined with the help of conventional machining processes, either the tool undergoes extreme wear (while machining hard workpiece) or the workpiece material is damaged (while machining brittle workpiece). This is because, in conventional machining, there is a direct contact between the tool and the workpiece. Large cutting forces are involved and material is removed in the form of chips. Huge amounts of heat are produced in the workpiece. This induces residual stresses, which degrades the life and quality of the workpiece material. Hence, conventional machining produces poor quality workpiece with poor surface finish (if the workpiece is made of hard and brittle material).

To overcome all these drawbacks, we use unconventional machining processes to machine hard and brittle materials. We also use unconventional machining processes to machine soft materials, in order to get better dimensional accuracy.

Some of the major requirements of developing non-tradition machining processes are as follow.

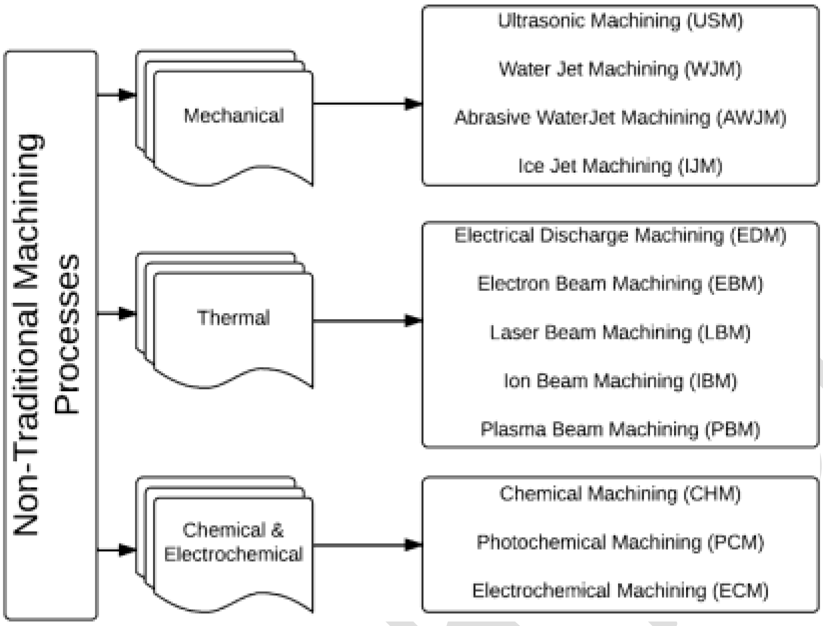
- Machining too hard material.
- Forming complex parts.
- Required better surface finish and negligible tolerance.
- Work piece is heat sensitive or temperature can change internal properties of work piece.
- Work piece is too slender and flexible to clamp.

Classification:

Unconventional machining processes can be broadly classified into several types based on four main criteria. The classification of unconventional machining processes is given below:

- Based on type of energy used.
- Based on source of energy used.
- Based on the medium of energy transfer.
- Based on the mechanism of material removal.

- Based on **type of energy** used.



- Based on **source of energy** used.
  - Current
  - Voltage
  - Hydraulic Pressure
  - Pneumatic Pressure
  - Ionized Particles
  - Light
- Based on the **medium of energy transfer.**
  - Electrons
  - Chemical reagent
  - Atmosphere
  - Radiation
  - Ions
  - Laser
  - Electrolyte
  - Pressurized gas
  - Water
  - Ultrasonic waves
  - Plasma
- Based on the **mechanism of material removal.**
  - Erosion
  - Blasting
  - Electric
  - Discharge
  - Shear
  - Chemical Etching
  - Vaporization
  - Melting
  - Ion Displacement

Classification of Unconventional Machining Processes based on Energy Used.

1. Mechanical Energy based Unconventional Machining Processes:

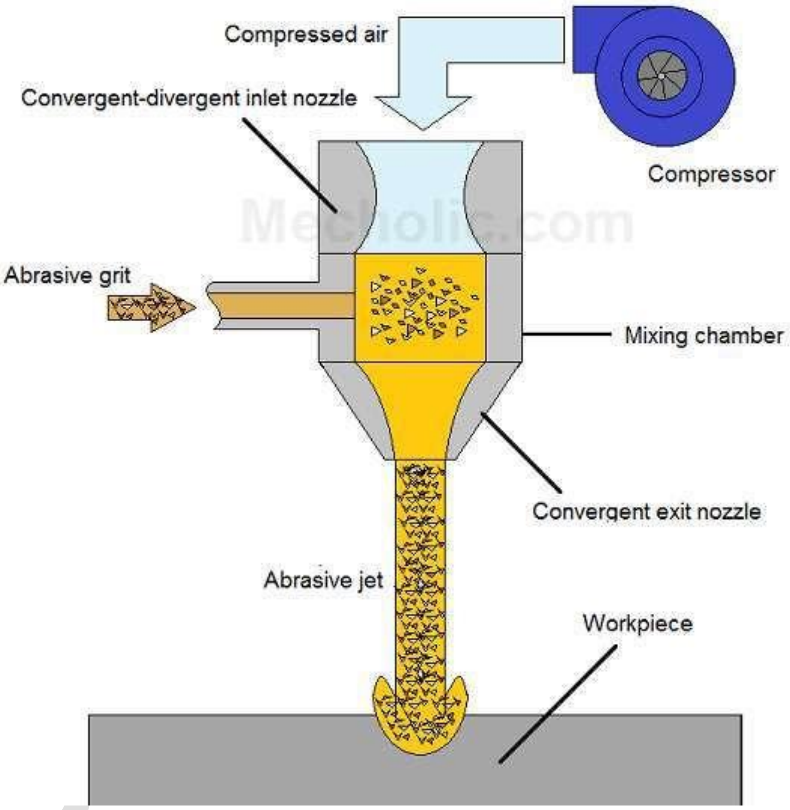
In these processes, unwanted material in the workpiece is removed by mechanical erosion. The mechanical erosion can be facilitated by using any medium. For example, in abrasive jet machining, high velocity abrasive jet is used for eroding material from the workpiece. In water jet machining, high velocity water jet is used for cutting the workpiece material. The four main mechanical energy based unconventional machining processes are:

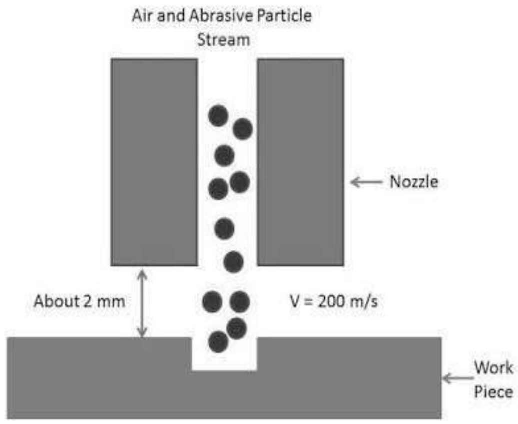
- Abrasive Jet Machining
- Water Jet Machining or Water Jet Cutting
- Abrasive Water Jet Machining
- Ultrasonic Machining

Abrasive Jet Machining

Abrasive Jet Machining (AJM), also known as micro-abrasive blasting, is a mechanical energy based unconventional machining process, used to remove unwanted material from a given workpiece. The process makes use of an abrasive jet with high velocity, to remove material and provide smooth surface finish to hard metallic workpieces. In this machining process, a high stream of abrasive particles forced towards work piece, this will remove metal from striking surface due to erosion. The metal removal process takes place due to brittle fracture and micro cutting action of abrasive particles. The abrasive particles carried by high velocity gas which act as transportation medium for abrasive particles. This machining is mostly used for machining hard material.

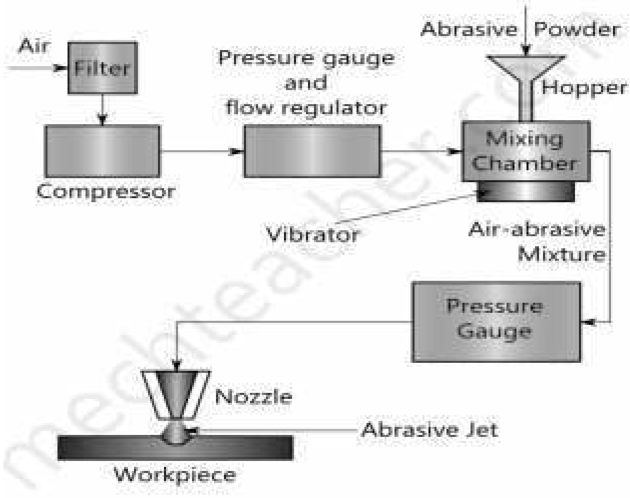
Abrasive Jet Machining: *Principle*





This machining process works on the basic principle of abrasive erosion. If a high velocity abrasive particles strike on a hard or brittle work piece, it remove some metal at the striking surface. This metal removal process takes place due to brittle fracture of metal and also due to micro cutting by abrasive particle. This is principle process of abrasive jet machining.

Abrasive Jet Machining: *Construction*



The constructional requirements of Abrasive Jet Machining (AJM) are listed and described below:

- **Abrasive jet:** It is a mixture of a gas (or air) and abrasive particles. Gas used is carbon-di-oxide or nitrogen or compressed air. The selection of abrasive particles depends on the hardness and metal removal rate (MRR) of the workpiece. Most commonly, aluminium oxide or silicon carbide particles are used.
- **Mixing chamber:** It is used to mix the gas and abrasive particles.
- **Filter:** It filters the gas before entering the compressor and mixing chamber.
- **Compressor:** It pressurizes the gas.
- **Hopper:** Hopper is used for feeding the abrasive powder.
- **Pressure gauges and flow regulators:** They are used to control the pressure and regulate the flow rate of abrasive jet.
- **Vibrator:** It is provided below the mixing chamber. It controls the abrasive powder feed rate in the mixing chamber.
- **Nozzle:** It forces the abrasive jet over the workpiece. Nozzle is made of hard and resistant material like tungsten carbide.

Abrasive Jet Machining: *Working*

Dry air or gas is filtered and compressed by passing it through the filter and compressor. A pressure gauge and a flow regulator are used to control the pressure and regulate the flow rate of the compressed air. Compressed air is then passed into the mixing chamber. In the mixing chamber, abrasive powder is fed. A vibrator is used to control the feed of the abrasive powder. The abrasive powder and the compressed air are thoroughly mixed in the chamber. The pressure of this mixture is regulated and sent to nozzle. The nozzle increases the velocity of the mixture at the expense of its pressure. A fine abrasive jet is rendered by the nozzle. This jet is used to remove unwanted material from the workpiece.

Abrasive Jet Machining: *Applications*

The following are some of the operations that can be performed using Abrasive Jet Machining:

- Drilling
- Boring
- Surface finishing
- Cutting
- Cleaning
- Deburring
- Etching
- Trimming
- Milling

Abrasive Jet Machining: *Advantages*

- Surface of the workpiece is cleaned automatically.

- Smooth surface finish can be obtained.

- Equipment cost is low.
- Hard materials and materials of high strength can be easily machined.

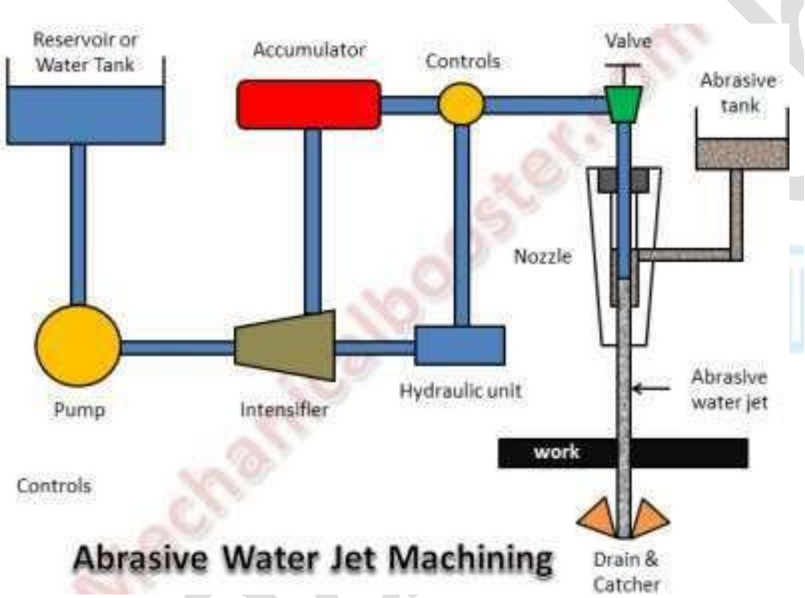
Abrasive Jet Machining: Dis*advantages*

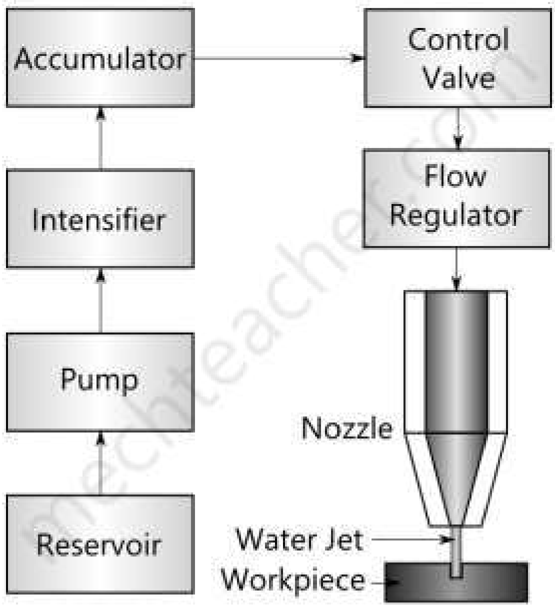
- Metal removal rate is low.
- In certain circumstances, abrasive particles might settle over the workpiece.
- Nozzle life is less.
- Nozzle should be maintained periodically.
- Abrasive Jet Machining cannot be used to machine soft materials.

Water Jet Machining:

Water Jet Machining (WJM) is a mechanical energy based non-traditional machining process, used to cut and machine soft and non-metallic materials. It involves the use of high velocity water jet to smoothly cut a soft workpiece. It is similar to Abrasive jet machining(AJM). In water jet machining, high velocity water jet is allowed to strike a given workpiece. During this process, its kinetic energy is converted to pressure energy. This induces a stress on the workpiece. When this induced stress is high enough, unwanted particles of the workpiece are automatically removed.

Water Jet Machining: *Construction*





The apparatus of water jet machining consists of the following components:

Reservoir: It is used for storing water that is to be used in the machining operation.
- **Pump:** It pumps the water from the reservoir.
- **Intensifier:** It is connected to the pump. It pressurizes the water acquired from the pump to a desired level.
- **Accumulator:** It is used for temporarily storing the pressurized water. It is connected to the flow regulator through a control valve.
- **Control Valve:** It controls the direction and pressure of pressurized water that is to be supplied to the nozzle.
- **Flow regulator:** It is used to regulate the flow of water.
- **Nozzle:** It renders the pressurized water as a water jet at high velocity.

Water Jet Machining: *Working*

- Water from the reservoir is pumped to the intensifier using a hydraulic pump.
- The intensifier increases the pressure of the water to the required level. Usually, the water is pressurized to 200 to 400 MPa.
- Pressurized water is then sent to the accumulator.
- The accumulator temporarily stores the pressurized water.

- Pressurized water then enters the nozzle by passing through the control valve and flow regulator.

- Control valve controls the direction of water and limits the pressure of water under permissible limits.
- Flow regulator regulates and controls the flow rate of water.
- Pressurized water finally enters the nozzle.
- Here, it expands with a tremendous increase in its kinetic energy.
- High velocity water jet is produced by the nozzle.
- When this water jet strikes the workpiece, stresses are induced.
- These stresses are used to remove material from the workpiece.
- The water used in water jet machining may or may not be used with stabilizers.
- Stabilizers are substances that improve the quality of water jet by preventing its fragmentation.

Water Jet Machining: *Applications*

- Water jet machining is used to cut thin non-metallic sheets.
- It is used to cut rubber, wood, ceramics and many other soft materials.
- It is used for machining circuit boards.
- It is used in food industry.

Water Jet Machining: *Advantages*

- Water jet machining is a relatively fast process.
- It prevents the formation of heat affected zones on the workpiece.
- It automatically cleans the surface of the workpiece.
- WJM has excellent precision.
- Tolerances of the order of ±0.005" can be obtained.
- It does not produce any hazardous gas.
- It is eco-friendly.

Water Jet Machining: Dis*advantages*

- Only soft materials can be machined.
- Very thick materials cannot be easily machined.
- Initial investment is high.

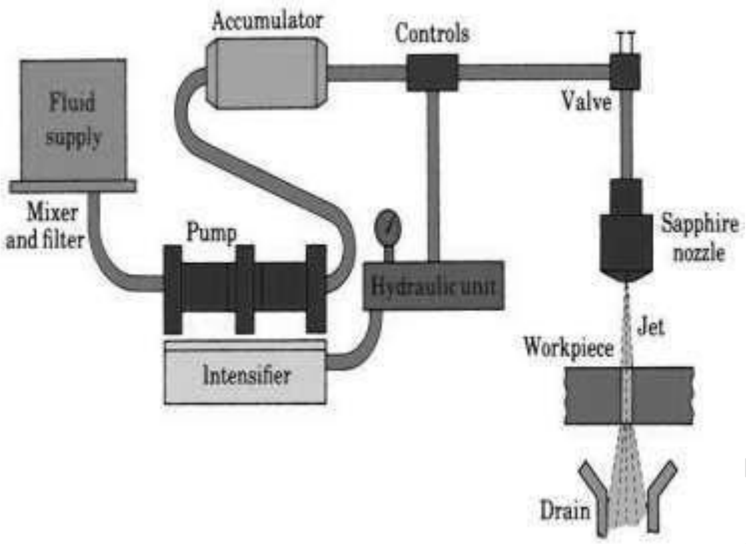
Abrasive Water Jet Machining:

It uses water jet working as a tool to cut the metal. It is same as **abrasive jet machining** except working medium is water. In this machining process a high speed steam of water jet impinge on the work piece which removes metal from contact surface by erosion. For machining hard materials like carbide, ceramic, etc. abrasive particles added in water steam which increases its machining quality. This process is known as abrasive water jet machining. It is mostly used in mining industries, aerospace industries for cutting required shape.

Abrasive Water Jet Machining: *Principle*

This process works on basic principle of water erosion. In this process, a high speed well concentrated water jet is used to cut the metal. It uses kinetic energy of water particle to erode metal at contact surface. The jet speed is almost 600 m/s. It does not generate any environmental hazards. For cutting hard materials, abrasive particles are used in water jet These abrasive particles erode metal from contact surface.

Abrasive Water Jet Machining: *Construction*



Hydraulic Pump: In the water jet machining process a **hydraulic pump** is used to pump the water from storage tank for machining process. It is connected by an electric motor of about 100 Horse power.

Hydraulic Intensifier: As the name implies, it is used to increase the water pressure for further process. Hydraulic intensifier accept water from pump at a small pressure about 4 bar. The water pressure at outlet of intensifier is about 3000-4000 bars.

Hydraulic Accumulator: Hydraulic accumulator is used when large amount of pressure energy is required for an instant. It used to eliminate pressure fluctuation It supplies fluid at high pressure when required.

Tubing System: Tubes are used to supply high pressure water to the nozzle for further cutting process. It increase the kinetic energy of fluid. It diameter is about 10-14 mm. It provide flexible movement and does not allow any significant loses.

Flow regulator: Flow regulators are used to regulate the flow according to cutting requirement. For high cutting load, high pressurized water is supplied at high rate.

Abrasive: Abrasive particles are used in abrasive water jet machining for machine hard material. Generally Aluminium oxide, Silicon carbide etc. used as abrasive particles.

Nozzle: As we know, **nozzles** are used to convert pressure energy into kinetic energy. This nozzle convert high pressure of water into high velocity jet. This high speed water jet strikes at work surface which is used for machining. There is possibility of erosion at orifice of the nozzle due to high pressure water jet. Therefor high wear resistance material is used for nozzle. The size of nozzle is about 0.2 – 0.4 mm. If abrasive water jet machining is used, abrasive particles mixed in water stream before entering into nozzle.

Drain and Catcher : The drain and catcher system is used to remove debris and other machined particle form water. It separate metal particle from water and this water is further send to reservoir. It also used to reduce noise associate with WJM.

Abrasive Water Jet Machining: *Working*

First water is filled in water reservoir. It provides water for cutting operation. A pump sucks water from water reservoir and send it to intensifier. Intensifier increases the water pressure from 4 bar to 4000 bars. It sends water to accumulator which store some pressurize water. This high pressure water now sends through tubing system to nozzle. The water passes through flow regulator valve which regulate the flow. Now this high pressure water enters into nozzle. Nozzle converts some pressure energy of water into kinetic energy. A high speed high pressurize water jet is available at nozzle exit. This water jet send to strike at work surface. It erode metal from the contact surface. Thus metal removal take place.

Abrasive Water Jet Machining: *Applications*

- It is used in aerospace industries.
- Abrasive water jet machining is used to cut hard metal like stainless steel, titanium, Inconel etc.
- It is used to machining or cutting reinforced plastic.
- Use to cut stone which reduce dust in environment.
- Used to machining PCB.

Abrasive Water Jet Machining: *Advantages*

- It does not change mechanical properties of work piece. It is useful for machining heat sensitive material.
- It is environment friendly because it does not form any dust particle and used water as cutting fluid.

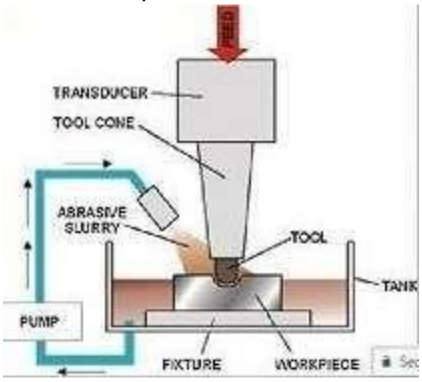
- Good surface finish.
- No physical tool is required.
- It can cut both soft and hard material. For machining soft materials, water jet machining is used and for machining hard materials, abrasive water jet machining is used.

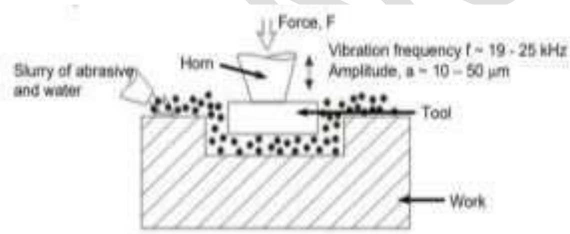
Abrasive Water Jet Machining: Dis*advantages*

- It cannot used for machining material which degrade in presence of water.
- Low metal removal rate.
- High initial cost.
- Thick material cannot be machined easily.

Ultrasonic Machining:

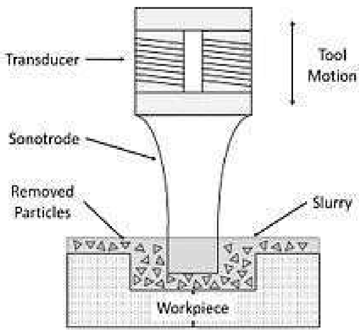
Ultrasonic machining is a non-traditional machining process. USM is grouped under the mechanical group NTM processes.
Fig. briefly depicts the USM process.





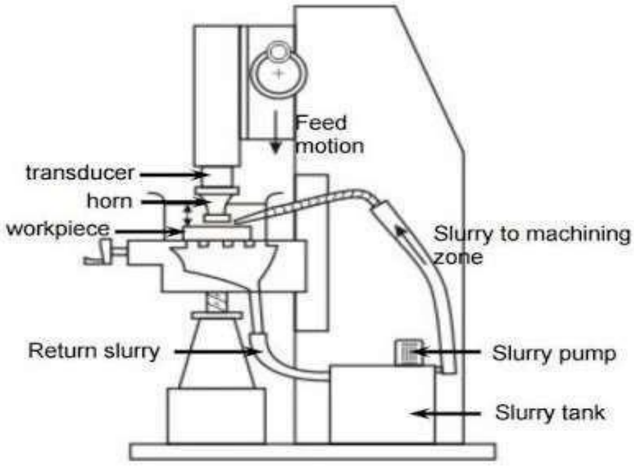
In ultrasonic machining, a tool of desired shape vibrates at an ultrasonic frequency (19 ~ 25 kHz) with an amplitude of around 10 – 50 μm over the workpiece. Generally the tool is pressed downward with a feed force, F. Between the tool and workpiece, the machining zone is flooded with hard abrasive particles generally in the form of a water based slurry. As the tool vibrates over the w/p, the abrasive particles act as the indenters and indent both the work material and the tool. The abrasive particles, as they indent, the work material, would remove the same, particularly if the work material is brittle, due to crack initiation, propagation and brittle fracture of the material. Hence, USM is mainly used for machining brittle materials {which are poor conductors of electricity and thus cannot be processed by Electrochemical and Electro-discharge machining (ECM and ED)}.

Ultrasonic Machining: Principle



It works on the same principle of ultrasonic welding. This machining uses ultrasonic waves to produce high frequency force of low amplitude, which act as driving force of abrasive. Ultrasonic machine generates high frequency vibrating wave of frequency about 19000 to 25000 Hz and amplitude about 10-50 micron. This high frequency vibration transfer to abrasive particle contains in abrasive slurry. This leads indentation of abrasive particle to brittle work piece and removes metal from the contact surface.

Ultrasonic Machining: *Construction*



- **Power Source:**

As we know, this machining process requires high frequency ultrasonic wave. So a high frequency high voltage power supply require for this process. This unit converts low frequency electric voltage (60 Hz) into high frequency electric voltage (20k Hz).

- **Magnetostrictive transducer:**

As we know, transducer is a device which converts electric single into mechanical vibration. In ultrasonic machining magnetostrictive type transducer is used to generate mechanical vibration. This transducer is made by nickel or nickel alloy.

- **Booster:**

The mechanical vibration generated by transducer is passes through booster which amplify it and supply to the horn.

- **Tool:**

The tool used in ultrasonic machining should be such that indentation by abrasive particle, does not leads to brittle fracture of it. Thus the tool is made by tough, strong and ductile materials like steel, stainless steel etc.

- **Tool holder or Horn:**

As the name implies this unit connects the tool to the transducer. It transfers amplified vibration from booster to the tool. It should have high endurance limit.

- **Abrasive Slurry:**

A water based slurry of abrasive particle used as abrasive slurry in ultrasonic machining. Silicon carbide, aluminum oxide, boron carbide are used as abrasive particle in this slurry. A slurry delivery and return mechanism is also used in USM.

Ultrasonic Machining: *Working*

First the low frequency electric current passes through electric supply. This low frequency current converts into high frequency current through some electrical equipment. This high frequency current passes through transducer. The transducer converts this high frequency electric single into high frequency mechanical vibration. This mechanical vibration passes through booster. The booster amplifies this high frequency vibration and send to horn. Horn which is also known as tool holder, transfer this amplified vibration to tool which makes tool vibrate at ultrasonic frequency. As the tool vibrates, it makes abrasive particle to vibrate at this high frequency. This abrasive particle strikes to the work piece and remove metal form it.

Ultrasonic Machining: *Applications*

- This machining is used to machine hard and brittle material like carbide, ceramic, glass etc.
- This is used in machining of die and tool of drill, wire drawing machine etc.
- Used in fabrication of silicon nitrite turbine blade.
- It is used to cut diamond in desire shape.
- It is used machining of machining non-conductive hard material which cannot be machined by ECM or EDM due to poor conductivity.

Ultrasonic Machining: *Advantages*

- Hard material can be easily machined by this method.
- No heat generated in work so there is no problem of work hardening or change in structure of work piece.
- Non-conductive metals or non-metals, which cannot be machined by ECM of EDM can be machined by it.

- It does not form chips of significant size.

Ultrasonic Machining: Dis*advantages*

- It is quite slower than other mechanical process.
- Tool wear is high because abrasive particle affect both work-piece and tool.
- It can machine only hard material. Ductile metal cannot be machine by this method.
- It cannot used to drill deep hole.

2. Electrical Energy based Unconventional Machining Processes:

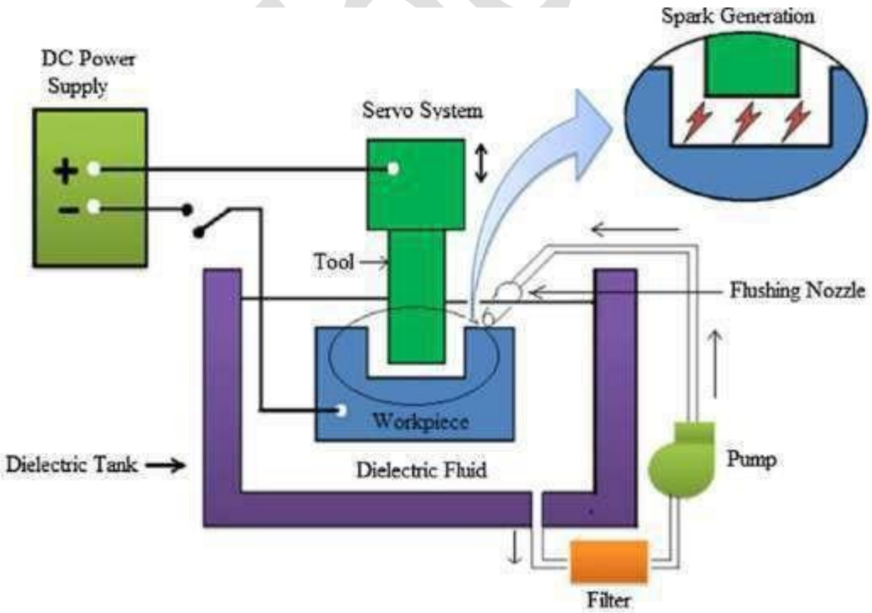
Here, electric spark discharge is used to cut and machine the workpiece. In electrical energy based processes thousands of sparks are produced every second. These sparks increase the temperature of the workpiece, melt the unwanted portions and vaporizes those portions. A dielectric fluid is used for cleaning the workpiece and facilitating a smooth spark discharge. Processes that come under this category are:

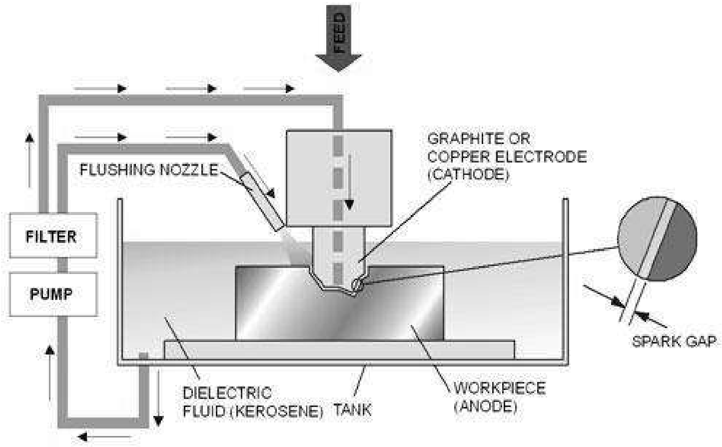
- Electrical Discharge Machining
- Wire Cut Electrical Discharge Machining

Electrical Discharge Machining (EDM)

Electrical Discharge Machining (EDM) is a nontraditional machining and electro thermal process in which material from the workpiece is removed by using electrical discharges (sparks). In EDM machine the material is removed by rapidly recurring (repeating) discharges of current in between the electrodes. The electrodes are separated by dielectric liquid and a high voltage is applied across it. It is used to machine those materials which are difficult to machine and have high strength temperature resistance. EDM can be used to machine only electrically conductive materials. Otherwise it cannot be used. One of the electrodes is called as tool and other is called as workpiece. Here the tool is connected with the negative terminal of the power supply and the workpiece is connected with the positive terminal.

Electrical Discharge Machining (EDM): *Principle*

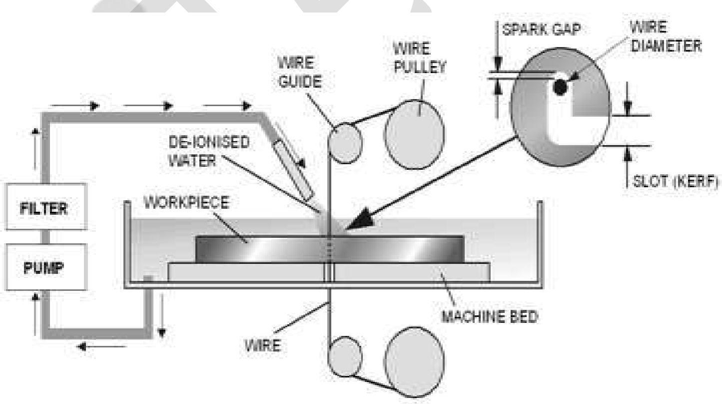




In Electrical discharge machining; a potential difference is applied across the tool and w/p in pulse form. The tool and workpiece must be electrically conductive and a small gap is maintained in between them.
The tool and workpiece is immersed in a dielectric medium (kerosene or deionized water). As the potential difference is applied, electrons from the tool start to move towards the workpiece. Here the tool is negative and w/p is positive.
The electrons moving from the tool to the w/p collide with the molecules of dielectric medium. Due to the collision of electrons with the molecule, it gets converted into ions. This increases the concentration of electrons and ions in the gap between the tool and w/p. The electron moves towards the w/p and ions towards the tool. An electric current is set up in between the tool and w/p and called as plasma. As the electrons and ions strikes the w/p and tool, its kinetic energy changes to heat energy.
The temperature of the heat produced is about 10000 degree Celsius. This heat vaporizes and melts the material from the workpiece. As voltage is break down, the current stops to flow between the tool and w/p and the molten material in the w/p is flushed by circulating dielectric medium leaving behind a crater.The spark generation is not continuous because constant voltage is not applied across the electrodes. The voltage is applied in pulse form.

Electrical Discharge Machining (EDM): ***Types***
(i) Ram/Sinker EDM :
This EDM machine consists of tool and workpiece immersed in a dielectric medium. It consists of ram type tool and it may be created according to the shape or form required to produce on the workpiece. It is also called as cavity type or volume EDM.
(ii) Wire EDM:
In wire EDM, thin single-strand wire is used to cut the material from the workpiece. The wire is usually made of brass. A constant gap is always maintain between the wire and w/p. The wire is continuously fed through the workpiece submerged in a tank with dielectric medium. Here spark is generated in the gap between the wire and workpiece.
It is used to cut metal as thick as 300 mm and to make punches, dies, and tools from hard metals that are difficult to cut from other methods.

Electrical Discharge Machining (EDM): ***Equipment.***



Dielectric Reservoir, Pump and Circulating system:
Pump is used to circulate the dielectric medium between the two electrodes (tool and workpiece). Kerosene or deionized water is used as dielectric medium.
Power Generator and Control Unit:
Generator is used to apply potential difference. The voltage used in this machining process is not constant but it is applied in pulse form. A control unit is used to control the different operation during machining process.
Working Tank with Work Holding Devices:
It has working tank with a work holding device. The workpiece is hold in the work holding devices. The tank contains dielectric medium.
Tool Holder:
It is used to hold the tool.
Servo System to Move the Tool:
A servo system is used to control the tool. It maintains the necessary gap between the electrodes (tool and workpiece).

Electrical Discharge Machining (EDM): ***Working***
In EDM, first the tool and w/p is clamped to the machine. After that with the help of a servo mechanism a small gap (of human hair) is maintain in between the tool and workpiece. The tool and workpiece is immersed in dielectric medium

(kerosene of deionised water). A potential difference is applied across the Electrode. An electric spark is generated in between the tool and workpiece. This spark generates a heat of about 10000 degree Celsius. And due to this heat the material from the workpiece starts to vaporize and melts. As the voltage breaks, the dielectric fluid flushes away the molten materials leaving behind a crater. This process keep continue and machined the workpiece.

Electrical Discharge Machining (EDM): ***Applications***

- It is mostly used by mold making and dies industries.
- It is used in prototype manufacturing in aerospace, automobile and electronic industries.
- It is used for coinage die making.
- It is used to create small holes in variety of application.
- It is used to disintegrate parts which cannot be disintegrate easily such as broken tools (studs, bolts drill bit and taps) form the workpiece.

Electrical Discharge Machining (EDM): ***Advantages***

- It can be used to machine any material that is electrically conductive.
- It can easily machine thin fragile sections such as webs or fins without deforming the part.
- Complex dies sections and molds are produced accurately, faster and at lower price.
- It is burr-free process.
- It does not involve contact between the tool and workpiece. So delicate sections and work material can be machined easily without any distortion.
- It can machined complex shapes which is not manufactured by the conventional machine tools.
- It can produce tapered holes.

Electrical Discharge Machining (EDM): ***Disadvantages***

- It can machine only electrically conductive materials.
- Low rate of metal removal.
- More tool wear during machining.
- Takes extra cost and time for the preparing electrodes for ram/sinker EDM.
- High power consumption.
- Overcut is formed in EDM.

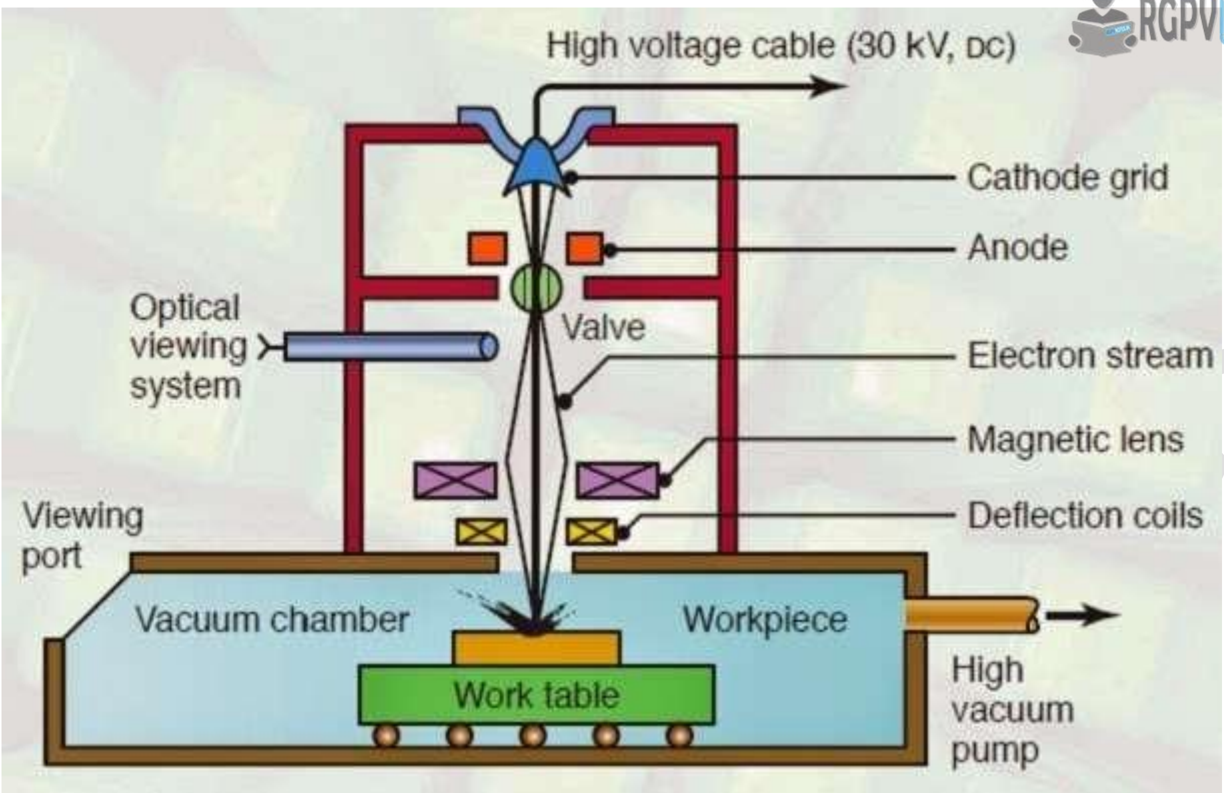
Electron Beam Machining (EBM):

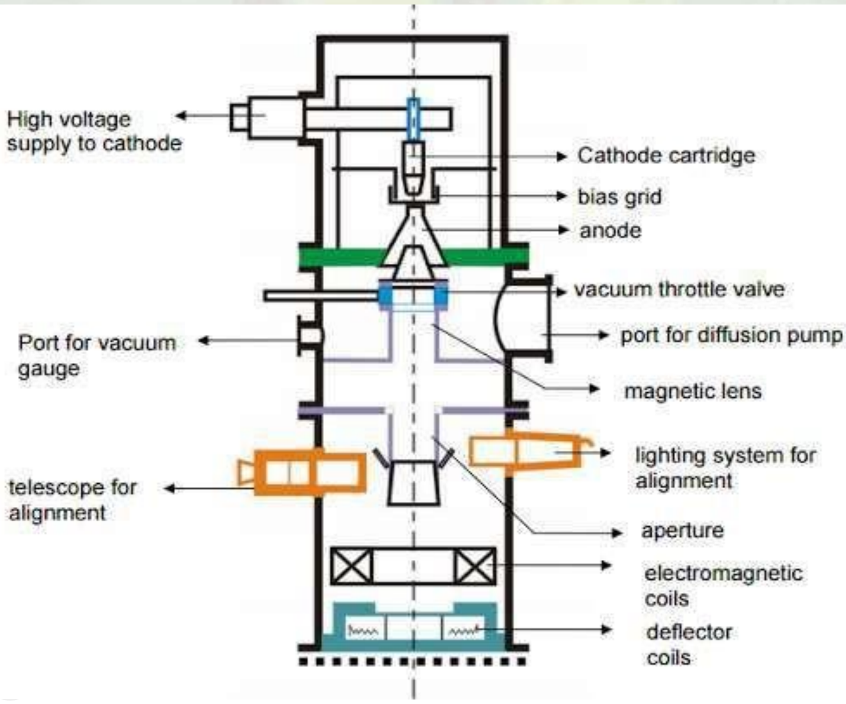
Electron Beam Machining is process in which high velocity electrons are concentrated in a narrow beam and then directed towards the workpiece for machining. When this high velocity electron strikes the workpiece, it melts and vaporizes the material from the workpiece.

Electron Beam Machining (EBM) Working Principle :

In an electron beam machining, the electrons strike the workpiece with a high velocity. As the electron strikes the workpiece, the kinetic energy of the electron changes into heat energy. The heat energy so produced is used to melt and vaporize the materials from the w/p. The whole process takes place in vacuum. Vacuum environment is used to prevent the contamination and avoid collision of electrons with air molecules. If the electrons collide with the air molecules, it will lost its Kinetic energy.

Electron Beam Machining (EBM) : Equipment/Construction





The various parts of the equipment used in EBM machine are

1. Cathode

The cathode is negatively charged and it is used to produce Electrons.

2. Annular Bias Grid

It is present next to the cathode. Annular bias grid is a circular shaped bias grid and prevents the diversion of electrons produced by the cathode. It works as a switch and makes the electron gun to operate in pulse mode.

3. Anode

It is placed after the annular bias grid. It is positively charged. Annular anode attracts the beam of electron towards it and gradually the velocity of the electron increases. As the electron beam leave the anode section, its velocity becomes half of the velocity of light.

4. Magnetic Lenses

The magnetic lenses reduce the divergence of electron beam and shape them. It allows only convergent electrons to pass and captures the low energy divergent electrons from fringes. It improves the quality of the beam.

5. Electromagnetic Lens

It helps the Electron beam to focus on the desired spot.

6. Deflector Coils

The deflector coil carefully guides the high velocity electron beam to a desired location on the workpiece and improves the shape of the holes.

Electron Beam Machining (EBM): Working

In EBM, first the electron is generated by the cathode and an annular biased grid does not allows the electron to diverge. From the annular bias grid, the electron produced by the cathode is attracted towards the anode and gradually its velocity increases. As the electron beam leaves the anode section, its velocity reaches to half of the velocity of the light. After that, it passes to the series of magnetic lenses. The magnetic lenses allows only convergent beam to pass through it and captures the divergent beam from the fringes. And then a high quality electron beam is made to pass through the electromagnetic lens and deflector coils. The electromagnetic lens focuses the electron beam to the desired spot on the workpiece. The deflector carefully guides the beam to the desired locations and improves the shape hole.

Electron Beam Machining (EBM) : Characteristics

- The Electron Beam machine is operated in pulse mode and this is achieved by the biasing annular biased grid.
- The beam current can be as low as 200 µamp to 1 amp.
- The pulse duration achieved in the EBM machine is 50 µs to 15 ms.
- The energy possessed by the pulse is 100 j/pulse.
- It utilizes voltage in the range of 150 kV to 200 kV. And this voltage is used to accelerate Electrons to about 200,000km/s.

Electron Beam Machining (EBM) : Applications

- It is used to produce very small size hole about 100 micro meters to 2 millimeter.
- It is used to produce holes in diesel injection nozzle.
- Used in aerospace industries for producing turbine blade for supersonic engines and in nuclear reactors.

Electron Beam Machining (EBM) : Advantages

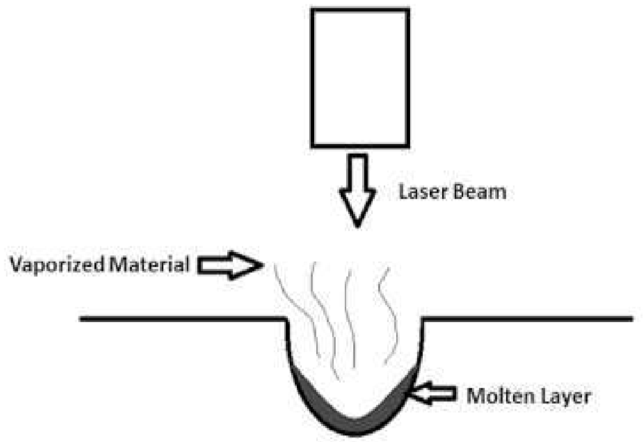
- It can produce bolts of small sizes.
- High accuracy and better surface finish.
- Almost all types of materials can be machined.
- Highly reactive metals such as Al and Mg can be machined easily.
- As it does not apply any mechanical cutting forces on the workpiece, so cost of work holding and fixtures is reduced.

Electron Beam Machining (EBM) : Disadvantages

- High equipment cost.
- Low metal removal rate.
- High skilled operator is required.
- High power consumption.
- Not applicable to produce perfectly cylindrical deep holes.

Laser Beam Machining (LBM)

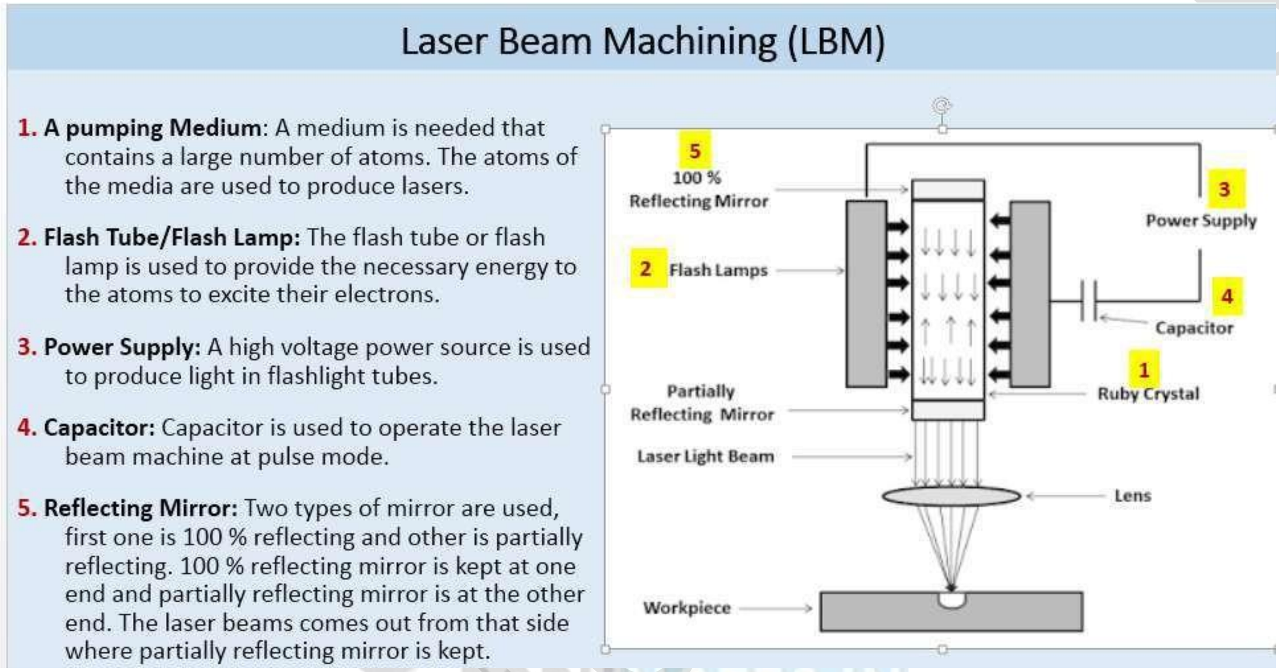
Laser Beam Machining (LBM) is a form of machining process in which laser beam is used for the machining of metallic and non-metallic materials. In this process, a laser beam of high energy is made to strike on the workpiece, the thermal energy of the laser gets transferred to the surface of the w/p (workpiece). The heat so produced at the surface heats, melts and vaporizes the materials from the w/p. Light amplification by stimulated emission of radiation is called **LASER**.



Laser Beam Machining (LBM) : Working Principle

It works on the principle that when a high energy laser beam strikes the surface of the workpiece. The heat energy contained by the laser beam gets transferred to the surface of the w/p. This heat energy absorbed by the surface heat melts and vaporizes the material from the w/p. In this way the machining of material takes place by the use of laser beam.

Laser Beam Machining (LBM) : Equipment/Construction



Laser Beam Machining (LBM) : How Laser is Produced

A high voltage power supply is applied across the flash tube. A capacitor is used to operate the flash tube at pulse mode. As the flash is produced by the flash tube, it emits light photons that contain energy. These light photons emitted by the flash tube are absorbed by the ruby crystal. The photons absorbed by the atoms of the ruby crystals excite the electrons to the high energy level and population inversion (situation when the number of exited electrons is greater than the ground state electrons) is attained. After short duration, this excited electrons jumps back to its ground state and emits a light photon. This emission of photon is called spontaneous emission. The emitted photon stimulates the excited electrons and they starts to return to the ground state by emitting two photons. In this way two light photons are produced by utilizing a single photon. Here the amplification (increase) of light takes place by stimulated emission of radiation. Concentration of the light photon increases and it forms a laser beam. 100 % reflecting mirror bounces back the photons into the crystal. Partially reflecting mirror reflects some of the photons back to the crystal and some of it escapes out and forms a highly concentrated laser beam. A lens is used to focus the laser beam to a desired location.

Laser Beam Machining (LBM) : Working

- A very high energy laser beam is produced by the laser machines.
- This laser beam produced is focused on the workpiece to be machined.
- When the laser beam strikes the surface of the w/p, the thermal energy of the laser beam is transferred to the surface of the w/p.
- This heats, melts, vaporizes and finally removes the material form the workpiece.
- In this way laser beam machining works.

Laser Beam Machining (LBM) : Application

- The laser beam machining is mostly used in automobile, aerospace, shipbuilding, electronics, steel and medical industries for machining complex parts with precision.
- In heavy manufacturing industries, it is used or drilling and cladding, seam and spot welding among others.
- In light manufacturing industries, it is used for engraving and drilling other metals.
- In the electronic industry, it is used for skiving (to join two ends) of circuits and wire stripping.

- In medical industry, it is used for hair removal and cosmetic surgery.

Laser Beam Machining (LBM) : Advantages

- It can be focused to a very small diameter.
- It produces a very high amount of energy, about 100 MW per square mm of area.
- It is capable of producing very accurately placed holes.
- Laser beam machining has the ability to cut or engrave almost all types of materials, when traditional machining process fails to cut or engrave any material.
- Since there is no physical contact between the tool and workpiece. The wear and tear in this machining process is very low and hence it requires low maintenance cost
- This machining process produces object of very high precision. And most of the object does not require additional finishing
- It can be paired with gases that help to make cutting process more efficient. It helps to minimize the oxidation of w/p surface and keep it free from melted of vaporized materials. Produces a very high energy of about 100 MW per square mm of area.
- It has the ability to engrave or cut almost all types of materials. But it is best suited for the brittle materials with low conductivity.

Laser Beam Machining (LBM) : Disadvantages

- High initial cost. This is because it requires many accessories which are important for the machining process by laser.
- Highly trained worker is required to operate laser beam machining machine.
- Low production rate since it is not designed for the mass production.
- It requires a lot of energy for machining process.
- It is not easy to produce deep cuts with the w/p that has high melting points and usually cause a taper.
- High maintenance cost.

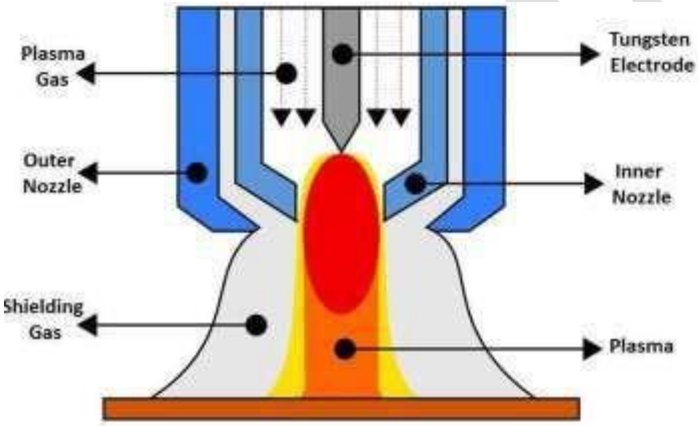
Plasma Arc Machining (PAM)

What is Plasma?

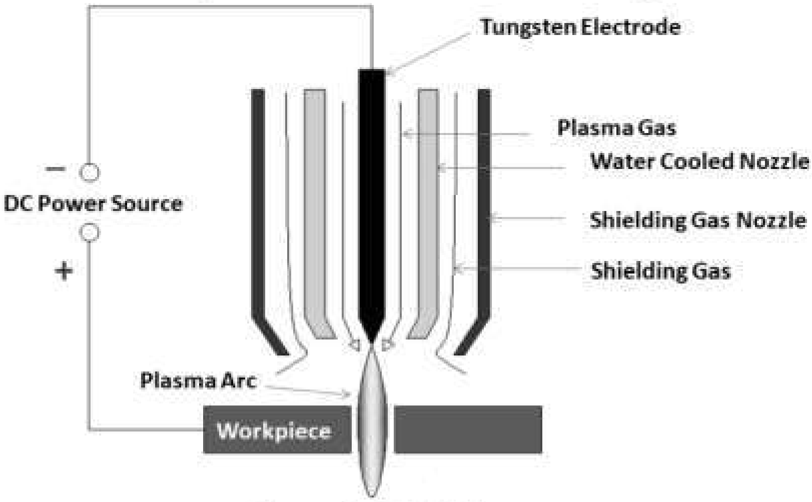
When a gas or air heated at high temperatures, the number of collisions between atoms increases. When you heat the gas above 5500ºC, it partially ionizes into positive ions, negative ions and neutral ions. When you further heat the gas above 11000ºC then, it completely ionizes. Such a completely ionized gas is called as Plasma. Plasma State lies in between temperatures 11,000ºC to 28,000ºC.

Basically, Plasma Arc Machining (PAM) is a metal cutting process where metals are cut with plasma arc, tungsten-inert-gas arc or a torch. It is mostly used for the metals that cannot be cut by an oxyacetylene torch. PAM was introduced in the industries in 1964 as a method that would help in the arc welding and that would require less current supply .Plasma Arc machining is also referred as PAM. In PAM, different gases are used according to different material. Different material means a workpiece. Your workpiece may be made up of aluminum, iron or steel. For example, for aluminum nitrogen is used, for argon hydrogen is used. In most of the cases, nitrogen and hydrogen are used. Plasma Arc Machining employs a high-velocity jet of high-temperature gas to melt and displace material in its path.

Plasma Arc Machining (PAM) : Construction



Principle of Plasma Arc Welding



Plasma Arc Machining

- Plasma arc machining consists of a Plasma gun. Plasma gun has an electrode made up of tungsten situated in the chamber.
- Here, this tungsten electrode is connected to the negative terminal of DC power supply.
- Thus, the tungsten acts as a cathode.
- While the positive terminal of DC power supply is connected to the work piece.
- Thus, work piece acts as an anode.

Plasma Arc Machining (PAM) : *Working*

As we give the power supply to the system, an electric arc develops between the cathodic tungsten electrode and the workpiece. As the gas comes in contact with the arc, there is a collision between the atoms of a gas and electrons of an electric arc and, as a result we get an ionized gas That, means we get the plasma state that we wanted for Plasma Arc machining. Now, this plasma is targeted towards the workpiece with a high velocity and the machining process starts. One thing to note down is that a high potential difference is applied in order to get the plasma state. In the whole process, high temperature conditions are required. As hot gases come out of nozzle there are chances of overheating. In order to prevent this overheating, a water jacket is used.

Plasma Arc Machining (PAM) : *Process Parameters*

- Current: Up to 500A
- Voltage: 30-250V
- Cutting speed: 0.1-7.5 m/min.
- Plate thickness: Up to 200mm
- Power require: 2 to 200 KW
- Material removal rate: 150 cm^3/min
- Velocity of Plasma: 500m/sec
- Material of workpiece: We can use any metal as material of workpiece. For instance, aluminum and stainless steel are highly recommended for this process.
-

Plasma Arc Machining (PAM) : *Applications*

- It is mostly used for cryogenic, high temperature corrosion resistant alloys.
- It is also used in case of titanium plate up to 8mm thickness.
- PAM is used in nuclear submarine pipe system and for welding steel rocket motor case.
- PAM is prominent for the applications related to stainless tube and tube mills.

Plasma Arc Machining (PAM) : *Advantages*

- In Plasma Arc Machining, hard as well as brittle metals can be easily machined.
- It can be applied to almost all types of metals.
- The best part of this process is that we get high cutting rate.
- We get a better dimensional accuracy in case of machining small cavities.
- It is a simple process to carry out and a very efficient process.
- It takes a big part in automatic repair of jet engine blades.

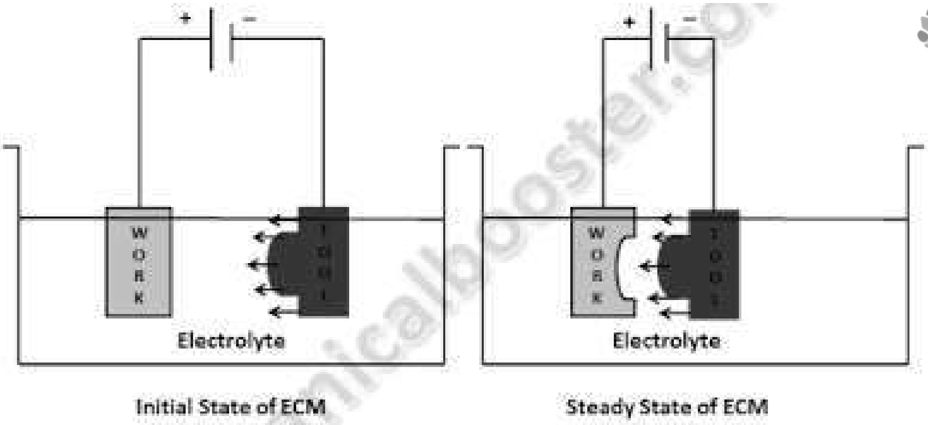
Plasma Arc Machining (PAM) : Dis*advantages*

- PAM involves various equipment but the cost of this equipment is very high.
- This entire machining process consumes high amount of inert gases.
- Production of narrower surfaces takes place which is unnecessary.
- The most harmful part of PAM is that metallurgical changes takes place on the surface.
- The operator or person handling whole process must take proper precautions. This process can affect human eyes so a proper goggles or helmet must be wear by an operator.

Electrochemical Machining (ECM)

Electrochemical machining (ECM) is a machining process in which electrochemical process is used to remove materials from the workpiece. In the process, workpiece is taken as anode and tool is taken as cathode. The two electrodes workpiece and tool is immersed in an electrolyte (such as NaCl). When the voltage is applied across the two electrodes, the material removal from the workpiece starts. The workpiece and tool is placed very close to each other without touching. In ECM the material removal takes place at atomic level so it produces a mirror finish surface. This process is used to machine only conductive materials.

Electrochemical Machining (ECM) : *Principle*



Working Principle of Electrochemical Machining

During electrochemical machining process, the reactions take place at the electrodes i.e. at the anode (workpiece) and cathode (tool) and within the electrolyte. Let's take an example of machining low carbon steel which is mainly composed of ferrous alloys (Fe). We generally use neutral salt solution of sodium chloride (NaCl) as the electrolyte to machine ferrous alloys. The ionic dissociation of NaCl and water takes place in the electrolyte as shown below.

$$NaCl \rightarrow Na^{+} + Cl^{-}$$

$$H_2O \rightarrow H^{+} + OH^{-}$$

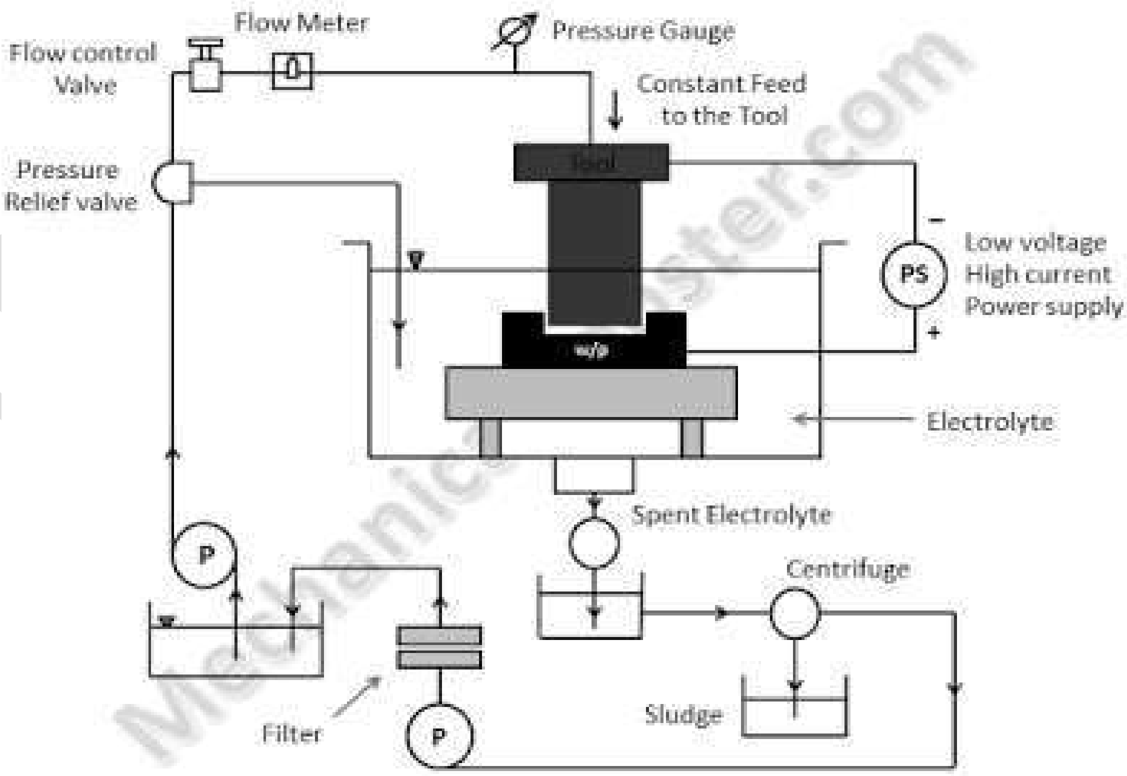
As the potential difference is applied across the electrode, the movement of ions starts in between the tool and w/p. The positive ions moves towards the tool (cathode) and negative ions move towards the workpiece. At cathode the hydrogen ions takes electrons and gets converted into hydrogen gas.

$$2H^{+} + 2e^{-} \rightarrow H_2 \uparrow$$

In the same way the iron atoms comes out from the anode (w/p) as Fe++ ions.

$$Fe \rightarrow Fe^{++} + 2e^{-}$$

Electrochemical Machining (ECM) : *Equipment/Construction*



Schematic Diagram of Electrochemical Drilling Unit

The ECM system has the following modules-

- Power Supply
- Electrolyte filtration and delivery system
- Tool Feed system
- Working Tank

Electrochemical Machining (ECM): *Working*

First the workpiece is assembled in the fixture and tool is brought close to the workpiece. The tool and workpiece is immersed in a suitable electrolyte. After that, potential difference is applied across the w/p (anode) and tool (cathode). The removal of material starts. The material is removed as in the same manner as we have discussed above in the working principle. Tool feed system advances the tool towards the w/p and always keeps a required gap in between them. The material from the w/p is comes out as positive ions and combine with the ions present in the electrolyte and precipitates as sludge. Hydrogen gas is liberated at cathode during the machining process. Since the dissociation of the material from the w/p takes place at atomic level, so it gives excellent surface finish. The sludge from the tank is taken out and separated from the electrolyte. The electrolyte after filtration again transported to the tank for the ECM process.

Electrochemical Machining (ECM): *Applications*

- ECM is used to machining disk or turbine rotor blade.
- It can be used for slotting very thin walled collets.
- ECM can be used to generate internal profile of internal cam.
- Production of satellite rings and connecting rod, machining of gears and long profile etc.

Electrochemical Machining (ECM): *Advantages*

- It can machine very complicated surface.
- A single tool can be used to machining large number of work-piece. Theoretically no tool wear occur.
- Machining of metal is independent on strength and hardness of tool.
- ECM gives very high surface finish.

Electrochemical Machining (ECM): Dis*advantages*

- High initial cost of machine.
- Design and tooling system is complex.
- Fatigue property of machined surface may reduce.
- Nonconductive material cannot be machined.
- Blind hole cannot be machined form ECM.
- Space and floor area requirement is high compare to conventional machining.

NON DESTRUCTIVE TESTING

Nondestructive testing (NDT) is the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or differences in characteristics without destroying the serviceability of the part or system. In other words, when the inspection or test is completed the part can still be used. In contrast to NDT, other tests are destructive in nature and are therefore done on a limited number of samples ("lot sampling"), rather than on the materials, components or assemblies actually being put into service. These destructive tests are often used to determine the physical properties of materials such as impact resistance, ductility, yield and ultimate tensile strength, fracture toughness and fatigue strength, but discontinuities and differences in material characteristics are more effectively found by NDT. Today modern nondestructive tests are used in manufacturing, fabrication and in-service inspections to ensure product integrity and reliability, to control manufacturing processes, lower production costs and to maintain a uniform quality level. During construction, NDT is used to ensure the quality of materials and joining processes during the fabrication and erection phases, and in-service NDT inspections are used to ensure that the products in use continue to have the integrity necessary to ensure their usefulness and the safety of the public.

NDT Test Methods

Current NDT methods are:

- Acoustic Emission Testing (AE),
- Electromagnetic Testing (ET),
- Guided Wave Testing (GW),
- Ground Penetrating Radar (GPR),
- Laser Testing Methods (LM),
- Leak Testing (LT),
- Magnetic Flux Leakage (MFL),
- Microwave Testing,
- Liquid Penetrant Testing (PT),
- Magnetic Particle Testing (MT),
- Neutron Radiographic Testing (NR),
- Radiographic Testing (RT),
- Thermal/Infrared Testing (IR),
- Ultrasonic Testing (UT),
- Vibration Analysis (VA) and
- Visual Testing (VT).
- **The six most frequently used test methods are MT, PT, RT, UT, ET and VT**

Visual Testing

Visual testing is the most commonly used test method in industry. Because most test methods require that the operator look at the surface of the part being inspected, visual inspection is inherent in most of the other test methods. As the name implies, VT involves the visual observation of the surface of a test object to evaluate the presence of surface discontinuities. VT inspections may be by Direct Viewing, using line-of sight vision, or may be enhanced with the use of optical instruments such as magnifying glasses, mirrors, boroscopes, charge-coupled devices (CCDs) and computer-assisted viewing systems (Remote Viewing). Corrosion, misalignment of parts, physical damage and cracks are just some of the discontinuities that may be detected by visual examinations. Visual inspection is commonly defined as "the examination of a material, component, or product for examination of a material, component, or product for conditions of nonconformance using light and the eyes, conditions of nonconformance using light and the eyes, alone or in conjunction with various aids. Visual inspection often also involves, shaking, listening, feeling, and sometimes even smelling the component being inspected.

Visual inspection consists of at least two major processes. The first is a **search process**. The second is a process of combining relevant knowledge, sensory input, and pertinent logical processes to provide an identification that some anomaly or pattern represents a flaw that poses a risk to the performance of the part. Visual inspection is commonly employed to support other NDT methods. Digital detectors and computer technology have made it possible to automate some visual inspections, this is known as "machine vision inspection." Visual inspection is the most basic and most commonly employed NDT method. It is applicable to a wide variety of material types and product forms. Several characteristics about the part being examined may be determined, which include dimensional conformance, the presence of discontinuities, general fit and wear, and simple discontinuities, and simple cosmetic compliance. It can be performed by direct or indirect methods during various stages of manufacturing or after the component has been placed in-service. The quality of an inspection are affected by four factors

- The quality of the detector (eye or camera).
- The lighting conditions.
- The capability to process the visual data.

- The level of training and attention to detail.

The majority of visual inspections are completed by an inspector, but machine vision is becoming more common. The primary advantage of an inspector is his ability to quickly adapt variety of lighting and other non-typical conditions, and their ability to use other senses. The primary advantage of a machine vision inspection system is their ability to make very consistent and rapid inspections of specific details of a component. Machine vision is primarily used in production applications where a large number of components require inspection.

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