UNIT - I

THEORY OF METAL CUTTING

1.1 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.

1.2 MATERIAL REMOVAL PROCESSES

1.2.1 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).

1.2.2 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.

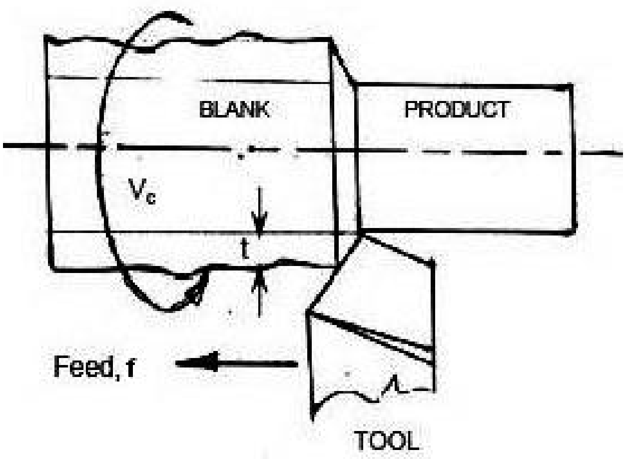


Fig. 1.1 Principle of machining (Turning)

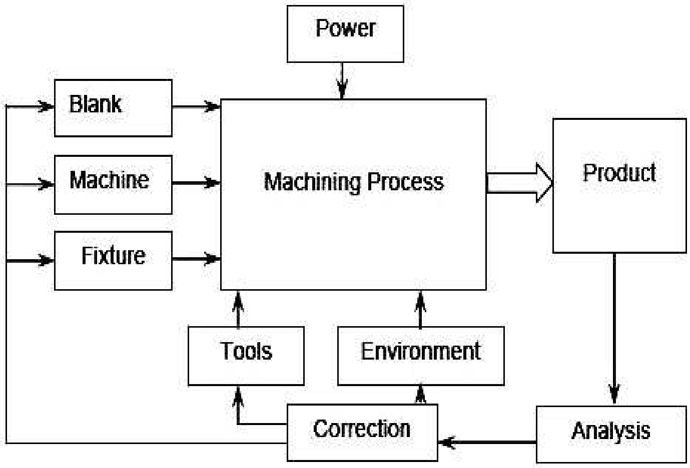


Fig. 1.2 Requirements for machining

1.2.3 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.

1.2.4 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.

1.3 TYPES OF MACHINE TOOLS

1.3.1 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).

1.3.2 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.

1.3.3 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. $\geq$ 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.

1.3.4 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.

1.4 THEORY OF METAL CUTTING

1.4.1 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.

1.4.2 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.

1.4.2.1 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.*

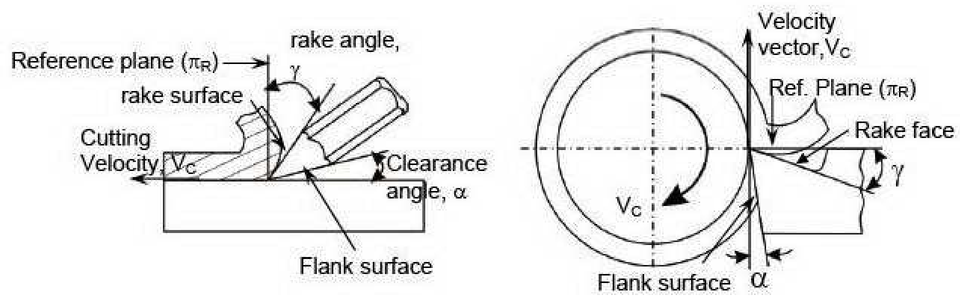
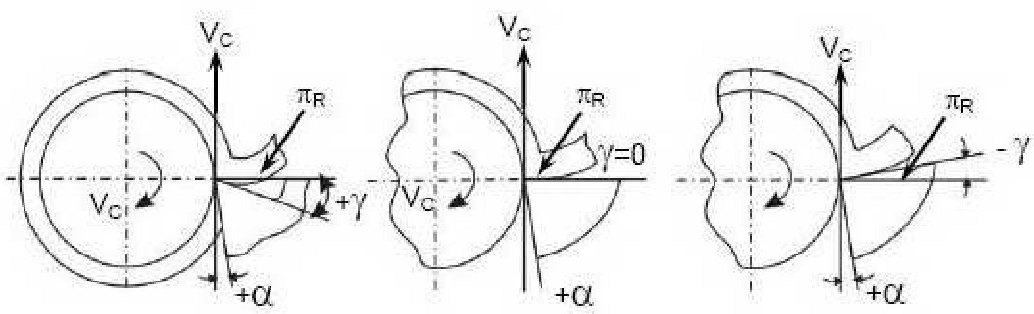


Fig. 1.3 Rake and clearance angles of cutting tools

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 ($3^0 \sim 15^0$) depending upon tool-work materials and type of the machining operations like turning, drilling, boring etc.

1.4.2.2 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.

1.4.2.3 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).*

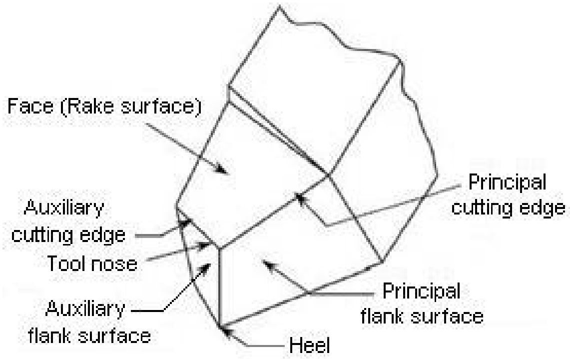


Fig 1.5 (a) Basic features of single point cutting (turning) tool

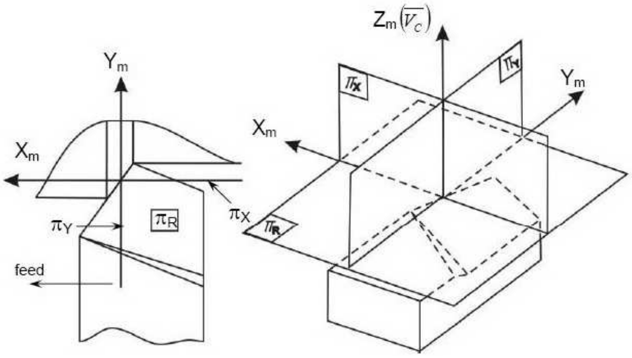


Fig. 1.5 (b) Planes and axes of reference in ASA system

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.*

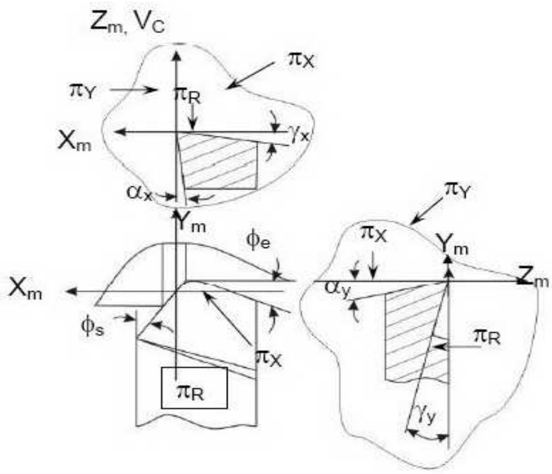


Fig. 1.6 Tool angles in ASA system

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.

1.4.3 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 - $\boldsymbol{\gamma_y, \gamma_x, \alpha_y, \alpha_x, \varphi_e, \varphi_s, r}$ (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

1.4.4 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.

1.4.4.1 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, $\rho_c = 0^0$.
- When $\lambda \neq 0^0$, the chip flow is deviated from π_o and $\rho_c = \lambda$ where ρ_c is chip flow deviation (from π_o) angle.

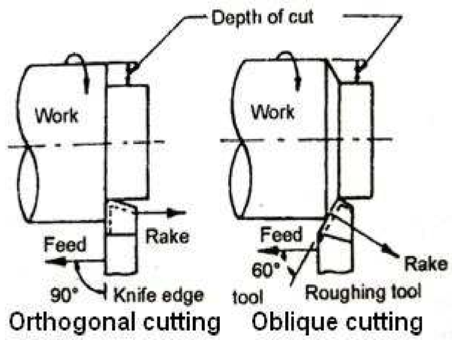


Fig. 1.7 (a) Setup of orthogonal and oblique cutting

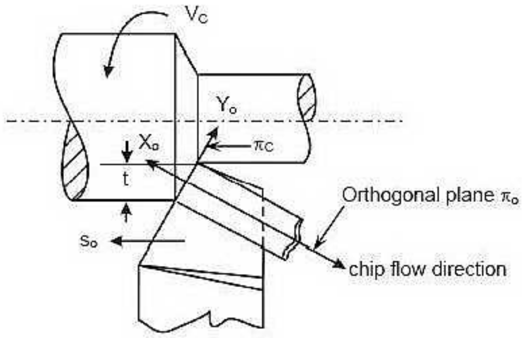


Fig. 1.7 (b) Ideal direction of chip flow in turning

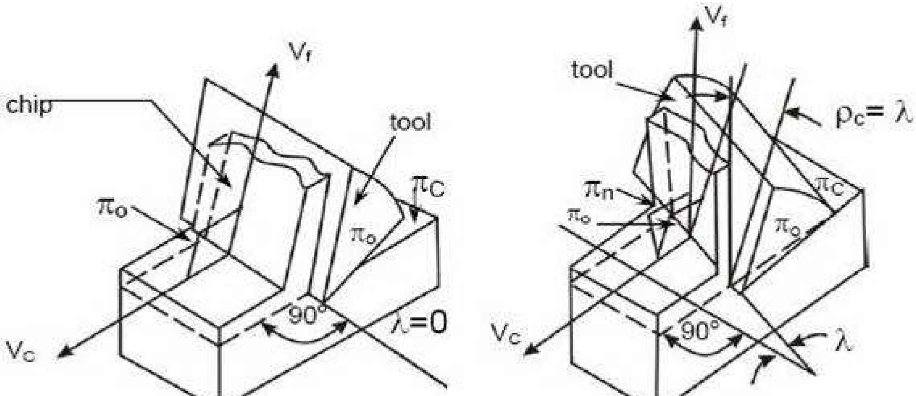


Fig. 1.8 Role of inclination angle, λ on chip flow direction

Orthogonal cutting: When chip flows along orthogonal plane, π_o, i.e., $\rho_c = 0^0$.

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

But practically ρ_c may be zero even if $\lambda = 0^0$ and ρ_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.

1.4.4.2 Pure orthogonal cutting

This refers to chip flow along π_o and $\varphi = 90^0$ *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 $\varphi = 90^0$ resulting chip flow along π_o which is also π_x in this case.

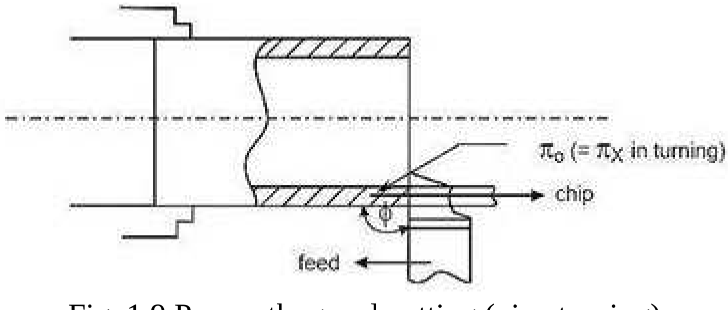


Fig. 1.9 Pure orthogonal cutting (pipe turning)

1.5 CHIP FORMATION

1.5.1 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 behavior 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.

The form of machined chips depends mainly upon:

- 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 favorable chip forms.

1.5.1.1 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.*

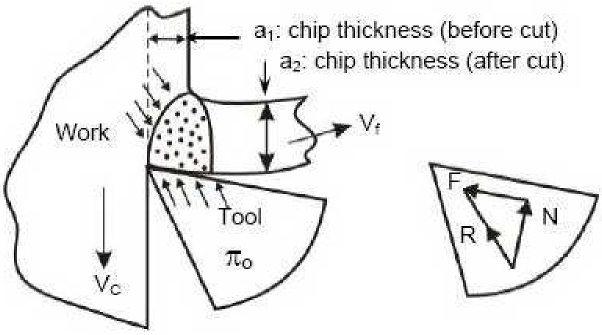
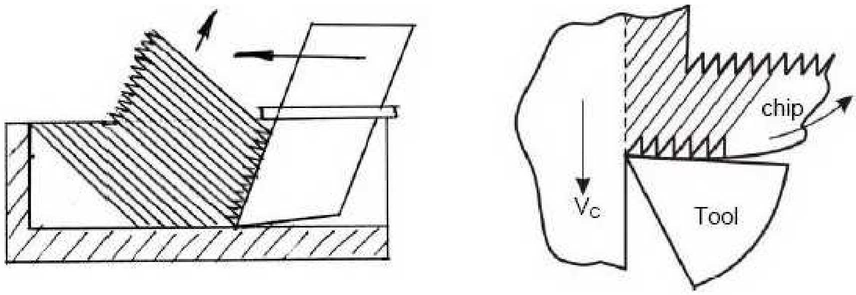


Fig. 1.10 Compression of work material (layer) ahead of the tool tip

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.

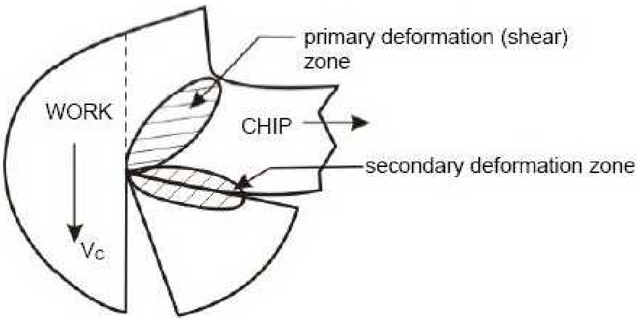
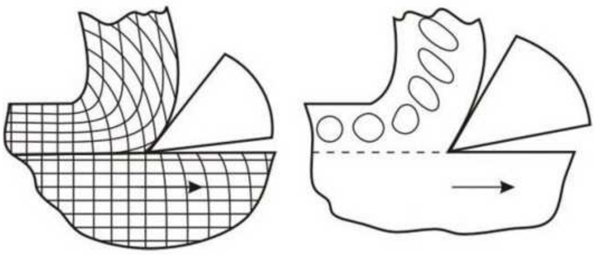


Fig. 1.12 Primary and secondary deformation zones in the chip

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[*2] for this purpose are:

- 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

Fig. 1.13 Pattern of grid deformation during chip formation

1.5.1.2 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.*

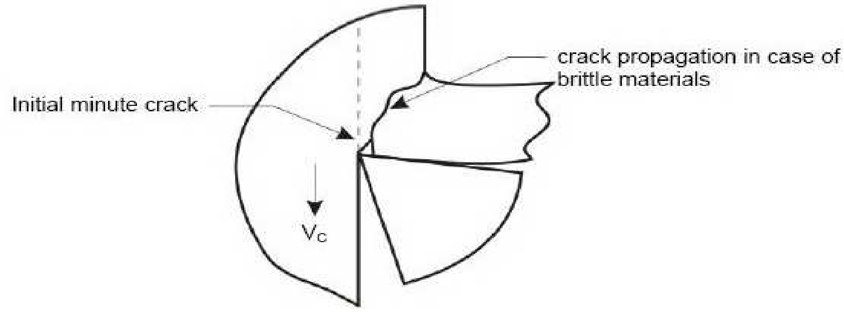
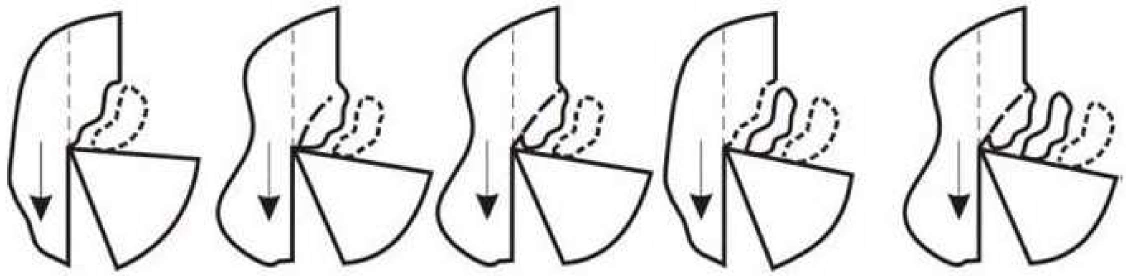


Fig. 1.14 Development and propagation of crack causing chip separation.

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).*



(a) Separation (b) Swelling (c) Further swelling (d) Separation (e) Swelling again

Fig. 1.15 Schematic view of chip formation in machining brittle materials

1.5.2 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.

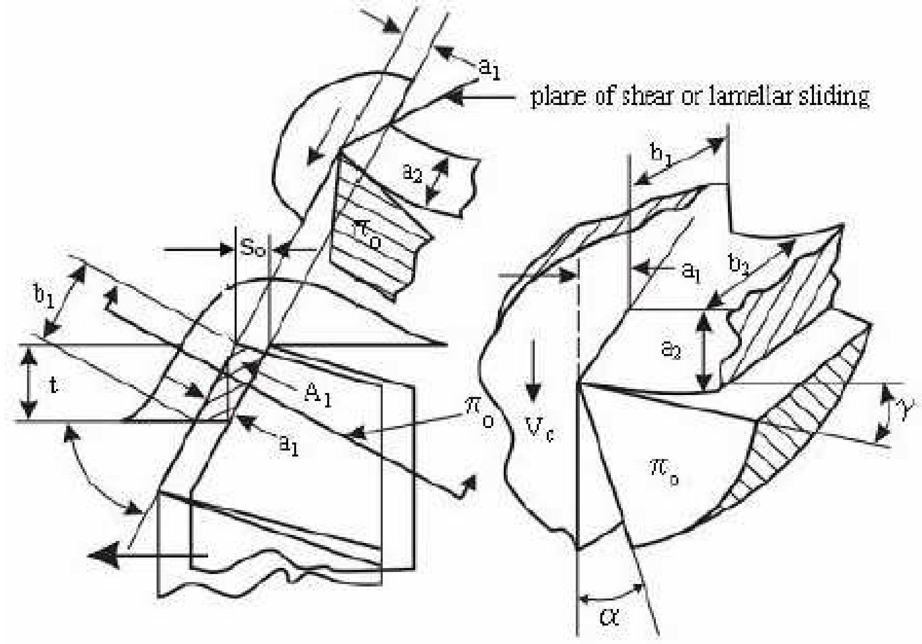


Fig. 1.16 Geometrical features of continuous chip formation.

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

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

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

$$\mathbf{r_c} = e^{\mu(\frac{\pi}{2} - \gamma)} \text{ (for orthogonal cutting)} \qquad 1.4$$

$\frac{\pi}{2}$ 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.

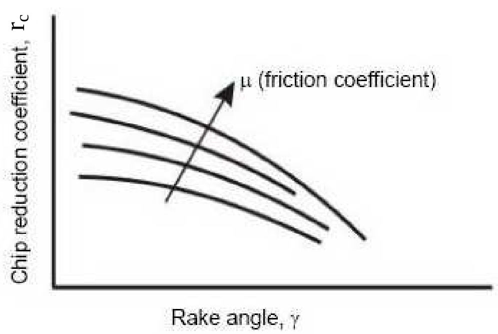


Fig. 1.17 Role of rake angle and friction on chip reduction coefficient

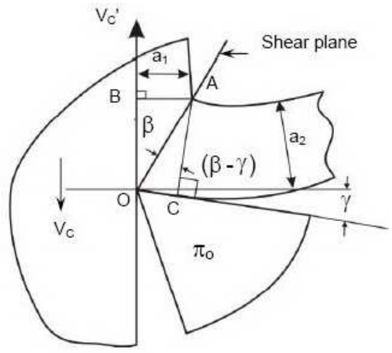


Fig. 1.18 Shear plane and shear angle in chip formation

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,

$$\mathbf{a_1 b_1 L_1 = a_2 b_2 L_2} \qquad 1.5$$

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,

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

Again considering unchanged material flow (volume) ratio, Q

$$Q = \mathbf{(a_1 b_1) V_C = (a_2 b_2) V_f} \qquad 1.7$$

Taking $b_1=b_2$,

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

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

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

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

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.*

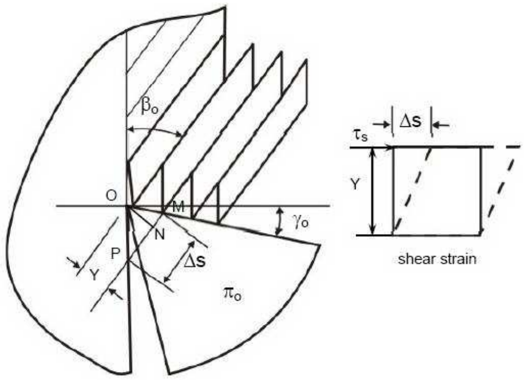


Fig. 1.19 Cutting strain in machining

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 $\varepsilon = PN + NM / ON$

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

1.5.3 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.

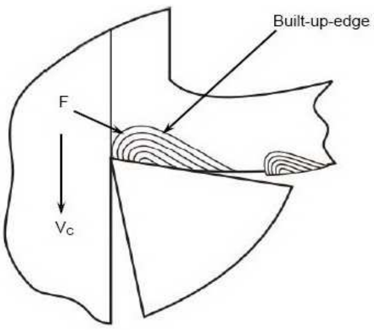


Fig. 1.20 Scheme of built-up-edge formation

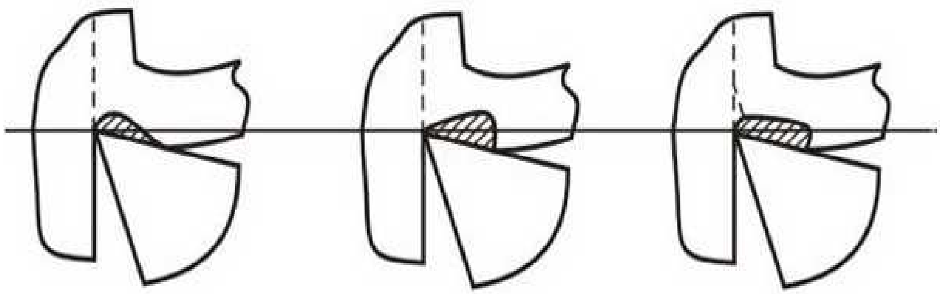
With the growth of the BUE, the force, F (shown in Fig. 1.20) also gradually increases due to wedging action of the tool tip along with the BUE formed on it. Whenever the force, F exceeds the bonding force of the BUE, the BUE is broken or sheared off and taken away by the flowing chip. Then again BUE 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. 1.21 Different forms of built-up-edge.

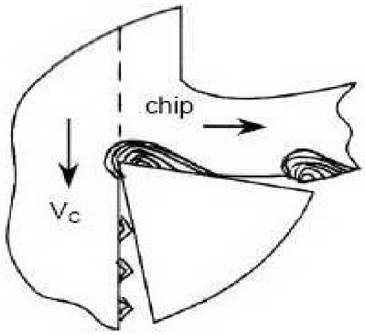


Fig. 1.22 Overgrowing and overflowing of BUE causing surface roughness

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.

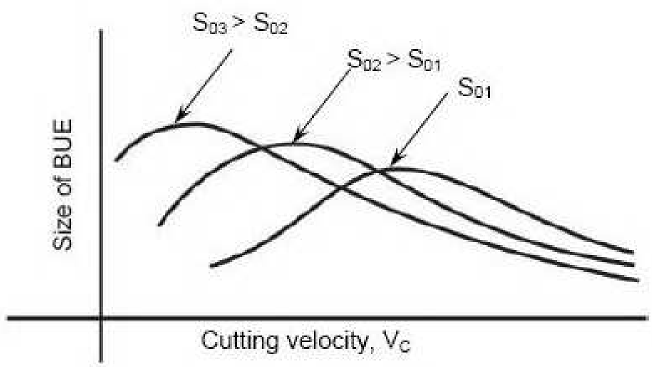


Fig. 1.23 Role of cutting velocity and feed on BUE formation

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.

1.5.4 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.*

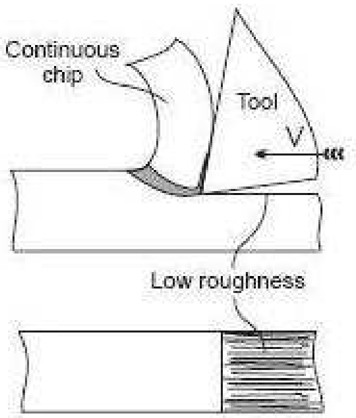


Fig. 1.24 Formation of continuous chips

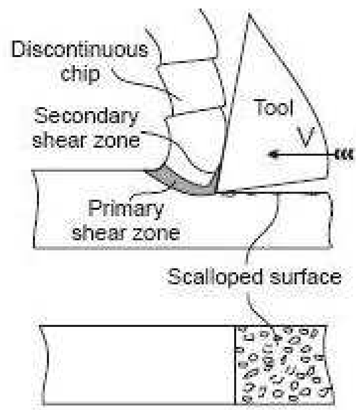


Fig. 1.25 Formation of discontinuous chips

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.*

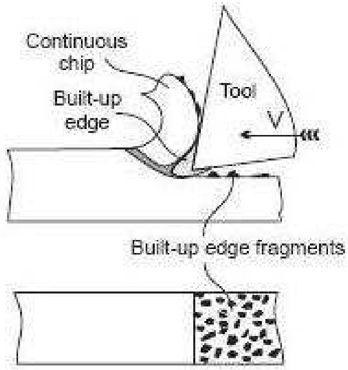


Fig. 1.26 Formation of continuous chips with BUE

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.

1.5.5 Chip breakers

1.5.5.1 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.

1.5.5.2 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:

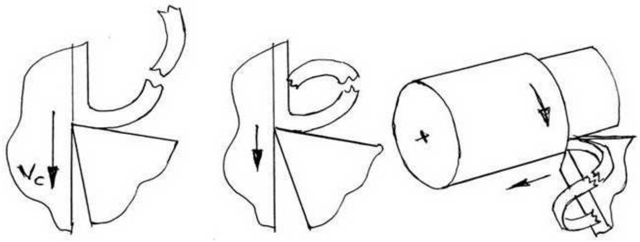
- ***Self chip breaking*** **-** This is accomplished without using a separate chip-breaker either as an attachment or an additional geometrical modification of the tool.
- ***Forced chip breaking*** - This is accomplished by additional tool geometrical features or devices.

a) 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.

b) Forced chip-breaking

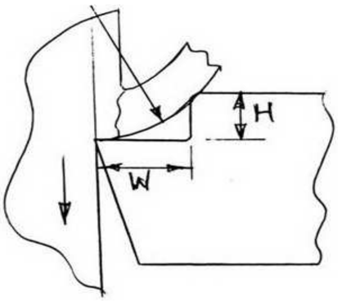
The hot continuous chip becomes hard and brittle at a distance from its origin due to work hardening and cooling. If the running chip does not become enough curled and work hardened, it may not break. In that case the running chip is forced to bend or closely curl so that it breaks into pieces at regular intervals. Such broken chips are of regular size and shape depending upon the configuration of the chip breaker. *Chip breakers are basically of two types:*

- In-built type.
- Clamped or attachment type.

In-built breakers are in the form of step or groove at the rake surface near the cutting edges of the tools. Such chip breakers are provided either:

- After their manufacture - in case of HSS tools like drills, milling cutters, broaches etc and brazed type carbide inserts.
- During their manufacture by powder metallurgical process - e.g., throw away type inserts of carbides, ceramics and cermets.

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.

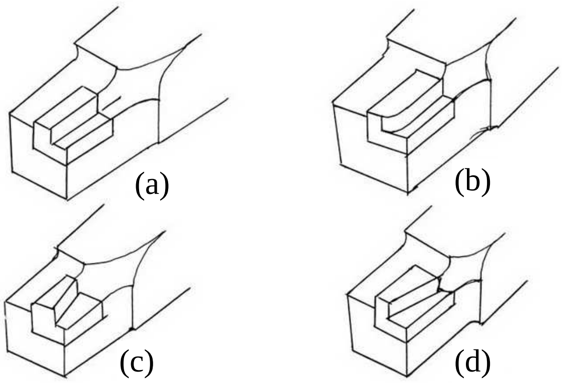
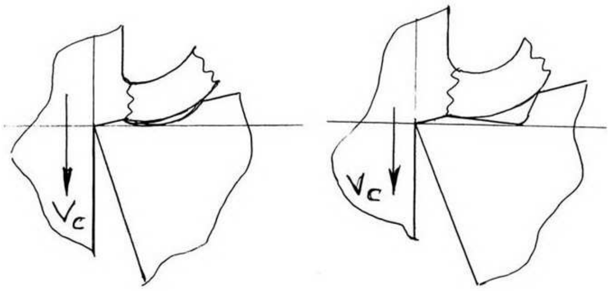


Fig. 1.29 Step type in-built chip breaker (a) Parallel step
(b) Parallel and radiused (c) Positive angular (d) Negative angular

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

- Circular groove.
- Tilted Vee groove.



(a) Circular groove (b) Tilted Vee groove

Fig. 1.30 Groove type in-built chip breaker

The unique characteristics of in-built chip breakers are:

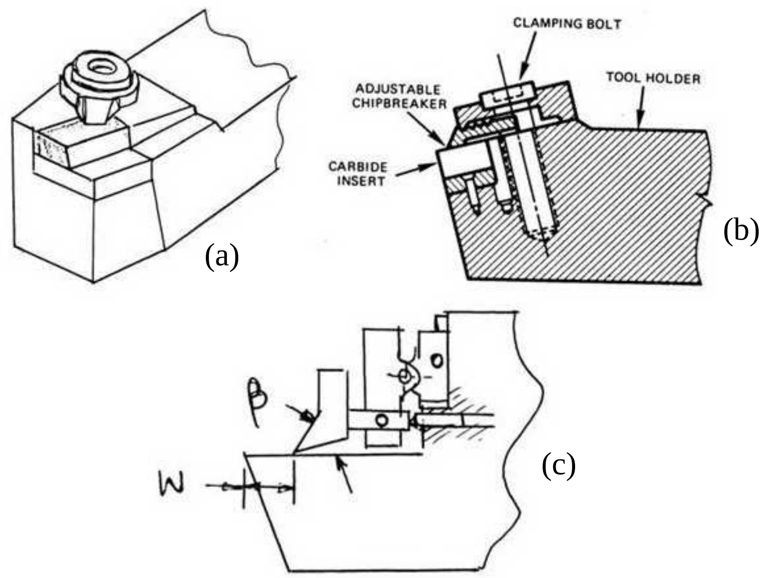
- The outer end of the step or groove acts as the heel that forcibly bends and fractures the running chip.
- Simple in configuration, easy manufacture and inexpensive.
- The geometry of the chip-breaking features is fixed once made. (i.e., cannot be controlled)
- Effective only for fixed range of speed and feed for any given tool-work combination.

(c) 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.

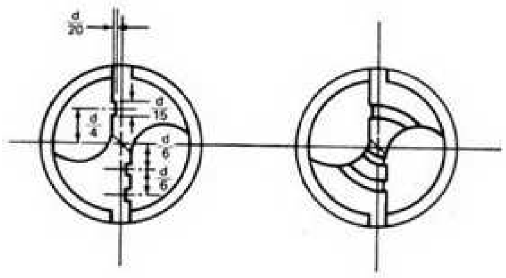


(a) Fixed geometry (b) Variable width (c) Variable width and angle
Fig. 1.31 Clamped type chip breakers

(d) 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.



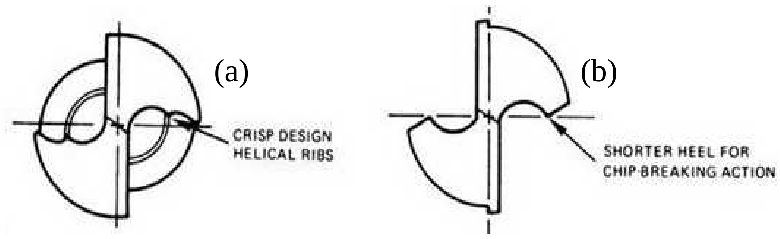


Fig. 1.32 Chip breaking grooves.

(a) Crisp design of chip-breaking drill
(b) 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.

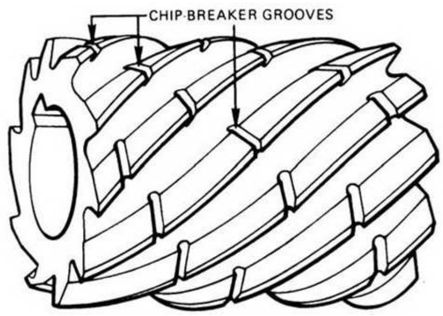


Fig. 1.34 Chip breaking grooves on a plain helical milling cutter

(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.*

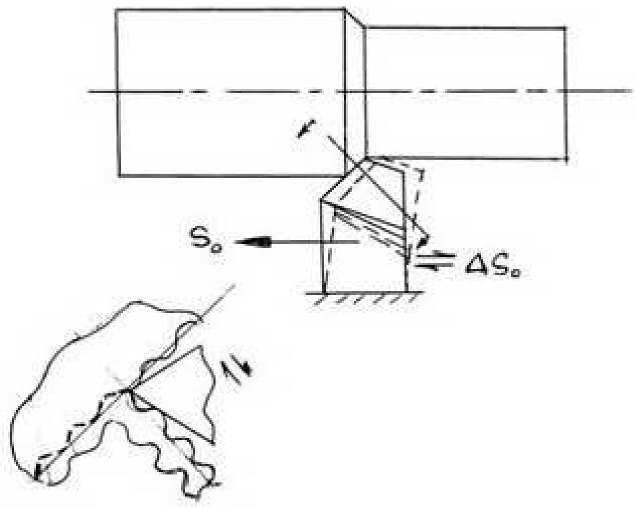


Fig 1.35 Self chip breaking in dynamic turning

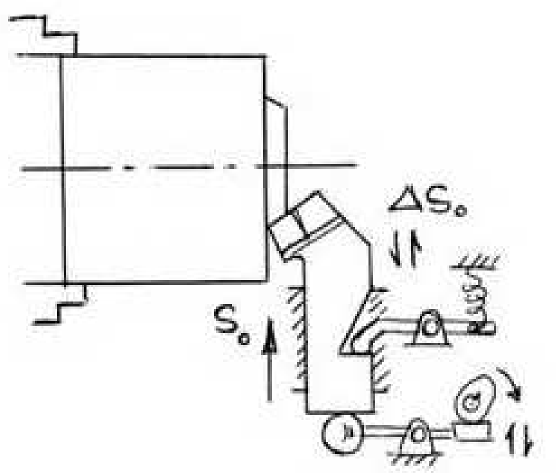


Fig 1.36 Dynamic chip breaking in radial operations in lathe

1.5.5.3 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.

1.6 ORTHOGONAL METAL CUTTING

1.6.1 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 behaviour and machinability characterization of the work materials.
- Condition monitoring of the cutting tools and machine tools.

1.6.2 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.

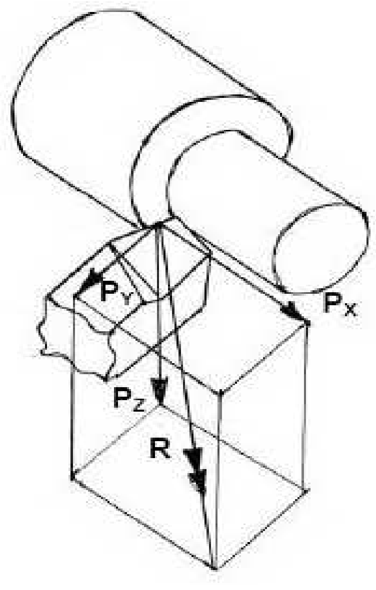


Fig. 1.37 Cutting force R resolved into P_X, P_Y and P_Z

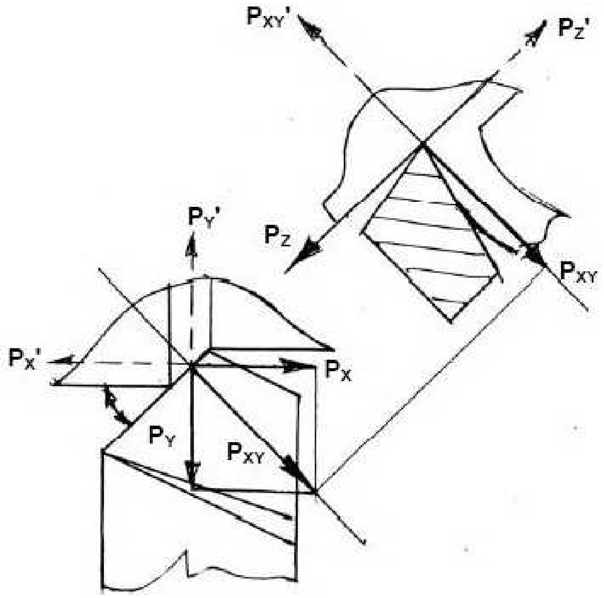


Fig. 1.38 turning force resolved into P_Z, P_X and P_Y

The resultant cutting force, R is resolved as,

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

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

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

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

1.6.3 Merchant's Circle Diagram and its use

In orthogonal cutting when the chip flows along the orthogonal plane, π_0, 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.

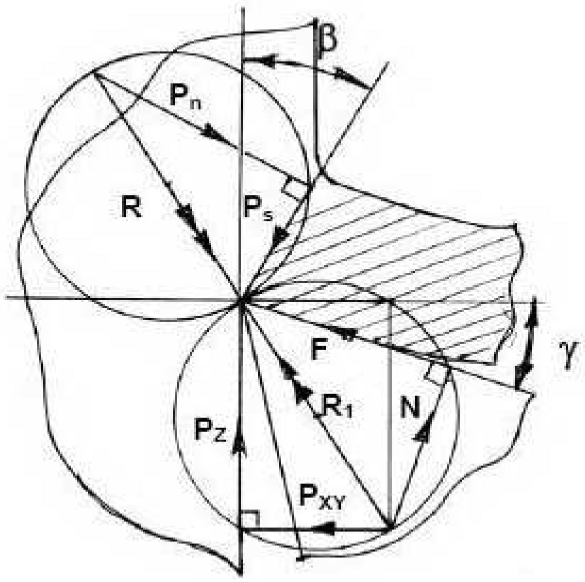


Fig 1.39 Development of Merchant's circle diagram

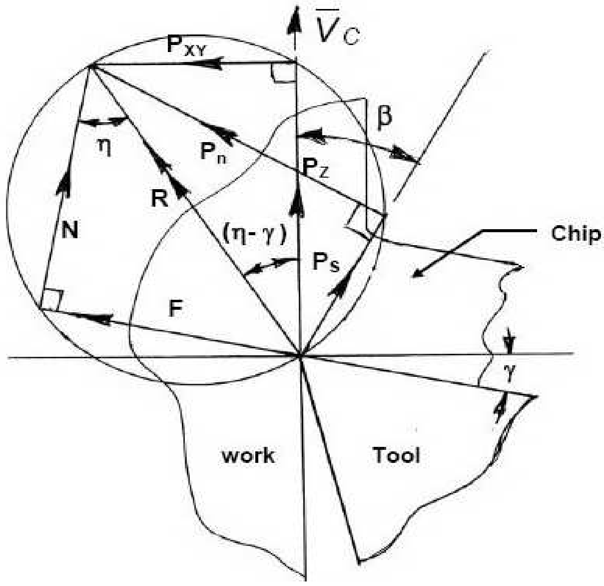


Fig. 1.40 Merchant's Circle Diagram with cutting forces

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.

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. 1.40.*

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.

1.6.4 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.

1.6.5 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.

1.6.6 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, 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, $\cot\beta = r_c - \tan\gamma$

$r_c = a_2 / a_1 = a_2 / f \sin\varphi$

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,

$P_X = P_{XY}\sin\varphi$ 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,

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

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

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

1.6.7 Metal cutting theories

1.6.7.1 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.

1.6.7.2 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:

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

- 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.

1.6.7.3 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.

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

1.6.8 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.

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

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

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

1.6.9 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.

1.6.10 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

1.7 CUTTING TOOL MATERIALS

1.7.1 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.
- 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.

1.7.2 Needs and chronological development of cutting tool materials

With the progress of the industrial world it has been needed to continuously develop and improve the cutting tool materials and geometry:

- To meet the growing demands for high productivity, quality and economy of machining.
- To enable effective and efficient machining of the exotic materials those are coming up with the rapid and vast progress of science and technology.
- For precision and ultra-precision machining.
- For micro and even nano machining demanded by the day and future.

It is already stated that the capability and overall performance of the cutting tools depend upon:

- The cutting tool materials.
- The cutting tool geometry.
- Proper selection and use of those tools.
- The machining conditions and the environments.

Out of which the tool material plays the most vital role. The relative contribution of the cutting tool materials on productivity, for instance, can be roughly assessed from Fig. 1.41.

The chronological development of cutting tool materials is briefly indicated in Fig. 1.42.

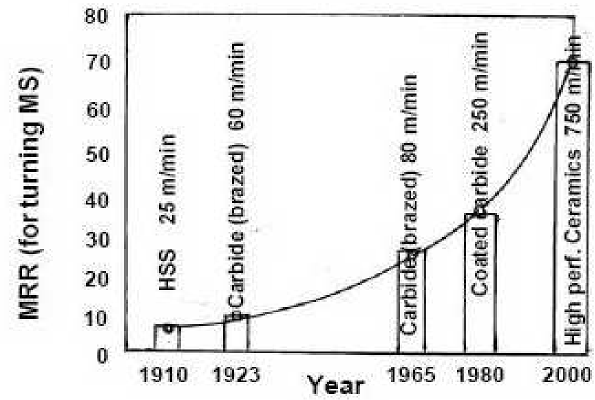


Fig. 1.41 Productivity raised by cutting tool materials

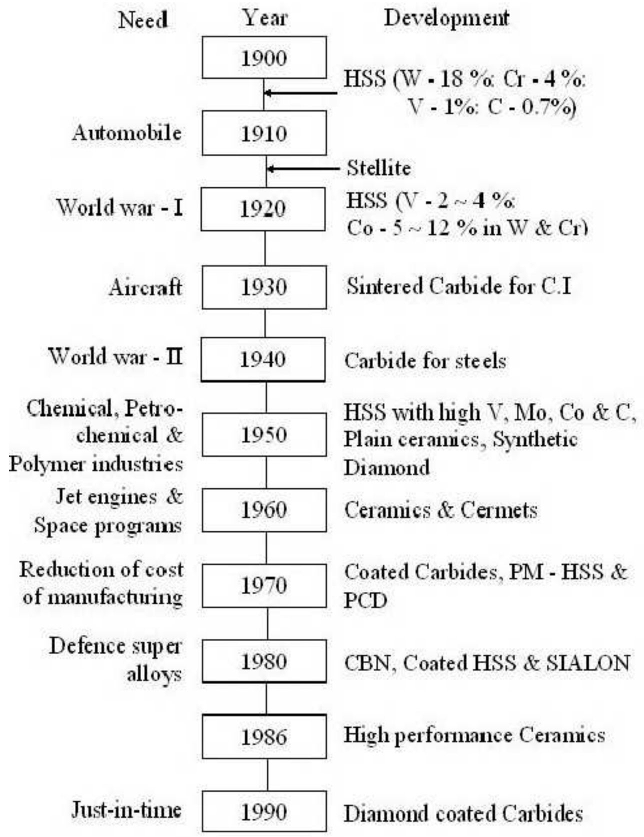


Fig 1.42 Chronological development of cutting tool materials

1.7.3 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. 1.43.

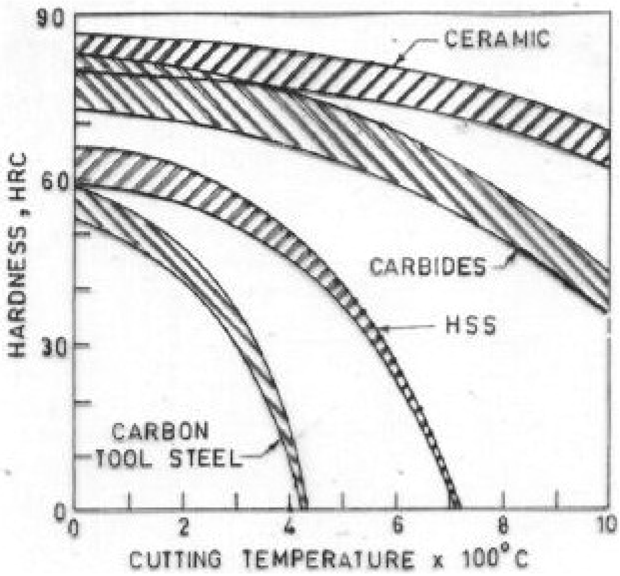


Fig. 1.43 Hot hardness of the different commonly used tool materials (Ref. Book by A. Bhattacharya)

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.

1.7.4 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. 1.44)*** 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.

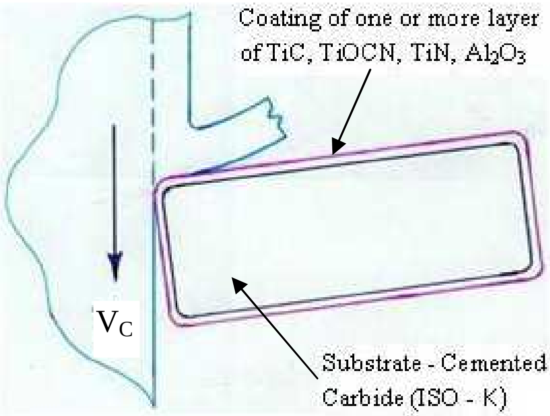


Fig. 1.44 Machining by coated carbide insert.

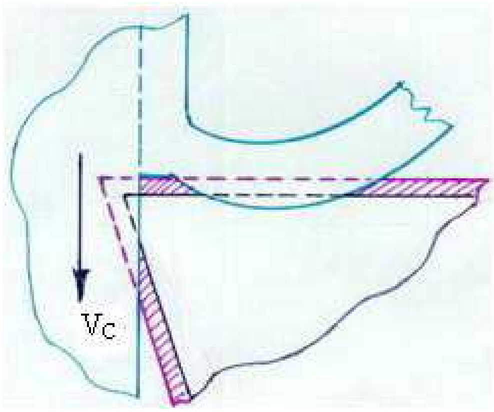


Fig. 1.45 Role of coating even after its wear and rupture

The contribution of the coating continues even after rupture of the coating as indicated in Fig. 1.45.

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.

Application wise, the modern TiCN based cermets with beveled or slightly rounded cutting edges are suitable for finishing and semi-finishing of steels at higher speeds, stainless steels but are not suitable for jerky interrupted machining and machining of aluminium and similar materials. Research and development are still going on for further improvement in the properties and performance of cermets.

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. 1.46.*

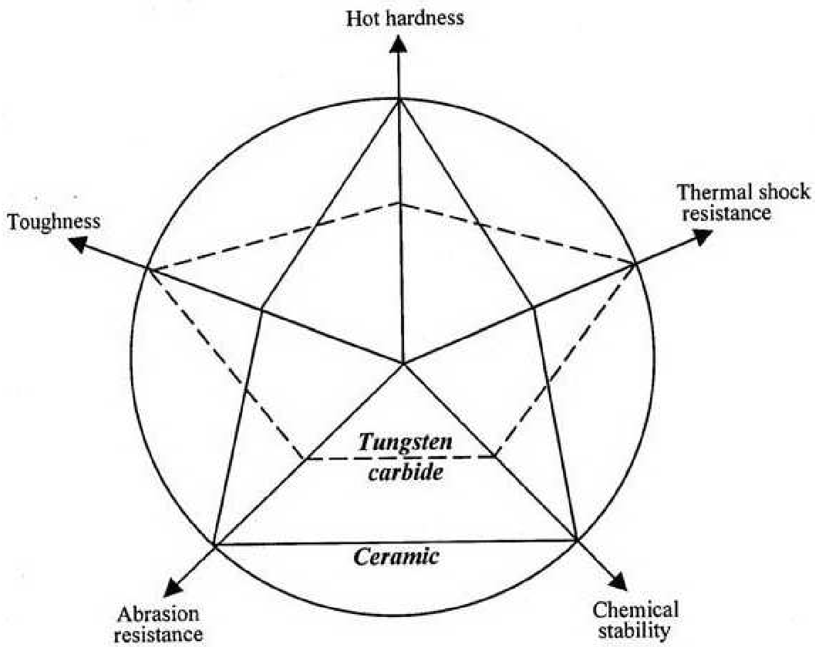


Fig. 1.46 Comparison of important properties of ceramic and tungsten carbide tools

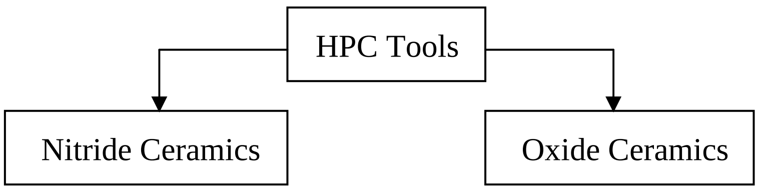
Through last few years' remarkable improvements in strength and toughness and hence overall performance of ceramic tools could have been possible by several means which include:

- 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:



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. 1.47* and micro crack nucleation toughening.

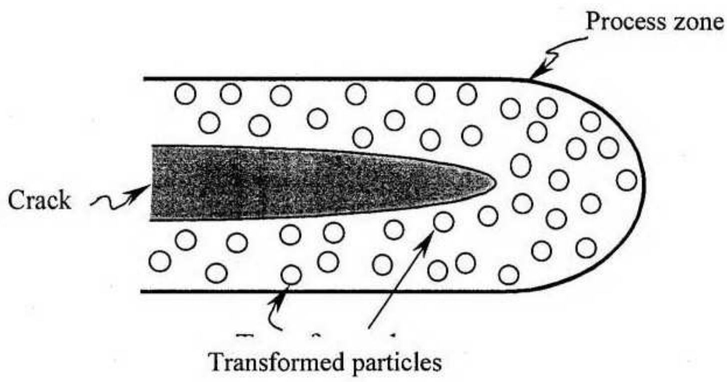


Fig. 1.47 The method of crack shielding by a transformation zone

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. 1.48.*

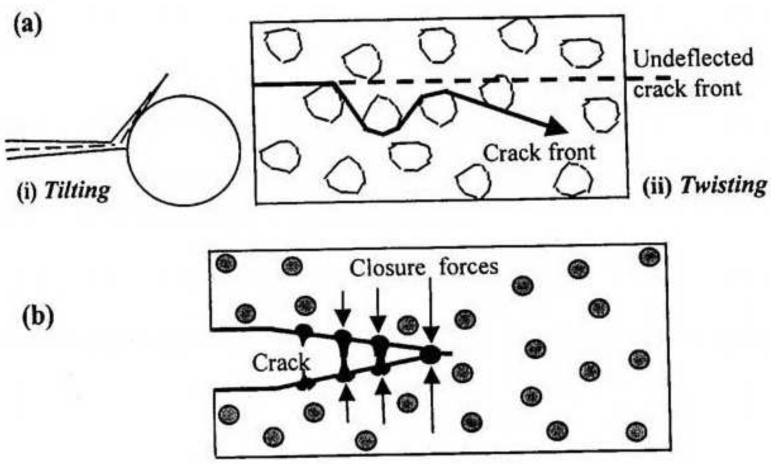


Fig. 1.48 Toughening mechanism of alumina by metal dispersion

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 0.5 - 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.*

1.8 TOOL WEAR

1.8.1 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.

1.8.2 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. 1.49 (a, b, c and d).

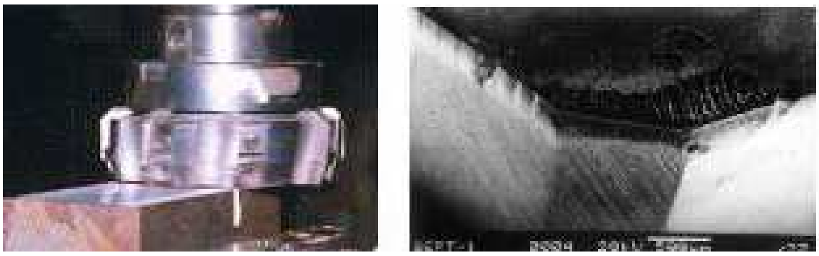


Fig. 1.49 (a) Schematic view of wear pattern of face milling insert

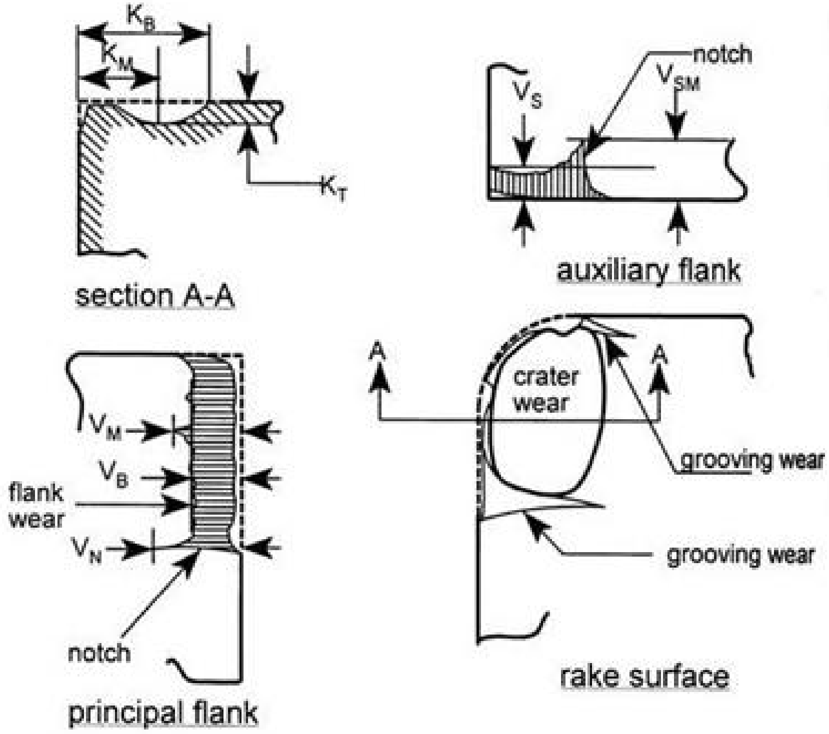


Fig. 1.49 (b) Geometry and major features of wear of turning tools

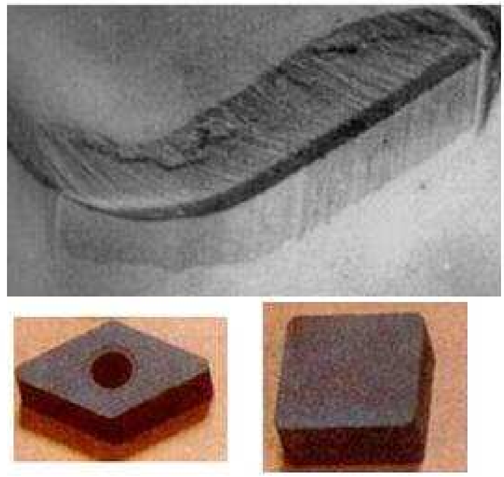


Fig. 1.49 (c) Photographic view of the wear pattern of a turning tool insert

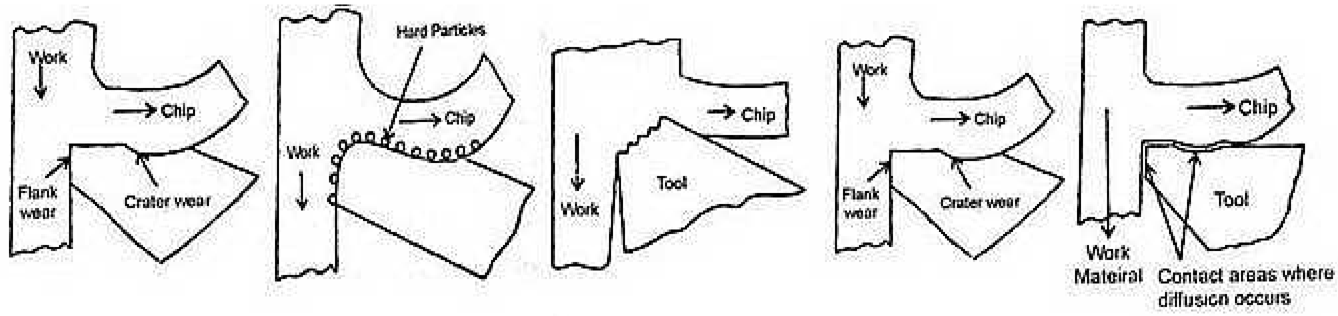


Fig. 1.49 (d) Different types of wears of turning tools

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.

1.8.3 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.

1.9 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.

1.9.1 Taylor's tool life equation

Wear and hence tool life of any tool for any work material is governed mainly by the level of the machining parameters i.e., cutting velocity (V_C), feed (f) and depth of cut (t). Cutting velocity affects maximum and depth of cut minimum.

The usual pattern of growth of cutting tool wear (mainly V_B), principle of assessing tool life and its dependence on cutting velocity are schematically shown in Fig. 1.50.

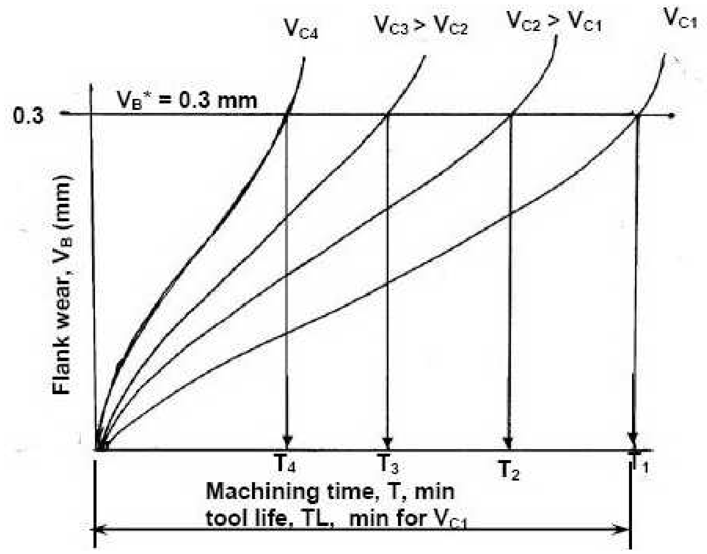
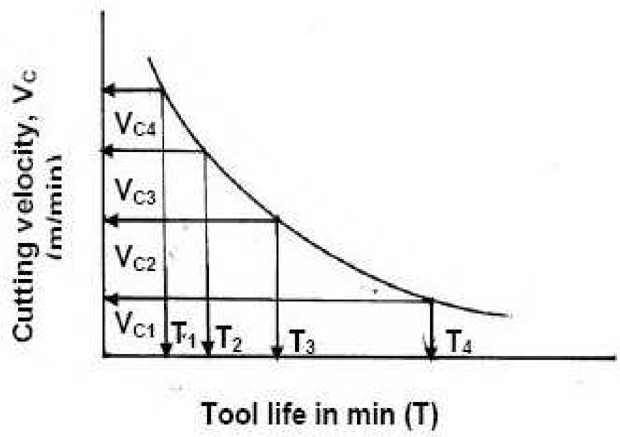


Fig. 1.50 Growth of flank wear and assessment of tool life

The tool life obviously decreases with the increase in cutting velocity keeping other conditions unaltered *as indicated in Fig. 1.51*. If the tool lives, T_1, T_2, T_3, T_4 etc are plotted against the corresponding cutting velocities, V_1, V_2, V_3, V_4 etc *as shown in Fig. 1.51,* a smooth curve like a rectangular hyperbola is found to appear. When F. W. Taylor plotted the same figure taking both V and T in log-scale, a more distinct linear relationship appeared *as schematically shown in Fig. 1.52.*



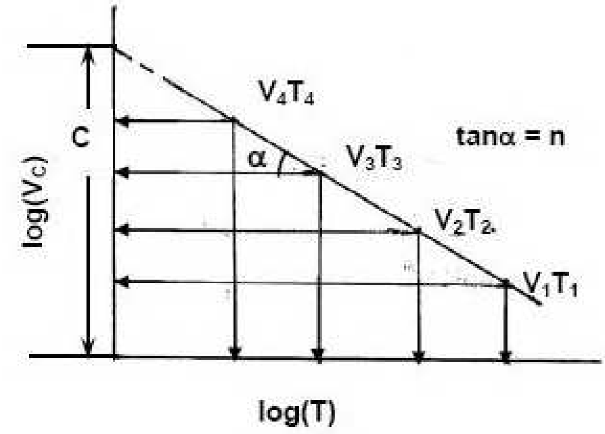


Fig. 1.51 Cutting velocity - tool life relationship   Fig. 1.52 Cutting velocity - tool life on a log-log scale

With the slope, n and intercept, c, Taylor derived the simple equation as,

$$\mathbf{V_C T^n = C} \quad 1.53$$

where, n is called, Taylor's tool life exponent. The values of both 'n' and 'c' depend mainly upon the tool-work materials and the cutting environment (cutting fluid application). The value of C depends also on the limiting value of V_B undertaken (i.e., 0.3 mm, 0.4 mm, 0.6 mm etc.).

1.9.2 Modified Taylor's tool life equation

In Taylor's tool life equation, only the effect of variation of cutting velocity, V_C on tool life has been considered. But practically, the variation in feed (f) and depth of cut (t) also play role on tool life to some extent. Taking into account the effects of all those parameters, the Taylor's tool life equation has been modified as,

$$\mathbf{T = C_T / V_C^x . f^y . t^z} \quad 1.54$$

where, T = tool life in minutes, C_T – a constant depending mainly upon the tool - work materials and the limiting value of V_B undertaken. x, y and z – exponents so called tool life exponents depending upon the tool - work materials and the machining environment. Generally, x > y > z as V_C affects tool life maximum and t minimum. The values of the constants, C_T, x, y and z are available in Machining Data Handbooks or can be evaluated by machining tests.

1.9.3 Effect of tool geometry on tool life

The tool life is also affected by tool geometry. The nose radius (R) tends to improve tool life and is evident from the relation: $\mathbf{V_C T^{0.0927} = 331\ R^{0.244}}$ 1.55

1.9.4 Effect of side cutting edge angle on tool life

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

$$\mathbf{V_C T^{0.11} = 78\ (\varphi_s + 15^0)^{0.264}} \quad 1.56$$

1.9.5 Tool life in terms of metal removal

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 $V_C = \pi DN / 1000$ 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 = $\pi.D.t.f\ mm^3$ 1.58

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

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

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

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

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

1.9.6 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.

1.9.7 Machinability

1.9.7.1 Concept, definition and criteria of judgement of machinability

The term; 'Machinability' 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 machinability. *People tried to describe "Machinability" 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 Machinability. *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 machinability 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 machinability.

$$\textbf{\textit{Machinability rating (MR)}} = \frac{speed(fpm) of machining\ the\ work\ giving\ 60\ minute\ tool\ life}{speed(fpm) of machining\ the\ standard\ metal\ giving\ 60\ minute\ tool\ life}\ x\ 100 \qquad 1.64$$

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), as indicated in Fig. 1.53, 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

But usefulness and reliability of such practice faced several genuine doubts and questions:

- Tool life cannot or should not be considered as the only criteria for judging machinability.
- Under a given condition a material can yield different tool life even at a fixed speed (cutting velocity); exact composition, microstructure, treatments etc. of that material may cause significant difference in tool life.
- The tool life - speed relationship of any material may substantially change with the variation in:
    - Material and geometry of the cutting tool.
    - Level of process parameters (Vc, f, t).
    - Machining environment (cutting fluid application).
    - Machine tool condition.

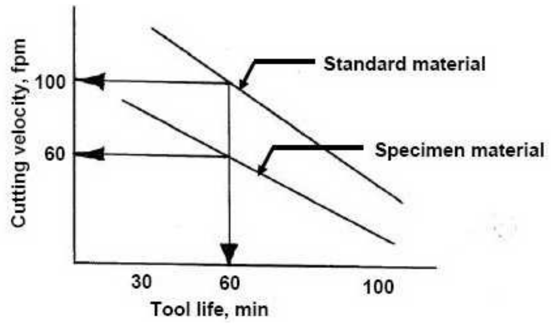


Fig. 1.53 Machinability rating in terms of cutting velocity giving 60 min tool life

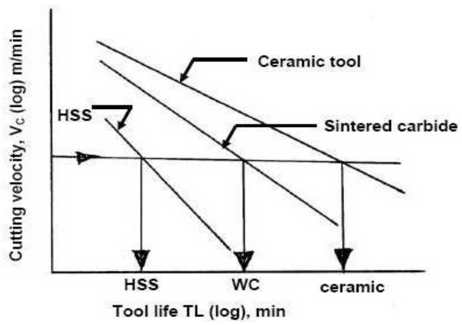


Fig. 1.54 Role of cutting tool material on machinability (tool life)

Keeping all such factors and limitations in view, ***Machinability can be tentatively defined as "ability of being machined" and more reasonably as "ease of machining".***

Such ease of machining or machinability characteristics of any tool-work pair is to be judged by:

- Magnitude of the cutting forces.
- Tool wear or tool life.
- Surface finish.
- Magnitude of cutting temperature.
- Chip forms.

Machinability will be considered desirably high when cutting forces, temperature, surface roughness and tool wear are less, tool life is long and chips are ideally uniform and short enabling short chip-tool contact length and less friction.

1.9.7.2 Role of the properties of the work material on machinability

The work material properties that generally govern machinability in varying extent are:

- The basic nature - brittleness or ductility etc.
- Microstructure.
- Mechanical strength - fracture or yield.
- Hardness and hot hardness, hot strength.
- Work hardenability.
- Thermal conductivity.
- Chemical reactivity.
- Stickiness / self lubricity.

1.10 SURFACE FINISH

Generally, surface finish of any product depends on the following factors:

- Cutting speed.
- Feed.
- Depth of cut.

Cutting speed

Better surface finish can be obtained at higher cutting speeds. Rough cutting takes place at lower cutting speeds.

Feed

Surface finish will not be good when coarse feed is applied. But better finish can be obtained in fine feeds.

Depth of cut

Lighter cuts provide good surface finish to the work piece. If depth of cut increases during machining, the quality of surface finish will reduce.

Therefore, higher cutting speeds, fine feeds and low depth of cuts or applied to ensure good surface finish. Usually, it is done in finishing cuts. But, lower cutting speeds, coarse feeds and heavier depth of cuts are applied in rough cutting operations.

1.11 CUTTING FLUIDS

1.11.1 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.

1.11.2 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.

1.11.3 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. 1.55.*

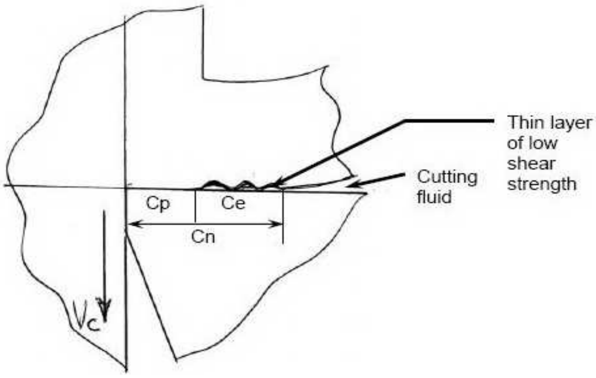


Fig. 1.55 Cutting fluid action in machining

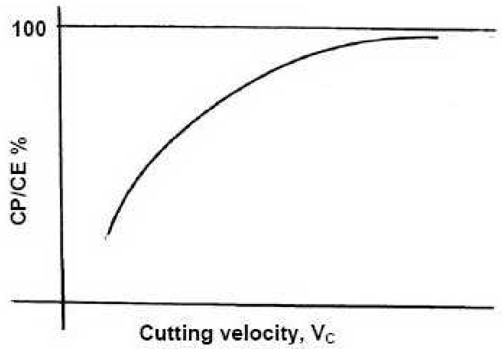


Fig. 1.56 Apportionment of plastic and elastic contact zone with increase in cutting velocity

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. 1.56.* 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.

1.11.4 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).

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.

1.11.5 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. 1.57.*

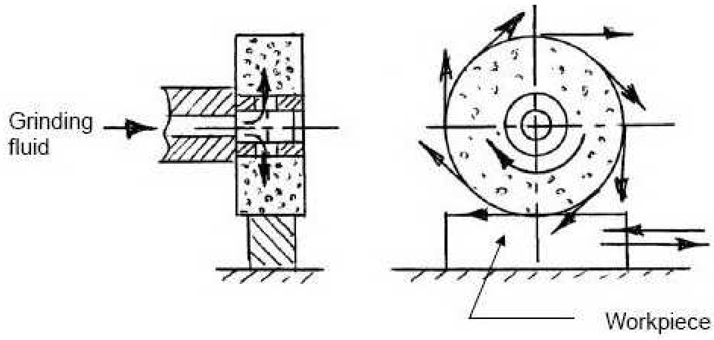


Fig 1.57 Z-Z method of cutting fluid application in grinding

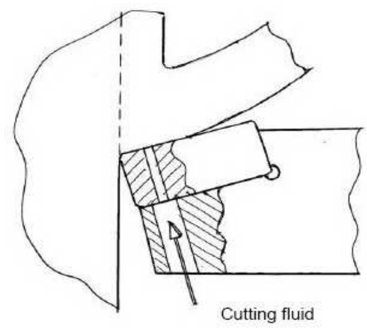


Fig. 1.58 Application of cutting fluid at high pressure through the hole in the tool

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. 1.58.*

1.11.6 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.