Module
2
Mechanics of Machining

Lesson
7
Use of chip breaker in machining

Instructional Objectives

At the end of this lesson the students would be able to

(i) identify the need and purposes of chip breaking
(ii) illustrate the various principles of chip breaking
(iii) design simple chip breakers
(iv) demonstrate configuration and working principle of some common type chip breakers
(v) state the overall effects of chip breaking.

(i) 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..

(ii) 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 :

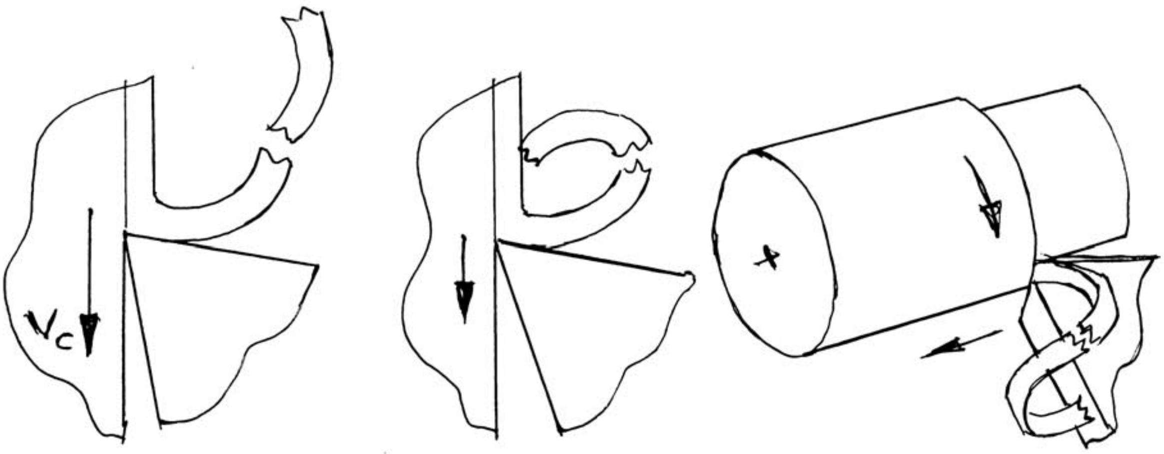
- Self breaking
  This is accomplished without using a separate chip-breaker either as an attachment or an additional geometrical modification of the tool.
- Forced chip breaking by additional tool geometrical features or devices.

(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.7.1 (a). This kind of chip breaking is generally observed under the condition close to that which favours formation of jointed or segmented chips
- By striking against the cutting surface of the job, as shown in Fig. 7.1 (b), mostly under pure orthogonal cutting
- By striking against the tool flank after each half to full turn as indicated in Fig. 7.1 (c).



(a) natural (b) striking on job (c) striking at tool flank

Fig. 7.1 *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 s_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.

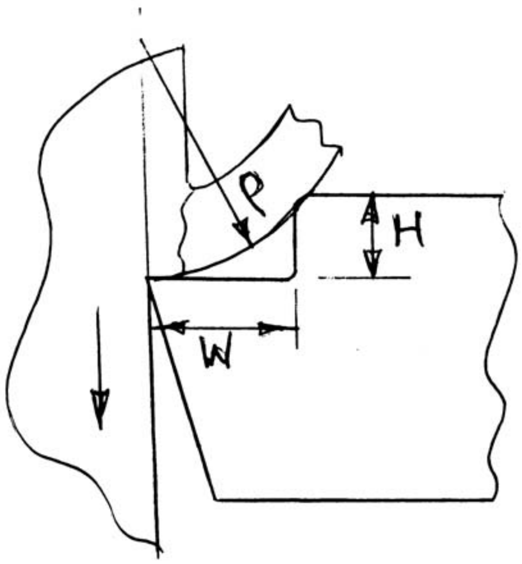
Chip breakers are basically of two types :

- 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. 7.2 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. 7.2 *Principle of forced chip breaking.*

Fig. 7.3 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.

Groove type in-built chip breaker may be of

- Circular groove or
- Tilted Vee groove

as schematically shown in Fig. 7.4

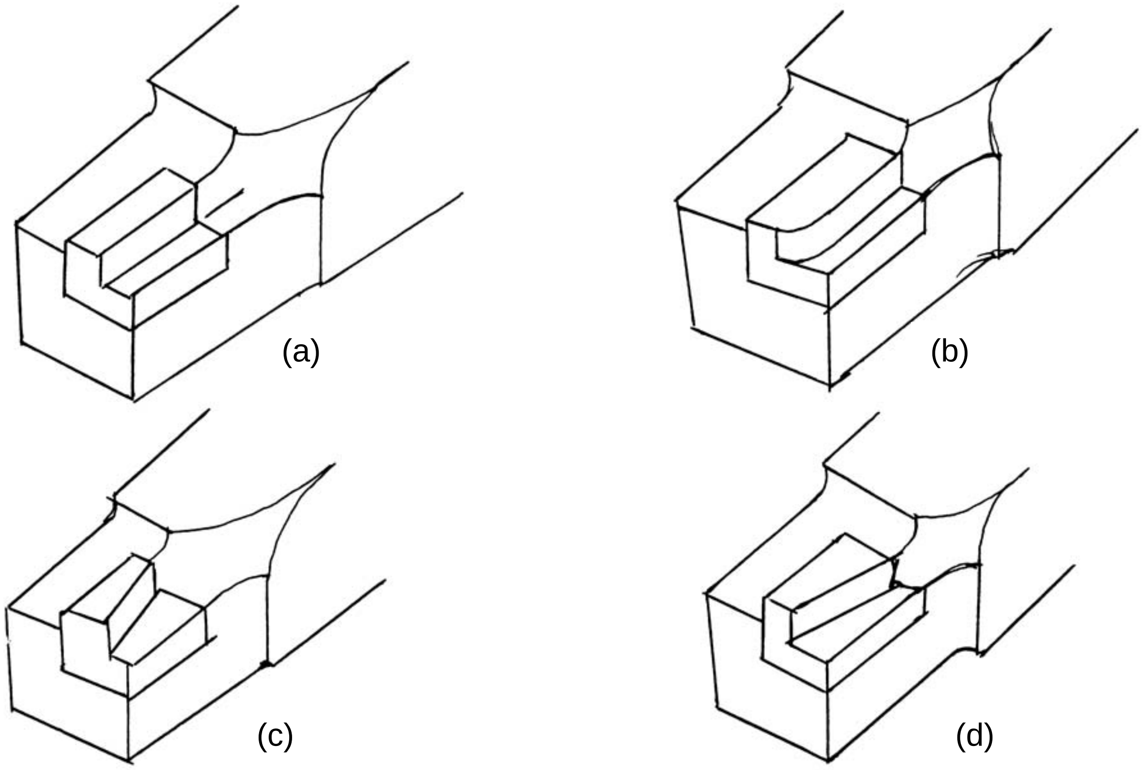
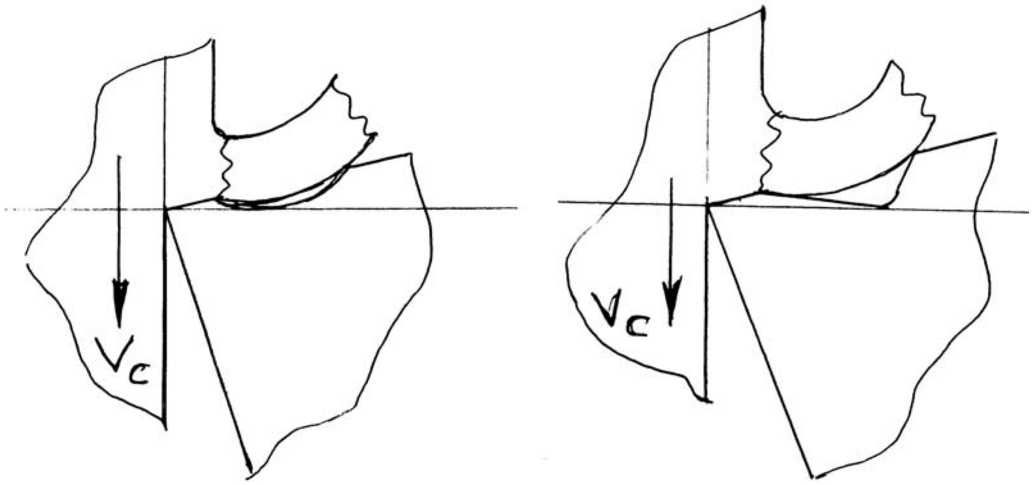


Fig. 7.3 *Step type in-built chip breaker (a) parallel step (b) parallel and radiused (c) positive angular (d) negative angular*



(a) circular groove (b) tilted Vee-groove

Fig. 7.4 *Groove type in-built chip breaker*

The unique characteristics of in-built chip breakers are :

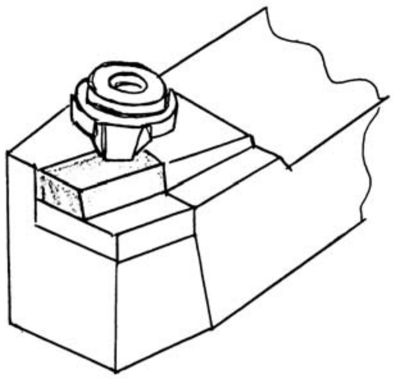
- The outer end of the step or groove acts as the heel that forcibly bend and fracture the running chip
- Simple in configuration, easy manufacture and inexpensive
- The geometry of the chip-breaking features are fixed once made (i.e., cannot be controlled)
- Effective only for fixed range of speed and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

(c) clamped type chip-breaker

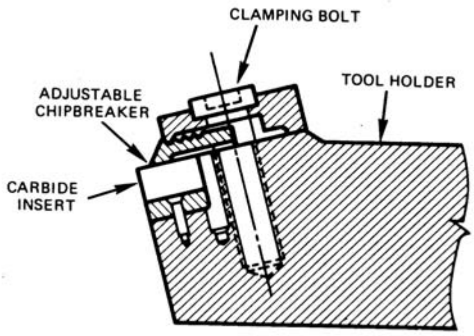
Clamped type chip breakers work basically in the principle of stepped type chip-breaker but have the provision of varying the width of the step and / or the angle of the heel.

Fig. 7.5 schematically shows three such chip breakers of common use :

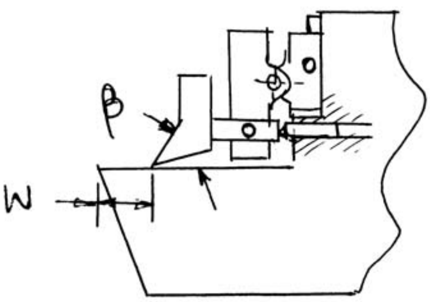
- With fixed distance and angle of the additional strip – effective only for a limited domain of parametric combination
- With variable width (W) only – little versatile
- With variable width (W), height (H) and angle (β) – quite versatile but less rugged and more expensive.



(a) fixed geometry



(b) variable width



(c) variable width and angle

Fig. 7.5 *Clamped type chip breakers.*

(iii) Design principle of simple step type chip breaker.

- **Parallel step type in-built chip breaker**

In machining like turning of ductile material the chip first leaves the hot plastic zone and then comes out as an elastic cantilever beam. The chip breaker (heel) forcibly bends the chip to shorter radius of curvature and raises the strain, resulting chip breaking as shown in Fig. 7.2.

Lot of study had been done on chip breaking and the results, briefly shown in Fig. 7.6 indicates that for a given value of uncut chip thickness, a_1, the chip effectively breaks when the radius of curvature (ρ) is brought to or slightly below some critical value.

From Fig. 7.2,

$$W^2 = (2\rho - H).H \qquad (7.1)$$

where,

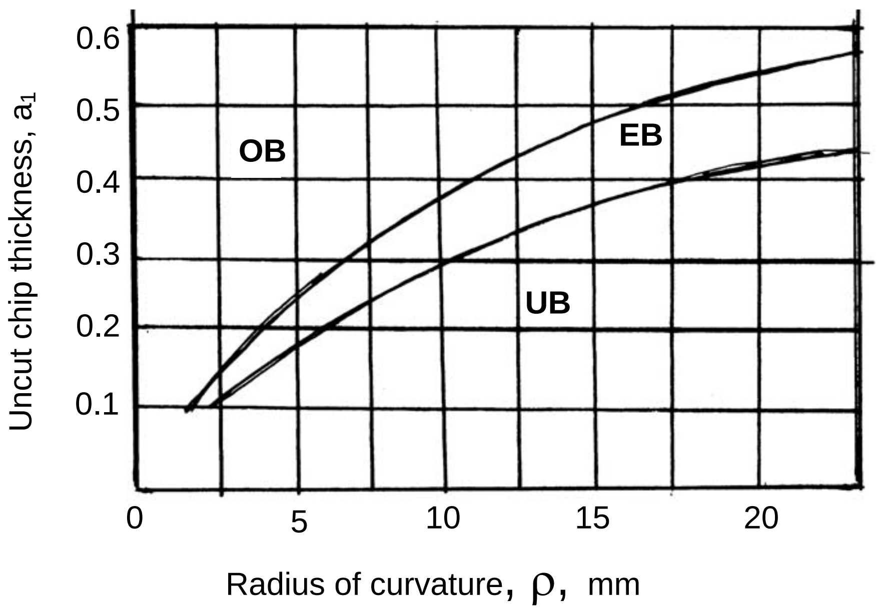
W = width of the step
H = height of the step
ρ = radius of curvature of the chip

Example : Design step type integrated chip breaker for plain turning of a mild steel rod at feed s_o = 0.24 mm/rev. with a tool whose PCEA (ϕ) = 60^o

Solution :

Here, $a_1 = s_o \sin\phi = 0.24 x \sin 60^o = 0.2$ mm
From the graph (a_1 vs ρ),
For a_1= 0.2 mm, the value of ρ is taken 5 for effective chip breaking
Assuming H = 2

$$W = \sqrt{(2x5-2).2} = 4.0 \text{ mm} \quad \text{Ans.}$$



OB – over breaking, EB – effective breaking, UB – under breaking
Fig. 7.6 *Critical radius of curvature for chip breaking.*

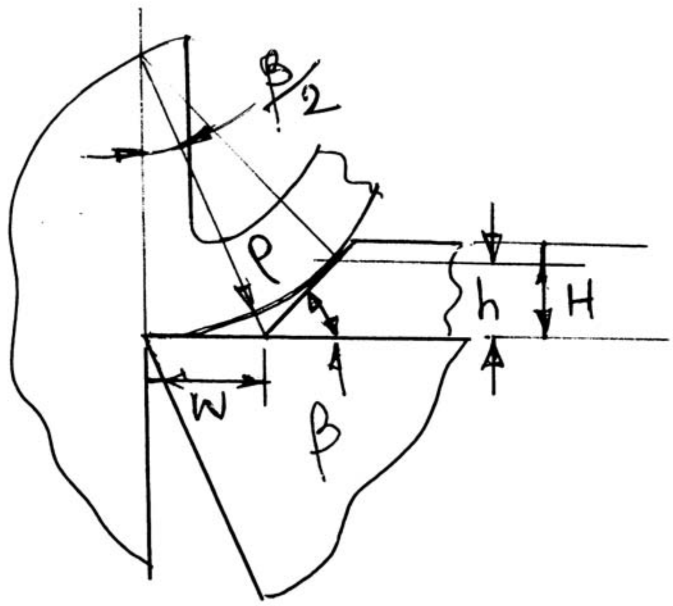


Fig. 7.7 *Design of clamped type chip breaker.*

- **Clamped type chip breaker**

 From the geometry of Fig. 7.7,

$$W = \rho \tan\frac{\beta}{2} \qquad (7.2)$$

and $$h = W \sin\beta \qquad (7.3)$$

where, β = angle of the chip-breaking strip

H is taken 1 ~ 2 mm greater than h.

For the same condition of previous problem, i.e., a_1 = 0.2 mm and ρ_c = 5 mm and assuming β = 60^o (varies from 45^o to 90^o)

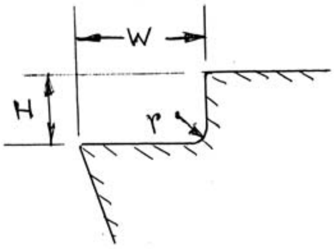
W = 5xtan30^o ≅ 3 mm, h = 3xsin60^o = 2.5 mm

∴ H = 2.5 + 1.0 = 3.5 mm Ans.

Previous researchers prepared a chart recommending the dimensions of step type chip breaker for different conditions under the following assumptions :

- ideally plastic chip, i.e., no work hardening
- chip flows straight if chip breaker does not exist
- plane sections remain plane
- heel of breaker exerts bending force on chip.

Chip breaker



step – type

Table 1 In-built chip breaker design

Depth of cut	Feed	0.15 ~ 0.3 mm	0.3 ~ 0.4 mm	0.4 ~ 0.6 mm	0.6 ~ 1.0 mm	> 1.0 mm
	r	0.25 ~ 0.6	1.0 ~ 2.0	1.0 ~ 2.0	1.0 ~ 2.0	1.0 ~ 2.0
	H	0.25	0.4	0.5	0.75	0.75
0.4 ~ 1.2 mm	W	1.6	2.0	2.8	3.2	-
1.6 ~ 6.4 mm	W	2.4	3.2	4.0	5.0	5.0
2.0 ~ 12.8 mm	W	3.2	4.0	5.0	5.0	5.0
3.6 ~ 20 mm	W	4.0	5.0	5.0	5.0	5.0
> 20 mm	W	5.0	5.0	5.0	5.0	6.4

(iv) Configuration and working principle of some chip breakers in practice

In-built type chip breakers once made are of fixed geometry and hence are effectively applicable for particular situations or materials but are very simple in construction and easy to handle. While designing the overall geometry of the tool inserts, several factors, in addition to chip-breaking, need to be considered, such as ;

- imparting mechanical strength to the cutting edge by its rounding and / or bevelling
- reduction of cutting forces having favourable (positive) rake
- controlled contact (chip-tool) cutting effect for lesser friction and wear
- better heat dissipation

Incorporation of all such aspects through integrated tool geometry require proper design and manufacture which fortunately have become now-a-days, quite easy and fast due to advent of CAD and processes like EDM, ECM etc. for manufacturing complex shaped die and punch. In-built type chip breakers with integrated tool geometry have been much popular and are getting widely used.

Fig. 7.8 shows the typical form of the modern cutting tool inserts with in-built chip-breaker. The curved portion BC is the edge radiusing, CD is the land with negative rake, DEF is the groove with positive rake and the point F acts as the heel to break the chip by fracturing. The actual length and angle of those features and their apportionment are decided and some special features are further incorporated to that geometry (Fig. 7.8) depending upon the operations like bulk machining or finishing and the characteristics of the work materials.

The configurations of some industrially used uncoated and coated carbide tool inserts with compound rake including chip-breaking feature are typically shown in Fig. 7.9. [Cutting Tools for Productive Machining – T.A.Sadanivan and D. Sarathy, WIDIA (I) Ltd.]

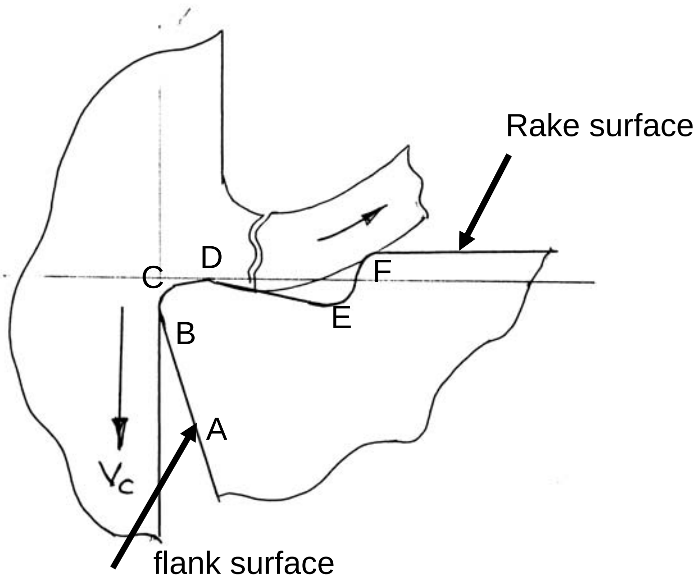


Fig. 7.8 *Schematic view of the typical form of inserts (cutting edge) with integrated chip-breaker.*

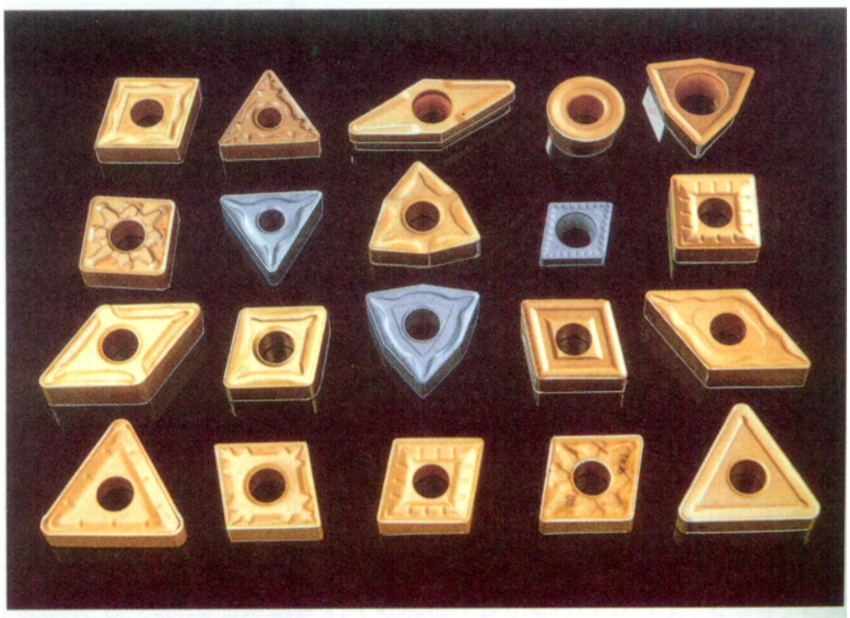


Fig. 7.9 *Various groove type inserts*

Throw away type indexable tool inserts are also widely used for drilling, milling, broaching etc. where the inserts of suitable geometry are mechanically clamped in the steel shank of the tools. The geometry of some of those uncoated and coated carbide inserts also essentially incorporates the chip-breaking feature.

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 become difficult particularly while drilling large diameter and deep holes. Grooves, either on the rake faces or on the flanks as shown in Fig. 7.10 help 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.

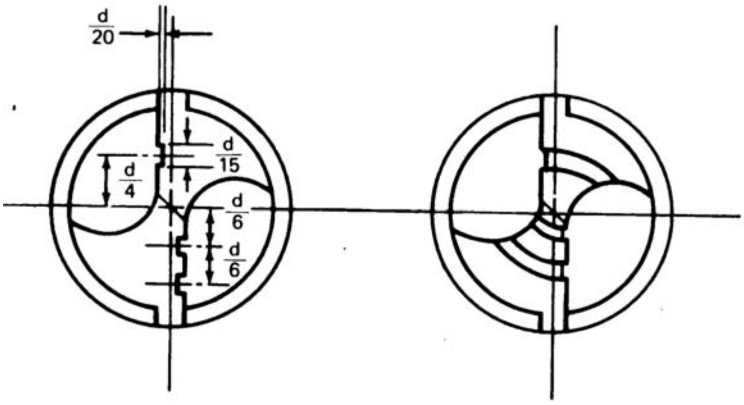
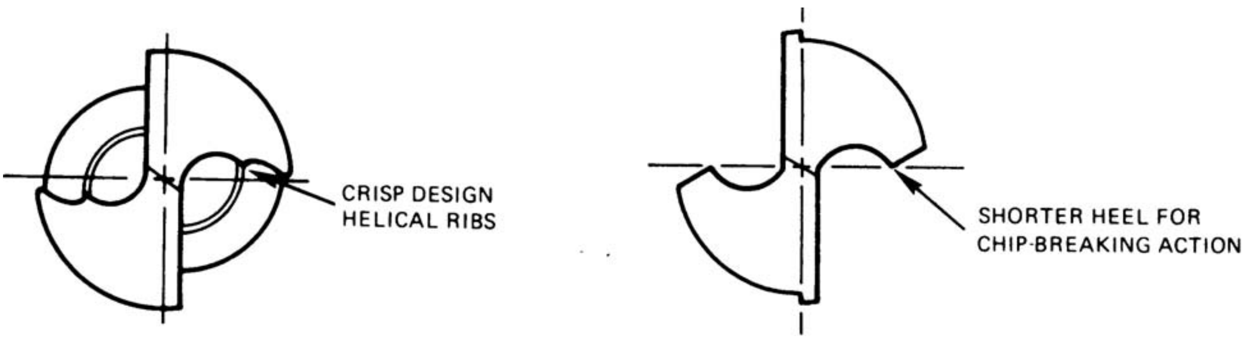


Fig. 7.10 *Chip breaking grooves.*

Fig. 7.11 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.



(a) Crisp design of chip-breaking drill

(b) US industrial design of chip-breaking drill

Fig. 7.11 *Designs of chip-breaking drill*

Plain milling and end milling inherently produces discontinuous 'coma' shaped chips of favourably 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. 7.12. 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.

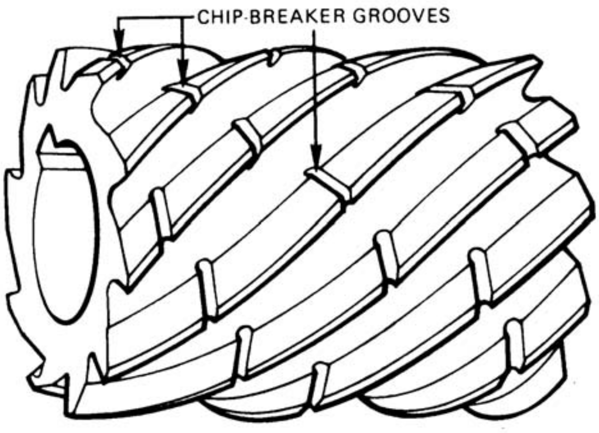


Fig. 7.12 *Chip breaking grooves on a plain helical milling cutter.*

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. 7.13 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^o, 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. 7.13. This technique of chip breaking can also be accomplished in dynamic drilling and dynamic boring.
Fig. 7.14 schematically shows another possible dynamic chip-breaking device suitable for radially fed type lathe operations, e.g., facing, grooving and parting.

(v) Overall effects of chip breaking

- Favourable effects
  - o safety of the operator(s) from the hot, sharp continuous chip flowing out at high speed
  - o convenience of collection and disposal of chips

- chances 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.

- Unfavourable 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

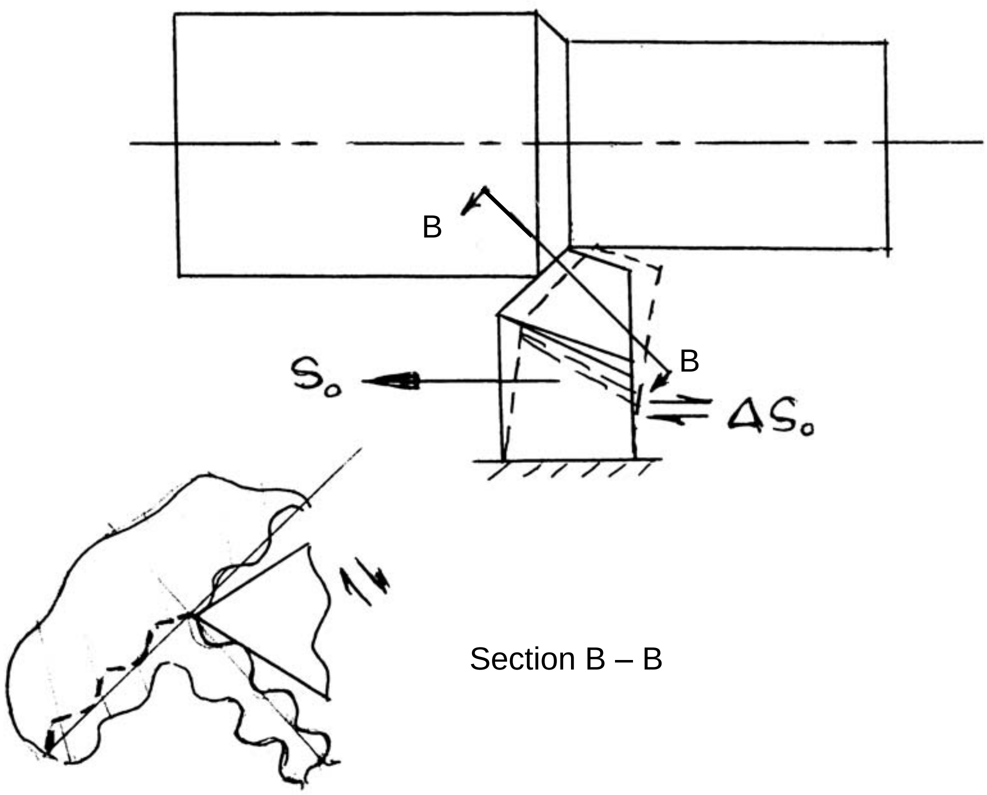


Fig. 7.13 *Self chip breaking in dynamic turning.*

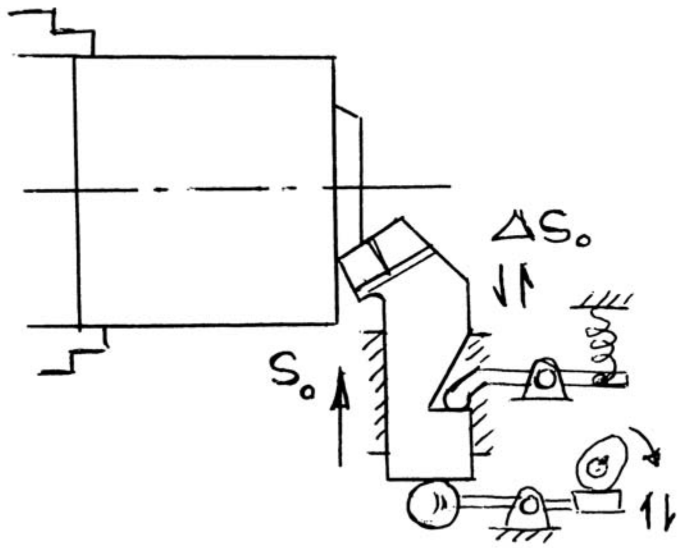


Fig. 7.14 *Dynamic chip breaking in radial operations in lathe.*

Exercise – 7

Q. 1 What factors are considered while designing the rake surface / cutting edge of carbide turning inserts ?

Q. 2 In which direction is the cutting tool vibrated and why in dynamic turning ?

Q. 3 Why are step type integrated chip breakers made angular ?

Q. 4 When is forced chip breaking necessary and why ?

Answers of the questions given in Exercise – 7

Ans. to Q. 1

- enhance thermal and mechanical strength at the sharp edge
- reduction of the cutting forces
- more effective cutting fluid action
- chip-breaking

Ans. to Q. 2

The tool is vibrated in feed direction only

- vibration in transverse direction will enhance surface roughness
- vibration in tangential direction is less effective and more difficult also.

Ans. to Q. 3

To produce close curling of chips which is safe and easy to collect and dispose.

Positive angle – shifts the coil away from the job

Negative angle – shifts the chip away from the operator

Ans. to Q. 4

When chips continuously form and come out very hot, sharp and at quite high speed – under the condition :

- soft ductile work material
- flat rake surface with positive or near zero rake

for

- safety and convenience of the operator
- easy collection and disposal of chips.

Module
2
Mechanics of Machining

Lesson
6
Orthogonal and oblique cutting

Instructional Objectives

At the end of this lesson, the student would be able to

(i) define and distinguish, with illustrations, between orthogonal cutting and oblique cutting
(ii) identify the causes of oblique cutting and chip flow deviation
(iii) determine angle of chip flow deviation.
(iv) illustrate and deduce effective rake angle
(v) state the effects of oblique cutting

(i) Orthogonal and oblique cutting

It is appears from the diagram in Fig. 6.1 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.

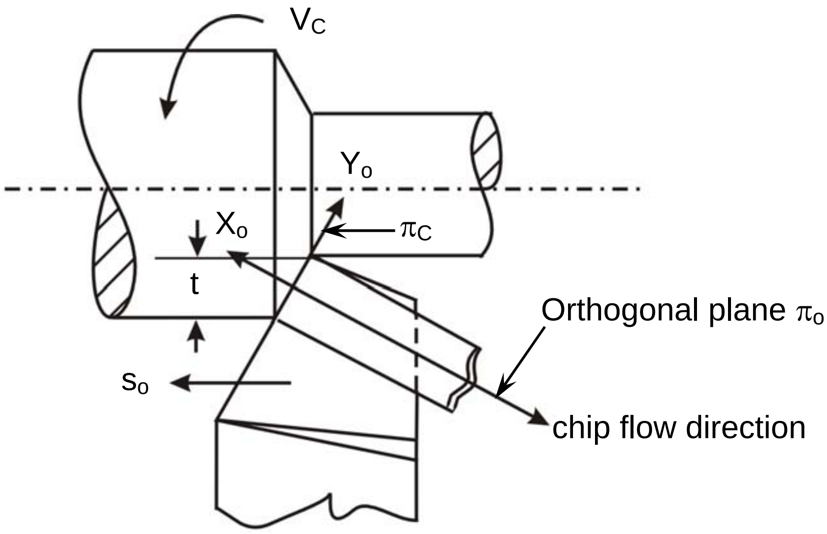
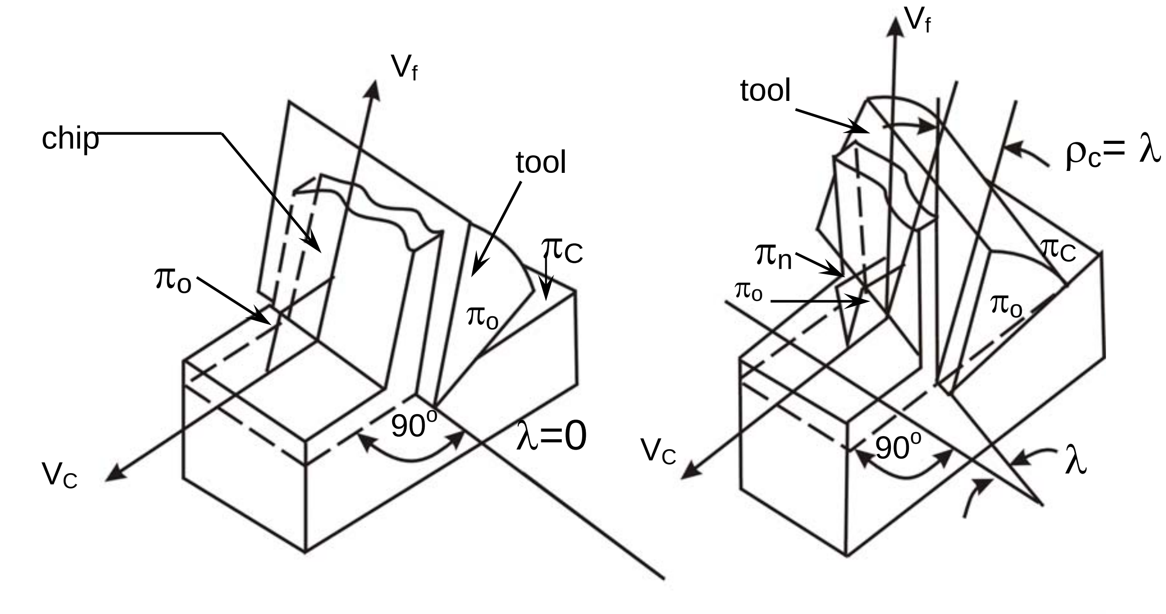


***Fig. 6.1** Ideal direction of chip flow in turning*

The role of inclination angle, λ on the direction of chip flow is schematically shown in Fig. 6.2 which visualises that,

- when λ=0, the chip flows along orthogonal plane, i.e, $\rho_c = 0$
- when $\lambda \neq 0$, the chip flow is deviated from π_o and $\rho_c = \lambda$ where ρ_c is chip flow deviation (from π_o) angle



(a) $\lambda = 0$ (b) $\lambda \neq 0$

Fig. 6.2 *Role of inclination angle, λ on chip flow direction*

Orthogonal cutting: when chip flows along orthogonal plane, π_o, i.e., $\rho_c = 0$
Oblique cutting : when chip flow deviates from orthogonal plane, i.e. $\rho_c \neq 0$
But practically ρ_c may be zero even if $\lambda = 0$ and ρ_c may not be exactly equal to λ even if $\lambda \neq 0$. Because there are some other (than λ) factors also which may cause chip flow deviation.
Pure orthogonal cutting: This refers to chip flow along π_o and $\phi = 90^o$ as typically shown in Fig. 6.3 where a pipe like job of uniform thickness is turned (reduced in length) in a center lathe by a turning tool of geometry; $\lambda = 0$ and $\phi = 90^o$ resulting chip flow along π_o which is also π_x in this case.

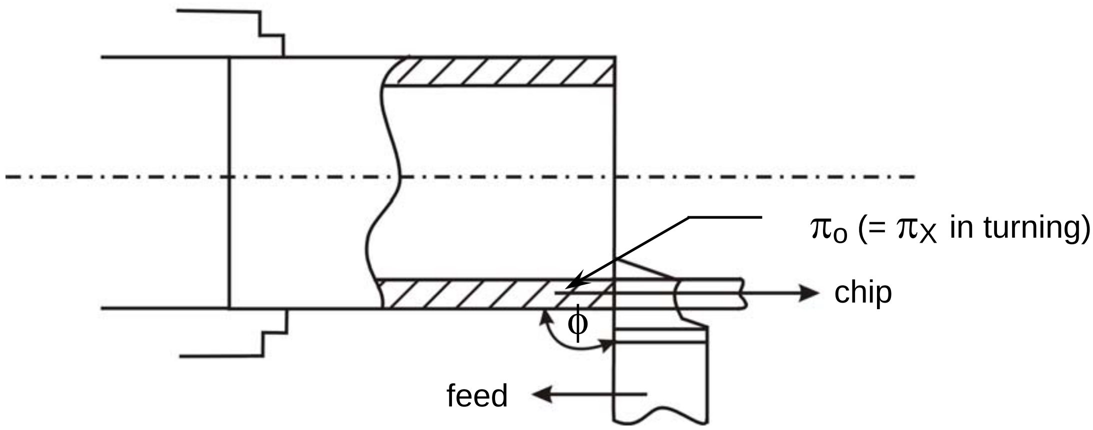


Fig. 6.3 *Pure orthogonal cutting (pipe turning)*

(ii) Causes and amount of chip flow deviation

The deviation of chip flow in machining like turning by single point tool may deviate from the orthogonal plane due to the following three factors:

- Restricted cutting effect (RCE)
- Tool-nose radius (r)
- Presence of inclination angle, $\lambda \neq 0$.

- **Restricted cutting effect**

In machining like turning, shaping etc by single point turning tool, the metal removal is accomplished mainly by the principal cutting edge. But the auxiliary cutting edge also takes part in machining to some extent depending upon the auxiliary cutting edge angle, ϕ_1 and the magnitude of feed, s_o, as indicated in Fig. 6.4. A small volume of the job in the form of a helical rib of small triangular section remains uncut. This causes surface roughness, in the form of fine threads called feed marks or scallop marks as shown in Fig. 6.4. The work material flows out in the form of chip at velocity V_A when the auxiliary cutting edge plays negligible role on chip formation. But when the auxiliary cutting edge keeps sizeable contact with the workpiece, then the material that comes out from that edge at velocity say V_B, interferes with the main stream of the chip causing chip flow deviation from the direction of V_A by an angle say ψ from the direction of V_A as shown in Fig. 6.4. This phenomenon is called **restricted contact cutting effect (RCE).**

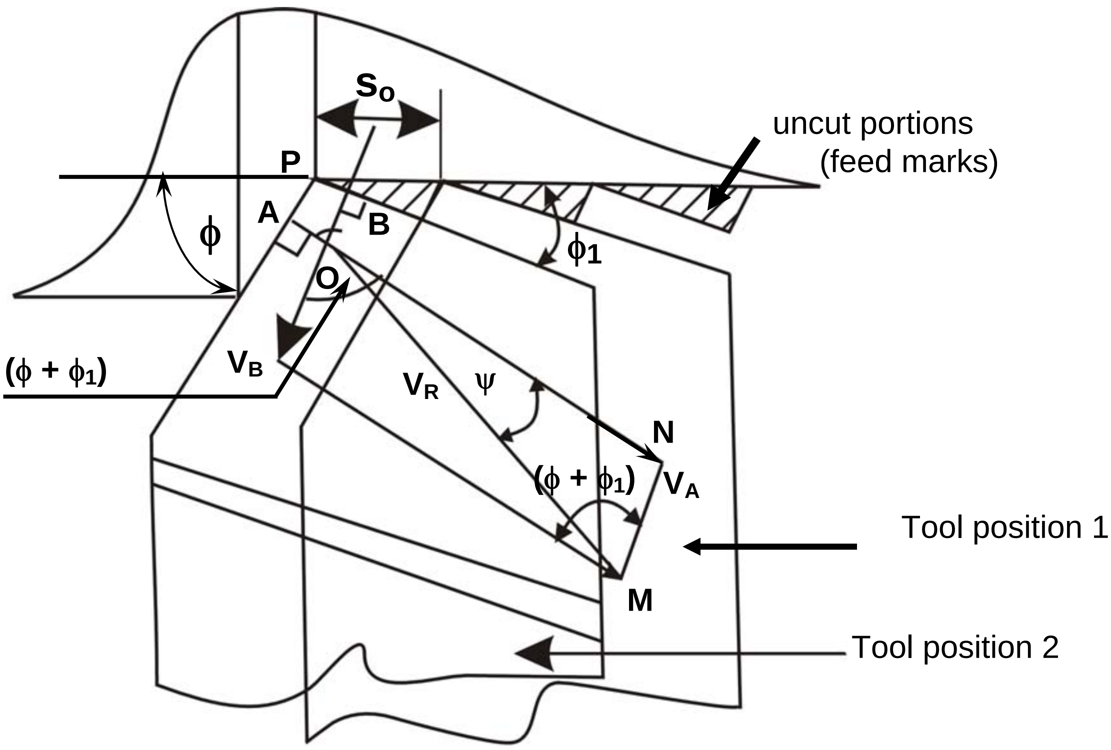


__Fig. 6.4__ Chip flow deviation by Restricted Cutting Effect (RCE)

From Fig. 6.4,

Angle $\angle APB = 180^o - (\phi + \phi_1)$ (6.1)

And $\angle AOB = (\phi + \phi_1)$ (6.2)

From properties of triangle, ΔAMN,

$$\frac{V_B}{\sin\psi} = \frac{V_A}{\sin(\phi + \phi_1 - \psi)}$$

or, $$\frac{\sin(\phi + \phi_1 - \psi)}{\sin\psi} = \frac{V_A}{V_B} \quad (6.3)$$

Assuming [Rozeinberg and Evemein] $$\frac{V_A}{V_B} = \frac{(t/\sin\phi)}{s_o/2} = \frac{2t}{s_o \sin\phi} \quad (6.4)$$

Equation (6.4) can be rewritten as

$$\frac{\sin(\phi + \phi_1)\cos\psi - \cos(\phi + \phi_1)\sin\psi}{\sin\psi} = \frac{2t}{s_o \sin\phi} \quad (6.5)$$

On simplification, equation (6.4), ψ can be expressed as,

$$\tan\psi = \frac{\sin(\phi + \phi_1)}{\frac{2t}{s_o \sin\phi} + \cos(\phi + \phi_1)} \quad (6.5)$$

Equation (6.5) indicates that even in absence of λ the chip flow may deviate, and the angle of deviation, ψ, though small, depends upon the cutting angles and depth of cut to feed ratio (t/s_o).

- **Effect of tool nose radius, r**

Equation (6.5) indicates that chip flow deviation is significantly influenced by the principal cutting edge angle, ϕ. In nose radiused tool, the value of ϕ continuously varies starting from zero over the curved portion of the principal cutting edge. Such variation in ϕ reasonably influences the chip flow deviation. Therefore, to incorporate the effect of tool nose radiusing also, the ϕ in equation (6.5) need to be replaced by the average value of ϕ i.e., ϕ_{avg} which can be determined with the help of the diagram shown in Fig. 6.5.

From Fig. 6.5,

$$\phi_{avg} = \frac{\overline{AB} x \frac{\phi}{2} + \overline{BC} x \phi}{\overline{AB} + \overline{BC}} \quad (6.6)$$

where, $\overline{AB} = r\phi$

and $\overline{BC} = \frac{t_2}{\sin\phi} = \frac{t - t_1}{\sin\phi}$

here $t_1 = r - r\cos\phi$

Thus, $$\phi_{avg} = \frac{\frac{\phi}{2} + [\frac{t}{r} + \cos\phi - 1]\frac{1}{\sin\phi}}{1 + \frac{[\frac{t}{r} + \cos\phi - 1]}{\phi\sin\phi}} \quad (6.7)$$

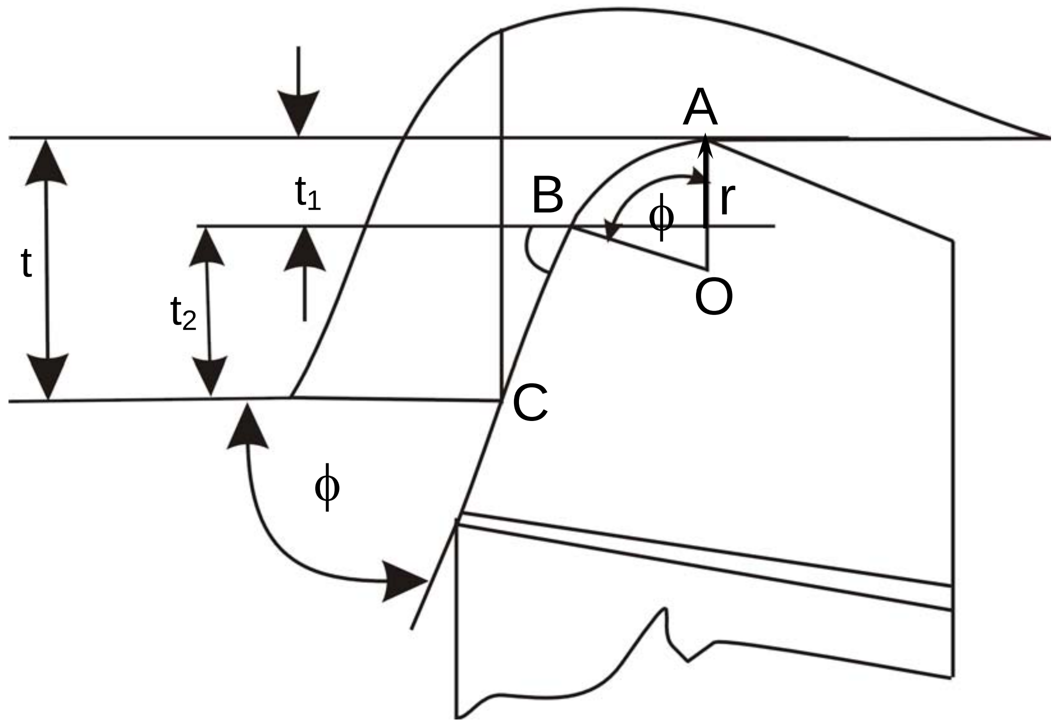


Fig. 6.5 *Variation of principal cutting edge angle in nose radiused tools.*

It is to be noted in equation (6.7) that the difference between ϕ and ϕ_{avg} is governed mainly by the depth of cut to nose radius ratio, i.e., $\frac{t}{r}$.

Therefore to incorporate the effect of nose radiusing along with restricted contact cutting effect, the ϕ in equation (6.5) has to be replaced by ϕ_{avg} to be determined by equation (6.7) resulting,

$$\tan\psi = \frac{\sin(\phi_{avg} + \phi_1)}{\frac{2t}{s_o \sin\phi_{avg}} + \cos(\phi + \phi_{avg})} \qquad (6.8)$$

- **Effect of inclination angle, λ**

In absence of RCE and nose radius the chip flow deviation will be governed only by the value of λ as indicated in Fig. 6.6.

Therefore the combined effects of RCE, tool nose radiused and presence of λ will cause chip flow deviation angle, ρ_c as

$$\rho_c = \psi + \lambda \qquad (6.9)$$

Generally, compared to λ, ψ is very small.

So approximately [s(S)tabler], $\rho_c = \lambda$ where λ may be positive or negative.

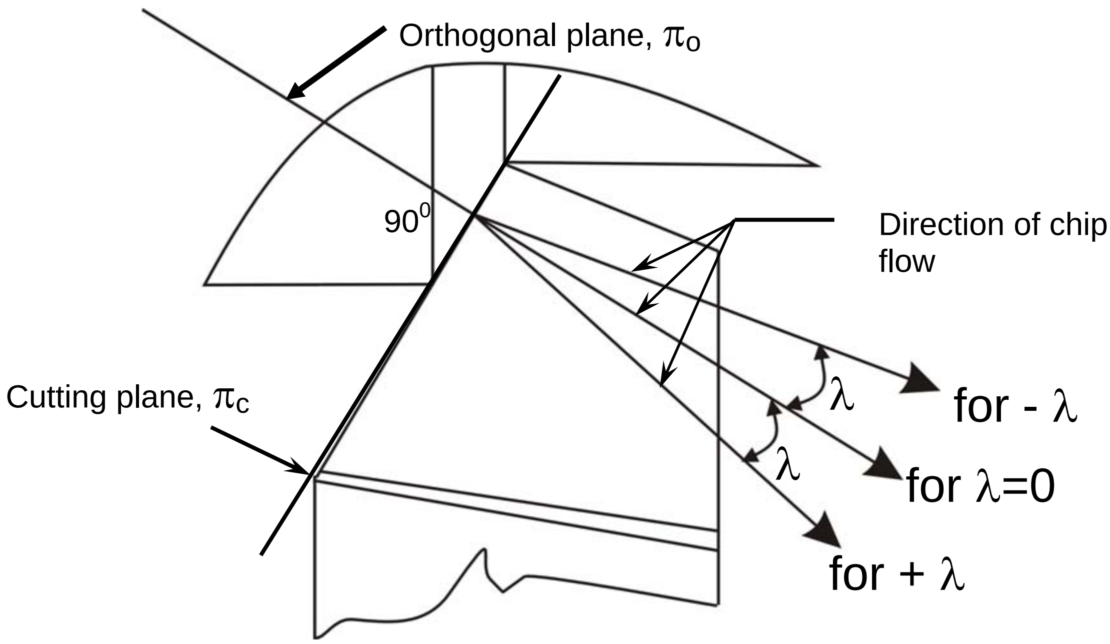


***Fig. 6.6** Role of inclination angle on chip flow direction*

(iii) Effective Rake, γ_e

It has already been realized that the value of rake angle plays vital roles on both mechanism and mechanics of machining. There are different rake angles but that rake angle is obviously the most significant which is taken in the direction of actual chip flow. This rake is called Effective Rake (γ_e)

Definition of γ_e: The angle of inclination of the rake surface from π_R and is measured on that plane which is perpendicular to the reference plane and is taken in the direction of actual chip flow as shown in Fig. 6.7.

In Fig. 6.7, OC is the deviation of apparent chip flow but OD represents the actual direction of chip flow which is deviated from OC by the chip flow angle, ρ_c. Z_o, AB and DE are perpendicular to π_R. Y_o' is parallel to Y_o and Y_n' is taken parallel to the axis Y_n.

In this figure, DOE represents effective rake angle, γ_e.

From Fig. 6.7,

$$\sin\gamma_e = \frac{DE}{OD} = \frac{DF + EF}{\dfrac{OC}{\cos\rho_c}} \qquad (6.10)$$

where, $DF = AB = \dfrac{AC}{\cos\lambda}$

$$EF = AF\sin\lambda$$

$$AF = BD = CD - BD$$
$$AC = OC \sin \gamma_n$$
$$CD = OC \tan \rho_c$$

Combining all those equations, it appears that,

$$\sin\gamma_e = \cos\lambda\cos\rho_c\lambda\sin\gamma_n + \sin\lambda.\sin\rho_c \qquad (6.11)$$

Assuming [stabler] $\lambda=\rho_c$

$$\sin\gamma_e = \cos^2\lambda\sin\gamma_n + \sin^2\lambda \qquad (6.12)$$

where,

$$\tan\gamma_n = \tan\gamma_o.\cos\lambda$$

it is again to be noted that

$$\text{if } \lambda = 0;\ \gamma_e \cong \gamma_n = \gamma_o \qquad (6.13)$$

In case of oblique cutting, which is practically more common, the actual direction of chip flow and the corresponding rake angle, i.e., effective rake should be used for more reasonably accurate analysis and assessment of cutting forces, friction and tool wear.

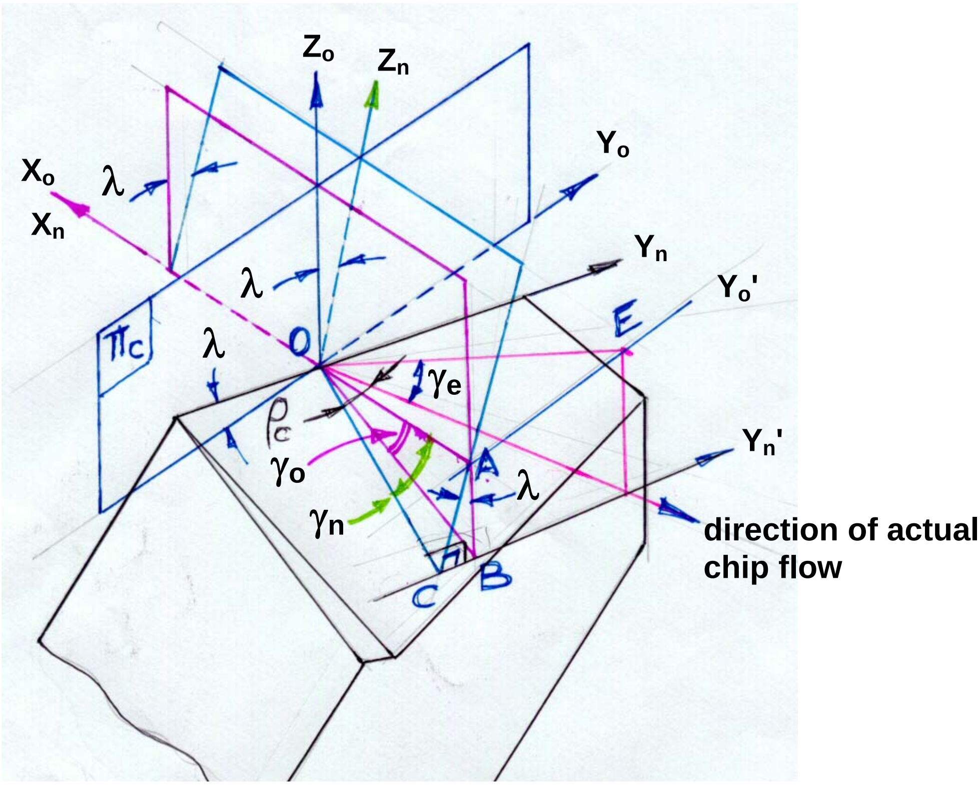


Fig. 6.7 Effective rake angle, γ_e

(iv) Effects of oblique cutting

In contrary to simpler orthogonal cutting, oblique cutting causes the following effects on chip formation and mechanics of machining:

- Chip does not flow along the orthogonal plane;
  Positive λ causes

- o Chip flow deviation away from the finished surface, which may result
  - — lesser further damage to the finished surface
  - — but more inconvenience to the operator
- o reduction of mechanical strength of the tool tip
- o increase in temperature at the tool tip
- o more vibration in turning slender rods due to increase in P_Y (transverse force)

On the other hand, negative λ may enhance tool life by increasing mechanical strength and reducing temperature at the tool tip but may impair the finished surface.

- The chip cross-section may change from rectangle (ideal) to skewed trapezium
- The ductile metals(materials) will produce more compact helical chips if not broken by chip breaker
- Analysis of cutting forces, chip-tool friction etc. becomes more complex.

NOTE: For specifying angles stick to ISO standards,

for ex:

shear angle is ϕ

Inclination angle is ***i***

Exercise - 6

A. Quiz test

Select the correct answer from the given four options

1.Cutting will be called orthogonal when

(a) $\lambda = 0$

(b) $\lambda = 0$ and $\phi = 90^o$

(c) chip flows along π_O plane

(d) $\lambda = 0$ and r (nose radius) = 0

2.In turning, chip will flow along π_O only when

(a) RCE is absent

(b) nose radius is zero

(c) $\lambda = 0$

(d) all of the above conditions

3.Deviation of chip flow from p_O (?)does not depend upon

(a) cutting velocity
(b) feed
(c) depth of cut
(d) nose radius

4.Effective rake in any turning process is measured on

(a) π_X
(b) π_O
(c) π_n
(d) none of the above

B. Problem

1. Under what geometrical condition the values of γ_e, γ_n, γ_o and γ_x (suffix properly) of a turning tool will be same ?

2. Estimate the value of γ_e for turning a rod at s_o= 0.24 mm/rev and t = 4.0 mm by a tool of geometry 10^o, 8^o, 7^o, 6^o, 15^o, 75^o, 1.2 (mm) – NRS

A. Quiz Test - answers

1 – (c)
2 – (d)
3 – (a)
4 – (d)

Q. 1 When γ_e, γ_n, γ_o and γ_x become same ?

Ans

- $\gamma_o = \gamma_x$ when $\phi = 90^o$ i.e., $\pi_o = \pi_x$
- $\gamma_n = \gamma_o$ when $\lambda = 0^o$ i.e., $\pi_n = \pi_o$
- $\gamma_e = \gamma_n$ when $\lambda = 0^o$ & $\rho_C = \psi \pm \lambda = 0$ i.e., $\psi = 0$
- $\psi = 0$ when nose radius, r = 0,
  i.e. $\phi_{avg} = \phi$ and RCE is absent i.e., $\phi_1 > 20^o$

Q. 2 Given : t = 4.0, s_o = 0.24 mm/rev and $\lambda = 10^o$, $\gamma_n = 8^o$, $\phi = 75^o$, $\phi_1 = 15^o$, r = 1.2 mm. Determine γ_e

Ans.

- $\sin\gamma_e = \cos\lambda\cos\rho_c\sin\gamma_n + \sin\lambda\sin\rho_c$ (1)
- $\rho_c = \psi + \lambda$ [Stabler's rule] (2)

$$\tan\psi = \frac{\sin(\phi_{avg} + \phi_1)}{\dfrac{2t}{s_o \sin\phi_{avg}} + \cos(\phi_{avg} + \phi_1)}$$

- ϕ_{avg}= [ϕ/2+(t/r-cosϕ+1)/sinϕ] / [1+(t/r–cosϕ+1)/ϕsinϕ = 62.71^o
- Put the values, get ψ = 1.65^o
- Hence ρ_c = 1.65^o + 10^o= 11.65^o
- Put values of λ, ρ_c and γ_n in equation 1;

  get γ_e = 5.69^o Ans

Module
2
Mechanics of Machining

Lesson
5
Mechanism of chip formation

Instructional Objectives

At the end of this lesson, the student would be able to

(i) describe with illustration the mechanism of chip formation in machining
   - ductile materials and
   - brittle materials

(ii) illustrate and assess geometrical characteristics of ductile chips :
   - chip reduction coefficient & cutting ratio
   - shear angle and cutting strain

(iii) Identify and state the causes, characteristics and effects of built – up – edge (BUE) formation.

(iv) Classify chips and identify the condition for different chip forms.

(i) Mechanism of chip formation in machining

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

- fulfill its basic functional requirements
- provide better or improved performance
- render long service life.

Machining is a process of gradual removal of excess material from the preformed blanks in the form of chips.

The form of the chips is an important index of machining because it directly or indirectly indicates :

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

The form of machined chips depend 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 favourable chip forms.

- **Mechanism of chip formation in machining ductile materials**

During continuous machining the uncut layer of the work material just ahead of the cutting tool (edge) is subjected to almost all sided compression as indicated in Fig. 5.1.

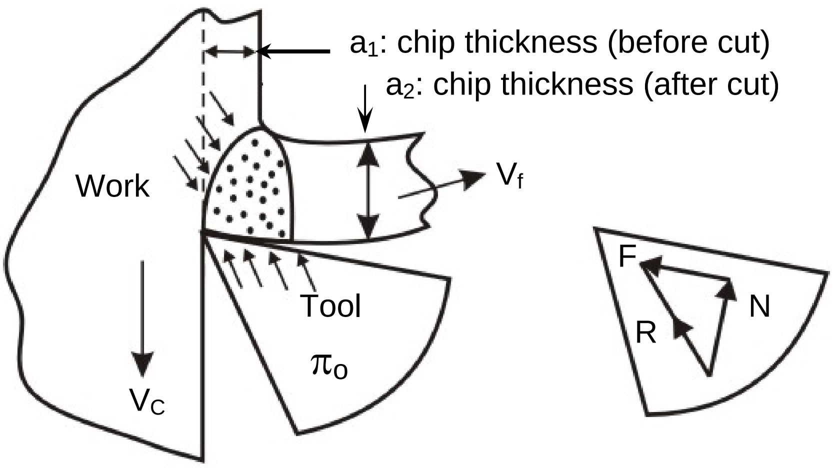


Fig. 5.1 *Compression of work material (layer) ahead of the tool tip*

The force exerted by the tool on the chip arises out of the normal force, N and frictional force, F as indicated in Fig. 5.1.
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. 5.2.

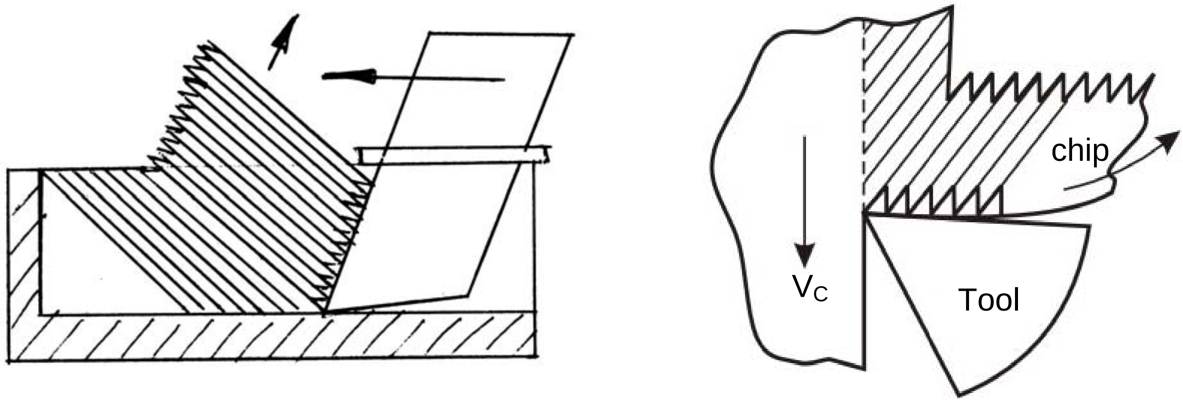
In actual machining chips also, such serrations are visible at their upper surface as indicated in Fig. 5.2. The lower surface becomes smooth due to further plastic deformation due to intensive rubbing with the tool at high pressure and temperature. The pattern of shear deformation by lamellar sliding, 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. 5.3, depend upon

[1] Piispannen V., "Theory of formation of metal chips", J. Applied Physics, Vol. 19, No. 10, 1948, pp. 876.

- work material
- tool; material and geometry
- the machining speed (V_C) and feed (s_o)
- cutting fluid application



(a) Shifting of the postcards by partial sliding against each other

(b) Chip formation by shear in lamella.

Fig. 5.2 *Piispanen model of card analogy to explain chip formation in machining ductile materials*

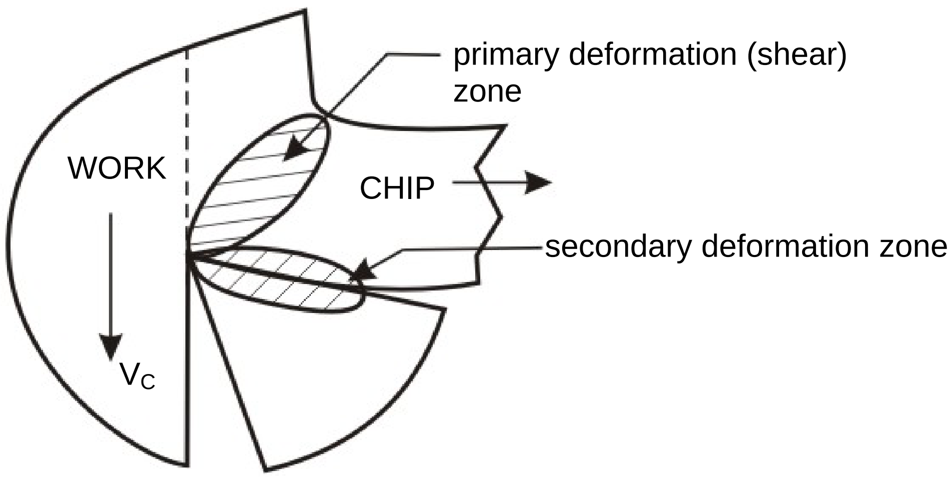


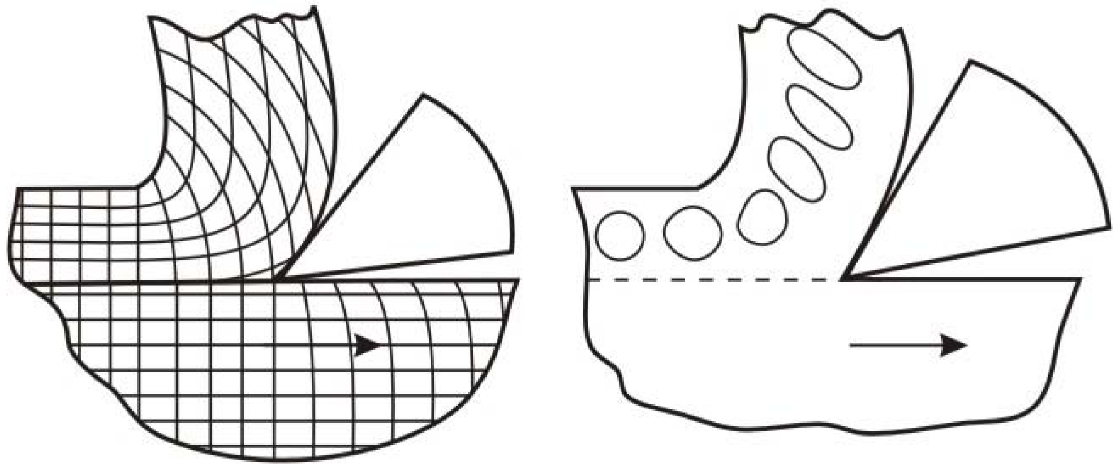
Fig. 5.3 *Primary and secondary deformation zones in the chip.*

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 the side surface as shown in Fig. 5.4

[2] Bhattacharya, A.., "Metal cutting – Theory and Practice", Book, New Central Book Agency, Kolkata.

- 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.



(a) rectangular grids (b) circular grids

Fig. 5.4 *Pattern of grid deformation during chip formation.*

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.

- **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. 5.5 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 workpiece through the minimum resistance path as indicated in Fig. 5.5.
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. 5.6.

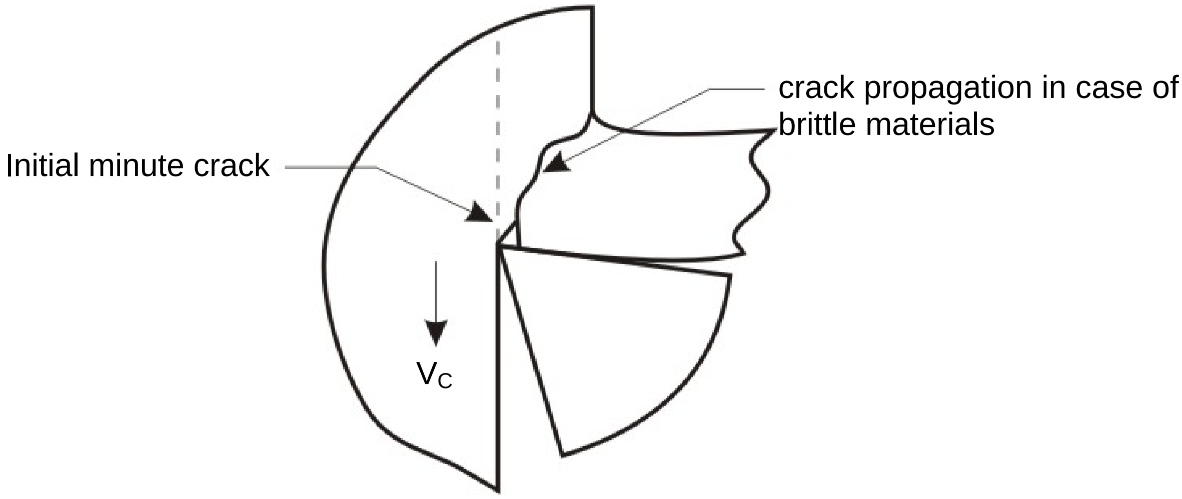


Fig. 5.5 *Development and propagation of crack causing chip separation.*

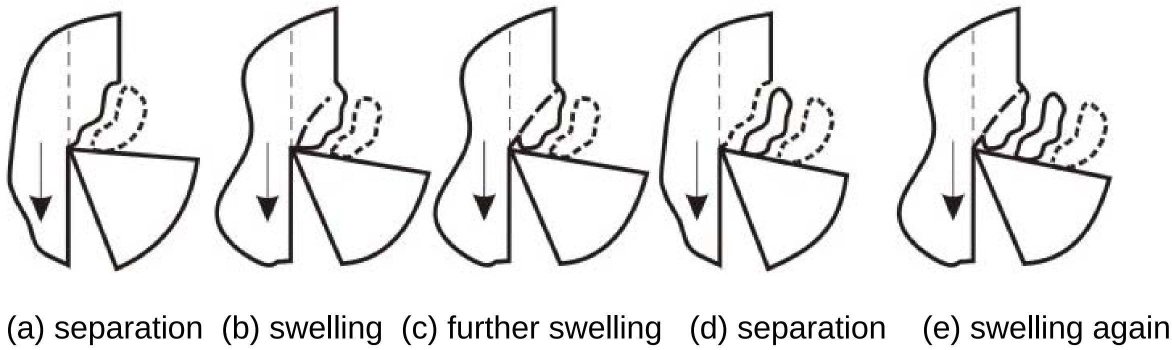


Fig. 5.6 *Schematic view of chip formation in machining brittle materials.*

(ii) Geometry and characteristics of chip forms

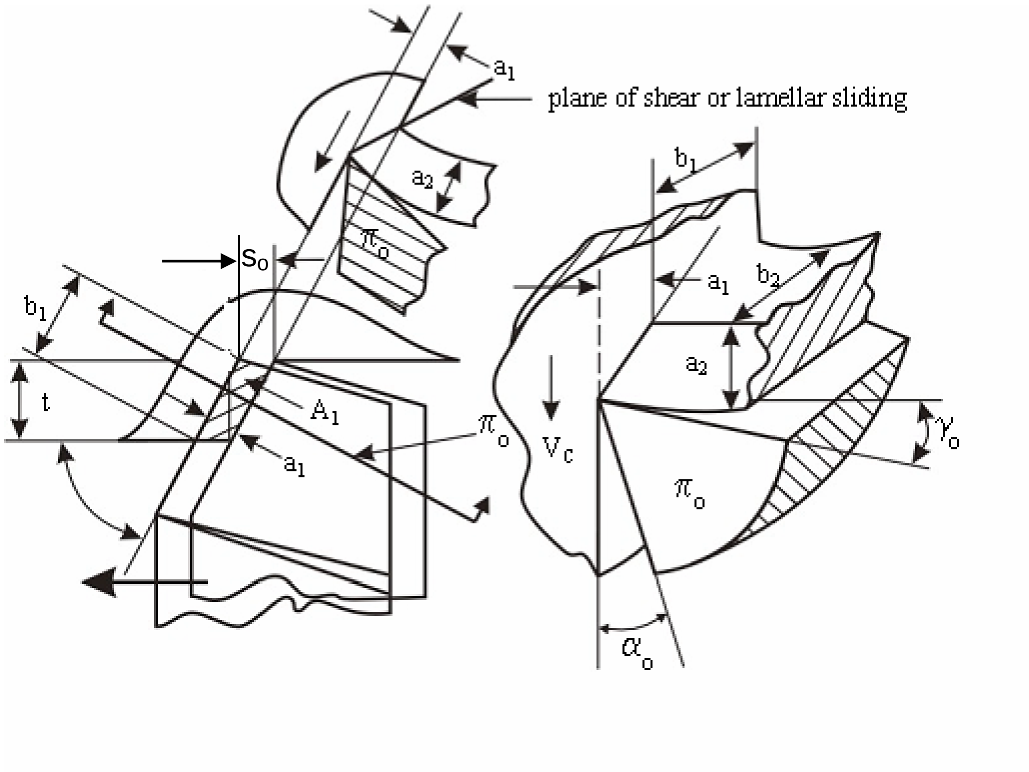
The geometry of the chips being formed at the cutting zone follow a particular pattern especially in machining ductile materials. The major section of the engineering materials being machined are ductile in nature, even some semi-ductile or semi-brittle materials behave ductile under the compressive 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. 5.7.
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



(a) (b)

Fig. 5.7 *Geometrical features of continuous chips' formation.*

The significant geometrical parameters involved in chip formation are shown in Fig. 5.7 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
s_o = 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, mm^2) of chip before cut

The degree of thickening of the chip is expressed by

$$\zeta = \frac{a_2}{a_1} > 1.00 \text{ (since } a_2 > a_1\text{)} \quad (5.1)$$

where, ζ = chip reduction coefficient

$a_1 = s_o \sin\phi$ (5.2)

where ϕ = principal cutting edge angle

Larger value of ζ 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 ζ without sacrificing productivity, i.e. metal removal rate (MRR).

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

$$\frac{1}{\zeta} = r = \frac{a_1}{a_2} \qquad (5.3)$$

where, r = cutting ratio

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

- tool rake angle, γ
- chip-tool interaction, mainly friction, μ

Roughly in the following way [3]

$$\zeta = e^{\mu(\frac{\pi}{2} - \gamma_o)} \quad \text{[for orthogonal cutting]} \qquad (5.4)$$

$\pi/2$ and γ_o are in radians

The simple but very significant expression (5.4) clearly depicts that the value of ζ 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. 5.8.

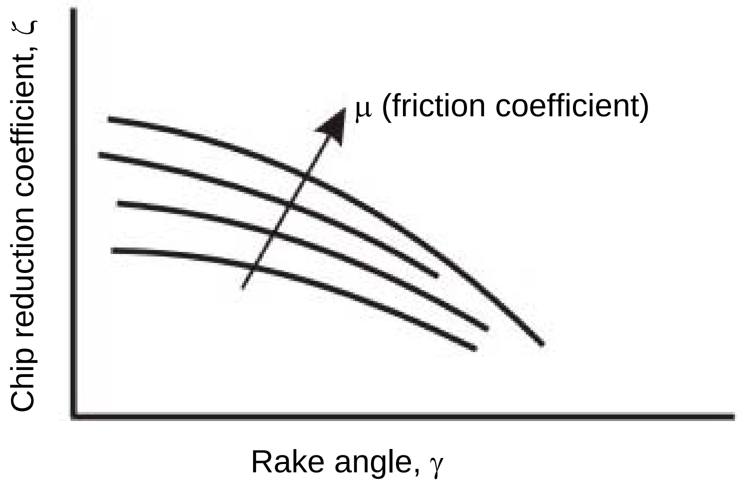


Fig. 5.8 *Role of rake angle and friction on chip reduction coefficient*

Chip reduction coefficient, ζ is generally assessed and expressed by the ratio of the chip thickness, after (a_2) and before cut (a_1) as in equation 5.1.

But ζ can also be expressed or assessed by the ratio of

[3] Kronenberg, M., “A new approach to some relationships in the Theory of Metal Cutting”, J. Applied Physics, Vol.6, No. 6, 1945.

- Total length of the chip before (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,

$$a_1b_1L_1 = a_2b_2L_2 \qquad (5.5)$$

The width of chip, b generally does not change significantly during machining unless there is side flow for some adverse situation.
Therefore assuming, $b_1=b_2$ in equation (5.5), ζ comes up to be,

$$\zeta\left(=\frac{a_2}{a_1}\right)=\frac{L_1}{L_2} \qquad (5.6)$$

Again considering unchanged material flow (volume) ratio, Q

$$Q = (a_1b_1)V_C = (a_2b_2)V_f \qquad (5.7)$$

Taking $b_1=b_2$,

$$\zeta\left(=\frac{a_2}{a_1}\right)=\frac{V_C}{V_f} \qquad (5.8)$$

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, $r\left(=\frac{1}{\zeta}\right)$

- **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, V_C 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. 5.9.

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. 5.9].

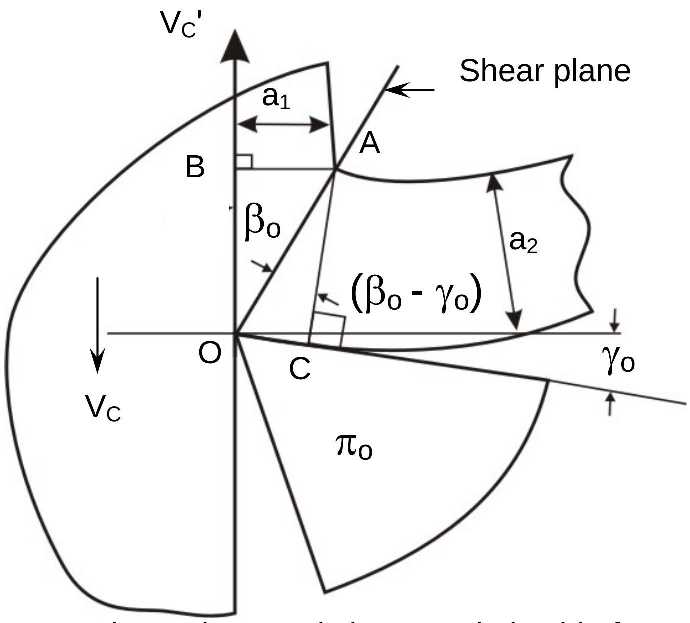


Fig. 5.9 *Shear plane and shear angle in chip formation*

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

- Chip thickness before and after cut i.e. ζ
- Rake angle, γ_o (in orthogonal plane)

From Fig. 5.9,

$AC = a_2 = OA\cos(\beta_o - \gamma_o)$

And $AB = a_1 = OA\sin\beta_o$

Dividing a_2 by a_1

$$\frac{a_2}{a_1} = \zeta = \frac{\cos(\beta_o - \gamma_o)}{\sin\beta_o} \qquad (5.9)$$

or, $$\tan\beta_o = \frac{\cos\gamma_o}{\zeta - \sin\gamma_o} \qquad (5.10)$$

Replacing chip reduction coefficient, ζ by cutting ratio, r, the equation (5.10) changes to

$$\tan\beta_o = \frac{r\cos\gamma_o}{1 - r\sin\gamma_o} \qquad (5.11)$$

Equation 5.10 depicts that with the increase in ζ, shear angle decreases and vice-versa. It is also evident from equation (5.10) as well as equation (5.4) that shear angle increases both directly and indirectly with the increase in tool rake angle. Increase in shear angle means more favourable 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. 5.10.

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. 5.10,

Cutting strain (average), $\varepsilon = \frac{\Delta s}{Y} = \frac{PM}{ON}$

or, $\varepsilon = \frac{PN + NM}{ON} = \frac{PN}{ON} + \frac{NM}{ON}$

or, $$\varepsilon = \cot\beta_o + \tan(\beta_o - \gamma_o) \qquad (5.12)$$

(iii) 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 favourable location and thus gradually grows as schematically shown in Fig. 5.11.

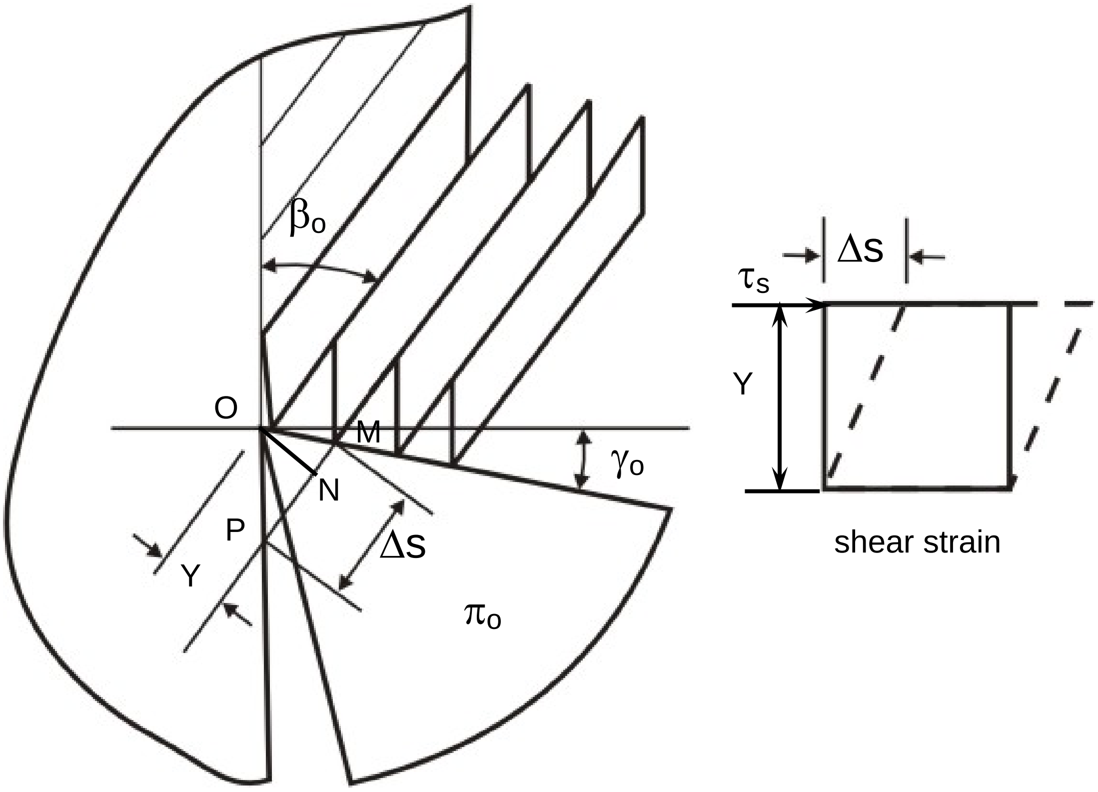


Fig. 5.10 *Cutting strain in machining*

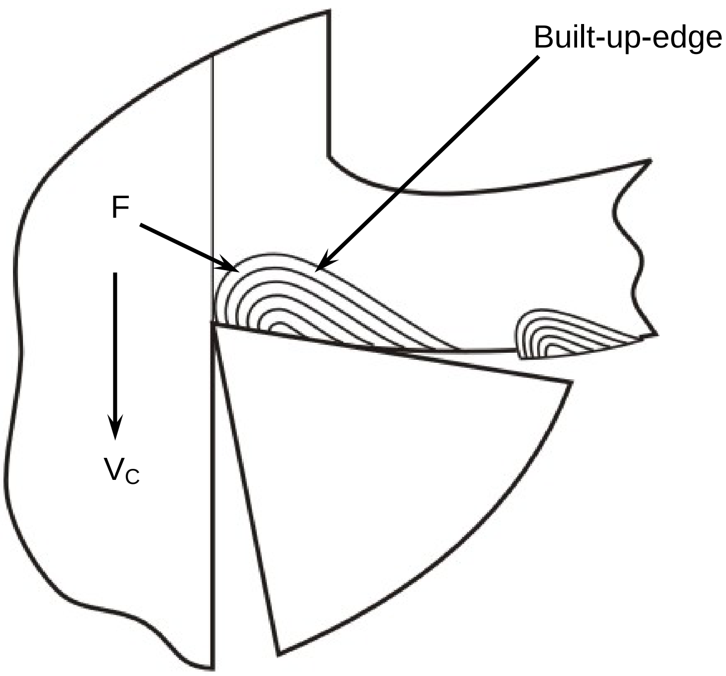


Fig. 5.11 *Scheme of built-up-edge formation*

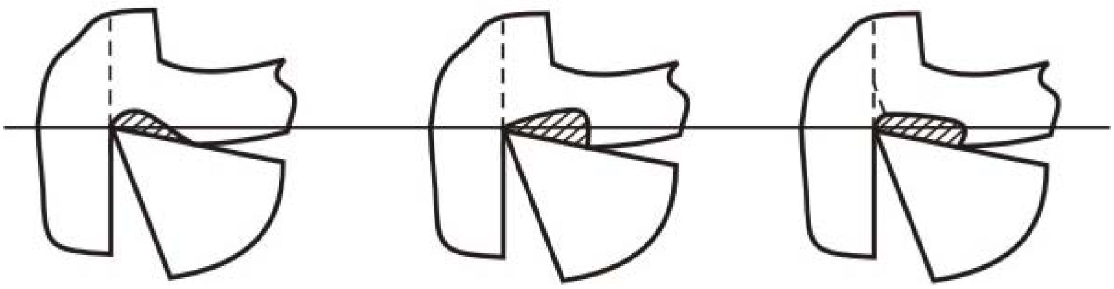
With the growth of the BUE, the force, F (shown in Fig. 5.11) also gradually increases due to wedging action of the tool tip along with the BUE formed on it. Whenever the force, F exceeds the bonding force of the BUE, the BUE is broken or sheared off and taken away by the flowing chip. Then again BUE 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. 5.12.



(a) positive wedge (b) negative wedge (c) flat type

Fig. 5.12 *Different forms of built-up-edge.*

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. 5.13

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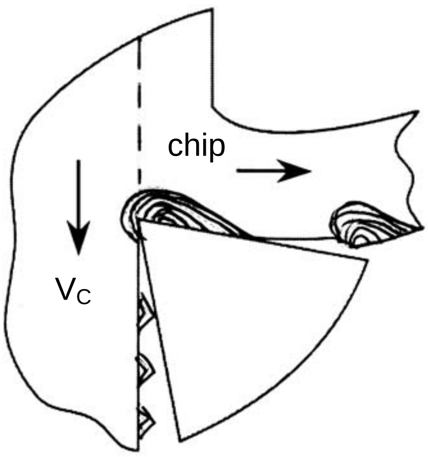


Fig. 5.13 *Overgrowing and overflowing of BUE causing surface roughness*

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 s_o the cutting temperature rises and favours 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. 5.14 shows schematically the role of increasing V_C and s_o 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 detrimental situation occurs in case of certain tool-work materials and at speed-feed conditions which strongly favour adhesion and welding.

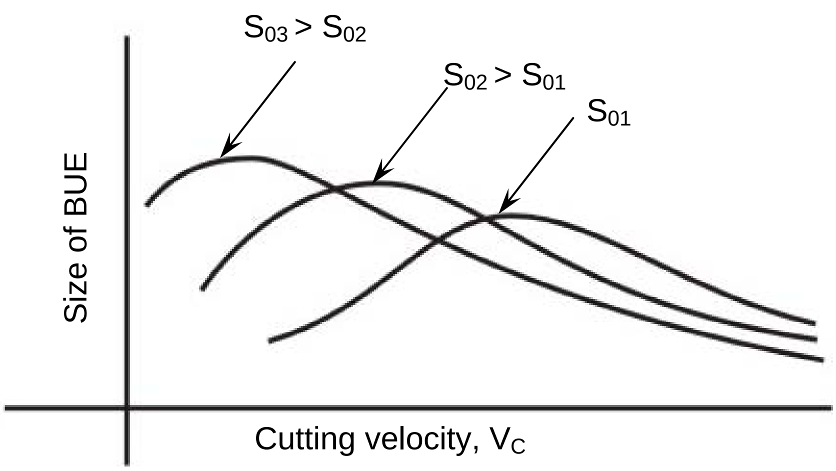


***Fig. 5.14** Role of cutting velocity and feed on BUE formation.*

- Effects of BUE formation

Formation of BUE causes several harmful effects, such as:

- It unfavourably 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.

(iv) Types of chips and conditions for formation of those 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:

- Discontinuous type
  - 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 – large
    - tool rake – negative
    - cutting fluid – absent or inadequate
- Continuous type
  - Without BUE : work material – ductile
    Cutting velocity – high
    Feed – low
    Rake angle – positive and large
    Cutting fluid – both cooling and lubricating
  - With BUE : - work material – ductile
    - cutting velocity – medium
    - feed – medium or large
    - cutting fluid – inadequate or absent.
- Jointed or segmented type
  - work material – semi-ductile
  - cutting velocity – low to medium
  - feed – medium to large
  - tool rake – negative
  - cutting fluid – 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.

Exercise - 5

A. Quiz Test

Identify the correct one out of the four given answers

1.In turning mild steel the value of ζ will be

(a) > 1.0
(b) < 1.0
(c) = 1.0
(d) none of the above

2.The value of shear angle, β_o depends upon

(a) tool rake angle
(b) friction at chip-tool interface
(c) built – up – edge formation
(d) all of the above

3.Shaping grey cast iron block will produce

(a) continuous chip with BUE
(b) continuous chip without BUE
(c) discontinuous chip of irregular size & shape
(d) discontinuous chip of regular size & shape

4.The value of chip reduction coefficient, ζ does not depend upon

(a) cutting velocity
(b) depth of cut
(c) cutting tool material
(d) tool rake angle

B. Numerical Problem

1.During plain turning mild steel by a tool of geometry, 0^o, 0^o, 8^o, 7^o, 15^o, 90^o, 0 (mm) at s_o= 0.2 mm/rev, the chip thickness was found to be 0.5 mm. Determine the values of ζ and β_o in the above case.

Answers

A. Quiz Test

1 – (a)
2 – (d)
3 – (c)
4 – (b)

B. Numerical Problem

$$\zeta = \frac{a_2}{a_1} = \frac{a_2}{s_o \sin\phi} = \frac{0.5}{0.2x \sin 90^o} = 2.5$$

$$\tan\beta_o = \frac{\cos\gamma_o}{\zeta - \sin\gamma_o} = \frac{\cos 0^o}{2.5 - \sin 0^o} \; [\because \gamma_o = 0^o]$$

$$= \frac{1}{\zeta} = \frac{1}{2.5} = 0.4$$

$$\therefore \beta_o = \tan^{-1}(0.4) = 21.8^o$$

Module 2

Mechanics of Machining (Metal Cutting)

Lesson
3
Geometry of single point cutting tools

Instructional objectives

At the end of this lesson, the student should be able to :

(a) conceive rake angle and clearance angle of cutting tools
(b) classify systems of description of tool geometry
(c) demonstrate tool geometry and define tool angles in :
- Machine Reference System
- Orthogonal Rake System and
- Normal Rake System

(d) designate cutting tool geometry in ASA, ORS and NRS

Geometry of single point 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.
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.

(i) 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. 3.1

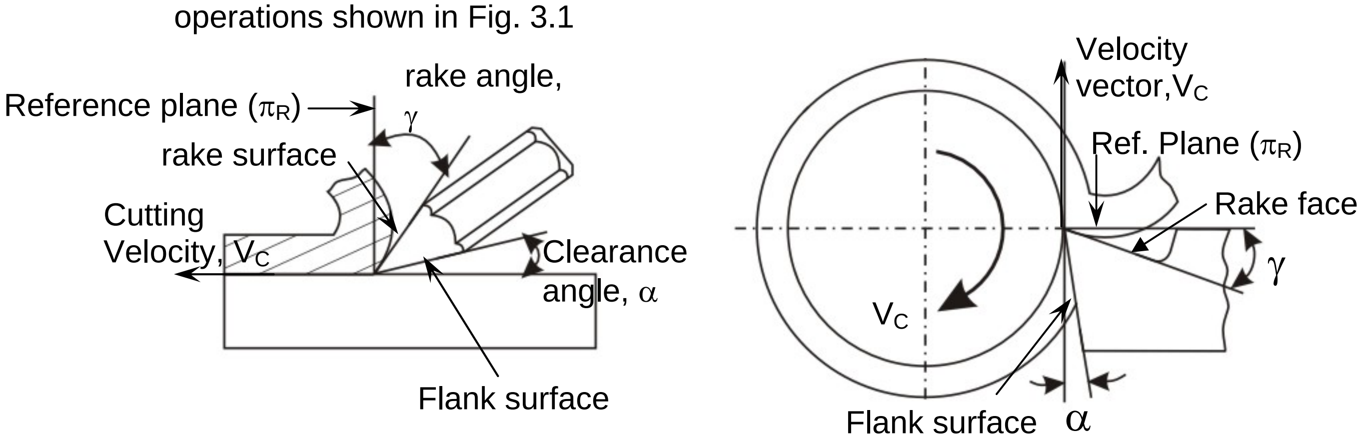
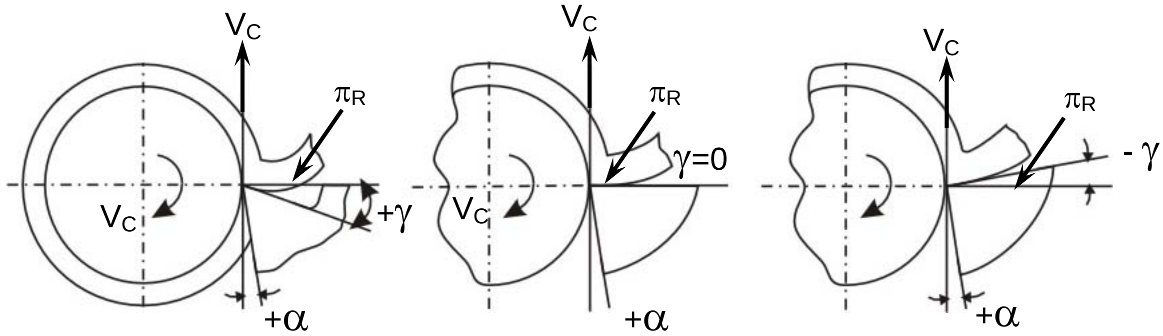


Fig. 3.1 *Rake and clearance angles of cutting tools.*

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. 3.2.



(a) positive rake (b) zero rake (c) negative rake

Fig. 3.2 *Three possible types of rake angles*

Relative advantages of such rake angles are:

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

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^o ~ 15^o depending upon tool-work materials and type of the machining operations like turning, drilling, boring etc.)

(ii) 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. 3.3. There is no quantitative information, i.e., value of the angles.
- Machine Reference System – ASA system
- Tool Reference Systems
    - ∗ Orthogonal Rake System – ORS
    - ∗ Normal Rake System – NRS
- Work Reference System – WRS

(iii) Demonstration (expression) of tool geometry in :

- **Machine Reference System**

This system is also called ASA system; ASA stands for American Standards Association. Geometry of a cutting tool refers mainly to its several angles or slope of its salient working surfaces and cutting edges. Those angles are expressed w.r.t. 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. 3.4.

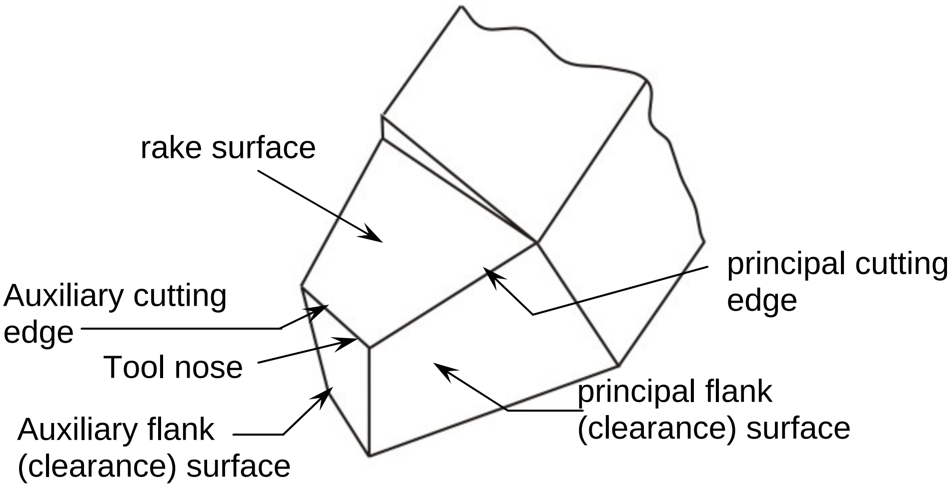


Fig. 3.3 *Basic features of single point tool (turning) in Tool-in-hand system*

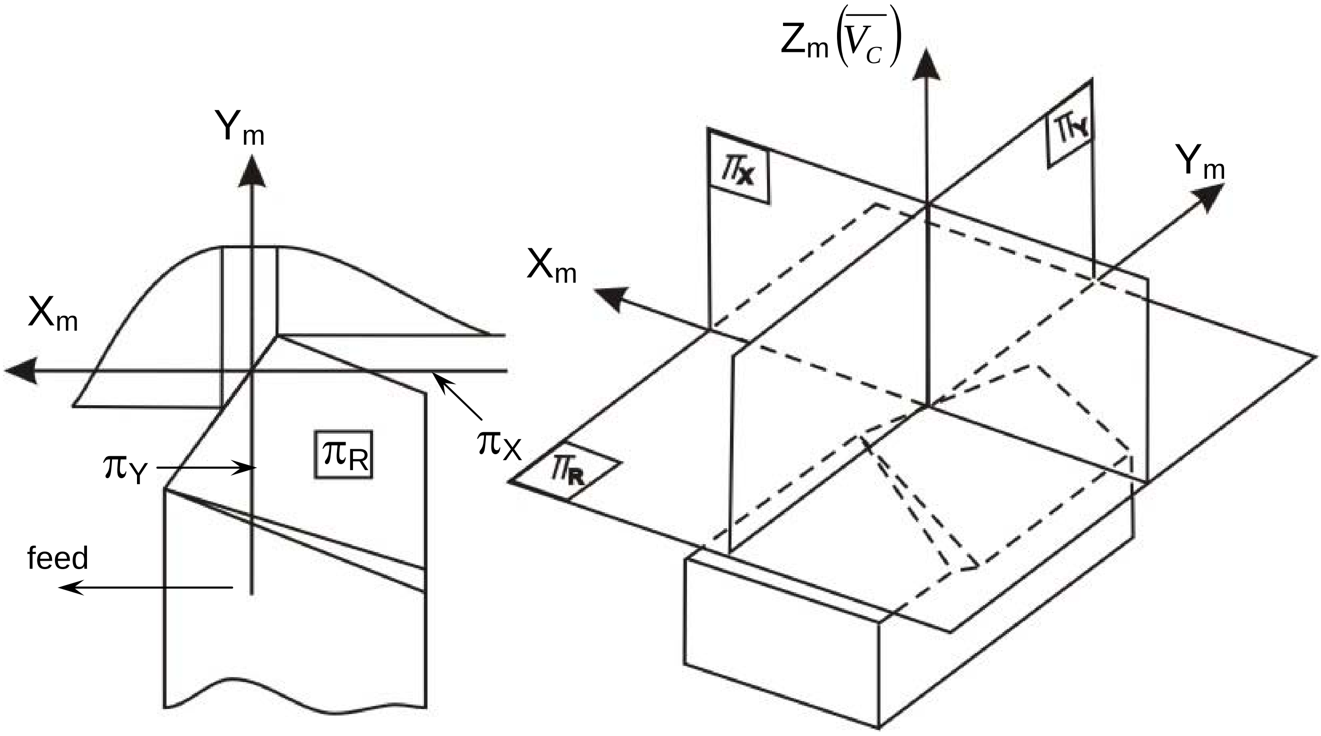


Fig. 3.4 *Planes and axes of reference in ASA system*

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

$$\pi_R - \pi_X - \pi_Y \text{ and } X_m – Y_m - Z_m$$

where,

π_R = Reference plane; plane perpendicular to the velocity vector (shown in Fig. 3.4)

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. 3.5.

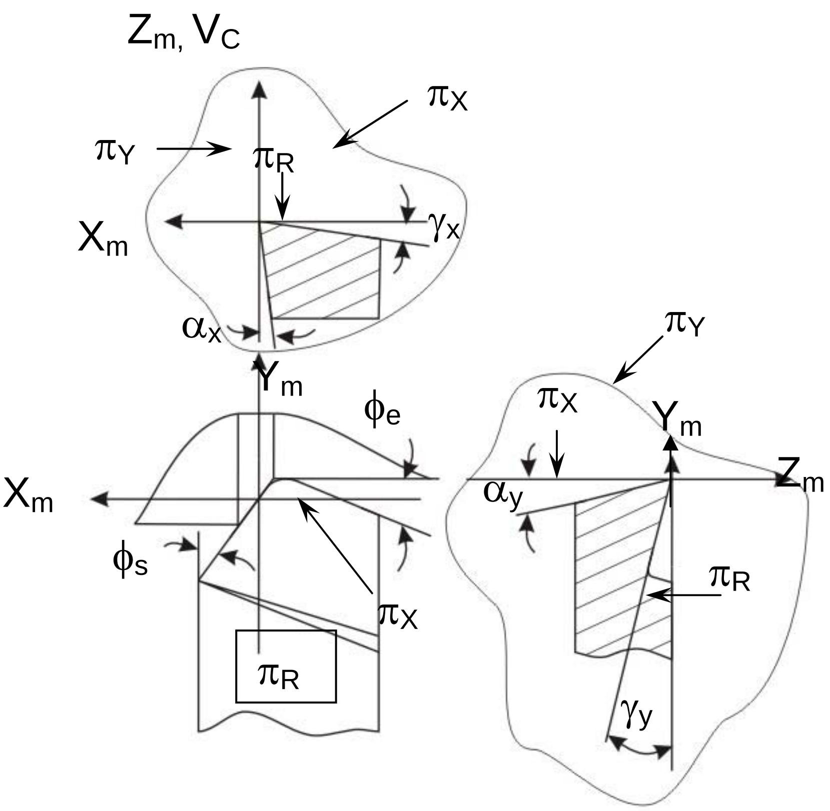


Fig. 3.5 *Tool angles in ASA system*

Definition of:

- Rake angles: [Fig. 3.5] in ASA system

γ_X = side (axial rake: angle of inclination of the rake surface from the reference plane (π_R) and measured on Machine Ref. Plane, π_X.

γ_Y = back rake: angle of inclination of the rake surface from the reference plane and measured on Machine Transverse plane, π_Y.

- Clearance angles: [Fig. 3.5]

α_X = side clearance: angle of inclination of the principal flank from the machined surface (or $\overline{V_C}$) and measured on π_X plane.

α_Y = back clearance: same as α_x but measured on π_Y plane.

- Cutting angles: [Fig. 3.5]

ϕ_S = 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

- Nose radius, r (in **inch**)

r = nose radius : curvature of the tool tip. It provides strengthening of the tool nose and better surface finish.

- **Tool Reference Systems**
  - **Orthogonal Rake System – ORS**

    This system is also known as ISO – old.

The planes of reference and the co-ordinate axes used for expressing the tool angles in ORS are:

$\pi_R - \pi_C - \pi_O$ and $X_o - Y_o - Z_o$

which are taken in respect of the tool configuration as indicated in Fig. 3.6

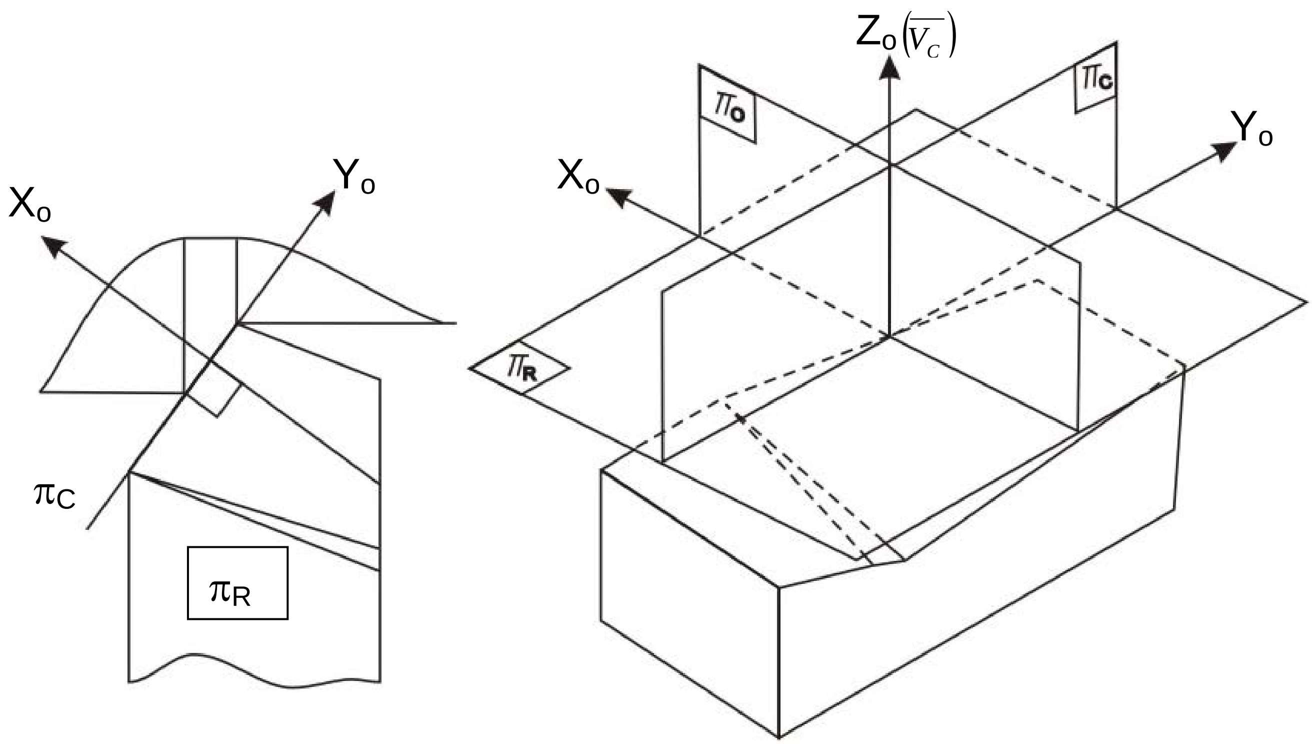


Fig. 3.6 *Planes and axes of reference in ORS*

where,

π_R = Refernce plane perpendicular to the cutting velocity vector, $\overline{V_C}$

π_C = cutting plane; plane perpendicular to π_R and taken along the principal cutting edge

π_O = Orthogonal plane; plane perpendicular to both π_R and π_C

and the axes;

X_o = along the line of intersection of π_R and π_O

Y_o = along the line of intersection of π_R and π_C

Z_o = along the velocity vector, i.e., normal to both X_o and Y_o axes.

The main geometrical angles used to express tool geometry in Orthogonal Rake System (ORS) and their definitions will be clear from Fig. 3.7.

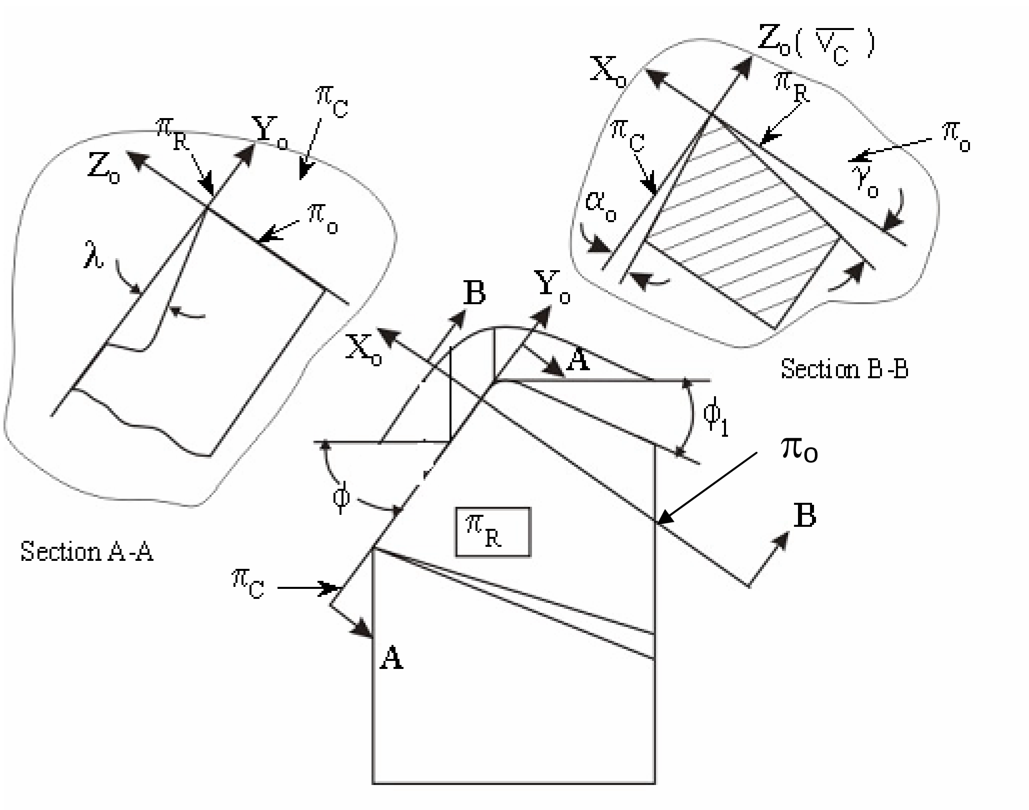


Fig. 3.7 *Tool angles in ORS system*

Definition of –

- Rake angles [Fig. 3.7] in ORS

γ_o = orthogonal rake: angle of inclination of the rake surface from Reference plane, **π_R** and measured on the orthogonal plane, **π_o**

λ = inclination angle; angle between π_C from the direction of assumed longitudinal feed [π_X] and measured on π_C

- Clearance angles [Fig. 3.7]

α_o = orthogonal clearance of the principal flank: angle of inclination of the principal flank from π_C and measured on π_o

α_o' = auxiliary orthogonal clearance: angle of inclination of the auxiliary flank from auxiliary cutting plane, π_C' and measured on auxiliary orthogonal plane, π_o' as indicated in Fig. 3.8.

- Cutting angles [Fig. 3.7]

ϕ = principal cutting edge angle: angle between π_C and the direction of assumed longitudinal feed or π_X and measured on π_R

ϕ_1 = auxiliary cutting angle: angle between π_C' and π_X and measured on π_R

- Nose radius, r (mm)

r = radius of curvature of tool tip

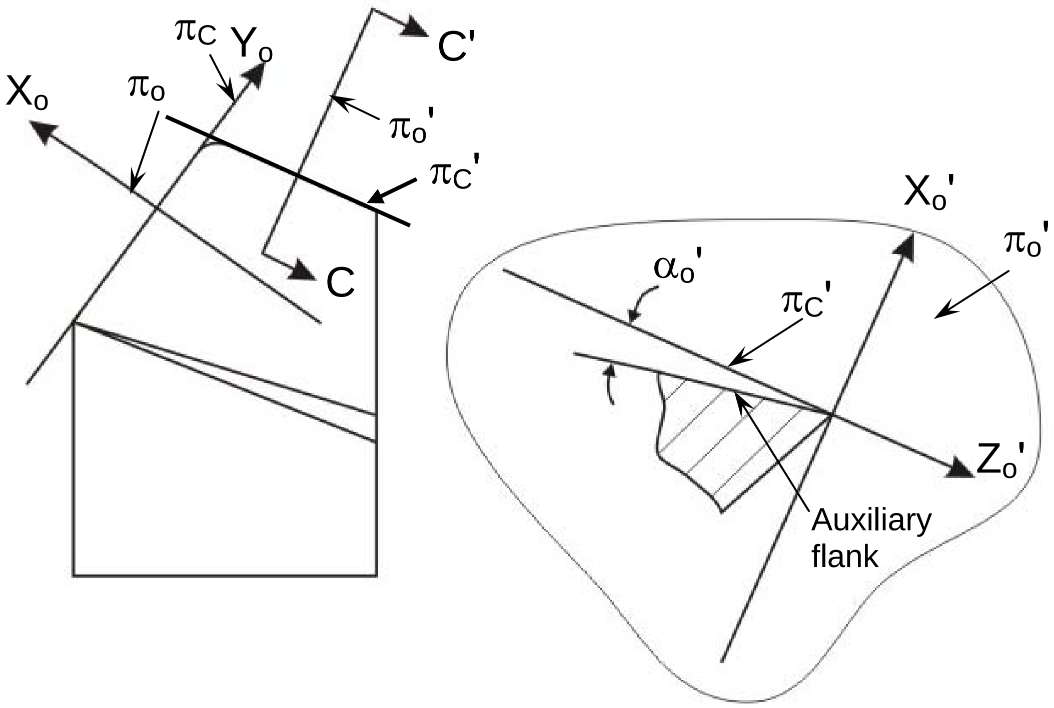


Fig. 3.8 Auxiliary orthogonal clearance angle

- **Normal Rake System – NRS**

  This system is also known as ISO – new.

ASA system has limited advantage and use like convenience of inspection. But ORS is advantageously used for analysis and research in machining and tool performance. But ORS does not reveal the true picture of the tool geometry when the cutting edges are inclined from the reference plane, i.e., $\lambda \neq 0$. Besides, sharpening or resharpening, if necessary, of the tool by grinding in ORS requires some additional calculations for correction of angles.

These two limitations of ORS are overcome by using NRS for description and use of tool geometry.
The basic difference between ORS and NRS is the fact that in ORS, rake and clearance angles are visualized in the orthogonal plane, π_o, whereas in NRS those angles are visualized in another plane called Normal plane, π_N. The orthogonal plane, π_o is simply normal to π_R and π_C irrespective of the inclination of the cutting edges, i.e., λ, but π_N (and π_N' for auxiliary cutting edge) is always normal to the cutting edge. The differences between ORS and NRS have been depicted in Fig. 3.9.
The planes of reference and the coordinates used in NRS are:

π_{RN} - π_C - π_N and X_n – Y_n – Z_n

where,

π_{RN} = normal reference plane

π_N = Normal plane: plane normal to the cutting edge

and

$X_n = X_o$

Y_n = cutting edge

Z_n = normal to X_n and Y_n

It is to be noted that when $\lambda = 0$, NRS and ORS become same, i.e. $\pi_o \cong \pi_N$, $Y_N \cong Y_o$ and $Z_n \cong Z_o$.
Definition (in NRS) of

- Rake angles

γ_n = normal rake: angle of inclination angle of the rake surface from π_R and measured on normal plane, π_N

α_n = normal clearance: angle of inclination of the principal flank from π_C and measured on π_N

α_n'= auxiliary clearance angle: normal clearance of the auxiliary flank (measured on π_N' – plane normal to the auxiliary cutting edge.

The cutting angles, ϕ and ϕ_1 and nose radius, r (mm) are same in ORS and NRS.

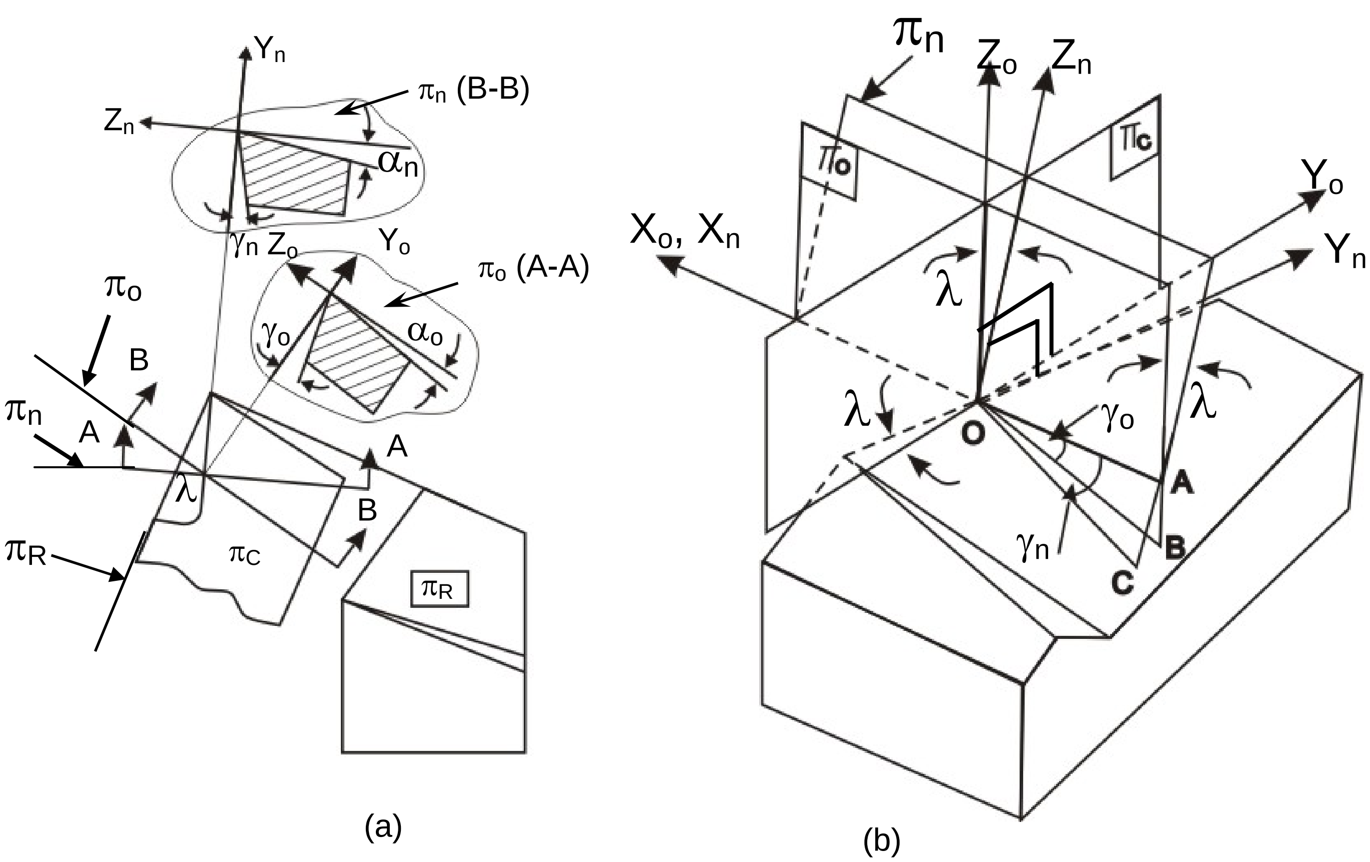


***Fig. 3.9** Differences of NRS from ORS w.r.t. cutting tool geometry.*

(b) 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 –

  γ_y, γ_x, α_y, α_x, ϕ_e, ϕ_s, r (inch)

- ORS System –

  λ, γ_o, α_o, α_o', ϕ_1, ϕ, r (mm)

- NRS System –

  λ, γ_n, α_n, α_n', ϕ_1, ϕ, r (mm)

Exercise – 3

Quiz Test:

Select the correct answer from the given four options :

1. Back rake of a turning tool is measured on its
   (a) machine longitudinal plane
   (b) machine transverse plane
   (c) orthogonal plane
   (d) normal plane

2. Normal rake and orthogonal rake of a turning tool will be same when its
   (a) $\phi = 0$
   (b) $\phi_1 = 0$
   (c) $\lambda = 0$
   (d) $\phi_1 = 90^o$

3. Normal plane of a turning tool is always perpendicular to its
   (a) π_X plane
   (b) π_Y plane
   (c) π_C plane
   (d) none of them

4. Principal cutting edge angle of any turning tool is measured on its
   (a) π_R
   (b) π_Y
   (c) π_X
   (d) π_o

5. A cutting tool can never have its
   (a) rake angle – positive
   (b) rake angle – negative
   (c) clearance angle – positive
   (d) clearance angle – negative

6. Orthogonal clearance and side clearance of a turning tool will be same if its perpendicular cutting edge angle is
   (a) $\phi = 30^o$
   (b) $\phi = 45^o$
   (c) $\phi = 60^o$
   (d) $\phi = 90^o$

7. Inclination angle of a turning tool is measured on its
   (a) reference plane
   (b) cutting plane
   (c) orthogonal plane
   (d) normal plane

8. Normal rake and side rake of a turning tool will be same if its
   (a) $\phi = 0^o$ and $\lambda = 0^o$
   (b) $\phi = 90^o$ and $\lambda = 0^o$
   (c) $\phi = 90^o$ and $\lambda = 90^o$
   (d) $\phi = 0^o$ and $\lambda = 90^o$

Answer of the objective questions

1 – (b)
2 – (c)
3 – (c)
4 – (a)
5 – (d)
6 – (d)
7 – (b)
8 – (b)

Module
3
Machinability

Lesson
15
Cutting Tool Materials of common use

Instructional Objectives

At the end of this lesson, the students will be able to

(i) Identify the needs and cite the chronological development of cutting tool materials.
(ii) Describe the characteristics and state the applications of the commonly used cutting tool materials;
   (a) High speed steel
   (b) Stellite
   (c) Sintered carbides
   (d) Plain ceramics

(i) 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 that 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. 3.3.1

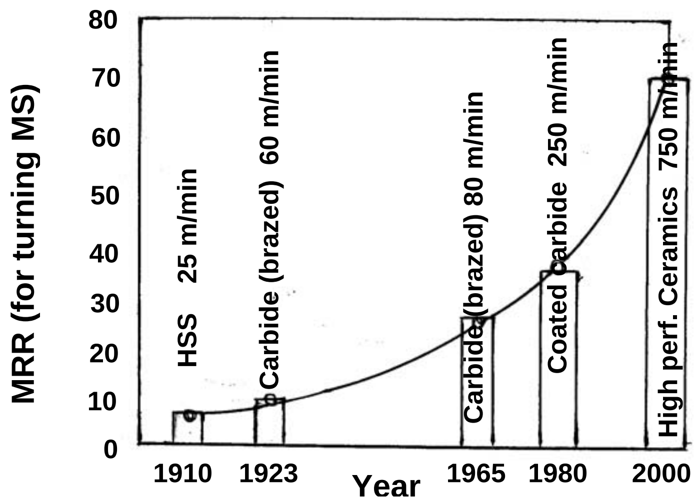


Fig. 3.3.1 Productivity raised by cutting tool materials.

The chronological development of cutting tool materials is briefly indicated in Fig. 3.3.2

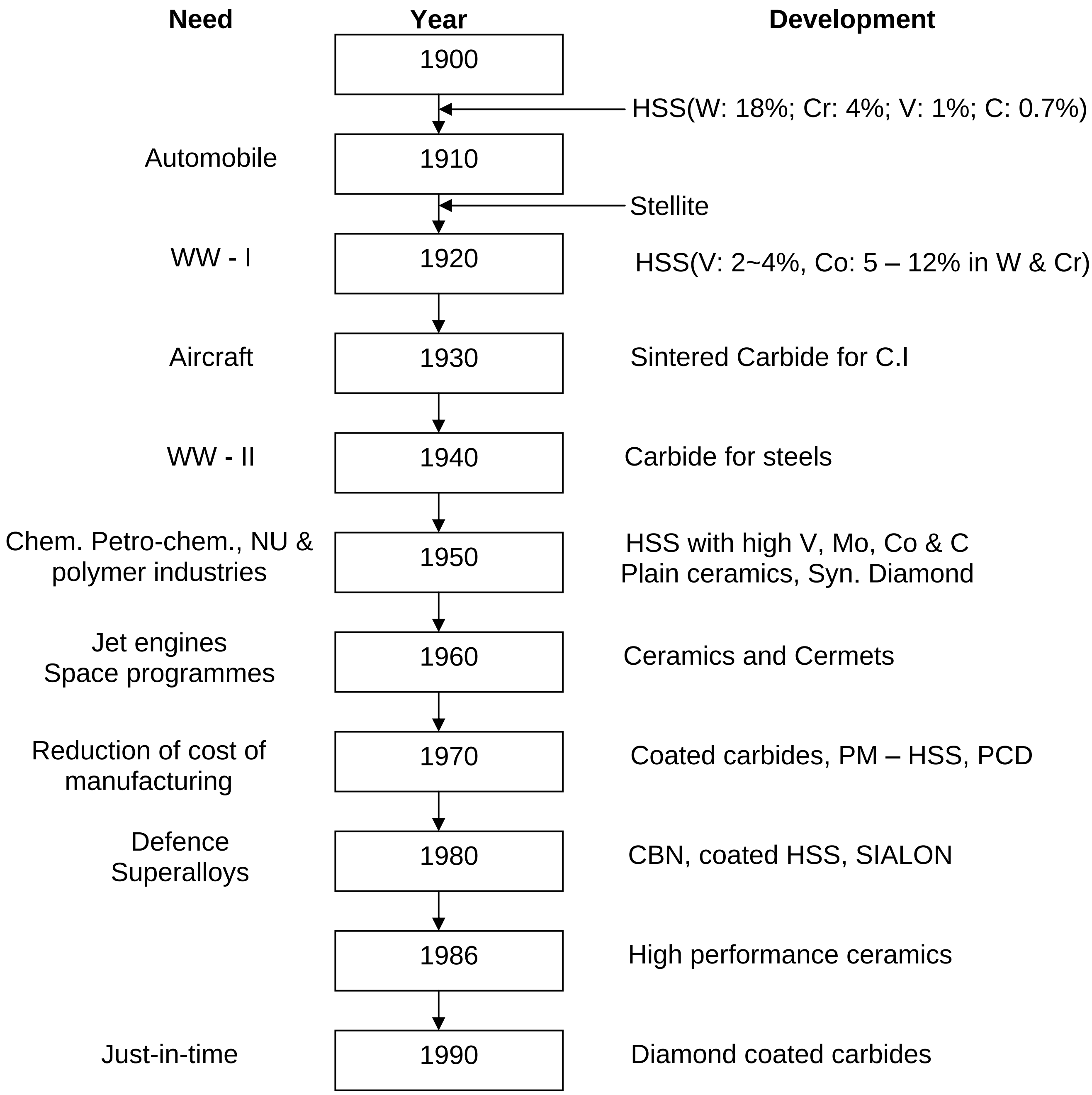


Fig. 3.3.2 *Chronological development of cutting tool materials.*

(ii) Characteristics And Applications Of The Primary 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 upto 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 3.3.1.

Table 3.3.1 Compositions and types of popular high speed steels

Type	C	W	Mo	Cr	V	Co	R_C
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 specially 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.

- **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.

- **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.

- **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 upto 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 3.3.2.

Table 3.3.2 Broad classification of carbide tools.

ISO Code	Colour Code	Application
P		For machining long chip forming common materials like plain carbon and low alloy steels
M		For machining long or short chip forming ferrous materials like Stainless steel
K		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 P_{10}, P_{20} etc., as shown in Table 3.3.3 depending upon their properties and applications.
Table 3.3.3 Detail grouping of cemented carbide tools

ISO Application 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, austentic 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, specially 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 3.3.4 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 3.3.4 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 V_C = 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 then existing tool materials in some application areas like high speed machining of softer steels mainly for higher hot hardness as indicated in Fig. 3.3.3

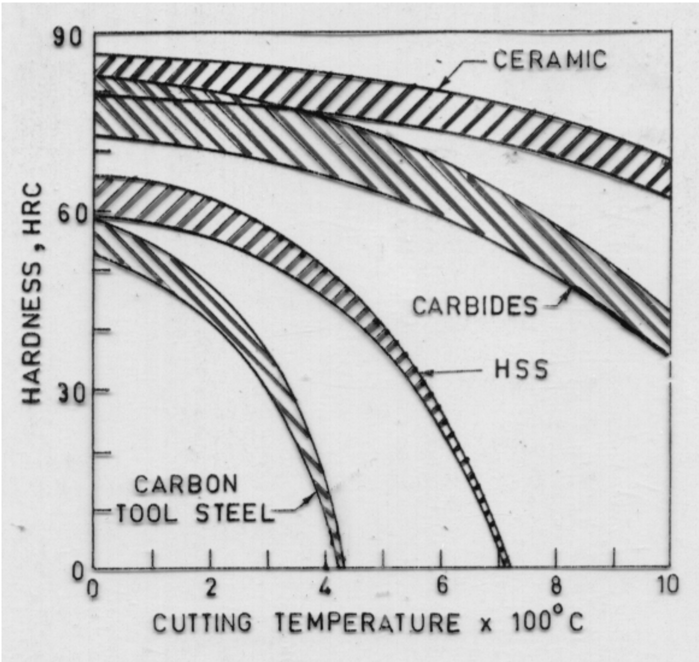


Fig. 3.3.3 *Hot hardness of the different commonly used tool materials.*
(Ref. Book by A.Bhattacharya)

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 then ceramics almost obsolete.

Module
3
Machinability

Lesson
16
Advanced Cutting Tool Materials

Instructional Objectives

At the end of this lesson, the students will be able to

(i) Classify, illustrate the properties and suggest the applications of the advanced cutting tool materials
- (a) Coated carbides
- (b) Cermets
- (c) Coronite
- (d) High Performance Ceramics (HPC)
- (e) Cubic Boron Nitride (cBN)
- (f) Diamond

(i) Development And Application 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 multilayers 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. 3.3.4) 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

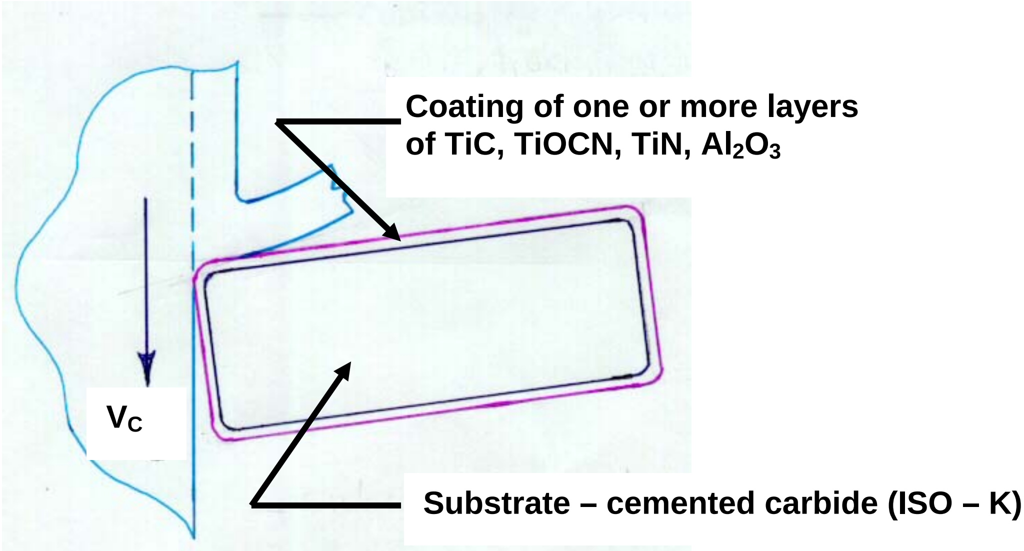


Fig. 3.3.4 *Machining by coated carbide insert.*

The contributions of the coating continues even after rupture of the coating as indicated in Fig. 3.3.5.

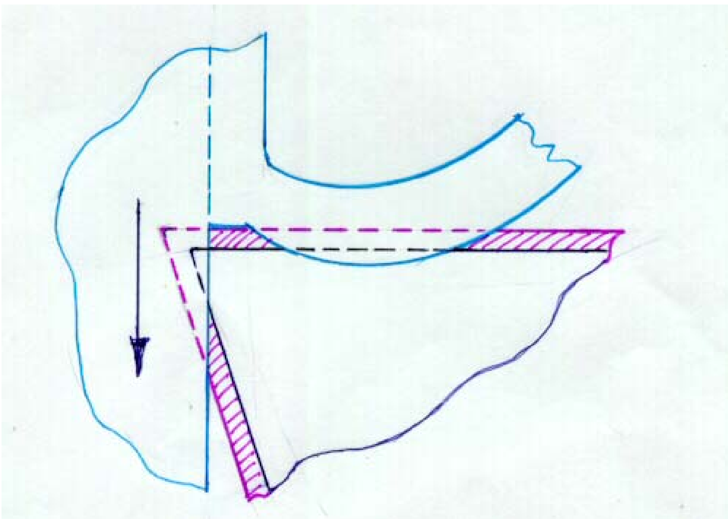


Fig. 3.3.5 *Role of coating even after its wear and rupture*

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;

- Δ Refining the microstructure of the coating
- Δ Multilayering (already upto 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 orn (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 bevelled 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 sizeably 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. Microfine TiCN particles are uniformly dispersed into the matrix.
Unlike a 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 provides better product quality.
The coronite tools made by hot extrusion followed by PVD-coatring 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. 3.3.6.

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 stabilised zirconia in Al_2O_3 powder
- Isostatic and hot isostatic pressing (HIP) – these are very effective but expensive route

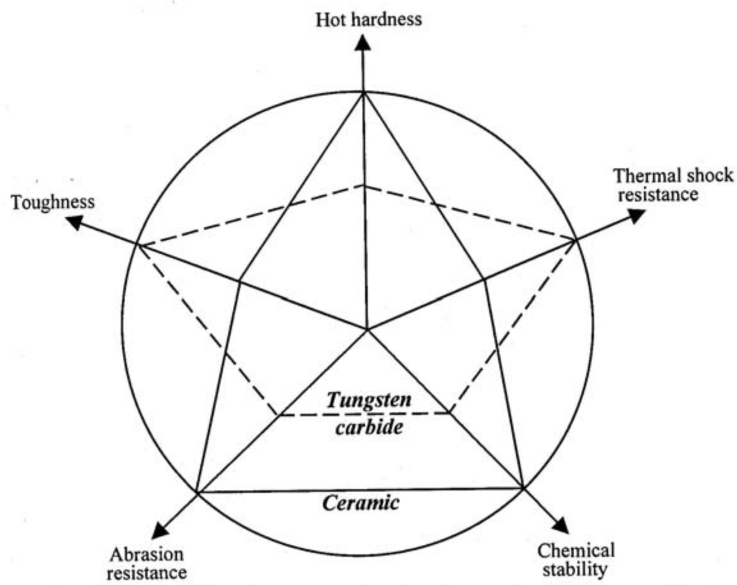


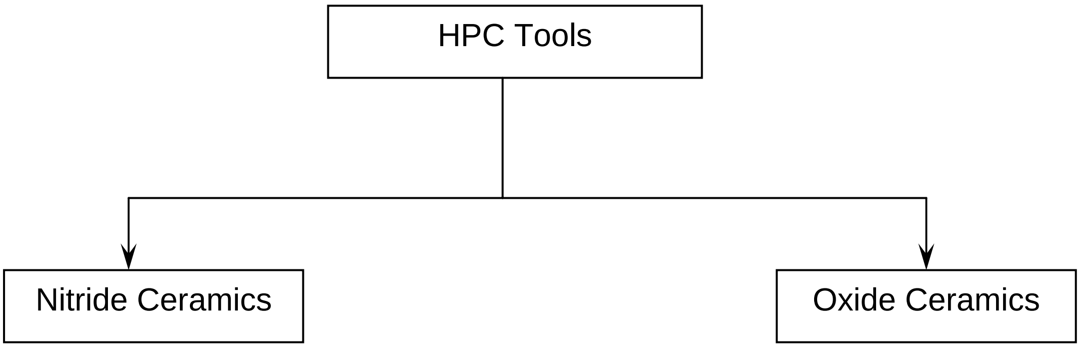
Fig. 3.3.6 *Comparison of important properties of ceramic and tungsten carbide tools*

- Introducing nitride ceramic (Si_3N_4) 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 specially 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

(i) Plain
(ii) SIALON
(iii) Whisker toughened

Alumina toughned by

(i) Zirconia
(ii) SiC whiskers
(iii) Metal (Silver etc)

Nitride based ceramic tools

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 diffusional 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.

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.

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 whsikers 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.

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 stabilised zirconia (PSZ) is mixed in proportion of ten to twenty volume percentage with pure alumina, then either cold pressed and sintered at 1600 – 1700^{o}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 desierd 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. 3.3.7 and microcrack nucleation toughening.

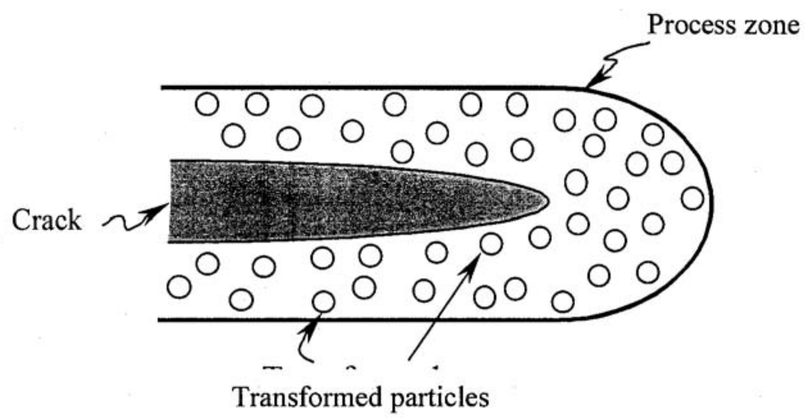


Fig. 3.3.7 *The method of crack shielding by a transformation zone.*

Their hardness have 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.

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 whsikers 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 to 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 toughned ceramic tools.

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-toguhened ceramics, the silver-toguhned 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-toguhened 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. 3.3.8. 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).

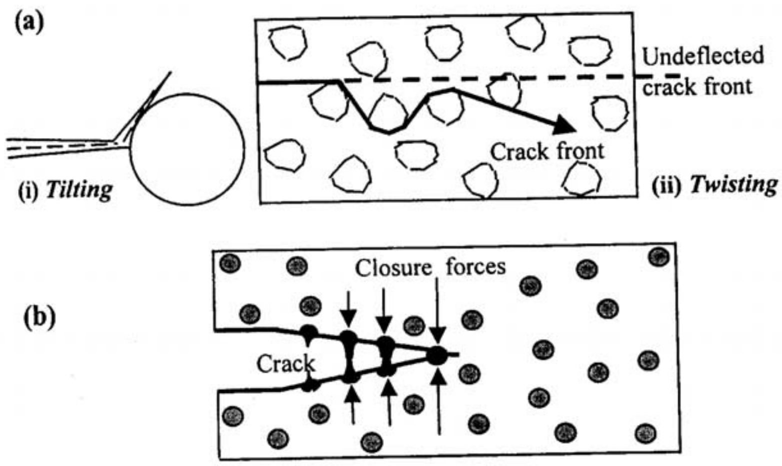


Fig. 3.3.8 *Toughening mechanism of alumina by metal dispersion.*

(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 toguhness 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 upto 1400^o 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 R_C) : 80 – 140 m/min
- Hardened steels (> 45 R_C) : 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 crytal 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.

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 (ususally 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 ususally 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 advanatage 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.

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 synthesised 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 :

1. good bonding of the diamond layetr
2. adequate properties of the film, e.g. wear resistance, micro-hardness, edge coverage, edge sharpness and thickness uniformity
3. 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 extreemly 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 ultraprecision as well as micro and nano machining.