RTU SYLLABUS

Introduction: Objective, scope and outcome of the course.

Classification of metal removal process and machines: Geometry of single point cutting tool and tool angles, tool nomenclature in ASA, ORS. Concept of orthogonal and oblique cutting.Type of chips, Mechanics of metal cutting; interrelationships between cutting force, shear angle, strain and strain rate. Thermal aspects of machining and measurement of chip tool interface temperature.

UNIT – I

MACHINE TOOLS

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.

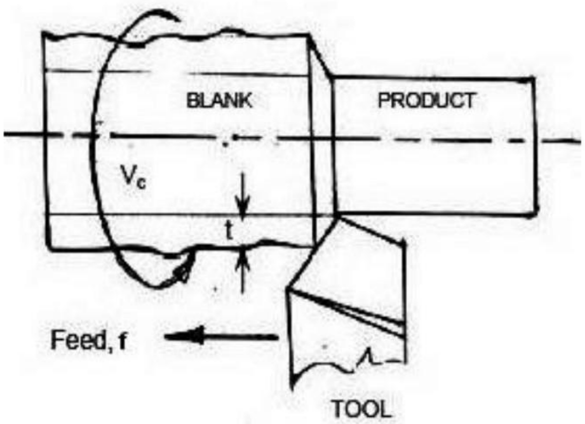


Fig. 1.1 Principle of machining (Turning)

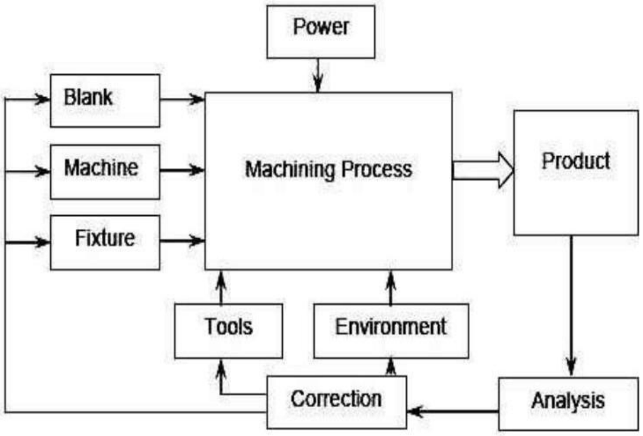


Fig. 1.2 Requirements for machining

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.

TYPES OF MACHINE TOOLS

Definition of machine tool

A machine tool is a non-portable power operated and reasonably valued device or system of devices in which energy is expended to produce jobs of desired size, shape and surface finish by removing excess material from the preformed blanks in the form of chips with the help of cutting tools moved past the work surface(s).

Basic functions of machine tools

Machine tools basically produce geometrical surfaces like flat, cylindrical or any contour on the preformed blanks by machining work with the help of cutting tools.

The physical functions of a machine tool in machining are:

Firmly holding the blank and the tool.

Transmit motions to the tool and the blank.

Provide power to the tool-work pair for the machining action.

Control of the machining parameters, i.e., speed, feed and depth of cut.

Classification of machine tools

Number of types of machine tools gradually increased till mid 20th century and after that started decreasing based on group technology.

However, machine tools are broadly classified as follows:

According to direction of major axis:

- ➢ Horizontal - center lathe, horizontal boring machine etc.
- ➢ Vertical - vertical lathe, vertical axis milling machine etc.
- ➢ Inclined - special (e.g. for transfer machines).

According to purpose of use:

- General purpose - e.g. center lathes, milling machines, drilling, machines etc.
- Single purpose - e.g. facing lathe, roll turning lathe etc.
- Special purpose - for mass production.

According to degree of automation:

- Non-automatic - e.g. center lathes, drilling machines etc.
- Semi-automatic - capstan lathe, turret lathe, hobbing machine etc.
- Automatic - e.g., single spindle automatic lathe, swiss type automatic lathe, CNC milling machine etc.

According to size:

- Heavy duty - e.g., heavy duty lathes (e.g. ≥ 55 kW), boring mills, planning machine, horizontal boring machine etc.
  Medium duty - e.g., lathes - 3.7 ~ 11 kW, column drilling machines, milling machines etc.
- Small duty - e.g., table top lathes, drilling machines, milling machines.
- Micro duty - e.g., micro-drilling machine etc.

According to blank type:

- Bar type (lathes).
- Chucking type (lathes).
- Housing type.

According to precision:

- Ordinary - e.g., automatic lathes.
- High precision - e.g., Swiss type automatic lathes.

According to number of spindles:

- Single spindle - center lathes, capstan lathes, milling machines etc.
- Multi spindle - multi spindle (2 to 8) lathes, gang drilling machines etc.

According to type of automation:

- Fixed automation - e.g., single spindle and multi spindle lathes.
- Flexible automation - e.g., CNC milling machine.

According to configuration:

- Stand alone type - most of the conventional machine tools.
- Machining system (more versatile) - e.g., transfer machine, machining center, FMS etc.

Specification of machine tools

A machine tool may have a large number of various features and characteristics. But only some specific salient features are used for specifying a machine tool. All the manufacturers, traders and users must know how machine tools are specified.

The methods of specification of some basic machine tools are as follows:

Centre lathe:

- Maximum diameter and length of the jobs that can be accommodated.
- Power of the main drive (motor).
- Range of spindle speeds and range of feeds.
- Space occupied by the machine.

Shaper:

- Length, breadth and depth of the bed.
- Maximum axial travel of the bed and vertical travel of the bed / tool.
- Maximum length of the stroke (of the ram / tool).
- Range of number of strokes per minute.
- Range of table feed.

- Power of the main drive.
- Space occupied by the machine.

Drilling machine (column type):

- Maximum drill size (diameter) that can be used.
- Size and taper of the hole in the spindle.
- Range of spindle speeds.
- Range of feeds.
- Power of the main drive.
- Range of the axial travel of the spindle / bed.
- Floor space occupied by the machine.

Milling machine (knee type and with arbor):

- Type; ordinary or swiveling bed type.
- Size of the work table.
- Range of travels of the table in X - Y - Z directions.
- Arbor size (diameter).
- Power of the main drive.
- Range of spindle speed.
- Range of table feeds in X - Y - Z directions.
- Floor space occupied.

MACHINE TOOLS

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.*

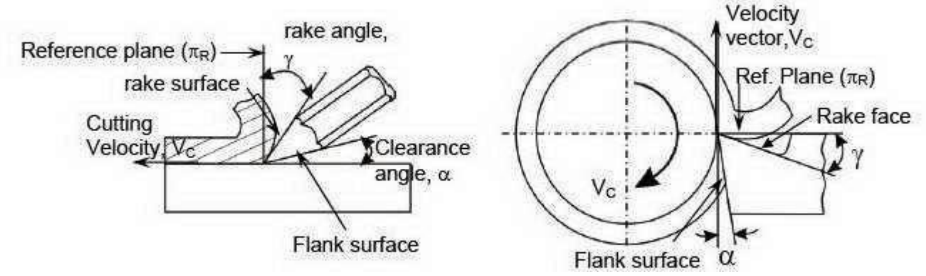


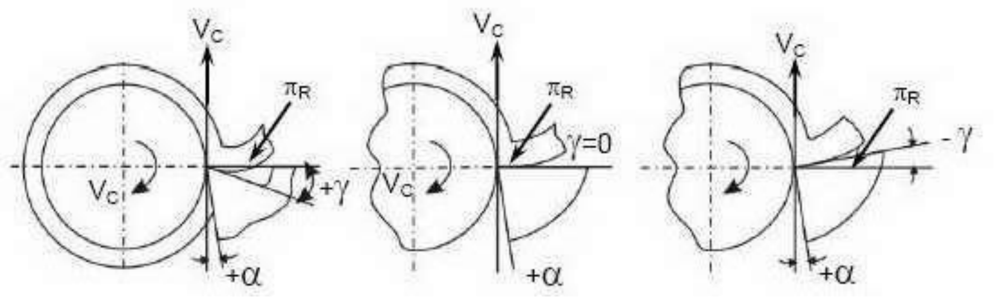
Fig. 1.3 Rake and clearance angles of cutting tools

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

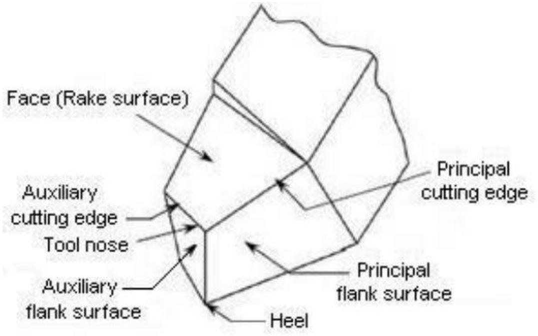
Tool-in-Hand System - where only the salient features of the cutting tool point are identified or visualized *as shown in Fig. 1.5 (a).* There is no quantitative information, i.e., value of the angles.

- ➢ 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).*



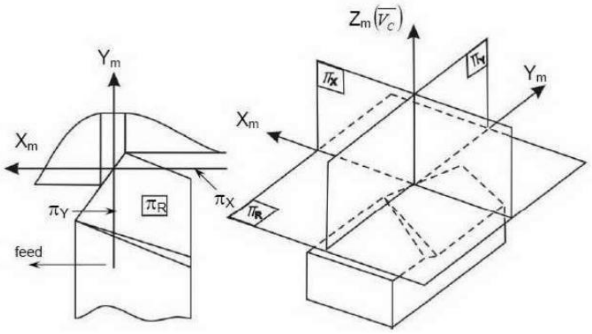


Fig 1.5 (a) Basic features of single point Fig. 1.5 (b) Planes and axes of reference
cutting (turning) tool in ASA system

The planes of reference and the coordinates used in ASA system for tool geometry are: ΠR - ΠX - ΠY 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 ΠR and taken in the direction of assumed longitudinal feed.

Π**Y** = Machine transverse plane; plane perpendicular to both ΠR and ΠX. [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.*

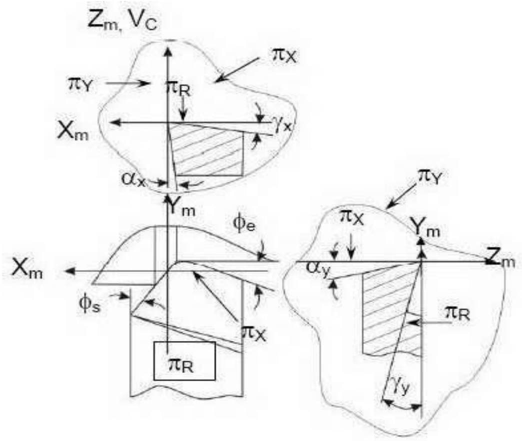


Fig. 1.6 Tool angles in ASA system

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]

γx = Side rake angle (axial rake): angle of inclination of the rake surface from the reference plane (ΠR) and measured on machine reference plane, ΠX.

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

Clearance angles: [Fig. 1.6]

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

αy = Back clearance angle (End relief angle): same as αx but measured on ΠY plane.

Cutting angles: [Fig. 1.6]

φs = Side cutting edge angle (Approach angle): angle between the principal cutting edge (its projection on ΠR) and ΠY and measured on ΠR.

φe = End cutting edge angle: angle between the end cutting edge (its projection on ΠR) from ΠX and measured on ΠR.

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 - **γy, γx, αy, αx, φe, φs, 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 velocity vector. Its analysis is more difficult of its three dimensions.

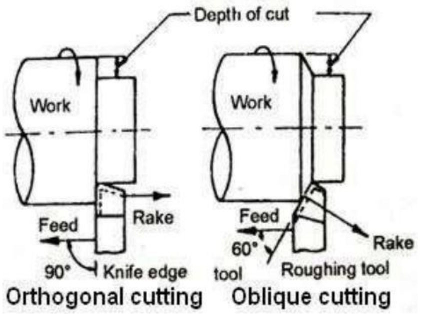
Orthogonal and oblique cutting

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 λ = 0^0, the chip flows along orthogonal plane, i.e., ρc = 0^0.

When λ ≠ 0^0, the chip flow is deviated from πo and ρc = λ where ρc is chip flow deviation (from πo) angle.



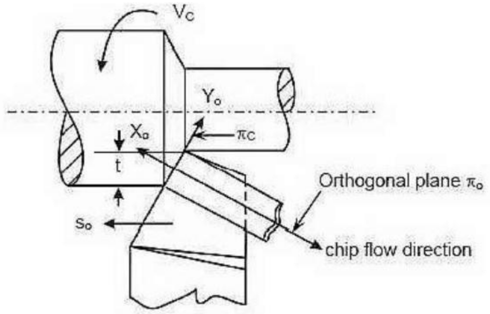


Fig. 1.7 (a) Setup of orthogonal and oblique cutting Fig. 1.7 (b) Ideal direction of chip flow in turning

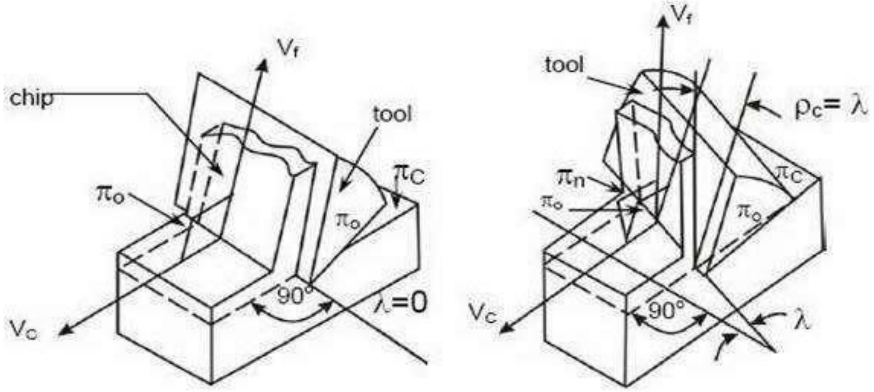


Fig. 1.8 Role of inclination angle, λ on chip flow direction

Orthogonal cutting: When chip flows along orthogonal plane, πo, i.e., ρc = 0^0.

Oblique cutting: When chip flow deviates from orthogonal plane, i.e. ρc ≠ 0^0.

But practically ρc may be zero even if λ ≠ 0^0 and ρc may not be exactly equal to λ even if λ ≠ 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 πo and φ = 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; λ = 0^0 and φ = 90^0 resulting chip flow along πo which is also πx in this case.

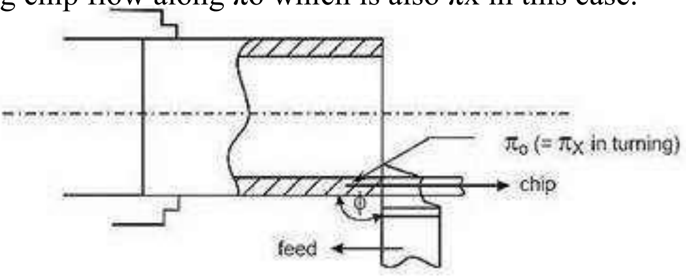


Fig. 1.9 Pure orthogonal cutting (pipe turning)

CHIP FORMATION

Mechanism of chip formation

Machining is a semi-finishing or finishing process essentially done to impart required or stipulated dimensional and form accuracy and surface finish to enable the product to:

Fulfill its basic functional
requirements. Provide better or
improved performance. Render long
service life.

Machining is a process of gradual removal of excess material from the preformed blanks in the form of chips. *The form of the chips is an important index of machining because it directly or indirectly indicates:*

Nature and behaviour of the work material under machining condition.
Specific energy requirement (amount of energy required to remove unit volume of work material) in machining work.
Nature and degree of interaction at the chip-tool interfaces.

Work material.
Material and geometry of the cutting tool.
Levels of cutting velocity and feed and also to some extent on depth of cut.
Machining environment or cutting fluid that affects temperature and friction at the chip-tool and Work-tool interfaces.

Knowledge of basic mechanism(s) of chip formation helps to understand the characteristics of chips and to attain favourable chip forms.

Mechanism of chip formation in machining ductile materials

During continuous machining the uncut layer of the work material just ahead of the cutting tool (edge) is subjected to almost all sided compression *as indicated in Fig. 1.10.*

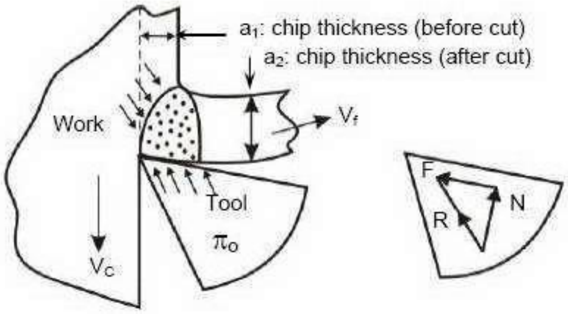
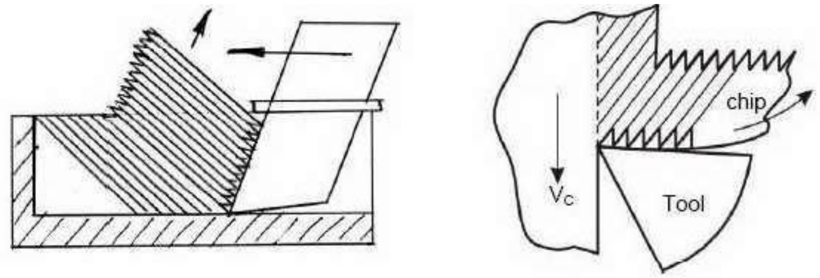


Fig. 1.10 Compression of work material (layer) ahead of the tool tip

The force exerted by the tool on the chip arises out of the normal force, N and frictional force, F as indicated in Fig. 1.10. Due to such compression, shear stress develops, within that compressed region, in different magnitude, in different directions and rapidly increases in magnitude. Whenever and wherever the value of the shear stress reaches or exceeds the shear strength of that work material in the deformation region, yielding or slip takes place resulting shear deformation in that region and the plane of maximum shear stress. But the forces causing the shear stresses in the region of the chip quickly diminishes and finally disappears while that region moves along the tool rake surface towards and then goes beyond the point of chip-tool engagement.

As a result the slip or shear stops propagating long before total separation takes place. In the mean time the succeeding portion of the chip starts undergoing compression followed by yielding and shear. This phenomenon repeats rapidly resulting in formation and removal of chips in thin layer by layer. *This phenomenon has been explained in a simple way by Piispannen*[*1] *using a card analogy as shown in Fig. 1.11 (a).*



(a) Shifting of the postcards by partial sliding against each other (b) Chip formation by shear in lamella Fig. 1.11 Piispannen model of card analogy to explain chip formation in machining ductile materials

In actual machining chips also, such serrations are visible at their upper surface *as indicated in Fig. 1.11 (b).* The lower surface becomes smooth due to further plastic deformation due to intensive rubbing with the tool at high pressure and temperature. The pattern of shear deformation by lamellar sliding, indicated in the model, can also be seen in actual chips by proper mounting, etching and polishing the side surface of the machining chip and observing under microscope.

The pattern and extent of total deformation of the chips due to the primary and the secondary shear deformations of the chips ahead and along the tool face, *as indicated in Fig. 1.12,* depend upon:

Work material.
Tool; material and geometry.
The machining speed (VC) and feed
(so). Cutting fluid application.

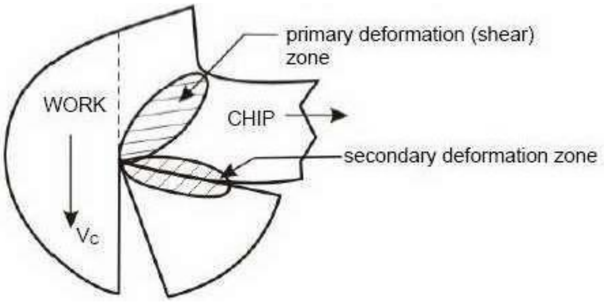


Fig. 1.12 Primary and secondary deformation zones in the chip

The overall deformation process causing chip formation is quite complex and hence needs thorough experimental studies for clear understanding the phenomena and its dependence on the affecting parameters. The feasible and popular experimental methods for this purpose are:

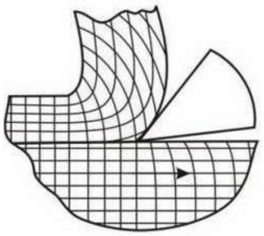
*2

Study of deformation of rectangular or circular grids marked on side surface *as shown in Fig. 1.13 (a and b).*

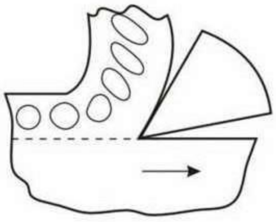
Microscopic study of chips frozen by drop tool or quick stop apparatus.

Study of running chips by high speed camera fitted with low magnification microscope.

It has been established by several analytical and experimental methods including circular grid Deformation that though the chips are initially compressed ahead of the tool tip, the final deformation is accomplished mostly by shear in machining ductile materials. *However, machining of ductile materials generally produces flat, curved or coiled continuous chips.*



(a) Rectangular grids



(b) Circular grids

Mechanism of chip formation in machining brittle materials

The basic two mechanisms involved in chip formation are:

Yielding - generally for ductile materials.
Brittle fracture - generally for brittle materials.

During machining, first a small crack develops at the tool tip as shown in Fig. 1.14 due to wedging action of the cutting edge. At the sharp crack-tip stress concentration takes place. In case of ductile materials immediately yielding takes place at the crack-tip and reduces the effect of stress concentration and prevents its propagation as crack. But in case of brittle materials the initiated crack quickly propagates, under stressing action, and total separation takes place from the parent work piece through the minimum resistance path *as indicated in Fig. 1.14.*

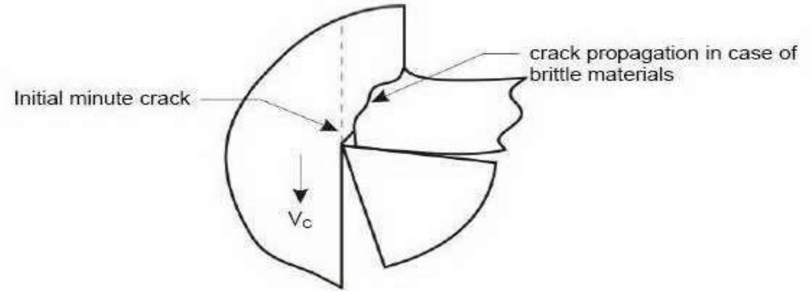
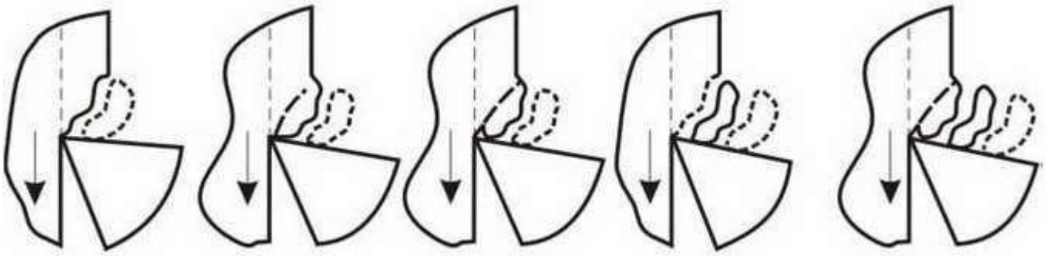


Fig. 1.14 Development and propagation of crack causing chip separation.

Machining of brittle material produces discontinuous chips and mostly of irregular size and shape. The process of forming such chips *is schematically shown in Fig. 1.15 (a, b, c, d and*



e).

Separation (b) Swelling (c) Further swelling (d) Separation (e) Swelling again Fig. 1.15 Schematic view of chip formation in machining brittle materials

Chip thickness ratio

Geometry and characteristics of chip forms

The geometry of the chips being formed at the cutting zone follow a particular pattern especially in machining ductile materials. The major sections of the engineering materials being machined are ductile in nature; even some semi-ductile or semi-brittle materials behave ductile under the compressive forces at the cutting zone during machining.

The pattern and degree of deformation during chip formation are quantitatively assessed and expressed by some factors, the values of which indicate about the forces and energy required for a particular machining work.

Chip reduction coefficient or cutting ratio

The usual geometrical features of formation of continuous chips are schematically shown in Fig. 1.16. The chip thickness (a_2) usually becomes larger than the uncut chip thickness (a_1). *The reason can be attributed to:*

- Compression of the chip ahead of the tool.
- Frictional resistance to chip flow.
- Lamellar sliding according to Piispannen.

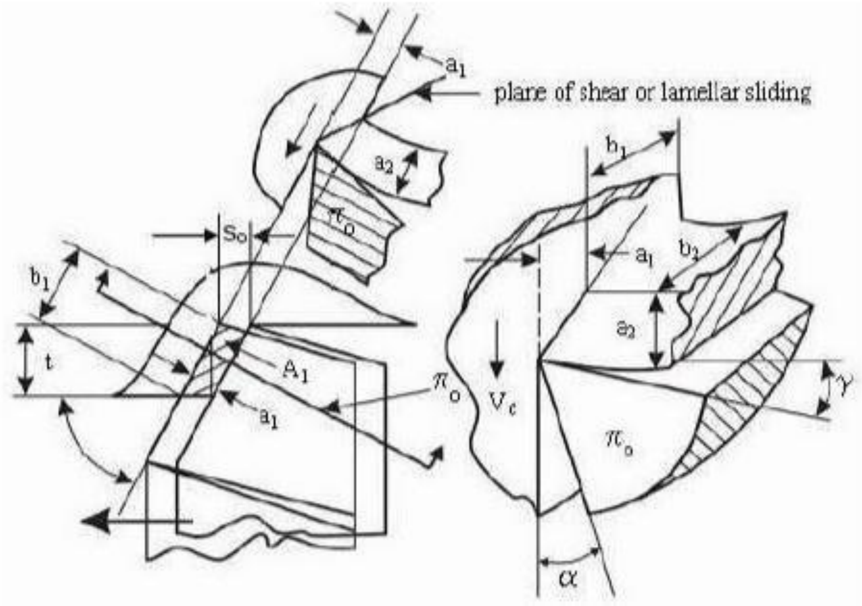


Fig. 1.16 Geometrical features of continuous chip formation.

The significant geometrical parameters involved in chip formation *are shown in Fig. 1.16* and those parameters are defined (in respect of straight turning) as:

t = depth of cut (mm) - perpendicular penetration of the cutting tool tip in work surface.
f = feed (mm/rev) - axial travel of the tool per revolution of the
job. b_1 = width (mm) of chip before cut.
b_2 = width (mm) of chip after cut.
a_1 = thickness (mm) of uncut layer (or chip before
cut). a_2 = chip thickness (mm) - thickness of chip
after cut. A_1 = cross section (area, mm2) of chip
before cut.

The degree of thickening of the chip is expressed by

$$\mathbf{r_c = a_2 / a_1 > 1.00} \quad \text{(since a2 > a1)} \qquad 1.1$$

where, r_c = chip reduction coefficient.

$$\mathbf{a_1 = f \sin\varphi} \qquad 1.2$$

where φ = principal cutting edge angle.

Larger value of r_c means more thickening i.e., more effort in terms of forces or energy required to accomplish the machining work. Therefore it is always desirable to reduce a_2 or r_c without sacrificing productivity, i.e. metal removal rate (MRR).

Chip thickening is also often expressed by the reciprocal of r_c as,

$$\mathbf{1 / r_c = r = a_1 / a_2} \qquad 1.3$$

where r = cutting ratio.

The value of chip reduction coefficient, r_c (and hence cutting ratio) depends mainly upon

⟶ Tool rake angle, γ ⟶ Chip-tool interaction, mainly friction,

μ Roughly in the following way,^{*3}

$$\mathbf{r_c =} \;\bar{}\; \quad \text{(for orthogonal cutting)} \qquad 1.4$$

‾ and γ are in radians.

The simple but very significant expression 1.4 clearly depicts that the value of r_c can be desirably reduced by

Using tool having larger positive
rake. Reducing friction by using
lubricant.

The role of rake angle and friction at the chip-tool interface on chip reduction coefficient are also schematically shown in Fig. 1.17.

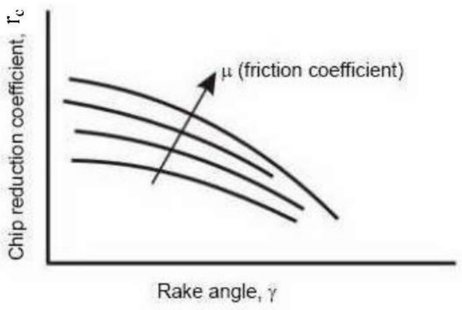


Fig. 1.17 Role of rake angle and friction on chip reduction coefficient

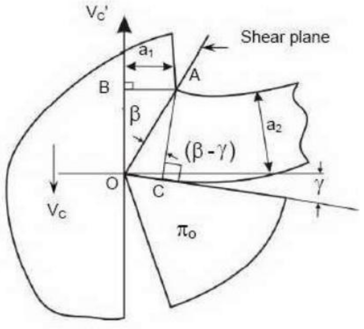


Fig. 1.18 Shear plane and shear angle in chip formation

Chip reduction coefficient, r_c is generally assessed and expressed by the ratio of the chip thickness, after cut (a_2) and before cut (a_1) as in equation 1.1. *But r_c can also be expressed or assessed by the ratio of:*

- ➢ Total length of the chip before cut (L_1) and after cut (L_2).
- ➢ Cutting velocity, V_C and chip velocity, V_f.

Considering total volume of chip produced in a given time,

$$\mathbf{a_1b_1L_1 = a_2b_2L_2} \tag{1.5}$$

The width of chip, b generally does not change significantly during machining unless there is side flow for some adverse situation. Therefore assuming, b1=b2 in equation 1.5, r_c comes up to be,

$$\mathbf{r_c = a_2 / a_1 = L_1 / L_2} \tag{1.6}$$

Again considering unchanged material flow (volume) ratio, Q

$$Q = \mathbf{(a_1b_1)V_C = (a_2b_2)V_f} \tag{1.7}$$

Taking $b_1=b_2$,

$$\mathbf{r_c = a_2 / a_1 = V_C / V_f} \tag{1.8}$$

Equation 5.8 reveals that the chip velocity, V_f will be lesser than the cutting velocity, V_C and the ratio is equal to the cutting ratio, $\mathbf{r = 1 / r_c}$

Shear angle

It has been observed that during machining, particularly ductile materials, the chip sharply changes its direction of flow (relative to the tool) from the direction of the cutting velocity, VC to that along the tool rake surface after thickening by shear deformation or slip or lamellar sliding along a plane. *This plane is called shear plane and is schematically shown in Fig. 1.18.*

Shear plane

Shear plane is the plane of separation of work material layer in the form of chip from the parent body due to shear along that plane.

Shear angle

Angle of inclination of the shear plane from the direction of cutting velocity as shown in Fig. 1.18.

The value of shear angle, denoted by β (taken in orthogonal plane) depends upon:

Chip thickness before cut and after cut i.e.

r_c. Rake angle, γ (in orthogonal plane).

From Fig. 1.18,

$\mathbf{AC = a_2 = OA\cos(\beta - \gamma)}$ and $\mathbf{AB = a_1 = OA\sin\beta}$ dividing a_2 by a_1

$$\mathbf{a_2 / a_1 = r_c = \cos(\beta - \gamma) / \sin\beta} \tag{1.9}$$

or $$\tan\beta = \mathbf{\cos}\gamma \mathbin{\mathbf{/}} \mathbf{r_c} - \mathbf{\sin}\gamma \qquad 1.10$$

Replacing chip reduction coefficient, r_c by cutting ratio, r, the equation 1.10 changes to,

$$\tan\beta = r\cos\gamma / 1 - r\sin\gamma \qquad 1.11$$

Equation 1.10 depicts that with the increase in r_c, shear angle decreases and vice-versa. It is also evident from equation 1.10 as well as equation 1.4 that shear angle increases both directly and indirectly with the increase in tool rake angle. Increase in shear angle means more favorable machining condition requiring lesser specific energy.

Cutting strain

The magnitude of strain, that develops along the shear plane due to machining action, is called cutting strain (shear). *The relationship of this cutting strain, ε with the governing parameters can be derived from Fig. 1.19.*

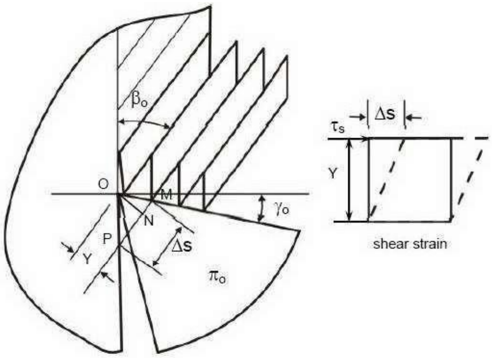


Fig. 1.19 Cutting strain in machining

Due to presence of the tool as an obstruction the layer 1 has been shifted to position 2 by sliding along the shear plane. From Fig. 1.19,

Cutting strain (average), $\varepsilon = \Delta s / Y = PM / ON$ or $\varepsilon = PN + NM / ON$

$$\varepsilon = PN / ON + NM / ON \quad \text{or} \quad \varepsilon = \cot\beta + \tan(\beta - \gamma) \qquad 1.12$$

Built-up-Edge (BUE) formation

Causes of formation

In machining ductile metals like steels with long chip-tool contact length, lot of stress and temperature develops in the secondary deformation zone at the chip-tool interface. Under such high stress and temperature in between two clean surfaces of metals, strong bonding may locally take place due to adhesion similar to welding. Such bonding will be encouraged and accelerated if the chip tool materials have mutual affinity or solubility.

The weldment starts forming as an embryo at the most favorable location and thus gradually grows as schematically shown in Fig. 1.20.

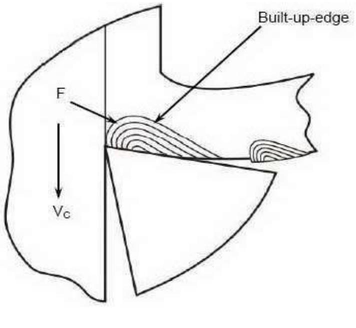


Fig. 1.20 Scheme of built-up-edge formation

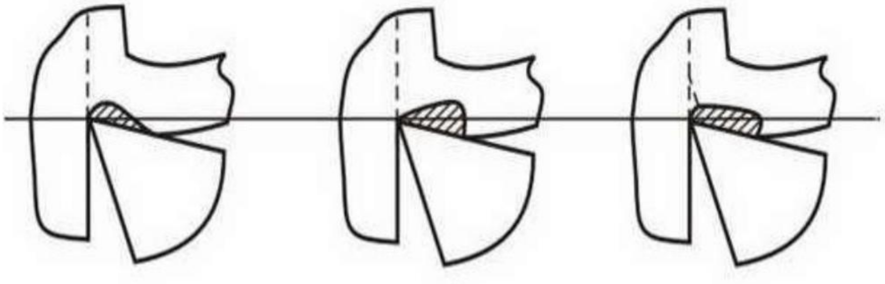
With the growth of the BUE, the force, F (shown in Fig. 1.20) also gradually increases due to wedging action of the tool tip along with the BUE formed on it. Whenever the force, F exceeds the bonding force of the BUE, the BUE is broken or sheared off and taken away by the flowing chip. Then again BUE starts forming and growing. This goes on repeatedly.

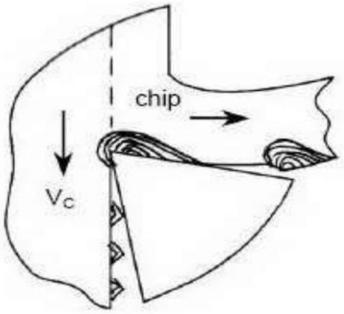
Characteristics of BUE

Built-up-edges are characterized by its shape, size and bond strength, which depend upon:

Work tool materials.
Stress and temperature, i.e., cutting velocity and feed.
Cutting fluid application governing cooling and lubrication.

BUE may develop basically in three different shapes as schematically shown in Fig. 1.21 (a, b and c).





(a) Positive wedge (b) Negative wedge (c) Flat type Fig. 1.22 Overgrowing and Fig. 1.21
Different forms of built-up-edge. overflowing of BUE causing surface roughness

In machining too soft and ductile metals by tools like high speed steel or uncoated carbide the BUE may grow larger and overflow towards the finished surface through the flank *as shown in Fig. 1.22*. While the major part of the detached BUE goes away along the flowing chip, a small part of the BUE may remain stuck on the machined surface and spoils the surface finish. BUE formation needs certain level of temperature at the interface depending upon the mutual affinity of the work-tool materials. With the increase in V_C and so the cutting temperature rises and favors BUE formation.

But if V_C is raised too high beyond certain limit, BUE will be squashed out by the flowing chip before the BUE grows. *Fig. 1.23 shows schematically the role of increasing V_C and so on BUE formation (size).* But sometime the BUE may adhere so strongly that it remains strongly bonded at the tool tip and does not break or shear off even after reasonably long time of machining. Such harmful situation occurs in case of certain tool-work materials and at speed-feed conditions which strongly favor adhesion and welding.

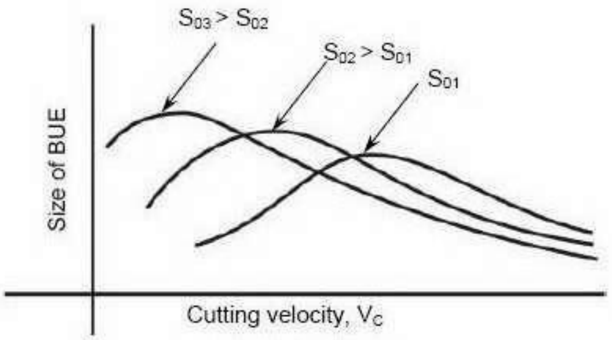


Fig. 1.23 Role of cutting velocity and feed on BUE formation

Effects of BUE formation

Formation of BUE causes several harmful effects, such as:

It unfavorably changes the rake angle at the tool tip causing increase in cutting forces and power consumption.

Repeated formation and dislodgement of the BUE causes fluctuation in cutting forces and thus induces vibration which is harmful for the tool, job and the machine tool.

Surface finish gets deteriorated.

May reduce tool life by accelerating tool-wear at its rake surface by adhesion and flaking occasionally, formation of thin flat type stable BUE may reduce tool wear at the rake face.

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. 1.24.*

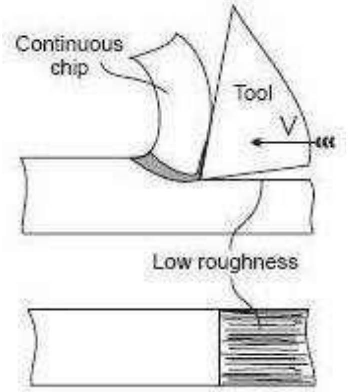


Fig. 1.24 Formation of continuous chips

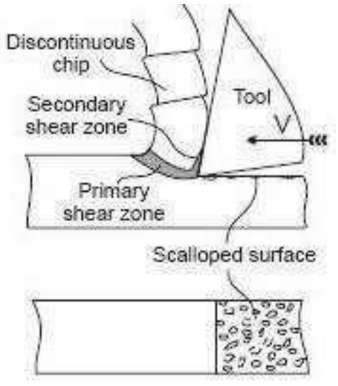


Fig. 1.25 Formation of discontinuous chips

The following condition favors the formation of continuous chips without BUE 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. 1.25.*

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.

Continuous chips with BUE

When cutting a ductile metal, the compression of the metal is followed by the high heat at tool face. This in turns enables part of the removed metal to be welded into the tool. This is known as built up edge, a very hardened layer of work material attached to the tool face, which tends to act as a cutting edge itself replacing the real cutting tool edge.

The built-up edge tends to grow until it reaches a critical size (~0.3 mm) and then passes off with the chip, leaving small fragments on the machining surface. Chip will break free and cutting forces are smaller, but the effect is a rough machined surface. The built-up edge disappears at high cutting speeds.

The weld metal is work hardened or strain hardened. While the cutting process is continued, some of built up edge may be combined with the chip and pass along the tool face. Some of the built up edge may be permanently fixed on the tool face. This produces a rough surface finish and the tool life may be reduced. *The formation of continuous chips with BUE is schematically shown in Fig. 1.26.*

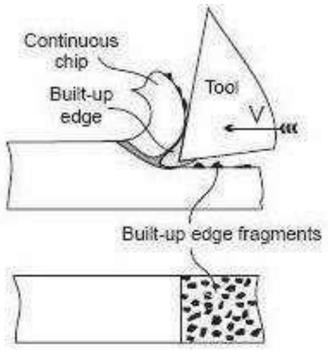


Fig. 1.26 Formation of continuous chips with BUE

The following condition favors the formation of continuous chips with BUE chips:

Work material - ductile.

Cutting velocity - low (~0.5 m/s,). Small or negative rake angles.

Feed - medium or large.

Cutting fluid - inadequate or absent.

Often in machining ductile metals at high speed, the chips are deliberately broken into small segments of regular size and shape by using chip breakers mainly for convenience and reduction of chip- tool contact length.

Chip breakers

Need and purpose of chip-breaking

Continuous machining like turning of ductile metals, unlike brittle metals like grey cast iron, produce continuous chips, which leads to their handling and disposal problems. The

problems become
acute when ductile but strong metals like steels are machined at high cutting velocity for high
MRR by

flat rake face type carbide or ceramic inserts. *The sharp edged hot continuous chip that comes out at very high speed:*

Becomes dangerous to the operator and the other people working in the vicinity. May impair the finished surface by entangling with the rotating job.
Creates difficulties in chip disposal.

Therefore it is essentially needed to break such continuous chips into small regular pieces for:

Safety of the working people.
Prevention of damage of the product. Easy collection and disposal of chips.

Chip breaking is done in proper way also for the additional purpose of improving machinability by reducing the chip-tool contact area, cutting forces and crater wear of the cutting tool.

Principles of chip-breaking

In respect of convenience and safety, closed coil type chips of short length and 'coma' shaped broken-to-half turn chips are ideal in machining of ductile metals and alloys at high speed.

The principles and methods of chip breaking are generally classified as follows:

Self chip breaking - This is accomplished without using a separate chip-breaker either as an attachment or an additional geometrical modification of the tool.

Forced chip breaking - This is accomplished by additional tool geometrical features or devices.

Self breaking of chips

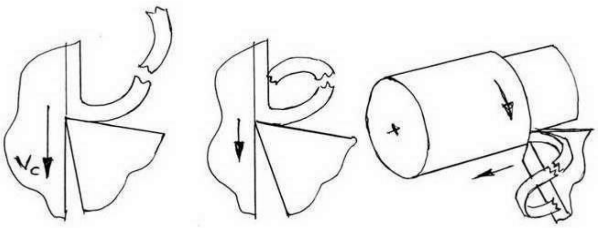
Ductile chips usually become curled or tend to curl (like clock spring) even in machining by tools with flat rake surface due to unequal speed of flow of the chip at its free and generated (rubbed) surfaces and unequal temperature and cooling rate at those two surfaces. With the increase in cutting velocity and rake angle (positive) the radius of curvature increases, which is more dangerous.

In case of oblique cutting due to presence of inclination angle, restricted cutting effect etc. the curled chips deviate laterally resulting helical coiling of the chips. *The curled chips may self break:*

By natural fracturing of the strain hardened outgoing chip after sufficient cooling and spring back *as indicated in Fig. 1.27 (a).* This kind of chip breaking is generally observed under the condition close to that which favors formation of jointed or segmented chips.

By striking against the cutting surface of the job, *as shown in Fig. 1.27 (b),* mostly under pure orthogonal cutting.

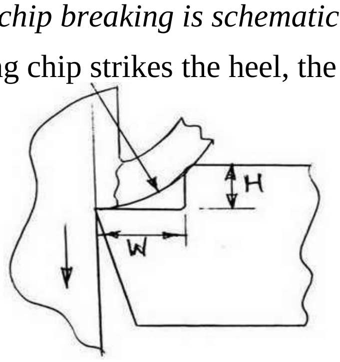
By striking against the tool flank after each half to full turn *as indicated in Fig. 1.27 (c).*



(a) Natural (b) Striking on job (c) Striking at tool flank Fig. 1.27 Principles of self breaking of chips

The possibility and pattern of self chip-breaking depend upon the work material, tool material and tool geometry (γ, λ, φ and r), levels of the process parameters (V_C and f_o) and the machining environment (cutting fluid application) which are generally selected keeping in view the overall machinability.

The basic principle of forced chip breaking is schematically shown in Fig. 1.28. When the strain hardened and brittle running chip strikes the heel, the cantilever chip gets forcibly bent and then breaks.



W = width, H = height, β = shear angle
Fig. 1.28 Principle of forced chip breaking

Fig. 1.29 (a, b, c and d) schematically shows some commonly used step type chip breakers:

Parallel step.
Angular step; positive and negative type.
Parallel step with nose radius - for heavy cuts.

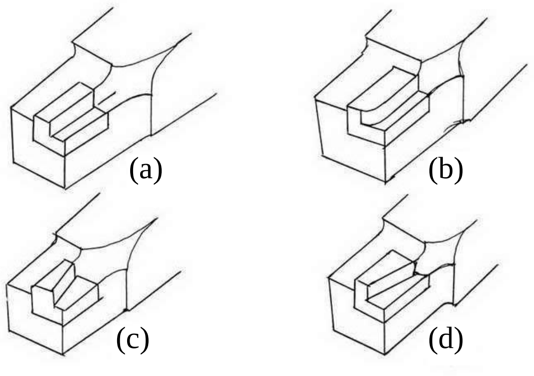
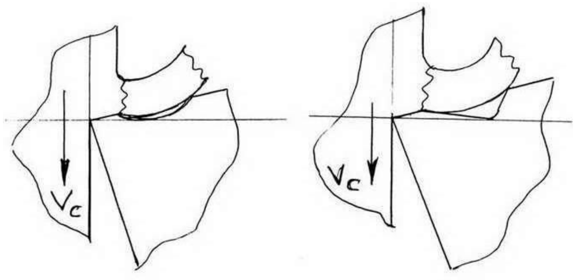


Fig. 1.29 Step type in-built chip breaker (a) Parallel step
(b) Parallel and radiused (c) Positive angular (d) Negative angular

Fig. 1.30 (a and b) schematically shows some commonly used groove type in-built chip breakers:

Circular groove.
Tilted Vee groove.



Circular groove (b) Tilted Vee groove Fig. 1.30 Groove type in-built chip breaker

The outer end of the step or groove acts as the heel that forcibly bends and fractures the running chip.
Simple in configuration, easy manufacture and inexpensive.

The geometry of the chip-breaking features is fixed once made. (i.e., cannot be controlled) Effective only for fixed range of speed and feed for any given tool-work combination.

Clamped type chip-breaker

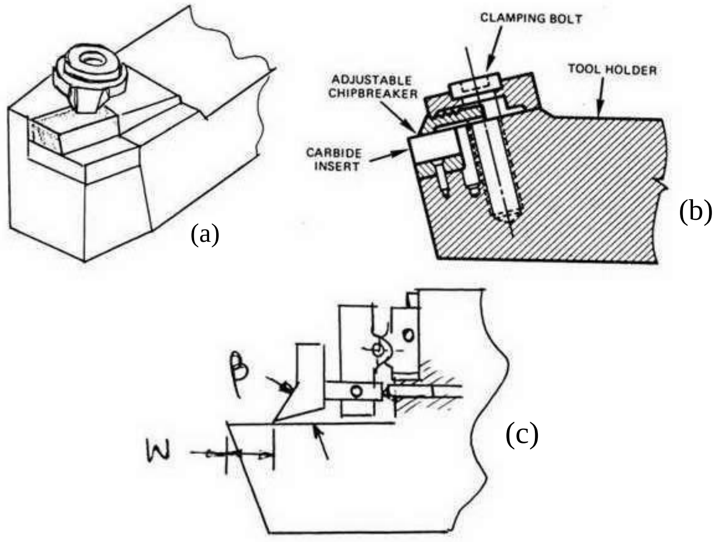
Clamped type chip breakers work basically in the principle of stepped type chip-breaker but have the provision of varying the width of the step and / or the angle of the heel.

Fig. 1.31 (a, b and c) schematically shows three such chip breakers of common use:

With fixed distance and angle of the additional strip - effective only for a limited domain of parametric combination.

With variable width (W) only - little versatile.

With variable width (W), height (H) and angle (β) - quite versatile but less rugged and more expensive.



Fixed geometry (b) Variable width (c) Variable width and angle Fig. 1.31 Clamped type chip breakers

Chip breakers in solid HSS tools

Despite advent of several modern cutting tool materials, HSS is still used for its excellent TRS (transverse rupture strength) and toughness, formability, grindability and low cost. The cutting tools made of solid HSS blanks, such as form tools, twist drills, slab milling cutters, broaches etc, are also often used with suitable chip breakers for breaking the long or wide continuous chips.

The handling of wide and long chips often becomes difficult particularly while drilling large diameter and deep holes. Grooves, either on the rake faces or on the flanks *as shown in Fig. 1.32* help to break the chips both along the length and breadth in drilling ductile metals. The locations of the grooves are offset in the two cutting edges.

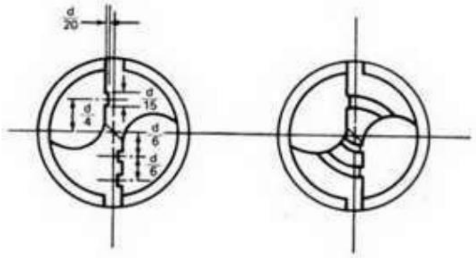
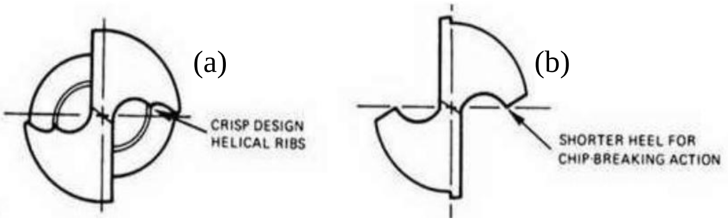


Fig. 1.32 Chip breaking grooves.



Crisp design of chip-breaking drill US industrial design of chip-breaking drill Fig. 1.33 Designs of chip-breaking drill

Fig. 1.33 (a and b) schematically shows another principle of chip-breaking when the drilling chips are forced to tighter curling followed by breaking of the strain hardened chips into *pieces.*

Plain milling and end milling inherently produces discontinuous ‘coma’ shaped chips of favorably shorter length. But the chips become very wide while milling wide surfaces and may offer problem of chip disposal. To reduce this problem, the milling cutters are provided with small peripheral grooves on the cutting edges *as shown in Fig. 1.34.* Such in-built type chip breakers break the wide chips into a number of chips of much shorter width. Similar groove type chip-breakers are also often provided along the teeth of broaches, for breaking the chips to shorter width and ease of disposal.

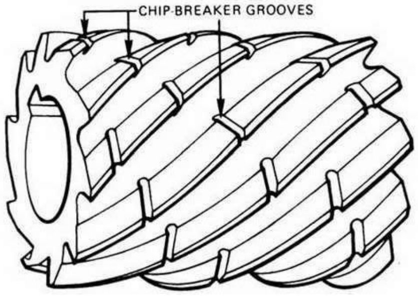


Fig. 1.34 Chip breaking grooves on a plain helical milling cutter

(e) Dynamic chip breaker

Dynamic turning is a special technique, where the cutting tool is deliberately vibrated along the direction of feed *as indicated in Fig. 1.35* at suitable frequency and amplitude. Such additional controlled tool oscillation caused by mechanical, hydraulic or electro-magnetic (solenoid) shaker improves surface finish. This also reduces the cutting forces and enhances the tool life due to more effective cooling and lubrication at the chip tool and work tool interfaces for intermittent break of the tool-work contact. Such technique, if further slightly adjusted, can also help breaking the chips. When the two surfaces of the chip will be waved by phase difference of about 90^0, the chip will either break immediately or will come out in the form of bids, which will also break with slight bending or pressure *as indicated in Fig. 1.35.* This technique of chip breaking can also be accomplished in dynamic drilling and dynamic boring. *Fig. 1.36 schematically shows another possible dynamic chip-breaking device suitable for radially fed type lathe operations, e.g., facing, grooving and parting.*

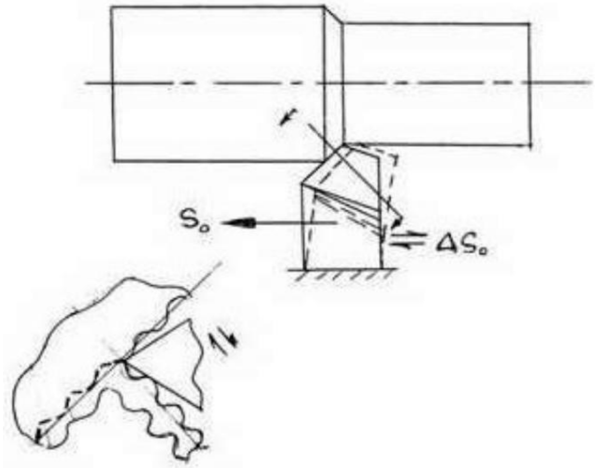


Fig 1.35 Self chip breaking in dynamic turning

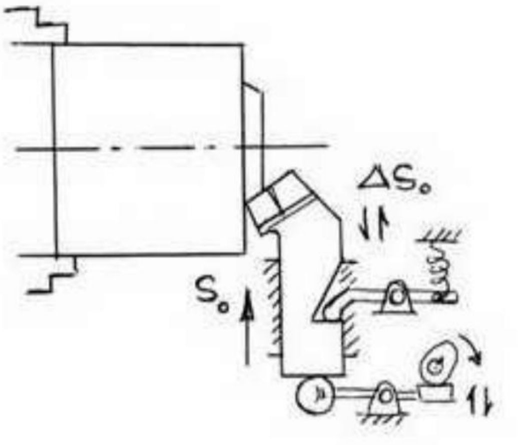


Fig 1.36 Dynamic chip breaking in radial operations in lathe

Overall effects of chip breaking

Favorable effects:

Safety of the operator(s) from the hot, sharp continuous chip flowing out at high speed.
Convenience of collection and disposal of chips.
A chance of damage of the finished surface by entangling or rubbing with the chip is eliminated.
More effective cutting fluid action due to shorter and varying chip tool contact length.

Unfavorable effects:

Chances of harmful vibration due to frequent chip breaking and hitting at the heel or flank of the tool bit.

More heat and stress concentration near the sharp cutting edge and hence chances of its rapid failure.

Surface finish may deteriorate.

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.

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.

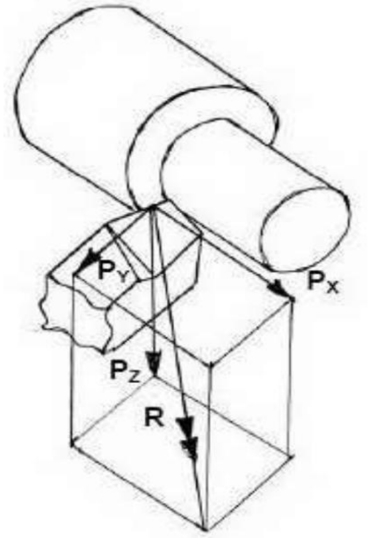
Evaluation of role of the various machining parameters (process - V_C, f_o, t, tool - material and geometry, environment - cutting fluid) on cutting forces.

Study of behaviour and machinability 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. 1.37 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. 1.38.



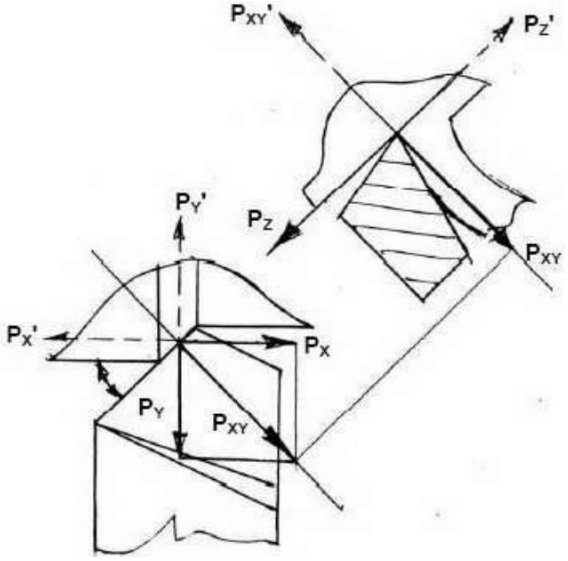


Fig. 1.37 Cutting force R resolved into P_X, P_Y and P_Z Fig. 1.38 turning force resolved into P_Z, P_X and P_Y

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

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

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. 1.37 and Fig. 1.38 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. 1.38.*

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, π0, the cutting force (resultant) and its components P_Z and P_{XY} remain in the orthogonal plane. *Fig. 1.39 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.

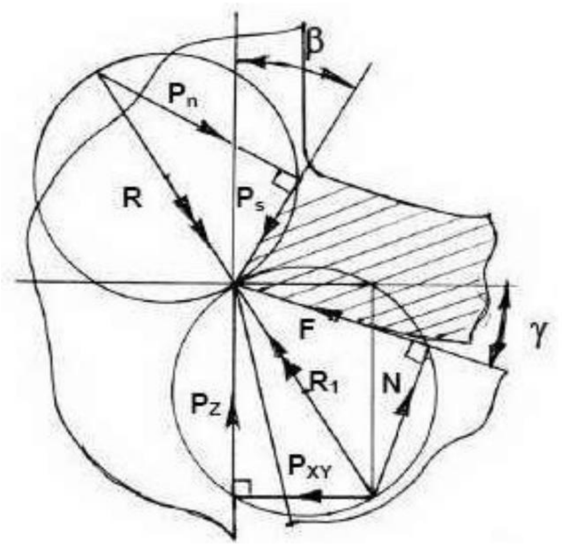


Fig 1.39 Development of Merchant's circle diagram

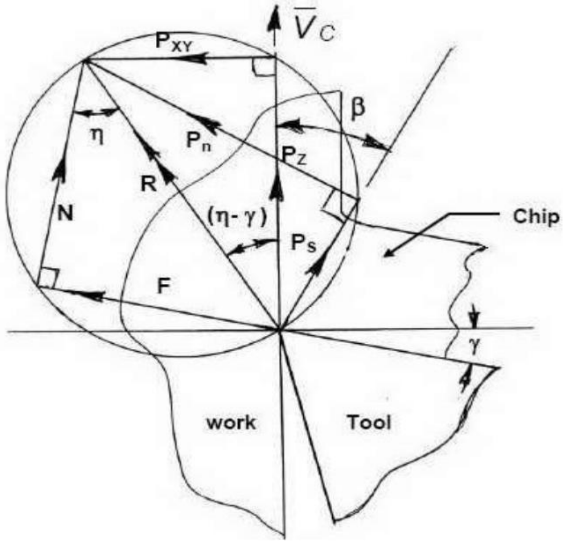


Fig. 1.40 Merchant's Circle Diagram with cutting forces

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.

$R_1 = P_Z + P_{XY}$ 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. 1.40.
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.

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: 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.

Experimental methods: Direct measurement.

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. 1.40. *From the MCD shown in Fig. 1.40,*

$P_Z = R\cos(\eta - \gamma)$ 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, τs - 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 τs remains almost unchanged.

Then for turning brittle material,

$PZ = t.f.\ \tau s \cos(90^0 - 2\beta) / \sin\beta \cos(90^0 - \beta)$ 1.22

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

Where, $\cot\beta = r_c - \tan\gamma$ $r_c = a_2 / a_1 = a_2 / f \sin\varphi$

It is difficult to measure chip thickness and evaluate the values of ζ while machining brittle materials and the value of τs 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 τs is obtained from,

$\tau s = 0.186\ BHN$ (approximate) 1.26

or $\tau s = 0.74 \sigma u \varepsilon^{0.6O}$ (more suitable and accurate) 1.27

where, σu - Ultimate tensile strength of the work material

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

- % elongation

Substituting Eqn. 1.25 in Eqn. 1.21,

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

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

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 $\beta + \eta - \gamma 0$
$= 45$, 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, $\tau s = 0.74\sigma u\varepsilon^{0.6O}$ or $\tau s = 0.186$ BHN

It is already known,

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

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

and $\mathbf{P_Y = t.f.\tau s(r_c - \tan\gamma - 1) \cos\varphi}$ 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,

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

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

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

$\mathbf{P_s = A_s\tau s}$

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

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

$\mathbf{\tau s = (P_Z \cos\beta - P_{XY} \sin\beta)\sin\beta / t.f}$ 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:

$\beta = - + \quad -$

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.

$\beta = - \eta + \gamma$

Velocity relationship

The velocity relationships for orthogonal cutting are illustrated in fig. 2.7 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.

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

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

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 workpiece). 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**) $\mathbf{= t.\ f.V_C}$ 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, $\mathbf{MRR = t.f.V_C}$ 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, $\mathbf{P_C = P_Z.V_C + P_X.V_f}$ 1.50

where, $\mathbf{V_f}$ = feed velocity = **Nf / 1000** m/min [N = rpm]

1.51