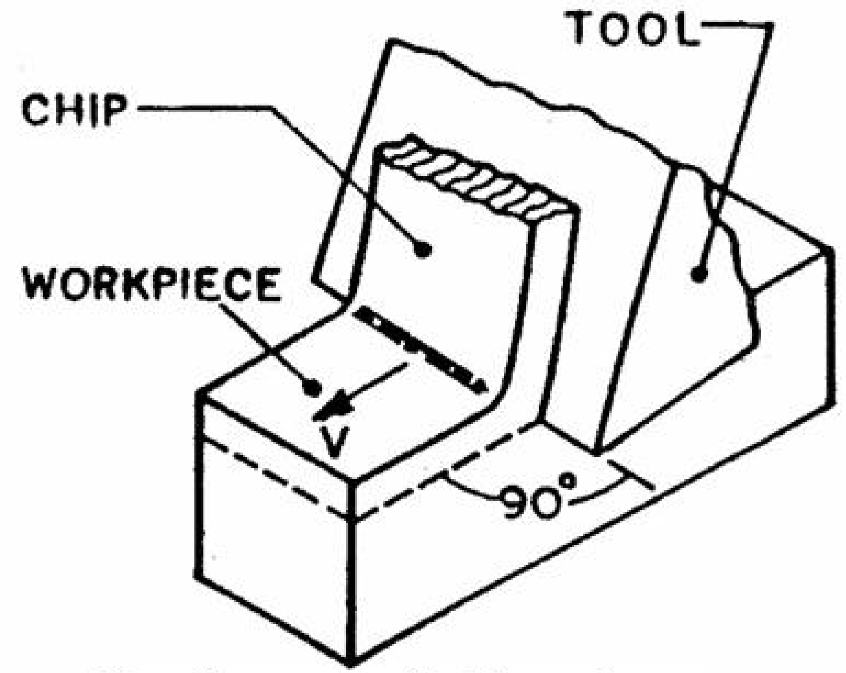
THEORY OF METAL CUTTING

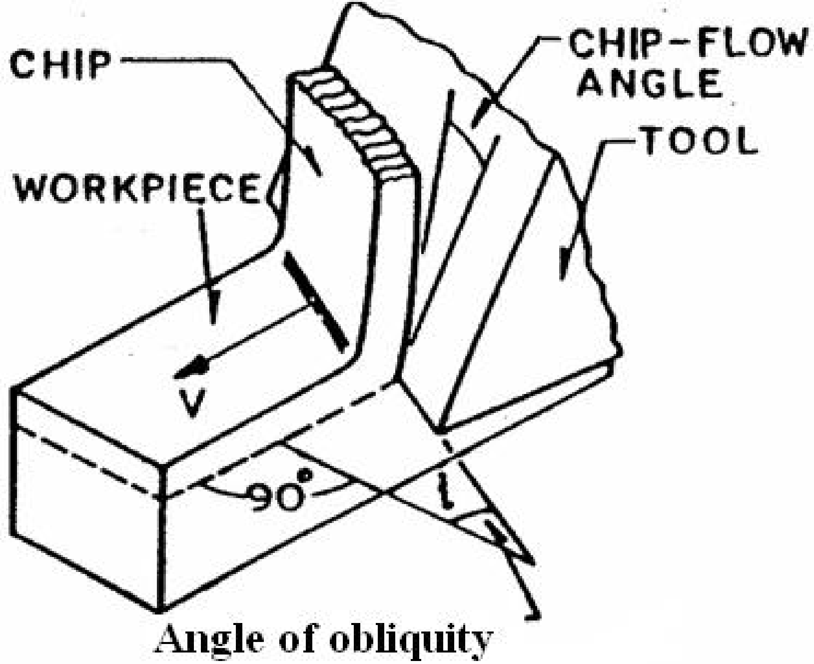
Theory of metal cutting:

- Orthogonal and oblique cutting,
- Mechanics of chip formation and types of chips produced,
- Chip thickness ratio, shear plane angle and its effect,
- Forces, coefficient of friction, shear strain, power in machining,
- Merchant circle diagram and its assumptions and use,
- Tool dynamometers,
- Chip breakers,
- Tool wears and methods of tool failure, tool life,
- Significance of temperature and sources of heat generation, temperature measurement,

Orthogonal and Oblique cutting:



Orthogonal Cutting



Oblique Cutting

- In orthogonal or two dimensional cutting Fig. the cutting edges is perpendicular to cutting velocity.

In oblique or three dimensional cutting Fig. the cutting edges is not perpendicular but at angle i to cutting velocity which is called angle of obliquity.

(Cont..):

- Orthogonal cutting is two dimensional cutting or plane strain cutting; strains are assumed only on a orthogonal plane which is perpendicular to cutting edge; strains perpendicular to orthogonal plane is assumed to be zero hence no change in width of chip.

  Oblique cutting is three dimensional cutting or three dimensional strain cutting and non-perpendicular to cutting plane hence chip length & cross section changes.

- In orthogonal cutting the direction of the chip flow velocity is normal to the cutting edge of the tool.

  In oblique cutting the direction of the chip flow velocity is at an angle with the normal to the cutting edge of the tool. The angle is known as chip flow angle.

- In orthogonal cutting only two components of forces are acting: Cutting Force and Thrust Force. so the metal cutting may be considered as a two dimensional cutting.

  In oblique cutting three components of forces are

(Cont..):

- In orthogonal cutting as there is no side flow of the chip the cross sectional area of the chip is rectangle.

In oblique cutting as there is side flow of the chip the cross sectional area of the chip is parallelogram and practically larger compare to orthogonal one so shear force per unit area is less so longer tool life.

- In orthogonal cutting as there is no side flow of the chip the direction of chip flow is perpendicular to the cutting edge and chip curls in to tight spiral.

In oblique cutting as there is side flow of the chip the chip flows at an angle β and curls into loose helix similar to helical spring.

- In orthogonal cutting the length of cutting edge is larger than the width of the cut.

In oblique cutting the length of the cutting edge may or may not be larger than the width of the cut.

(Cont..):

- In orthogonal cutting full length of cutting edge abruptly get engaged as per depth of the cut so high friction and chatter occur.

  In oblique cutting the cutting edge contact work at larger section away from tool point and progressively full length of cutting edge as depth of cut get engaged so less friction and low chatter.

- In orthogonal cutting surface generated after machining by the tool is parallel to unfinished surface.

  In oblique cutting the surface generated by tool after cutting may or may not be parallel to unfinished surface.

- The effective rake angle in orthogonal cutting remains the same as ground one.

  In oblique cutting the effective rake angle becomes larger (more +ve) without making tool weaker.

- In orthogonal cutting the width of the cut before cutting is equal after cutting also. $b = b_c$

  In oblique cutting width of the cut before cutting and

(Cont..):

- The chip thickness ratio in orthogonal cutting is calculated as

$t \times l \times b = t_c \times l_c \times b_c$ $r = t / t_c = l_c \times b_c / l \times b$

$b = b_c$ $r = t / t_c = l_c / l$

In oblique cutting chip thickness ratio is calculated as

$t \times l \times b = t_c \times l_c \times b_c$ $r = t / t_c = l_c \times b_c / l \times b$

$b \neq b_c$ & r_l b / b_c $r = t / t_c = 1/r_b \times 1/r_l$

$$\vec{V_c} = \vec{V} + \vec{V_s}$$

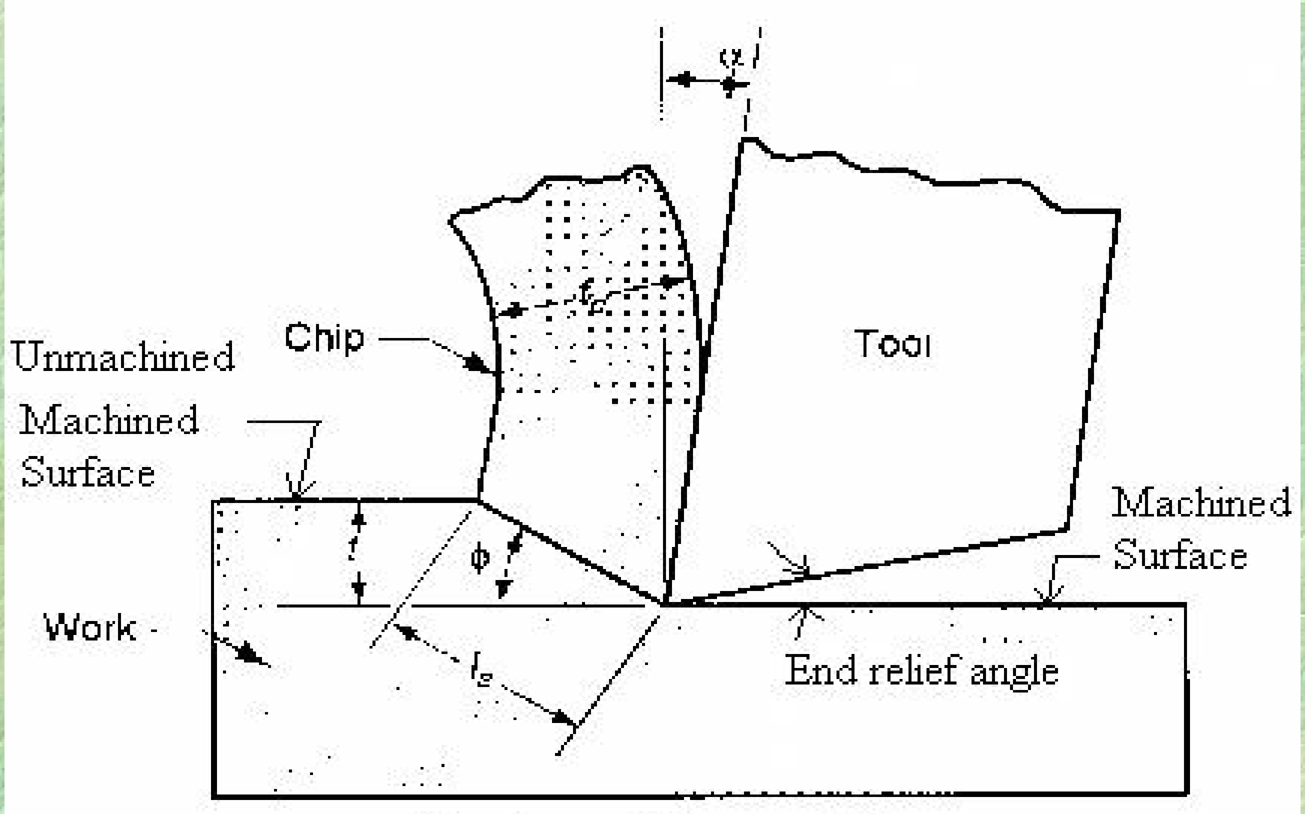
- In orthogonal cutting velocities of work piece V, same of chip V_c and same of shearing V_s lies in one plane and are calculated as shown

In oblique cutting velocities of work piece V, same of chip V_c and same of shearing V_s which does not lie in one plane and are calculated as shown

cutting:

- Stabler observed that during oblique cutting the width of the chip is nearly equal to the width of the cut. For this to happen, the chip flow angle β should be nearly equal to the obliquity angle i (i.e. inclination of cutting edge with the direction of tool motion.) The relation Stabler gave for chip flow angle is β = Ci; wher C is constant of proportionality and it lies between 0.9 to 1.0.

cutting)



Basic cutting action

t = Uncut chip thickness

t_c = Chip thickness after cutting

α = Rake angle of the tool

φ = Shear angle, the angle made by shear plane with direction of motion

formation:

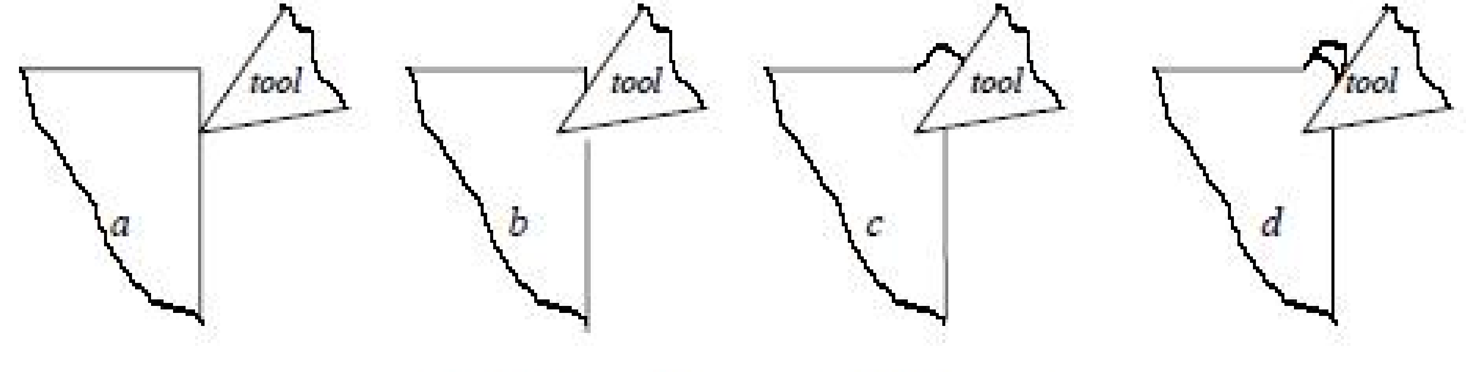


Fig. Progressive formation of a metal chip.

- Fig. shows progressive formation of a chip using a wedge shaped (single point) tool.
- At “a” tool contacts the work piece material.
- Stage I: At “b” initial compression of material takes place at point of contact which is elastic deformation.
- Stage II: At “c” the cutting force overcomes the resistance of penetration of tool is begins to deform initially by plastic flow.
- Stage III: As the cutting force increase, either a rupture or plastic flow in direction generally perpendicular to face of the tool occurs resulting in fracture & the chip is formed as shown at “d”, this

Mechanism of chip formation:

- The mechanism of chip formation in any machining operation is a rapid series of plastic flow & slip movements ahead of the cutting edge.
- The degree of plastic flow ahead of the cutting tool determines the type of chip that will be produced.
- If the work piece material is **brittle** & has little capacity for deformation before fracture the chip will separate along the shear plane to form what is known as a discontinuous segmental chip, the mechanism of rupture will be along cleavage planes similar to that of separation of mica layer by tearing.
- Material that are more **ductile** & have capacity for plastic flow will deform along the shear plane without rupture. The planes tend to slip & weld or remain attached or adhered to successive shear planes, & the result in movement of dislocations, their pile-up at grain boundary in each crystal and combining of dislocation between grains form void and then micro-cracks, combination of micro-cracks form macro or large cracks and these cracks propagate along slip planes

Types of Chips & conditions for each:

1) Segmental chips or Discontinuous chips
2) Continuous chips
3) Continuous chip with BUE or BUE chips.
4) Inhomogeneous chips.

1) **Discontinuous Chips:** These chips are in the form of small individual segments, which may adhere loosely to each other to form a loose chip. These chips are formed as result of machining of a brittle material such as gray cast iron or brass castings, etc. These chips are produced by actual rupture or fracture of metal ahead of the tool in brittle manner. Since the chips break up into small segments and also shorter chips have no interference with work surface. The friction between chip & tool reduces resulting in better surface finish. These chips are convenient to collect, handle & dispose of during production runs. The conditions favorable for formation of discontinuous chips are:

1) Brittle & non ductile metals (like cast iron brass castings Beryllium, titanium etc.) with any conditions.

Following conditions while cutting ductile materials produce discontinuous

Chip.

2) Low cutting speed.

3) Small rake angle of the tool.

(Cont..):

2) Continuous Chips: These chips are in the form of long coils having uniform thickness throughout. These chips are formed as result of machining of relatively ductile metals. Each segment remain attached sequentially with next segment firmly to form long continuous chip.

1) Large rake angle.
2) Low. Feed.
3) High speed.
4) Small chip thickness.
5) Sharp cutting edge.
6) Efficient cutting fluid.
7) Low friction between chip tool interfaces.

3) BUE Chip (or continuous Chip with BUE):

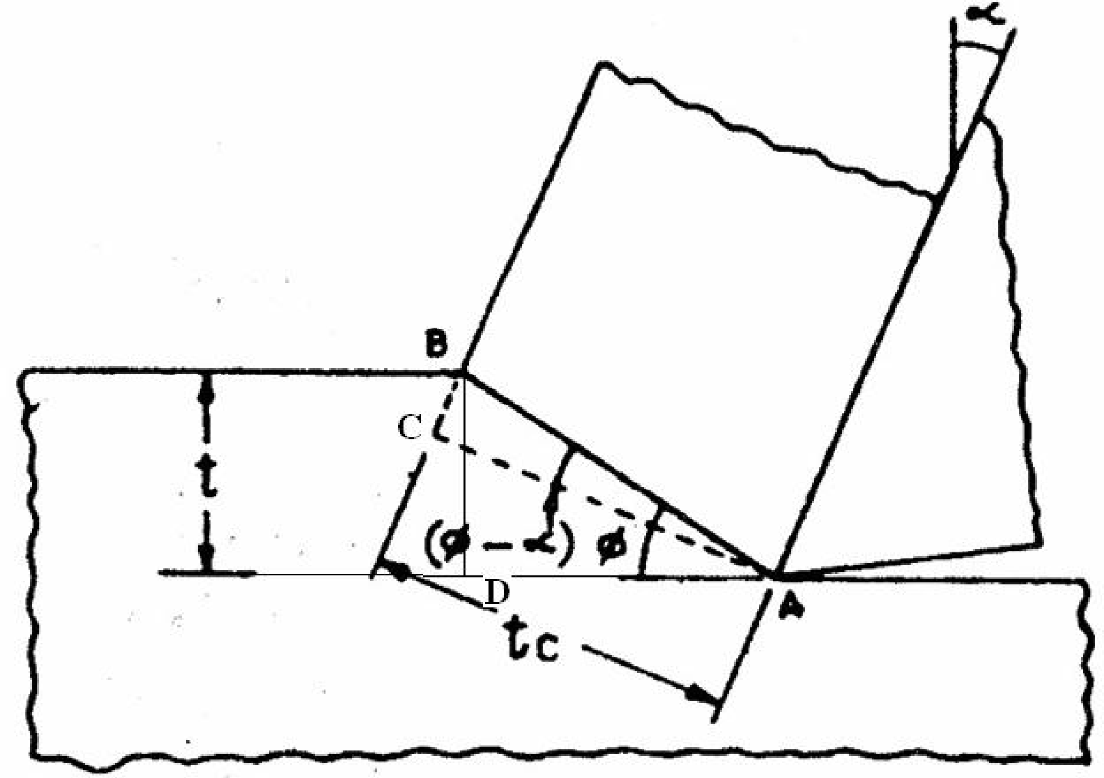
These chips are also produced in the form of long coils like continuous chips, but they are not as smooth as continuous chips. These chips are characterized by formation of built up edge on the nose of the tool owing to welding of chip material on to tool face because of high friction between chip tool interfaces. Presence of this welded material further increases the friction leading to building up of the edge, layer by layer. As the built-up edge continuous to grow, the chip flow breaks a portion of it into fragments. Some of them are deposited on the work piece material while the rest are carried away by the chips. The hardness of this BUE is two to three times higher than the work piece material. This is the reason why the cutting edge remains active even when it is covered with built-up edge. The only point in favor of BUE is that it protects the cutting edge from wear due to moving chips and the action of heat. This brings about an increase in tool life. These chips normally occur while cutting ductile

(Cont..):

BUE Chip (or continuous Chip with BUE) Conditions for formation:

1) Ductile material
2) Moderate cutting speed.
3) Moderate rake angle of tool.
4) Slightly dull cutting edge.
5) Moderate feed.
6) Insufficient cutting fluid.
7) High friction at chip tool interface.

φ :



t = Uncut chip thickness = BD

t_c = Chip thickness after cutting

α = Rake angle of the tool

φ = Shear angle, the angle made by shear plane with direction of motion.

Draw AC perpendicular to tool face. Angle BAC = $(\varphi - \alpha)$

Angle between horizontal & ⊥ar on tool face is α.

φ :

$r = t/t_c = AB \sin\varphi / AB \cos(\varphi - \alpha)$

$= \sin\varphi / \cos\alpha \cos\varphi + \sin\alpha \sin\varphi$

Dividing numerator and denominator by $\cos\varphi$

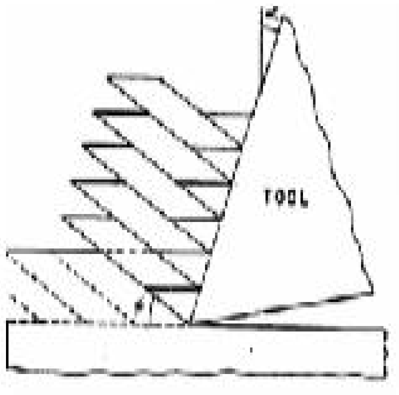
$r = (\sin\varphi / \cos\varphi) / (\cos\alpha \cos\varphi + \sin\alpha \sin\varphi) / \cos\varphi$

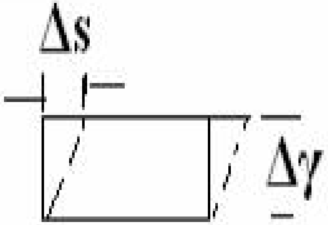
$= \tan\varphi / \cos\alpha + \sin\alpha \tan\varphi$

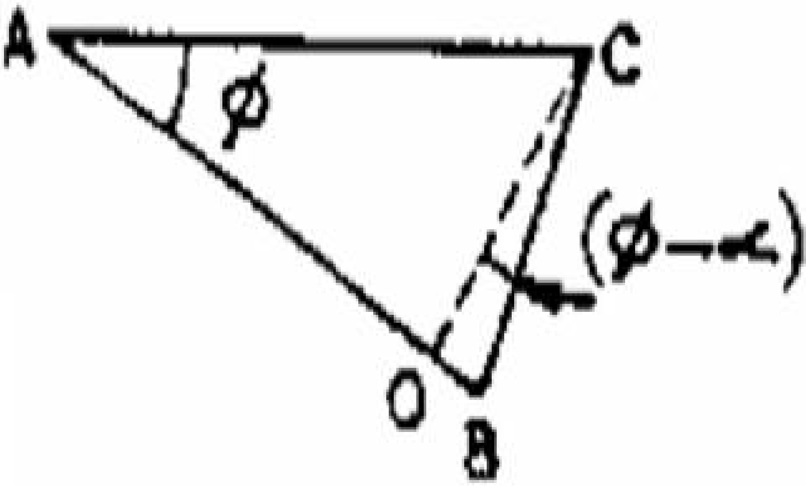
$r (\cos\alpha + \sin\alpha \tan\varphi) = \tan\varphi$

Solving **$\tan\varphi = r\cos\alpha / (1 - r \sin\alpha)$**

Shear Strain determination:







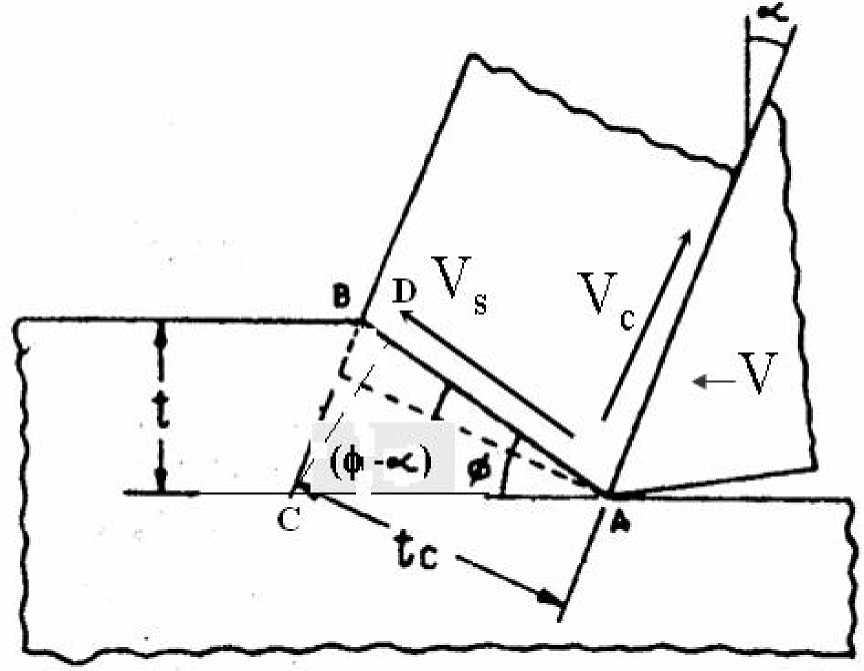
Shear strain $\varepsilon = \gamma = \dfrac{\Delta s}{\Delta \gamma} = \dfrac{AB}{CO} = \dfrac{AO}{OC} + \dfrac{OB}{OC}$

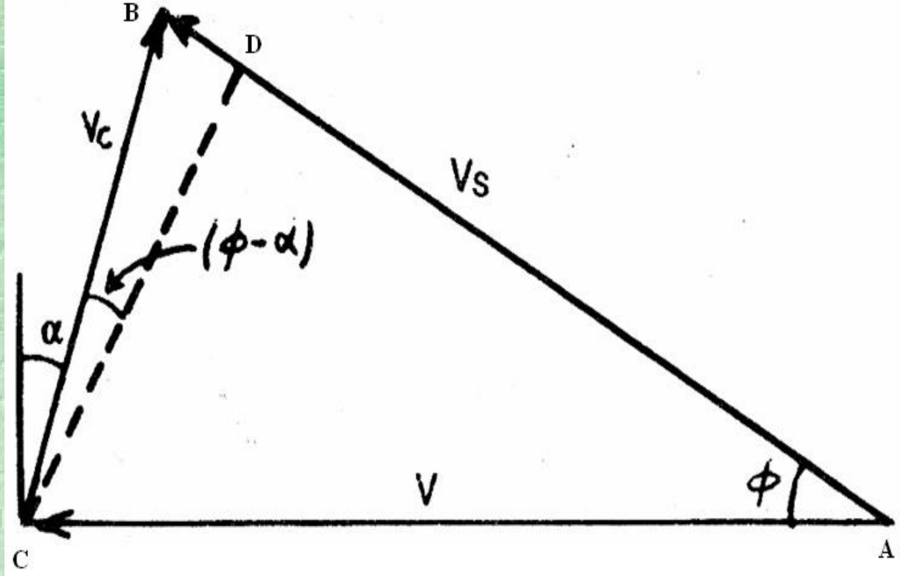
$$\varepsilon = \cot\varphi + \tan(\varphi - \alpha)$$

Strain rate $\varepsilon = \dfrac{d\varepsilon}{dt} = \dfrac{d}{dt}\left(\dfrac{AB}{OC}\right) = \dfrac{d(AB)/dt}{OC} = \dfrac{V_s}{OC} = \dfrac{V_s}{t_s}$

$OC = t_s$ = thickness of layer

Velocity in metal cutting:





The three velocities are

(i) velocity of cutting (V)

(ii)(ii) velocity of chip (Vc)

(iii)(iii) velocity of shear (Vs).

Velocity in metal cutting:

If the machining condition is steady state i.e. no operat parameter very during experiment then t velocities must form a close polygon as shown in figure-. Hence

$$Vc / V = \sin\phi / \cos(\phi-\alpha)$$

$$Vs/V = \sin\alpha / \cos(\phi-\alpha)$$

Knowing cutting velocity V the velocity of chip (Vc) and shear velocity (Vs) can

Cutting:

- The geometry of a cutting tool is determined by (3) factors:
  - Properties of the tool material.
  - Properties of the workpiece
  - Type of cut
- Factors to consider for tool angles
  - The hardness of the metal
  - Type of cutting operation
  - Material and shape of the cutting tool
  - The strength of the cutting edge

Cutting:

Rake Angles:

Negative, Small to medium rake angles cause:

- High compression
- High tool forces
- High friction
- Result in thick—highly deformed—hot chips
- More bending of chip
- Small shear plane angle & large area of deformation
- More cutting forces, power or energy are consumed
- More friction
- Stronger tool
- Less deflection of tool as large cross section.

(Cont..):

Rake Angles (Cont..):

- Larger positive rake angles
  - Reduce compression and less chance of a discontinuous chip
  - Reduce forces, less power or energy utilized
  - Reduce friction
  - Result in a thinner, less deformed, and cooler chip.
  - Large shear plane angle, less shear plane area
  - Less bending of chip due natural direction of flow towards workpiece
  - Slightly weaker tool due to less cross sectional area
  - Slightly more deflection due to weak cross section.
  - Side rake angle direct flow side way, back rake

(Cont..):

Positive vs. Negative Rake Angles:

Positive rake angles

- Initial shock of work to tool is on the face of the tool and not on the point or edge, this reduce the life of the tool.
- Higher cutting speeds/feeds can not be employed.
- Reduced cutting forces
- Smaller deflection of work, tool holder, and machine.
- Considered by some to be the most efficient way to cut metal.

Negative rake angles

- Initial shock of work to tool is on the face of the tool and not on the point or edge. This prolongs the life of the tool.
- Higher cutting speeds/ feeds can be employed.
- Increase cutting forces.
- Large deflection of work, tool holder, and machine.
- Inefficient way to cut metal by way of more power consumed.
- Creates small shear angle, increase shear area,

(Cont..):

Positive rake angles

- Allows chip to move freely up the chip-tool zone and allow it to flow in its natural direction.
- Generally used for continuous cuts on ductile materials which are not to hard or brittle.
- The nature of cutting force is shearing try to deflect tool.
- Resolving cutting force, the horizontal component of force try to pull tool inside work piece resulting in under

Negative rake angles

- Do not allow chip to move freely up the chip-tool zone but bent it more against direction of natural flow.
- Generally used for continuous cuts on ductile materials which are hard or brittle.
- The nature of cutting force is compressive and do not deflect tool much.
- Resolving cutting force, the horizontal component of force try to push tool away from work piece resulting in over size of work piece diameter.

(Cont..):

Positive rake angles

- Positive rake angles are preferred on tool steel, alloy steel, H. S. S., Super H. S. S. while cutting soft and ductile materials and machines which are less rigid.

- Positive rake is preferred while machining thin sectioned & slender parts, not suitable for interrupted heavy cuts.

- Provide less tool mass to absorb and distribute heat, so small amount of heat is dissipated keep tool tip hot

Negative rake angles

- Negative rake angles are provided on carbide tools, ceramic tools, CERMETs, CBN, UCON, Diamond etc. as they are very brittle, while cutting hard and brittle materials.
- Negative rake is preferred for heavy work with severe conditions, interrupted cuts and cut surfaces of casting with hard layer contaminated with sand and inclusions & on machine with heavy structure.
- Provide more tool mass to absorb and distribute heat, so large amount of heat is dissipated keep tool tip

(Cont..):

Relief Angles:

- Relief angles are provided to minimize physical interference or rubbing contact with machined surface and the work piece.
- Relief angles are for the purpose of helping to eliminate tool breakage and to increase tool life.
- If the relief angle is too large, the cutting tool may chip or break. If the angle is too small, the tool will rub against the workpiece and generate excessive heat and this will in turn, cause premature dulling of the cutting tool.
- Small relief angles are essential when machining hard and strong materials and they should be increased for the weaker and softer materials.
- A smaller angle should be used for interrupted cuts or heavy feeds, and a larger angle for semi-finish and finish cuts.
- The side relief and end relief decide the wedge

(Cont..):

Side relief angle:

- The Side relief angle prevents the side flank of the tool from rubbing against the work when longitudinal feed is given. Larger feed will require greater side relief angle.
- The tool may have primary & secondary relief angles also.

End relief angle:

- The End relief angle prevents the side flank of the tool from rubbing against the work. A minimum relief angle is given to provide maximum support to the tool cutting edge by increasing the lip angle.
- The front clearance angle should be increased for large diameter works.

(Cont..):

Side cutting edge angle:

The following are the advantages of increasing this angle:

- It increases tool life as, for the same depth of cut; the cutting force is distributed on a wider surface.
- It diminishes the chip thickness for the same amount of feed and
  permits greater cutting speed.
- It dissipates heat quickly for having wider cutting edge.
- The side cutting edge angle of the tool has practically no effect on the value of the cutting force or power consumed for a given depth of cut and feed.
- Large side cutting edge angles are lightly to cause the tool to chatter.

(Cont..):

End cutting edge angle:

- The function of end cutting edge angle is to prevent the trailing front cutting edge of the tool from rubbing against the work. A large end cutting edge angle unnecessarily weakens the tool.

- It varies from 8 to 15 degrees.

Nose radius:

The nose of a tool is slightly rounded in all turning tools.

The function of nose radius is as follows:

- Greater nose radius clears up the feed marks caused by the previous shearing action and provides better surface finish.

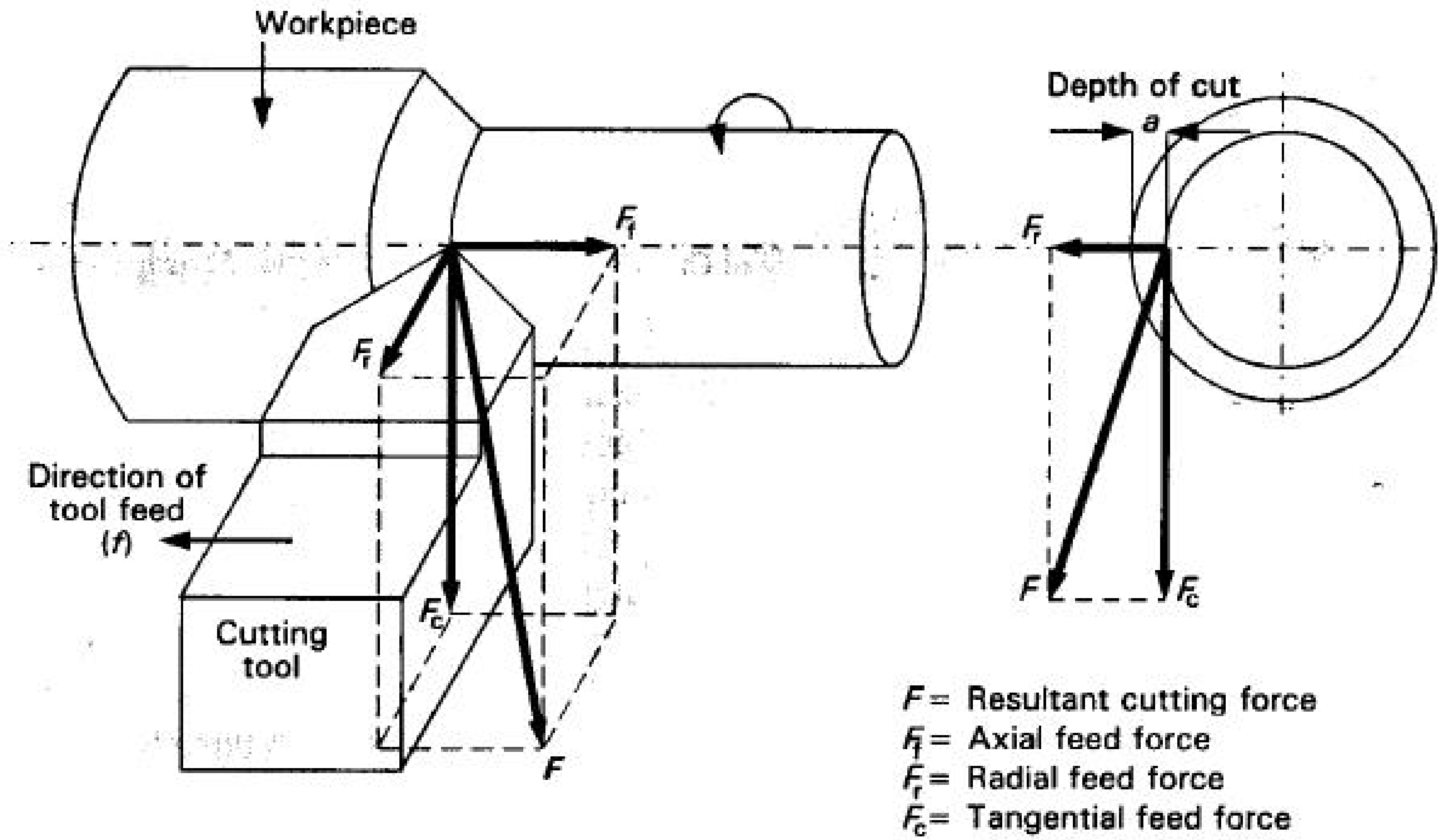
(Cont..):

Nose radius:

- It increases the strength of the cutting edge, tends to minimize the wear taking place in a sharp pointed tool with consequent increase in tool life.
- Accumulation heat is less than that in a pointed tool which permits higher cutting speeds.

Analysis:

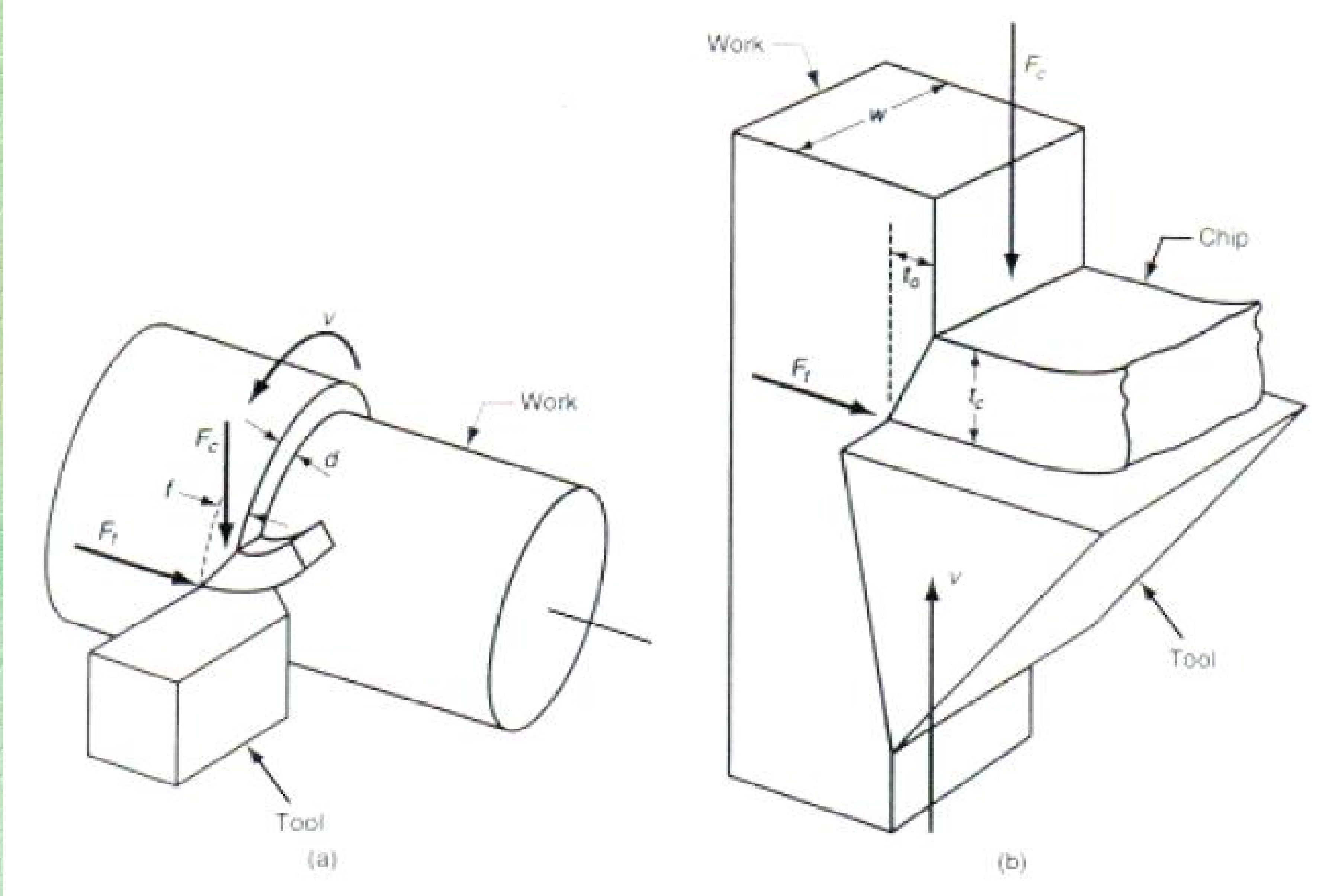
The force system in general case of conventional turning process



F = Resultant cutting force
F_f = Axial feed force
F_r = Radial feed force
F_c = Tangential feed force

Primary forces involved in single-edge cutting. (Courtesy of Sandvik Coromant, Halesowen.)

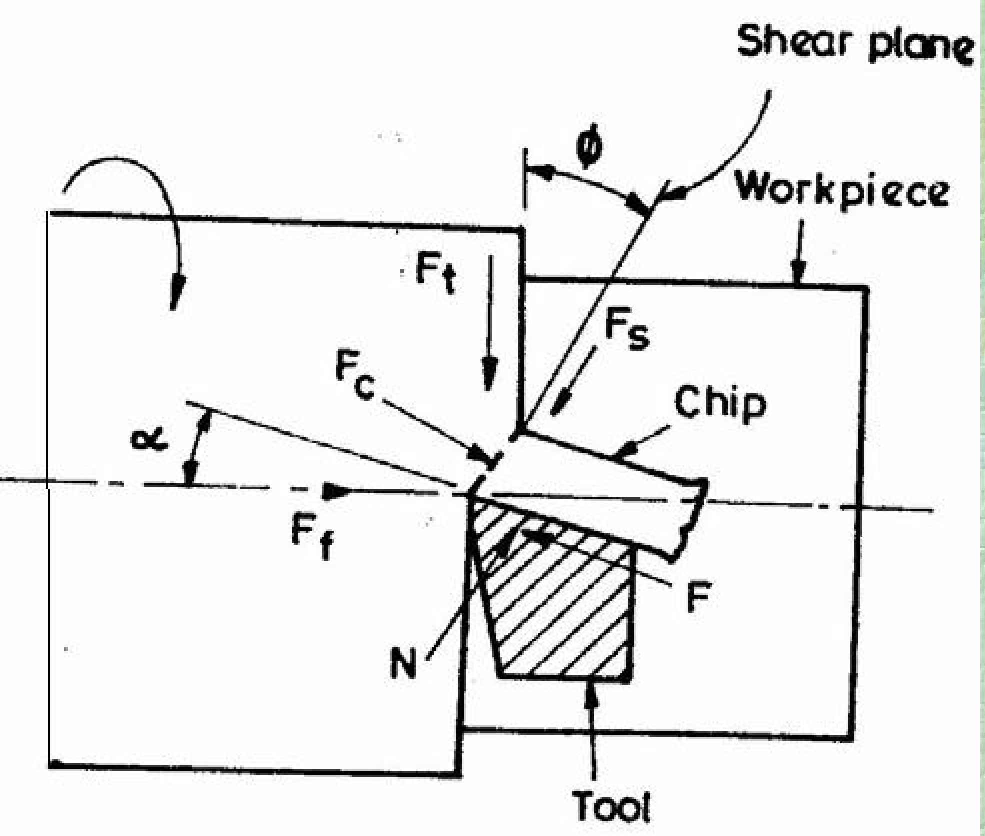
Cutting Forces & Merchant's Force Circle Analysis:

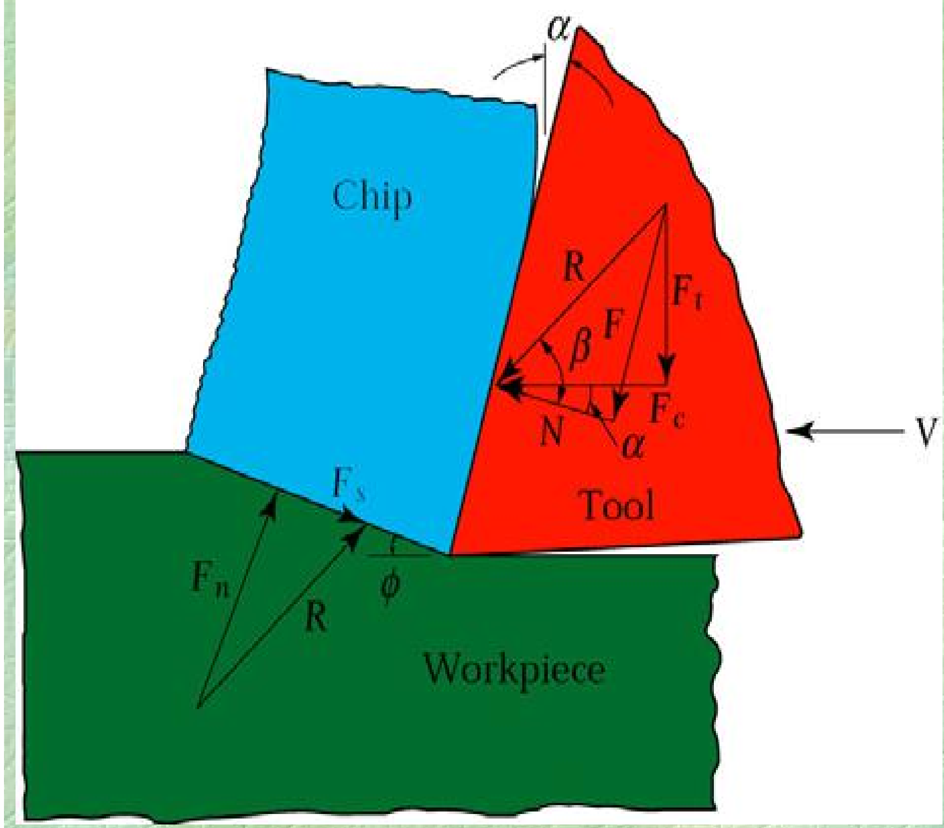


(a)

(b)

Analysis:

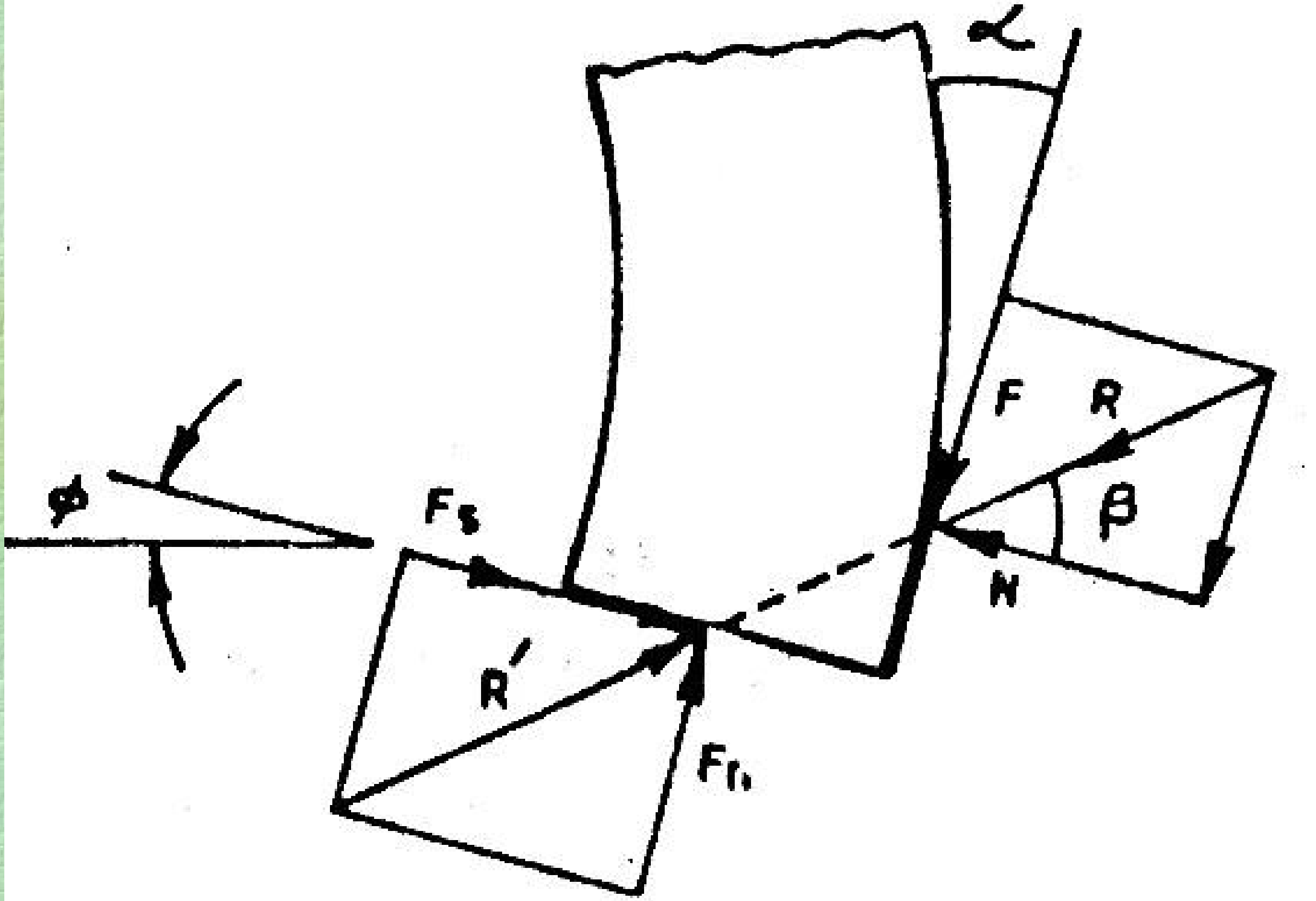




M. E. Merchant proposed an idealist simplified model for analysis for understanding metal cutting mechanism. To make analysis simple he made

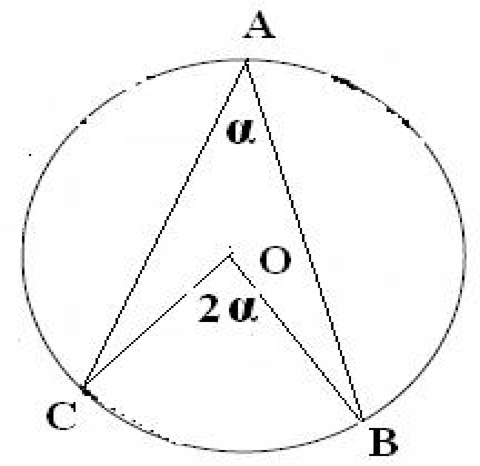
M. Eugene

Chip is a free body diagram:



Analysis:

- Why Merchant drawn Circle rather than any other shape?
- The figure on previous slides show that the forces like F_c & F_t, F & N, F_s & F_n, these pair of forces form individual force triangle. Each pair of forces has one resultant forming one triangle of force.
- In theorem of mathematics for a circle it was mentioned that two chords of a circle making angle at circumference make double angle that center.



In fig two chords AB & AC make an angle α at the circumference and make an angle 2α at the center as per above stated theorem.

In the force triangles the angle between forces is having angle 90 and resultant is straight line having angle 180 fulfill above theorem of chords in circle having α=90 and 2 α=180, so

Analysis:

Assumptions made by Merchant for Force circle Analysis:

1. The tool is perfectly sharp and there is no contact at clearance faces.
2. The shear surface is a plane extending upward from the cutting edge. (Thin zone model)
3. The cutting edge is a straight line extending perpendicular to the direction of motion and generate a plane surface as the work move past to it.
4. The chip does not flow to either side. (Orthogonal condition)
5. The width of the tool is greater than that of the work piece. (do)
6. The depth of cut is constant.
7. The work moves relative to the cutting edge with

Analysis:

- Fc = The main Cutting force (Measured by tool force dynamometer)
- Ft = Thrust force or feed force ((Measured by tool force dynamometer)
- Fs = Shear Force, which acts along the shear plane, is the resistance to shear of the metal in forming the chip. (To be computed)
- Fn = Force acting normal to the shear plane, is the backing up force on the chip provided by the workpiece. (To be computed)

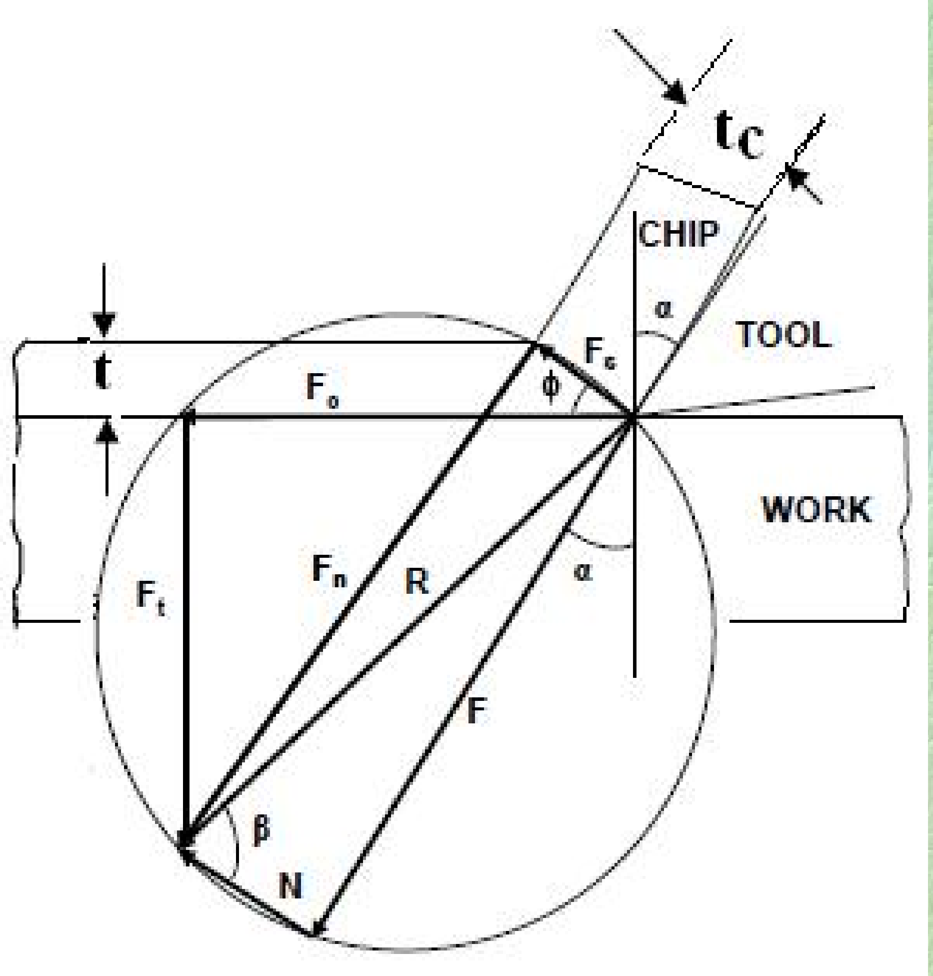
$$R = F_c + F_t$$

- F = Frictional resistance of the tool acting against the motion of the chip as it moves upward along the tool. (To be computed)
- N = Normal to the chip force, is provided by the tool. (To be computed)
- R = Resultant force. (To be computed)
- α = Rake angle of the tool. (To be measured by bevel protractor or angle gauge)

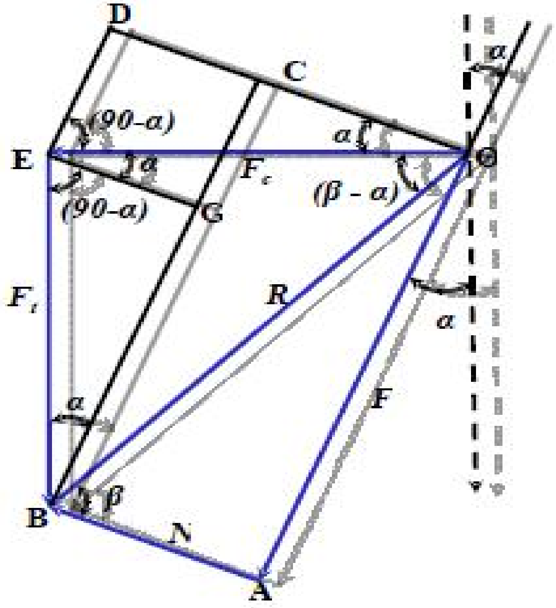
circle diagram:

- Set up x-y axis labeled with forces, and the origin in the centre of the page. The cutting force (Fc) is drawn horizontally, and the tangential force (Ft) is drawn vertically. (Draw in the resultant R) of Fc and Ft to suitable scale.
- Locate the centre of R, and draw a circle that encloses vector R. If done correctly, the heads and tails of all 3 vectors will lie on this circle.
- Draw in the cutting tool in the upper right hand quadrant, taking care to draw the correct rake angle (α) from the vertical axis.
- Extend the line that is the cutting face of the tool (at the same rake angle) through the circle. This now gives the friction vector (F).
- A line can now be drawn from the head of the friction vector, to the head of the resultant vector (R). This gives the normal vector (N). Also add a friction angle (**β**) between vectors R and N. Therefore, mathematically, R = Fc + Ft = F + N.
- Draw a feed thickness line parallel to the horizontal axis. Next draw a chip thickness line parallel to the tool cutting face using some scale.

Analysis:



Frictional Force System



$$F = OA = CB = CG + GB = ED + GB$$

$$\Rightarrow F = F_C \sin\alpha + F_t \cos\alpha$$

$$N = AB = OD - CD = OD - GE$$

$$\Rightarrow N = F_C \cos\alpha - F_t \sin\alpha$$

The coefficient of friction

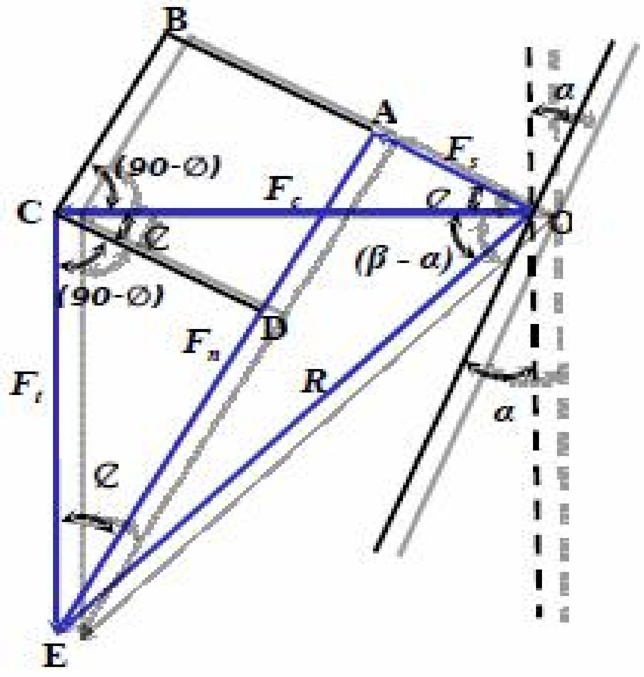
$$\mu = \tan\beta = \frac{F}{N}$$

Where β = *Friction angle*

Calculate shear angle φ from the relation tan φ = rcosα / (1- r Sinα) or measure graphically

Analysis:

Shear Force System



$$F_S = OA = OB - AB = OB - CD$$

$$\Rightarrow F_S = F_C \cos\phi - F_t \sin\phi$$

$$F_N = AE = AD + DE = BC + DE$$

$$\Rightarrow F_N = F_C \sin\phi + F_t \cos\phi$$

Also:

$$F_N = F_S \tan(\phi + \beta - \alpha)$$

- Final relations are

$$F = F_C \sin\alpha + F_t \cos\alpha$$

$$N = F_C \cos\alpha - F_t \sin\alpha$$

$$F_S = F_C \cos\phi - F_t \sin\phi$$

$$F_N = F_C \sin\phi + F_t \cos\phi$$

$$F_N = F_S \tan(\phi + \beta - \alpha)$$

Power required in Metal cutting:

- The Power consumed/ work done per sec *in* $P_C = F_C \times v_C$
- The Power consumed/ work done per sec *in* $P_s = F_s \times v_s$
- The Power consumed/ work done per sec *in* $P_F = F \times v_f$

The total Power required*:*

- P Work consumed in cutting per sec + work spent in feeding per sec
- P I $\Rightarrow P = F_c \times v_c + F_t \times \mathit{feed\ velocity}$ tor

- In comparison to the cutting velocity the feed velocity is very nominal. Similarly F_c is very small compared to F_c. So the work spent in feeding can be $P = P_c = P_s + P_f$ negligible.
- *Therefore, total power required in cutting*

Specific Energy:

- Specific Energy, u_t ,is defined as the total energy per unit volume of mate

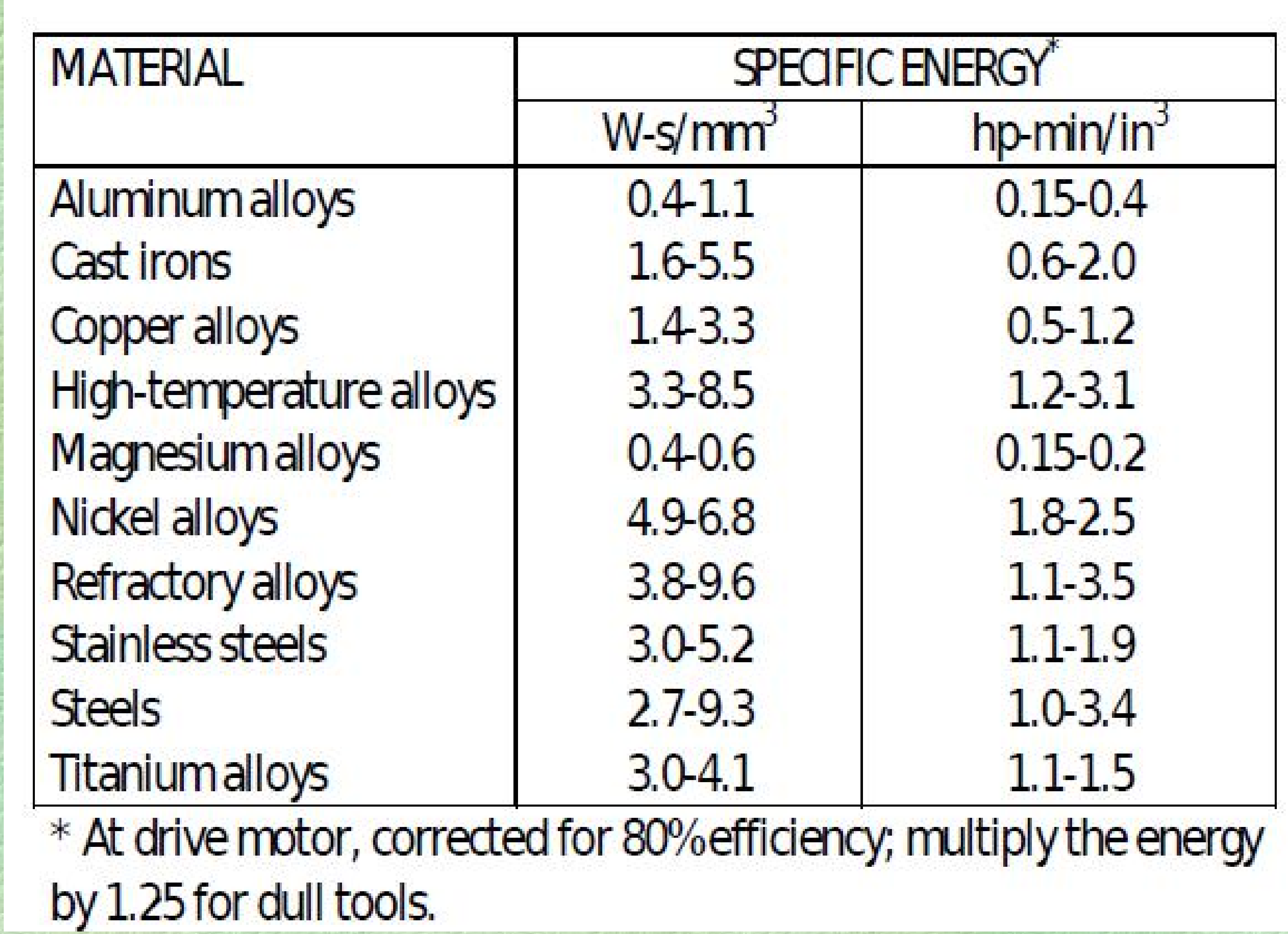
$$u_t = \frac{F_C v_c}{w t_0 v_c} = \frac{F_C}{w t_0}$$

- Therefore is simply the cutting force to the projected area of cut.
- If u_f and u_s be spec ecific energy for shearin

$$u_t = u_f + u_s = \frac{F_r v_f}{w t_0 v_c} + \frac{F_s v_s}{w t_0 v_c} = \frac{F_r}{w t_0} + \frac{F_s v_s}{w t_0 v_c}$$

- As the rake angle increases, the frictional specific energy remains more or less constant, where as the shear specific energy rapidly reduced.

Approximate specific energy requirements in cutting operations.



MATERIAL	SPECIFIC ENERGY*	
	W-s/mm^3	hp-min/in^3
Aluminum alloys	0.4-1.1	0.15-0.4
Cast irons	1.6-5.5	0.6-2.0
Copper alloys	1.4-3.3	0.5-1.2
High-temperature alloys	3.3-8.5	1.2-3.1
Magnesium alloys	0.4-0.6	0.15-0.2
Nickel alloys	4.9-6.8	1.8-2.5
Refractory alloys	3.8-9.6	1.1-3.5
Stainless steels	3.0-5.2	1.1-1.9
Steels	2.7-9.3	1.0-3.4
Titanium alloys	3.0-4.1	1.1-1.5

* At drive motor, corrected for 80% efficiency; multiply the energy by 1.25 for dull tools.

Source " Manufacturing Processes for Engineering Materials", 4th edition, Kalpakjian, Schmid, Prentice

forces:

- The basic principles used by Tool Force Dynamometers for Measurement of cutting force (s) is based on :

  (a) Measurement of elastic deflection of a body subjected to the cutting force

  (b) Measurement of elastic deformation, i.e. strain induced by the force

  (c) Measurement of pressure developed in a medium by the force.

(a) Measuring deflection caused by the cutting force (s)

Under the action of the rce, say Fc in turning, the tool or tool holder elastical as indicated in Fig. 10.2. Such tool deflection, δ is proportional to the magnitude of the cutting force, Fc, given by

$$\delta = Fc\left(\frac{L^3}{3EI}\right)$$

where,

L = overhang or equivalent projected length of the cantilever type tool (holder)

E = physical property (Young’s modulus of elasticity of the beam)

forces:

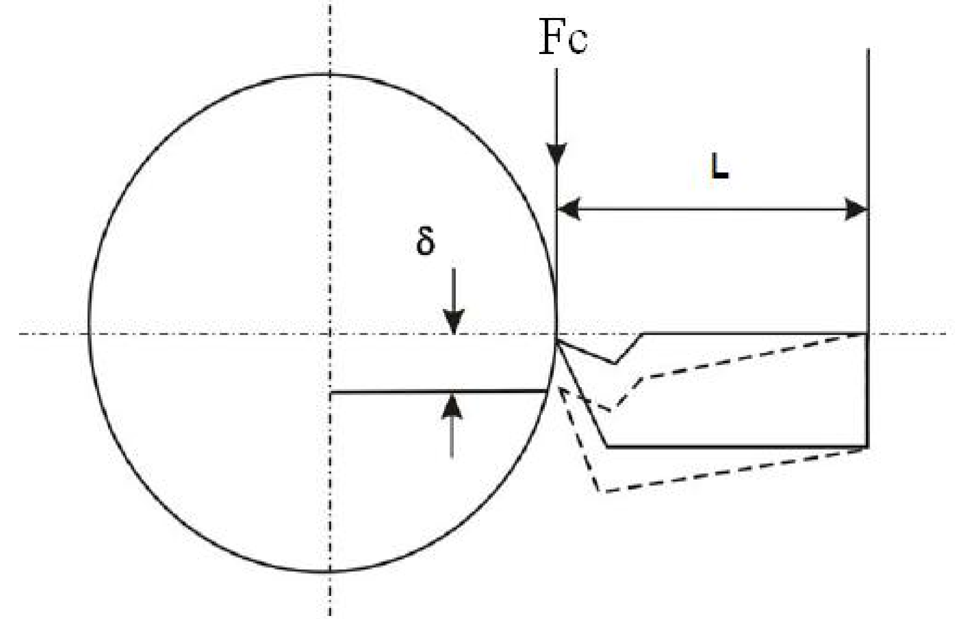


Fig. Cutting tool undergoing deflection δ deu to cutting force Fc

The deflection, δ, can be measured

- Mechanically by dial gauge (mechanical transducer)
- Electrically by using several transducers like;
  1. Potentiometer; linear or circular
  2. Capacitive pickup
  3. Inductive pickup
  4. LVDT

As schematically shown in Fig. on next slide

- Opto-electronically by photocell where the length of the slit through which light passes to the photocell changes proportionally with the tool – deflection

forces:

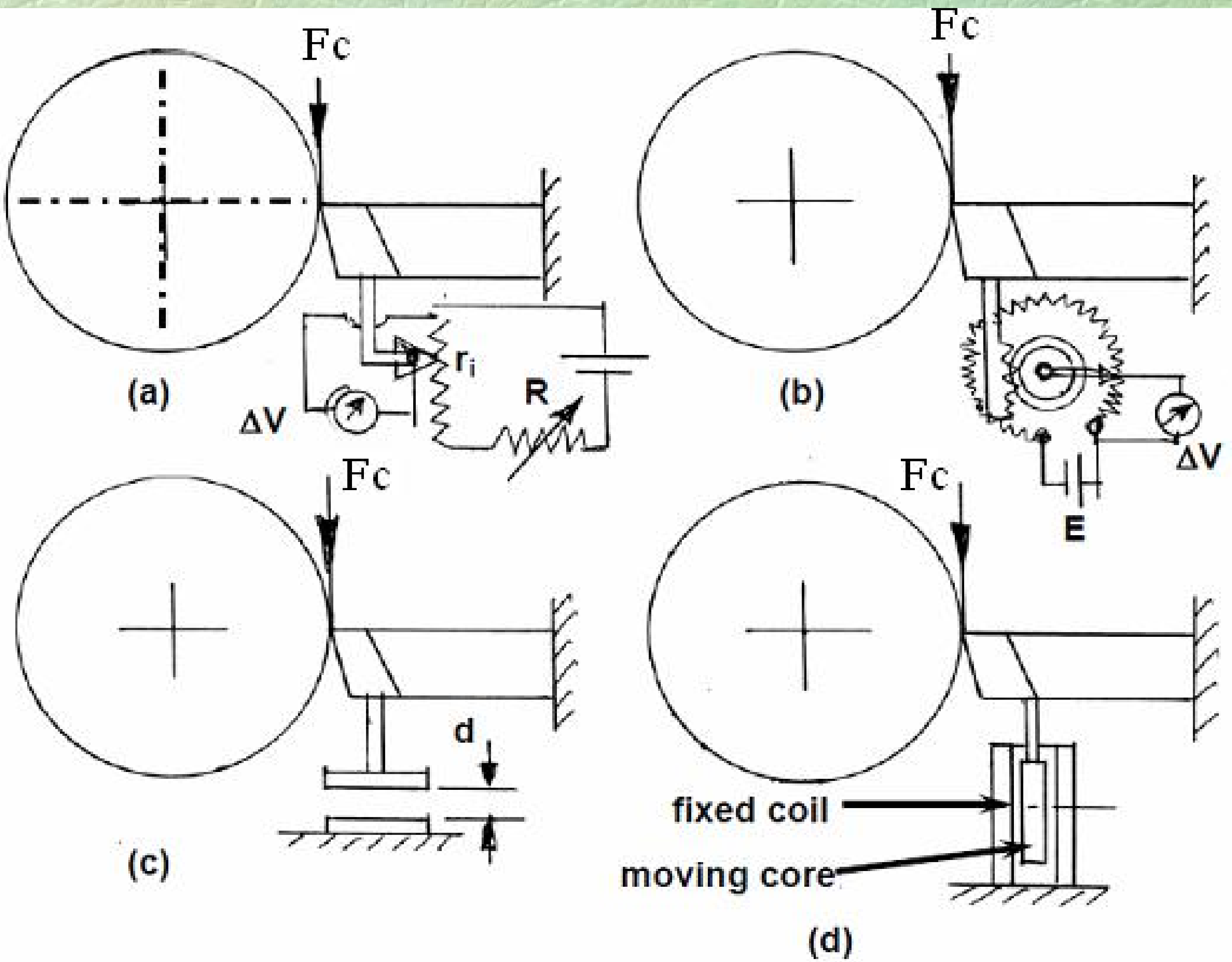


***Fig.** Electrical transducers working based on deflection measurment*
(a) linear pot (b) circular pot (c) capacitive pick up (d) LVDT type

forces:

- **All such transducers need proper calibration before use.**

In case of mechanical measurement of the tool deflection by dial gauge, calibration is done by employing known loads, W and the corresponding tool deflections, δ are noted and then plotted as shown in Fig. on next slide.

Here the slope of the curve represents the constant, k of the equation δ = kFc . Then while actual measurement of the cutting force, Fc, the δ* is noted and the corresponding force is assessed from the plot as shown.

In capacitive pick up type ometer, the cutting force causes proportional tool deflection, δ , which causes change in the gap (d) and hence capacitance, C as

$$C = \frac{\varepsilon . A}{3.6 \pi d}$$

The change in C is then measured in terms of voltage, ΔV which becomes proportional to the force. The final relation between Fc and ΔV is established by calibration

forces:

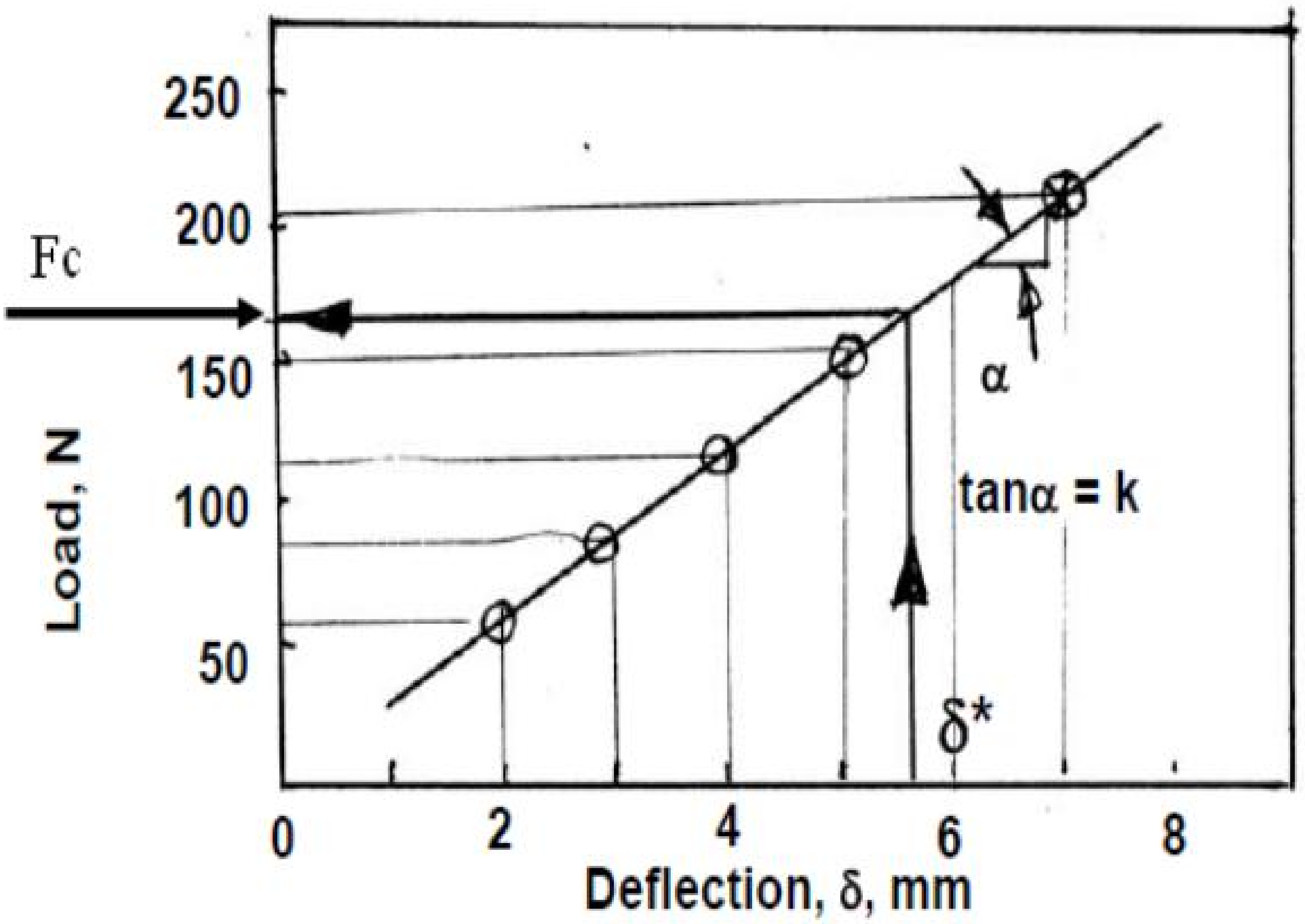


Fig. *Calibration of mechanical measurement system (dial gauge)*

forces:

(b) Measuring cutting force by monitoring elastic strain caused by the force.

Increasing deflection, δ enhances sensitivity of the dynamometer but may affect machining accuracy where large value of δ is restricted, the cutting forces are suitably measured by using the change in strain caused by the force. Fig. on next slide shows the principle of force measurement by measuring strain, ε, which would be proportic nitude of the force, Fc as,

$$\varepsilon = \frac{\sigma}{E} = \frac{M/Z}{E} = \frac{\mathrm{Fc}.l}{Z.E} = k_1\,\mathrm{Fc}$$

where, M = bending moment

Z = sectional modulus (I/y) of the tool section

I = plane moment of inertia of the plane section

y = distance of the straining surface from the neutral plane

forces:

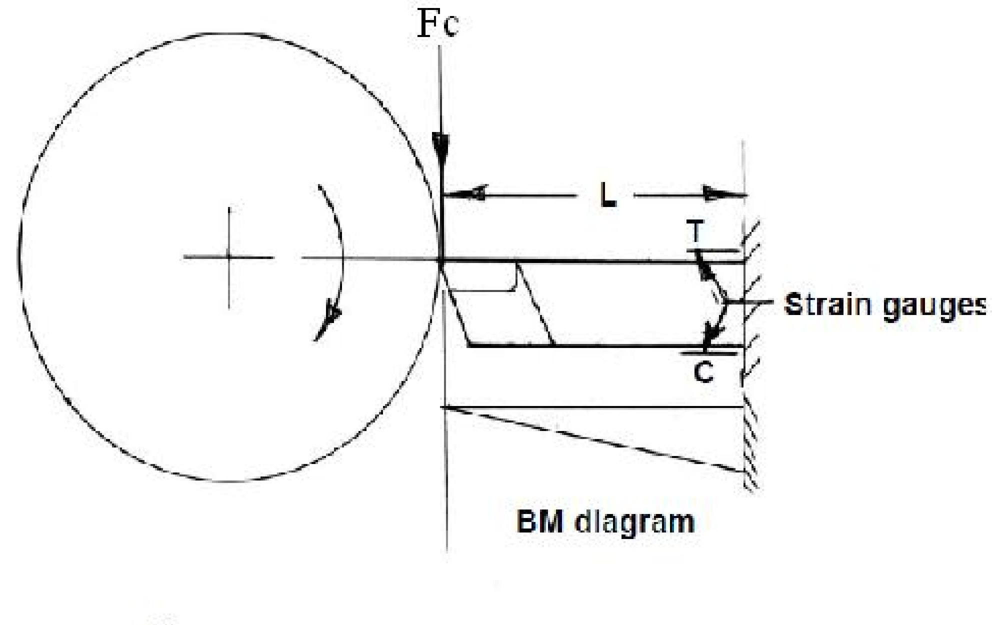


Fig. *Measuring cutting forces by strain gauges*

The strain, ε induced by the force changes the electrical resistance, R, of the strain gauges which are firmly pasted on th surface of the tool-h beam as

$$\frac{\Delta R}{R} = G\varepsilon$$

where, G = gauge factor (around 2.0 for conductive gauges)

The change in resistance of the gauges connected in a wheatstone bridge produces voltage output ΔV, through a strain measuring bridge (SMB) as indicated in Fig. on the next slide.

Out of the four gauges, R1, R2, R3 and R4, two are put in tension and two in compression as shown in Fig. 10.6. The output voltage, Δ e constant, G and the summation of strains as,

$$\Delta V = \frac{GE}{4}\left[\varepsilon_1 - (-\varepsilon_2) + \varepsilon_3 - (-\varepsilon_4)\right]$$

forces:

where, ε_1 and ε_2 are in tension and - $\varepsilon 3$ and - $\varepsilon 4$ are in compression

The gauge connections may be

- full bridge (all 4 gauges alive) – giving full sensitivity
- half bridge (only 2 gauges alive) – half sensitive
- quarter bridge (only 1 gauge alive) – ¼ th sensitivity

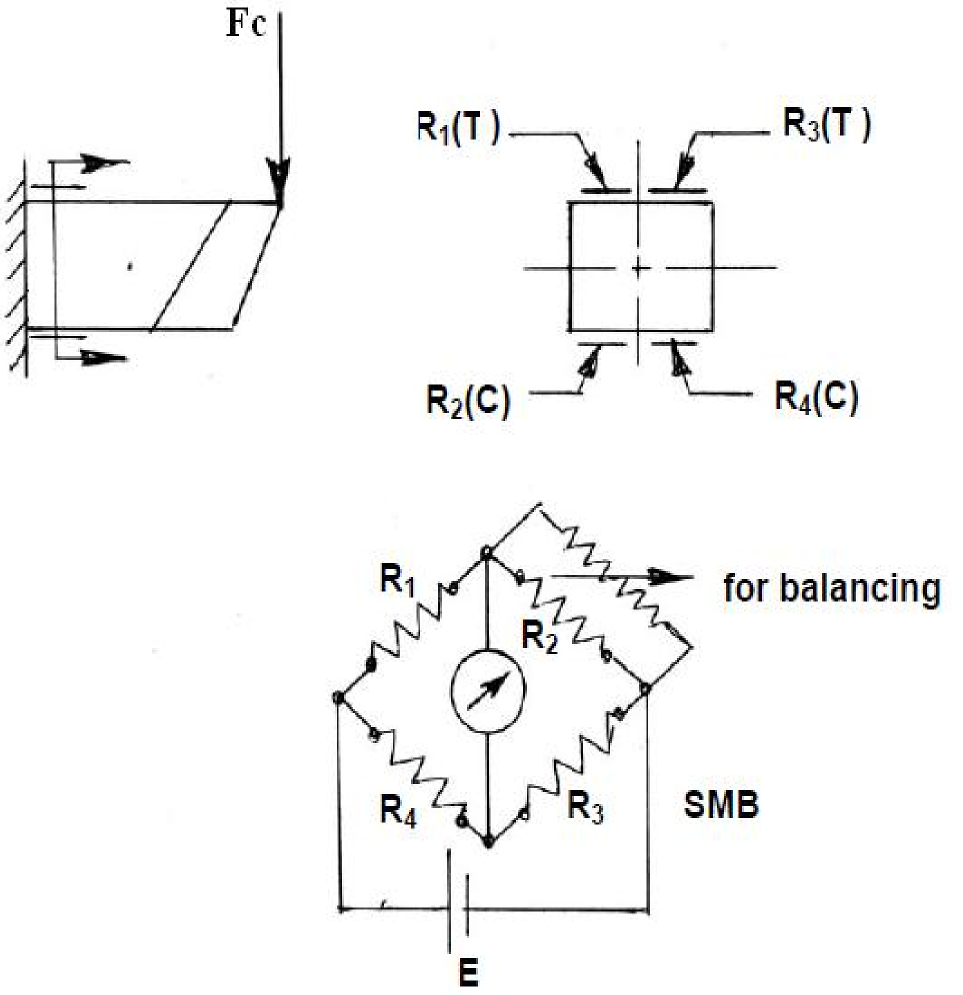


Fig. *Force measurement by strain gauge based transducer.*

forces:

(c) Measuring cutting forces by pressure caused by the force

This type of transducer functions in two ways :

- The force creates hydraulic pressure (through a diaphragm or piston) which is monitored directly by pressure gauge
- The force causes pressure on a piezoelectric crystal and produces an emf proportional to the force or pressure as indicated in Fig.

Here, emf = $\lambda t p$

where λ = voltage se

t = thickness of the c

p = pressure

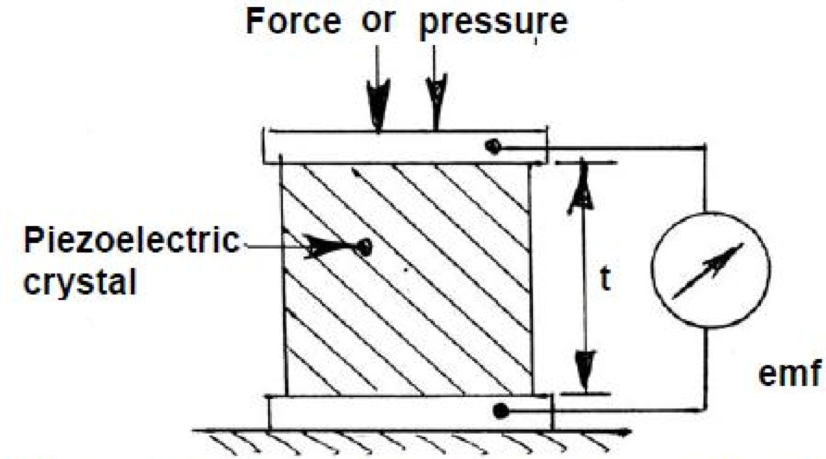


Fig. *Piezoelectric transducer for measuring force or pressure.*

forces:

Design requirements for Tool – force Dynamometers

For consistently accurate and reliable measurement, the following requirements are considered during design and construction of any tool force dynamometers :

- **Sensitivity** : the dynamometer should be reasonably sensitive for precision measurement
- **Rigidity** : the dynamometer need to be quite rigid to withstand the forces without causing much deflection which may affect the machining condition
- **Cross sensitivity** : the dynamometer should be free from cross sensitivity such that one force (say Fc) does not frequency response such that the readings are not affected by vibration affect measurement of the other forces (say Ft and Fr)
- Stability against humidity and temperature
- Quick time response
- High within a reasonably high range of frequency
- Consistency, i.e. the dynamometer should work

forces:

Classification of Tool Force Dynamometers:

- Classification as per number of forces measured:
  - Single force tool force dynamometer
  - Double forces tool force dynamometer
  - Triple forces tool force dynamometer
- Classification as per principle used by dynamometer:
  - Mechanical tool force dynamometer
  - Electrical tool force dynamometer
  - Hydraulic tool force dynamometer
- Classification as per element used by dynamometer:
  - Beam type tool force dynamometer
  - Strain gauge tool force dynamometer
  - Pizo-element tool force dynamometer.

Chip Breakers:

- A continuous chip flows away from the work at high speed.
- If this chip is allowed to continue, it may wrap around the tool post, the work piece, the chuck, and perhaps around the operator’s arm.
- Not only is the operator in danger of receiving a nasty laceration, but if the chip winds around the work piece and the machine, he must spend considerable time in removing it and a loss of production will be encountered.
- Therefore it is imperative that this chip be controlled and broken in some manner. Hence chip breakers are used to break up the long continuous chip in small pieces.
- 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.

Chip Breakers:

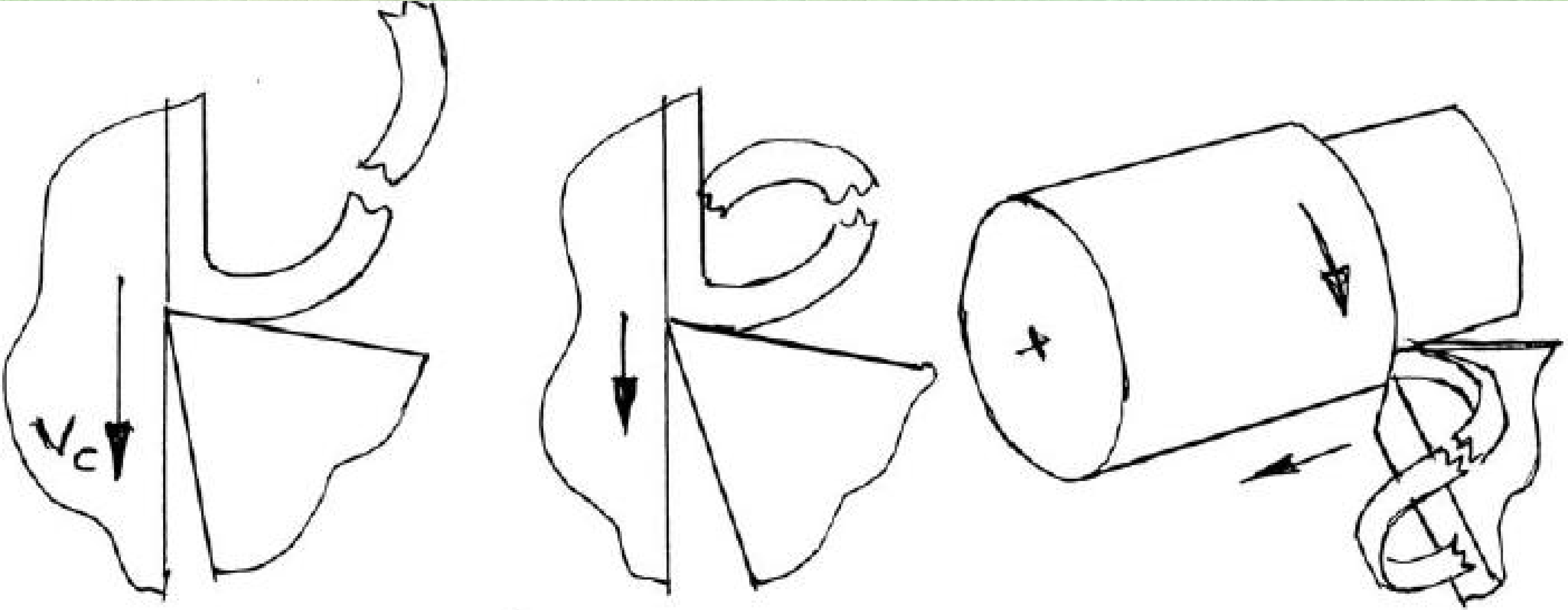
- Therefore it is essentially needed to break such continuous chips into small regular pieces for
  - safety of the working people
  - prevention of damage of the product
  - easy collection and disposal of chips.
- Chip breaking is done in proper way also for the additional purpose of improving machinability by reducing the chip-tool contact area, cutting forces and crater wear of the cutting tool..
- Principles of chip-breaking
- In respect of convenience and safety, closed coil type chips of short length and ‘coma’ shaped broken-to-half turn chips are ideal in machining of ductile metals and alloys at high speed.
- The principles and methods of chip breaking are generally classified as follows :
  - Self breaking

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

Chip Breakers:

- **(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 favors formation of jointed or segmented chips
  - By striking against the cutting surface of the job, as

Chip Breakers:



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

Fig. *Principles of self breaking of chips.*

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

Chip Breakers:

- Chip breakers are basically of two types :
  - In-built type
    - Step type: A step is ground on the face of the tool along the cutting edge.
    - Groove type: A small grove is ground behind the cutting edge.
  - Clamped or attachment type
    - A thin carbide plate or clamp is brazed or screwed on the face of the tool.
- 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

  Δ after their manufacture – in case of HSS tools like drills, milling cutters, broaches etc and brazed type carbide inserts

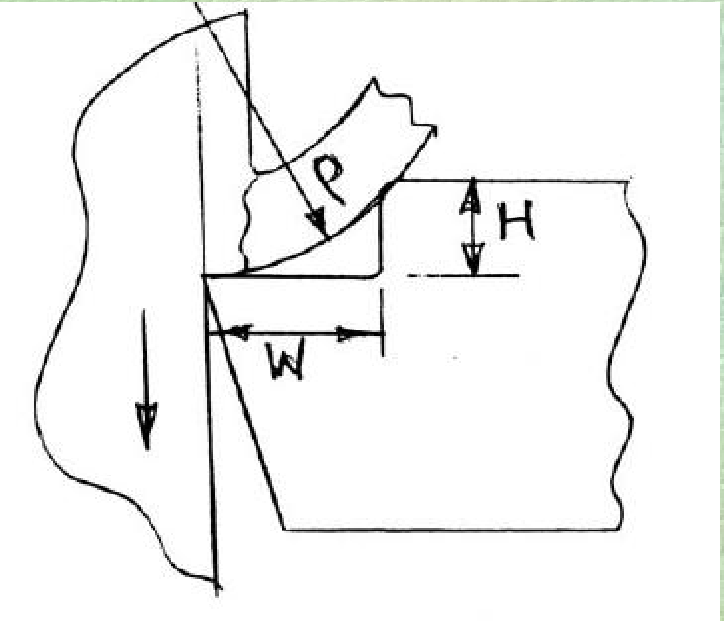
  Δ during their manufacture by powder metallurgical

Chip Breakers:

(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.
- The basic principle of forced chip breaking is schematically shown in Fig. when the strain hardened and brittle running chip strikes the heel, the cantilever chip gets forcibly bent and then breaks.
- Fig. on next slide schematically shows some commonly used step type chip breakers :
  - Parallel step
  - Angular step: positive and negative type

Chip Breakers:



W = width, H = height, β = shear angle

Fig. *Principle of forced chip breaking.*

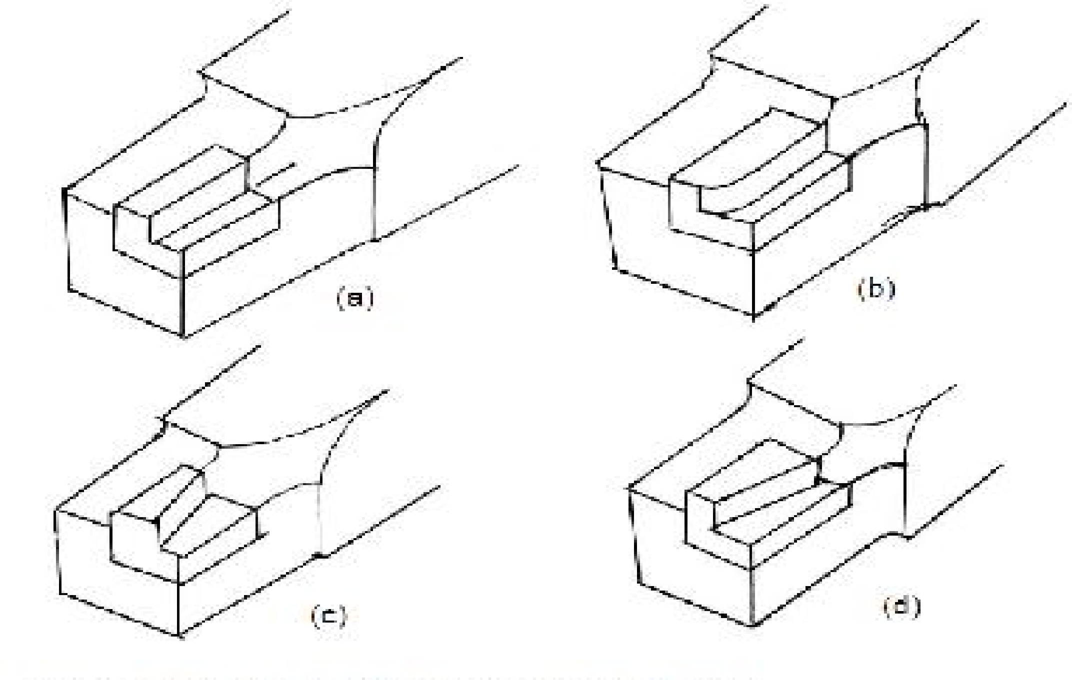
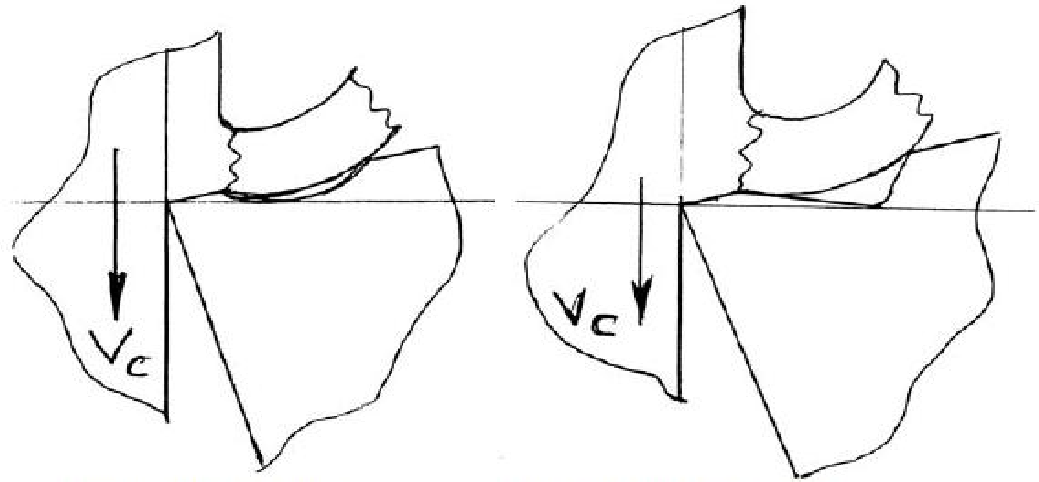


Fig. *Step type in-built chip breaker (a) parallel step (b) parallel and radiused (c) positive angular (d) negative angular*

Groove type in-built chip breaker may be of

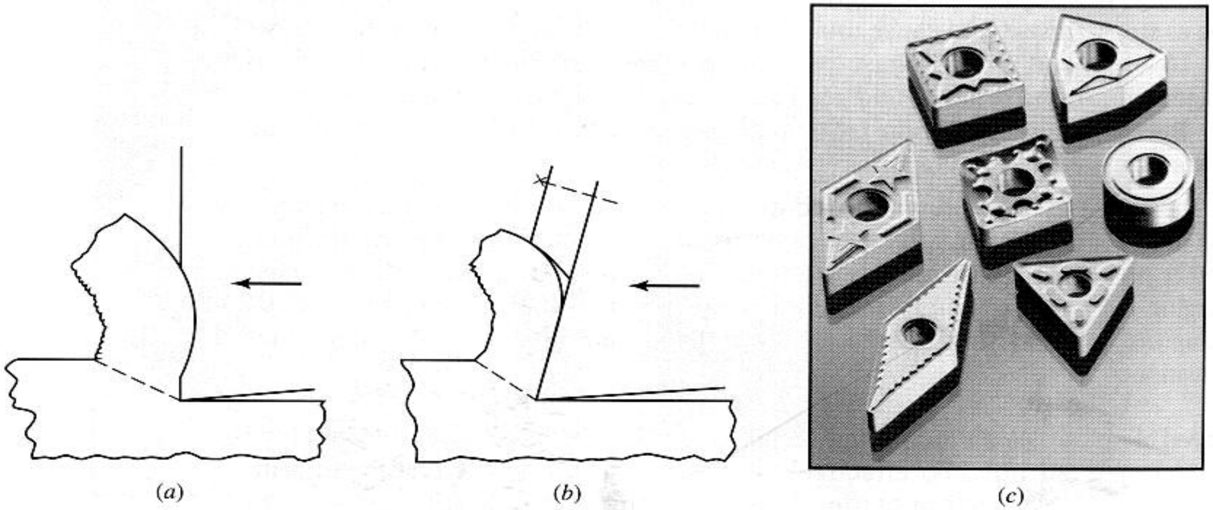
- Circular groove or
- Tilted Vee groove



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

Fig. *Groove type in-built chip breaker*

Breakers:



Chips are forced into tighter curls and break up when (*a*) groove-type or (*b*) obstruction-type chip breakers are used. (*c*) Complex chip-braking patterns may be incorporated into indexable inserts. [*Part (c) courtesy Kennametal, Latrobe, Pennsylvania.*]

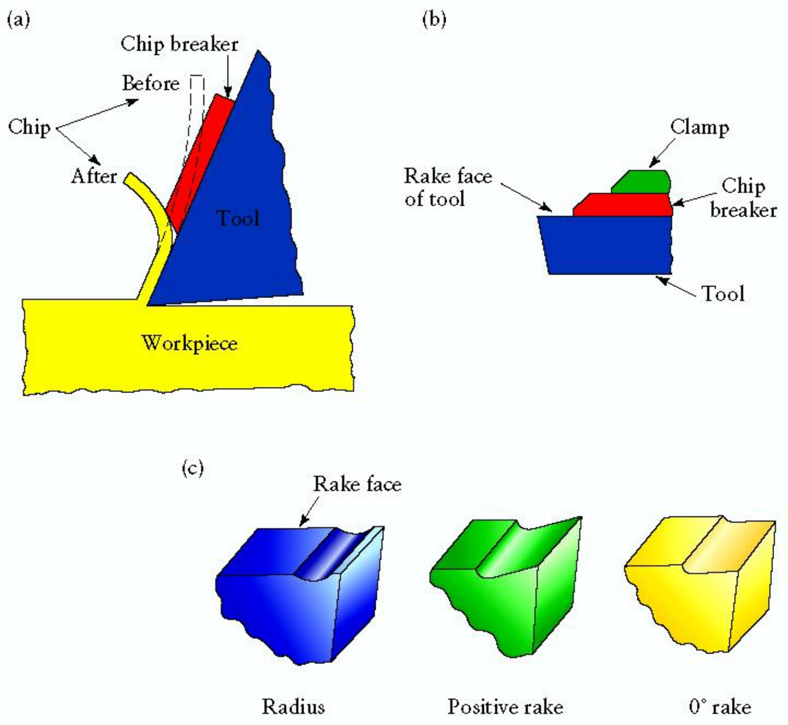


FIGURE : (a) Schematic illustration of the action of a chip breaker. Note that the chip breaker decreases the radius of curvature of the chip. (b) Chip breaker clamped on the rake face of a cutting tool. (c) Grooves in cutting tools, acting as chip breakers.

Source " Manufacturing Processes for Engineering

temperature:

- The heat generated is shared by the chip, cutting tool and the blank. The apportionment of sharing that heat depends upon the configuration, size and thermal conductivity of the tool – work material and the cutting condition. Fig. visualizes that maximum amount of heat is carried away by the flowing chip 60 to 80%. From 10 to 20% of the total heat goes into the tool and some heat about 4 to 10% is absorbed in th
velocity, the cl

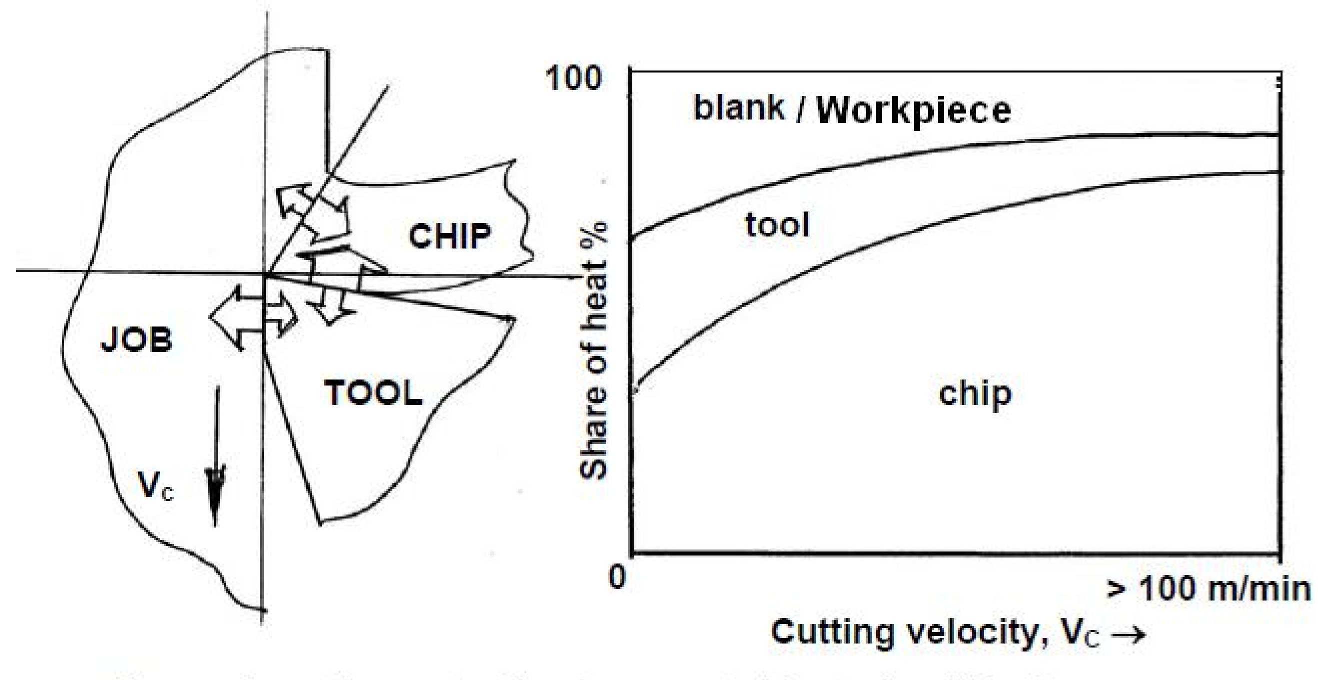


Fig. *Apportionment of heat amongst chip, tool and blank.*

distribution:

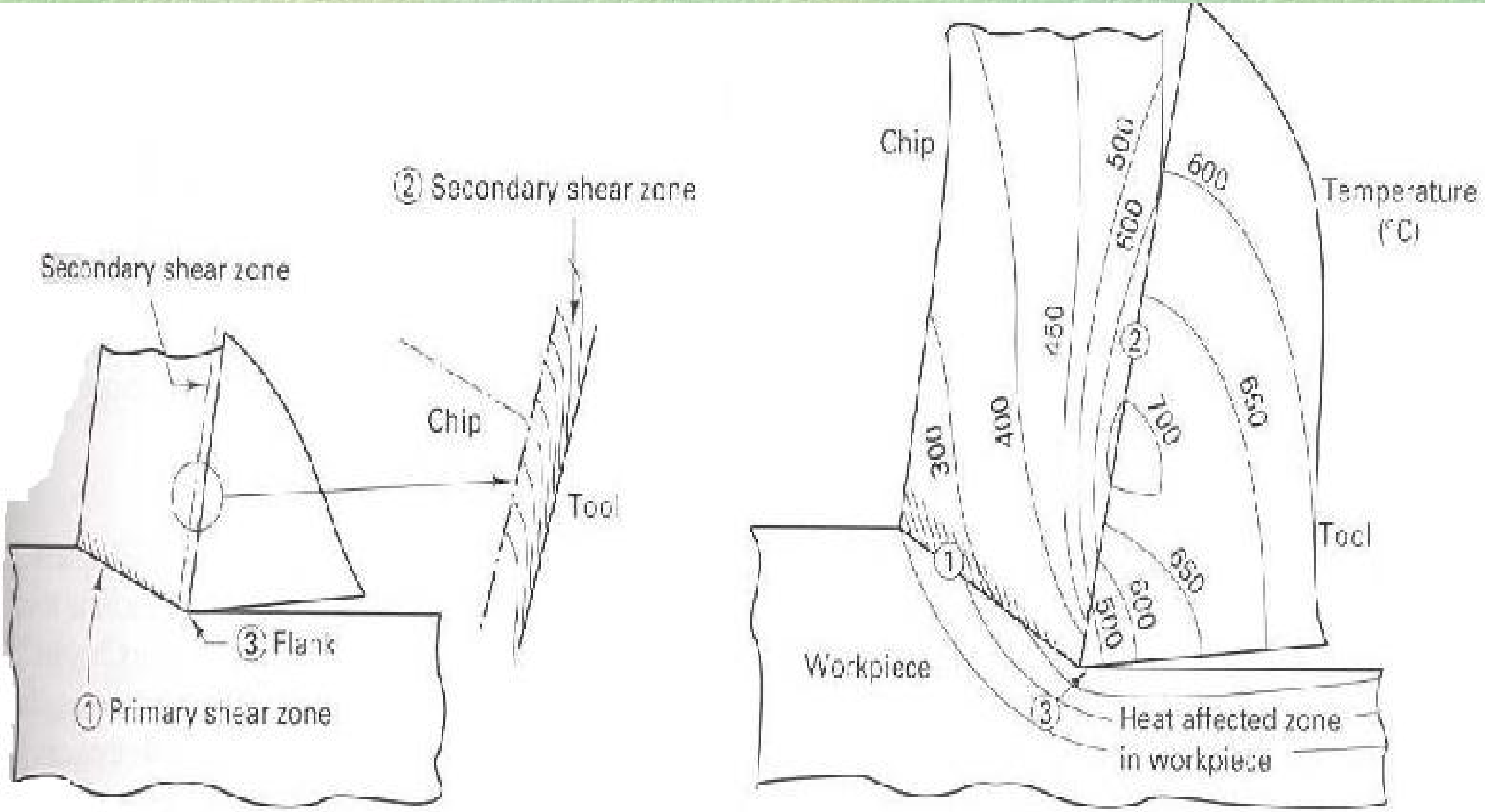


FIGURE There are three main sources of heat in metal cutting. (1) Primary shear zone. (2) Secondary shear zone-tool/chip (T/C) interface. (3) Tool flank.

The peak temperature occurs at the center of the T/C interface

effects:

Effect of high temperature on tool :

- The effect of high temperature is detrimental to both the tool and the job. The major portion of the heat is taken away by the chips. But it does not matter because chips are thrown out. So attempts should be made such that the chips take away more and more amount of heat leaving small amount of heat to harm the tool and the job.
- The possible detrimental effects of the high cutting temperature on cutting tool edge are :
- Rapid tool wear which reduces tool life.
- Plastic deformation of the cutting edge, if the tool material is not enough hot-hard and hot-strong.
- Thermal flaking and fracturing of the cutting edge due to thermal shocks.
- Built up edge formation

& effects:

Effect of high temperature on workpiece :

- Dimensional inaccuracy due to thermal distortion resulting from thermal expansion & contraction during and after machining.
- Surface damage due to oxidation, corrosion, burning etc.

- Induction of tensile residual stresses and micro-cracks at the surface / subsurface

However, often the high cutting temperature helps in reducing the magnitude of the cutting forces and cutting power consumption to some extent by softening or reducing the shear strength, τ_s of the work material ahead the cutting edge.

To attain or enhance such benefit the work material ahead the cutting zone is often additionally heated externally. This technique is known as Hot Machining and is beneficially applicable for the work materials

& effects:

Determination of cutting temperature:

The magnitude of the cutting temperature is required to be known or evaluated to facilitate:

- Assessment of machinability which is judged mainly by cutting forces and temperature and tool life.
- Design and selection of cutting tools
- Evaluate the role of variation of the different machining parameters on cutting temperature
- Proper selection and application of cutting fluid
- Analysis of temperature distribution in the chip, tool and job.

& effects:

The temperatures which are of major interests are:

- θs : average shear zone temperature
- θi : average (and maximum) temperature at the chip-tool interface
- θf : temperature at the work-tool interface (tool flanks)
- θavg : average cutting temperature

Cutting temperature can be determined by two ways :

- Analytically – using mathematical models (equations) if available or can be developed. This method is simple, quick and inexpensive but less accurate and precise.
- Experimentally – this method is more accurate,

& effects:

Analytical estimation of cutting temperature, θs:

(a) Average shear zone temperature, θs

Equations have to be developed for the purpose.

One simple method is presented:

The cutting energy per unit time, i.e., $P_C V_C$ gets used to cause primary shear and to overcome friction at the rake face as,

$$P_C.V_C = P_S.V_S + F.V_f$$

where, V_C = Velocity of cutting

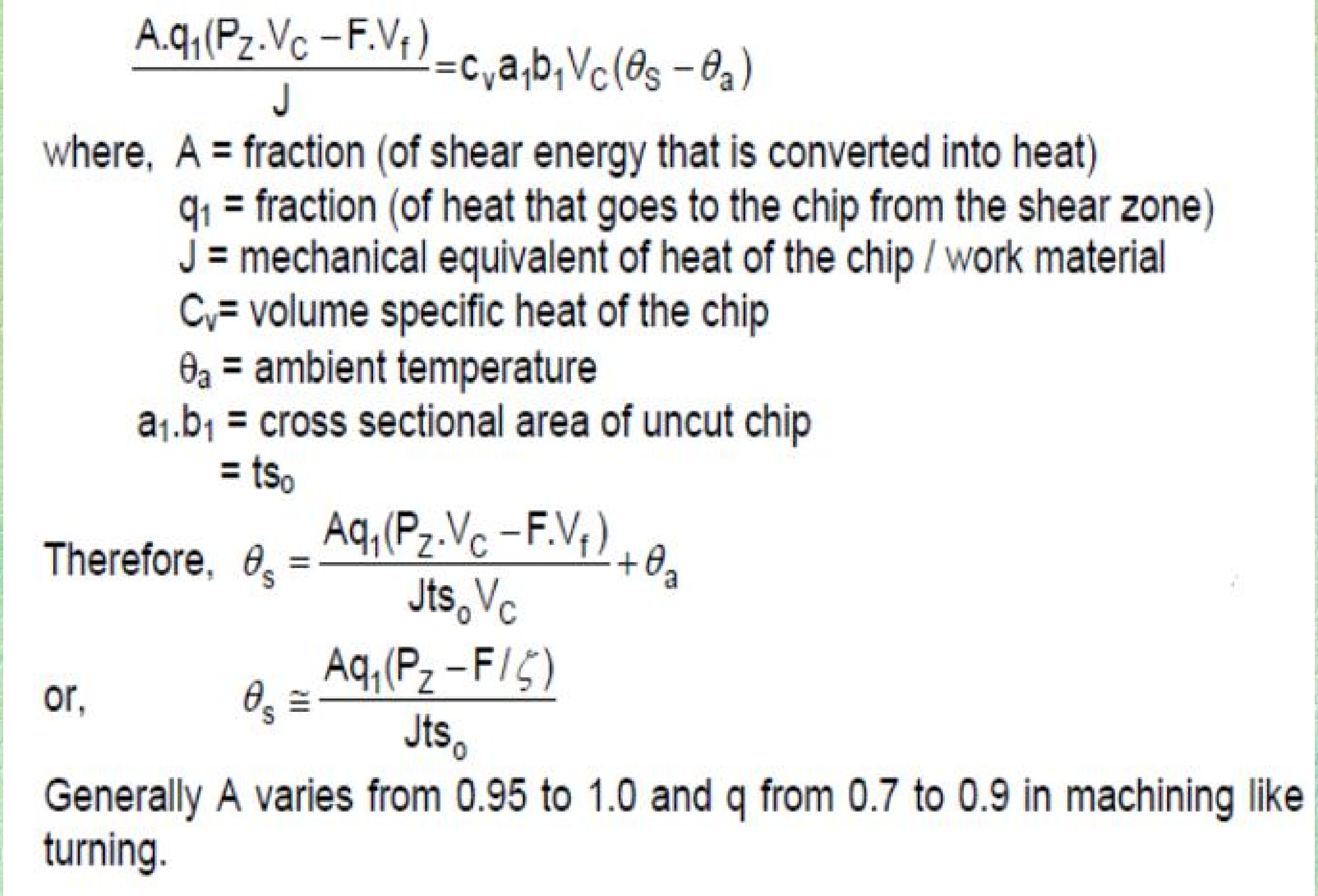
V_S = slip velocity along the shear plane

and V_f = average chip – velocity

So, $P_S.V_S = P_C.V_C – F.V_f$

Equating amount of heat received by the chip in one minute from the shear zone and the heat contained by that chip, it appears,

temperature:



$$\frac{A.q_1(P_Z.V_C - F.V_f)}{J} = c_v a_1 b_1 V_C(\theta_S - \theta_a)$$

where, A = fraction (of shear energy that is converted into heat)

q_1 = fraction (of heat that goes to the chip from the shear zone)

J = mechanical equivalent of heat of the chip / work material

C_v= volume specific heat of the chip

θ_a = ambient temperature

$a_1.b_1$ = cross sectional area of uncut chip

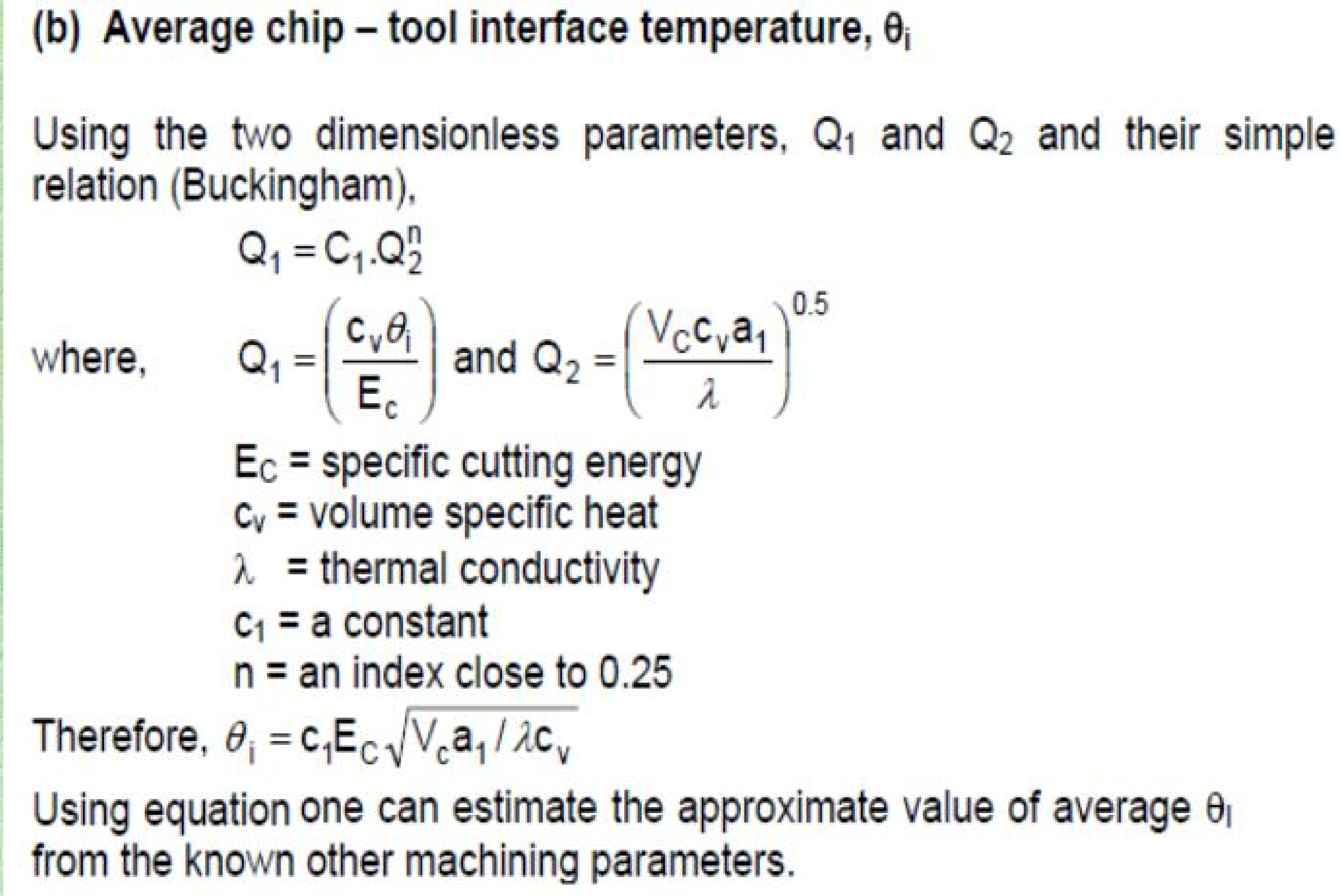
= ts_o

Therefore, $$\theta_s = \frac{Aq_1(P_Z.V_C - F.V_f)}{Jts_oV_C} + \theta_a$$

or, $$\theta_s \cong \frac{Aq_1(P_Z - F/\zeta)}{Jts_o}$$

Generally A varies from 0.95 to 1.0 and q from 0.7 to 0.9 in machining like turning.

temperature:



(b) Average chip – tool interface temperature, θ_i

Using the two dimensionless parameters, Q_1 and Q_2 and their simple relation (Buckingham),

$$Q_1 = C_1 . Q_2^n$$

where, $$Q_1 = \left(\frac{c_v \theta_i}{E_c}\right) \text{ and } Q_2 = \left(\frac{V_C c_v a_1}{\lambda}\right)^{0.5}$$

E_C = specific cutting energy
c_v = volume specific heat
λ = thermal conductivity
c_1 = a constant
n = an index close to 0.25

Therefore, $\theta_i = c_1 E_C \sqrt{V_c a_1 / \lambda c_v}$

Using equation one can estimate the approximate value of average θ_i from the known other machining parameters.

& effects:

Control of cutting temperature:

- It is already seen that high cutting temperature is mostly detrimental in several respects. Therefore, it is necessary to control or reduce the cutting temperature as far as possible.

- Cutting temperature can be controlled in varying extent by the following general methods:

  - proper selection of material and geometry of the cutting tools

  - optimum selection of VC – so combination without sacrificing MRR

  - proper selection and application of cutting fluid

Factors affecting cutting temperature:

- Work material
- Cutting variables speed, feed & depth of cut.

  Heat generated α Cutting force x cutting speed.
- Tool geometry
- Cutting fluid.

Tool wears tool failure & tool life:

- Cutting tools are subjected to extremely severe cutting conditions such as

  metal to metal contact with chip and work

  - very high stress
  - very high temperature
  - very high temperature gradients
  - very high stress gradients

- Because of all the above-mentioned factors, the tool-chip interface exhibit the type of wears found. As tool wear progresses, cutting forces increase and vibrations increase. Tool tip softens and flows plastically and gets blunt edge which will result in further progressing of plastic deformation from the tool tip to the interior.
- Cutting tool life is one of the most important economic considerations in metal cutting.
- Conditions giving a very short tool life will not be economical because tool-grinding, indexing, and tool replacement costs will be high.
- On the other hand, the use of very low speeds and feeds to give long tool life will not be economical because of the low production

Tool Wear:

Due to interaction between tool and chip at tool face, known as wear between work piece and tool flanks, between hard inclusions in work piece and tool and careless selection of cutting parameters & tool handling leads to wear at face known as crater wear, at flanks known as wear land, nose wear, cracking etc.

Types of Tool Wear:

- **Crater wear (Rake Face Wear)**
- **Flank (Clearance Surfaces) Wear**
- **Notch wear (Boundary Wear)**
- **Chipping**
- **Plastic deformation**
- **Ultimate failure**

Tool Wear:

Different types of wear on various tools: Oxide Ceramic Tools

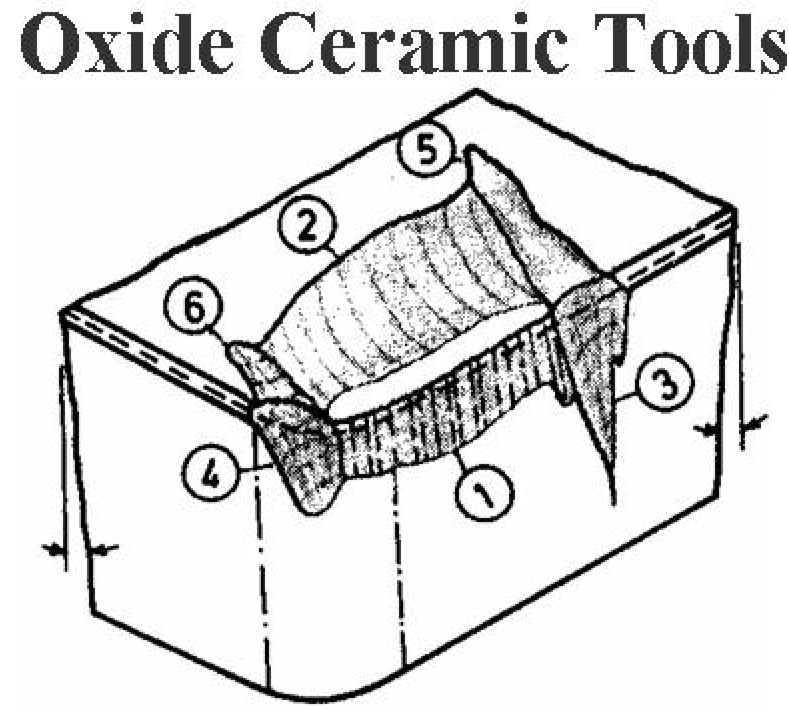
1. **Flank wear (wear land),**

2. **Crater wear**

3. **Primary groove (outer diameter groove or wear notch),**

4. **Secondary groove (oxidation wear) at nose,**

5. **Outer chip notch,**

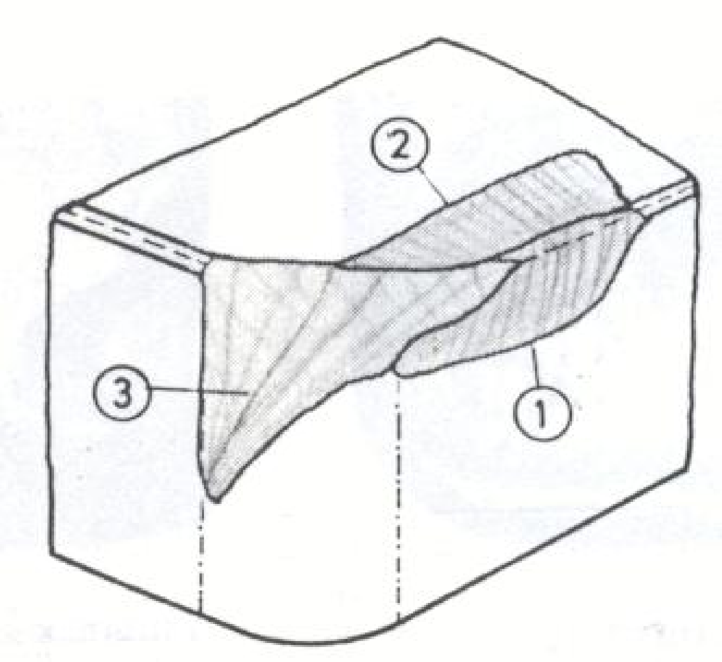


Tool Wear:

Catastrophic Tool Failures:

1. **Flank wear**
2. **Crater,**
3. **Failure face,**
4. **Primary groove,**
5. **Outer chip notch,**
6. **Plastically flown materials around failure face**

Oxide Ceramic Tools(by Chipping and Fracture)

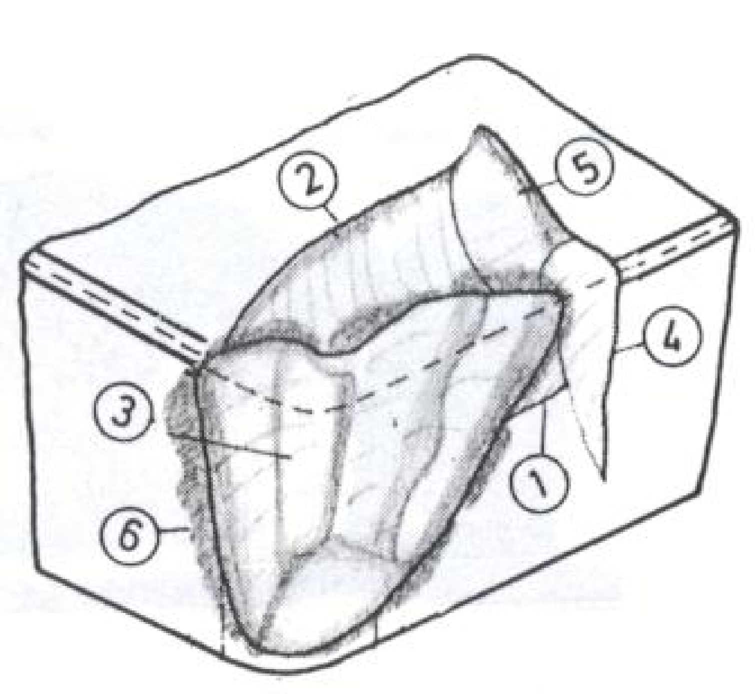


Tool Wear:

Catastrophic Tool Failure:

1. **Flank wear,**
1. **Crater,**
1. **Failure face,**
1. **Primary groove,**
1. **Outer chip notch,**
1. **Plastically flown materials around failure face**

HSS Tools (by Thermal Softening and Plastic Flow)



Crater Wear::

Typically, crater wear occurs on the rake face of the tool. It is essentially the erosion of an area parallel to the cutting edge. This erosion process takes place as the chip being cut, rubs the top face of the tool. Under very high-speed cutting conditions and when machining tough materials, crater wear can be the factor which determines the life of the tool. However, when tools are used under economical conditions, the edge wear and not the crater wear is more commonly the controlling

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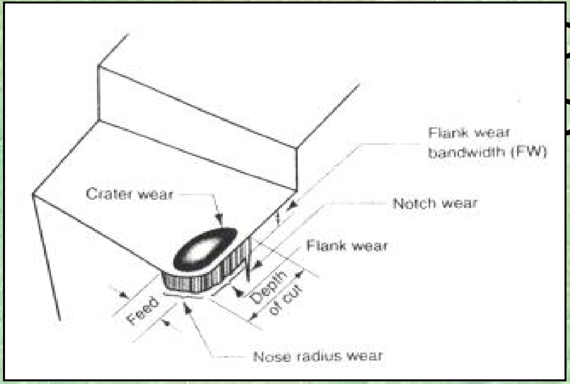
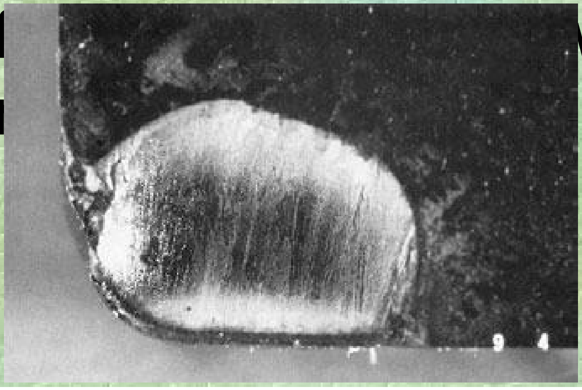
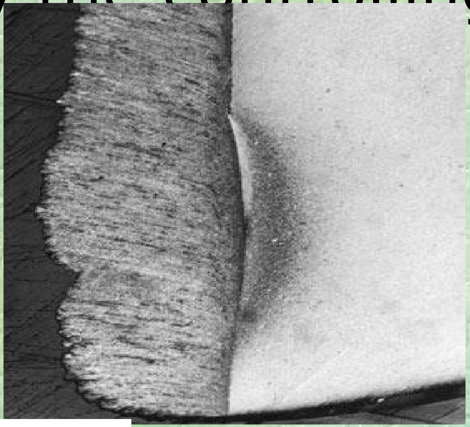
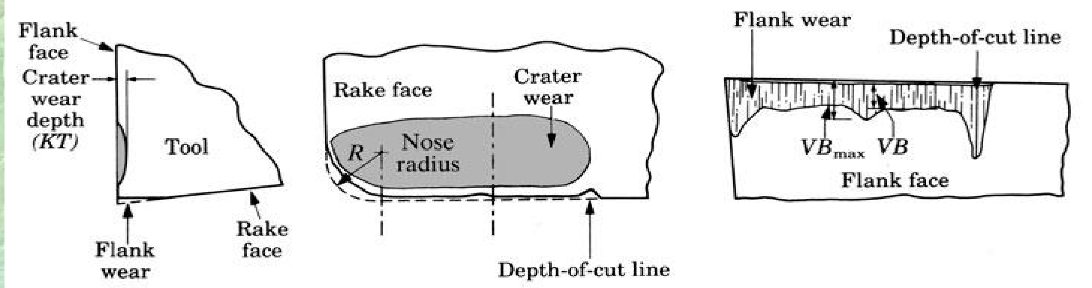








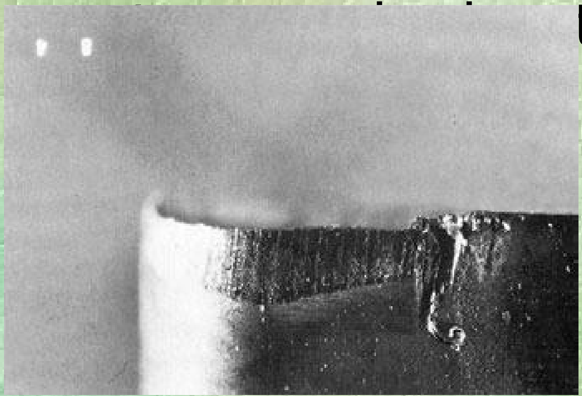
Flank or Edge Wear:

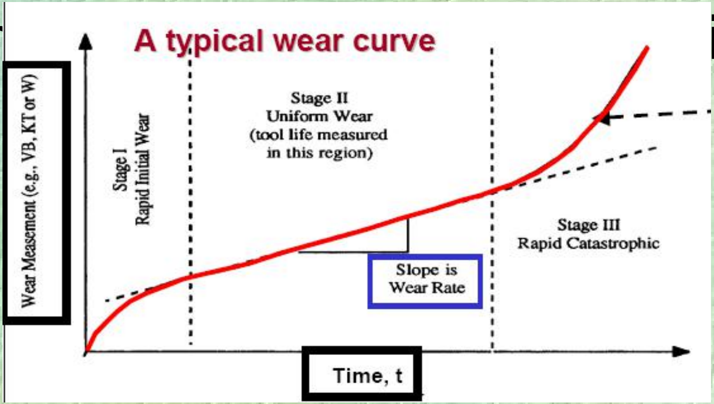
Flank wear occurs on the clearance face of the tool and is mainly caused by the rubbing of the newly machined workpiece surface on the contact area of the tool edge. This type of wear occurs on all tools while cutting any type of work material. Flank wear begins along the lead cutting edge and generally moves downward, away from the cutting edge. The edge wear is also commonly known as the wear land.

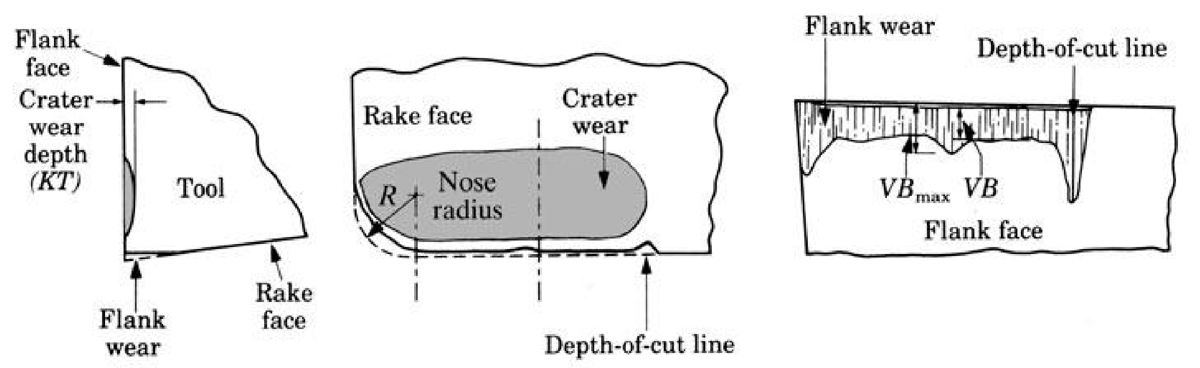
During the initial and steady wear phase (stage I & II), the

to abrasion, wh

it is







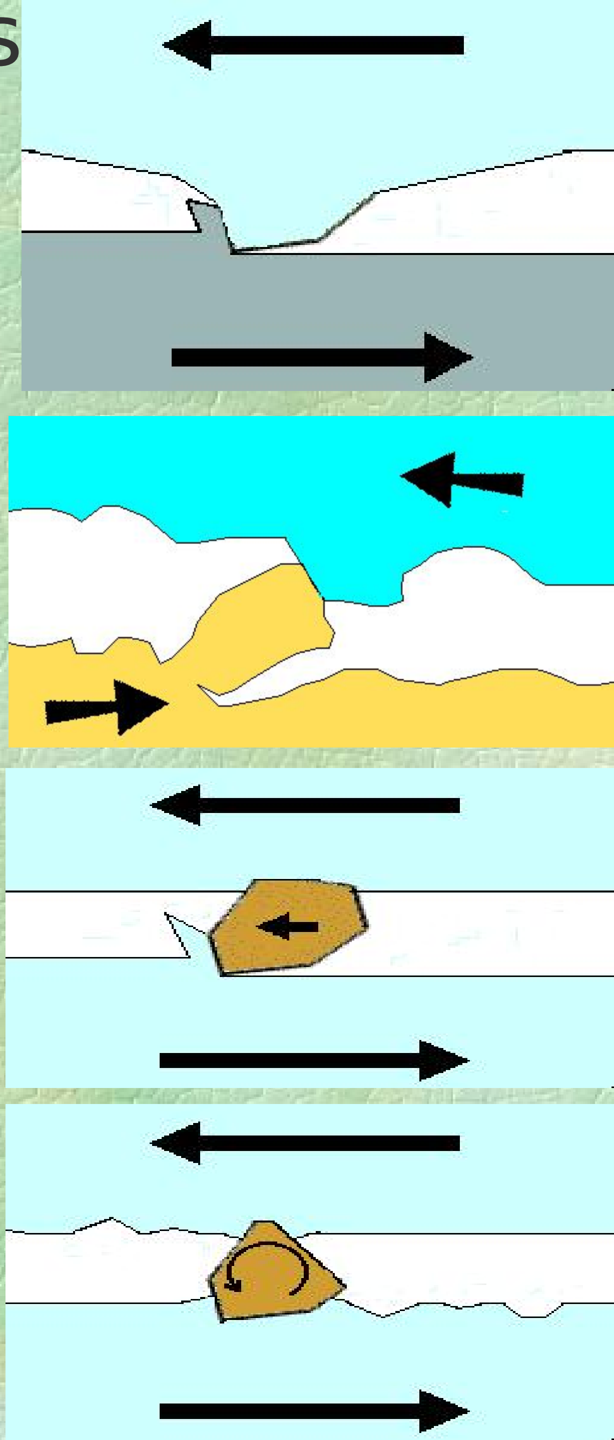
Abrasion Wear Mechanisms:

The hard inclusions in the work piece microstructure plow into the tool face and flank surfaces, abrasion wear predominates at relatively low cutting temperatures. The abrasion resistance of a tool material is proportional to its hardness.

- Wear can be described as **total loss of weight or mass of the sliding pairs accompanying friction**.
- Wear is not a process involving just one mechanism, **several different mechanisms can be operative simultaneously** between **a pair of dry sliding surfaces** to cause wear, depending on the physical conditions existing.

Macro-transfer type mechanical wear process like **abrasion** and **adhesion**,
Micro-transfer type thermo-chemical process like **diffusion**,
Electrochemical process like **localized**

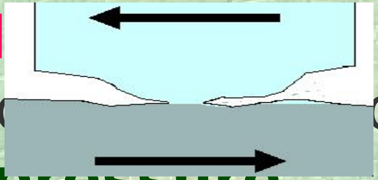
Abrasion Wear Mechanisms



- **Micro-cutting**: when high asperities on the underside of the chip pass over the tool face and "***ploughing***" takes place into the softer matrix of the tool material – **two-body abrasion**.
- **Micro-grinding**: when hard particles between the underside of the chip and the tool face act like cutting edges "***ploughing***" into the softer matrix of the tool material or causing damage by pressed rolling – **three-body abrasion**.
- These hard particles may be **highly strained-hardened fragments of built-up edge**, **segregated carbides**, **inclusions**, etc. of the

Adhesion Wear:

- This wear is caused by formation and subsequent destruction of minute welded junctions, adhesion wear is commonly observed as built-up edge (BUE) on the top face of the tool. This BUE may eventually disengage from the tool, causing a crater like wear. Adhesion can also occur when minute particles of the tool surface are instantaneously welded to the chip surface at the tool chip interface and carried away with the chip.



- The mechanism of **the fracture of welded junctions** between the two metals (chip and due to the presence of **high temperature** and **pressure** (Bowden and Tabor).

Severe Wear

  - Considerable welding and tearing of the softer rubbing surface at high wear rate,
  - The formation of relatively large wear particles.

Mild Wear

  - Low wear rate

Diffusion Wear:

When a metal is in sliding contact with another metal and the temperature at their interface is high, conditions may become right for the alloying atoms from the harder metal to diffuse into the softer matrix; thereby increasing the latter's hardness and abrasiveness. On the other hand atoms from the softer metals may also diffuse into harder metal, thus weakening the surface layer of the latter to such an extent that particles on it are dislodged and are carried away by flowing chip material. Because of high temperatures and pressures in diffusion wear, micro transfer on an atomic scale takes place. The rate of diffusion increases exponentially with increases in temperature.

- A wear process of **atomic transfer** at contacting asperities from a region of **high concentration** to one of ***low concentration***.
- **The diffusion rate increases exponentially with temperature increase**.
- Result in the ***changes of the tool*** *and* ***work piece***

Diffusion Wear:

- **Gross softening of the tool**

  Tool softening caused by diffusion of carbon in a relatively deep surface layer

  - plastic flow of the tool
  - major tool geometry changes
  - high forces and a sudden complete failure of the tool.

- **Diffusion of major/minor tool constituents into the work**

  Dissolving of the tool matrix or a major/minor strengthening constituent into the work and chip surfaces.

  Machining cast alloy with carbide or ceramic tools,

Diffusion Wear:

- **Diffusion of a work-material component into the tool**

  A constituent of the work material diffusing into the tool may alter the physical properties of a surface layer of the tool.

  Diffusion of Pb Š a thin brittle surface layer Š removed by fracture or chipping.

- **Diffusion of a tool constituent influencing the work material**

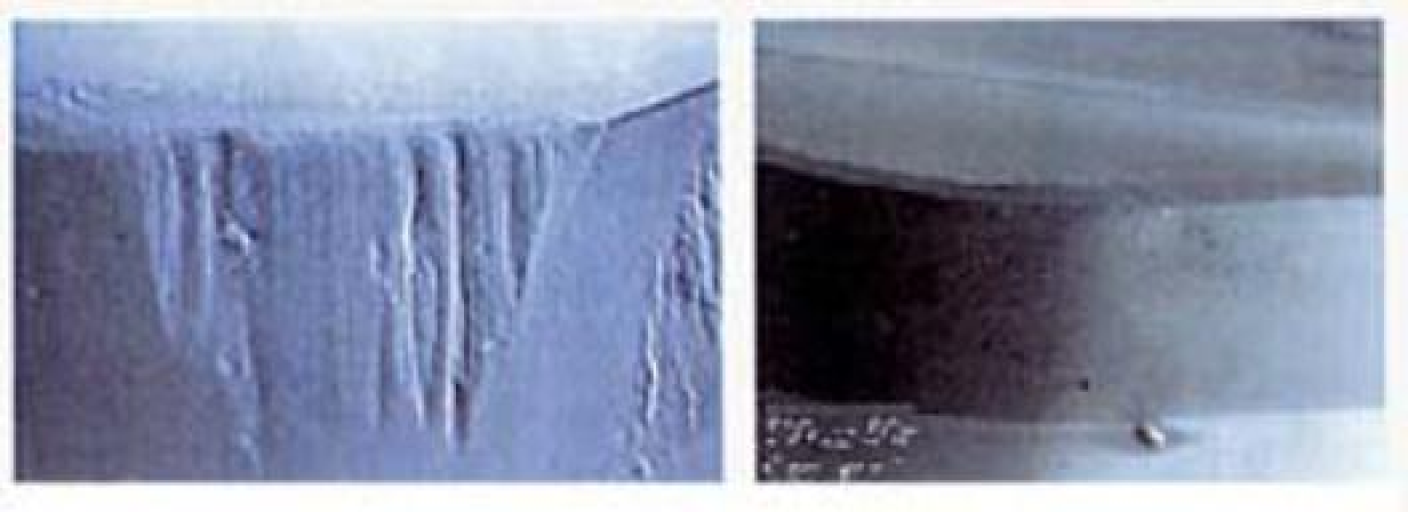
  Not the loss of the constituents but just the influence of these elements (principally carbon) on the strength of the chip materials.

  A carbon enrichment increases the strength of the chip surface and this in turn pulls more material

Oxidation Wear:

- At elevated temperature, the oxidation of the tool material can cause high tool wear rates. The oxides that are formed are easily carried away, leading to increased wear.
- **High temperatures** and **the presence of air (O_2)** – oxidation layer
- Periodically forming and removal.

Chemical Wear:



Corro
surfa

Galvanic Wear:

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

Fatigue Wear:

A **thermo-mechanical** combination - **temperature fluctuations** and **the loading and unloading** of cutting forces can lead to **cutting edge cracking and breaking**.

Intermittent cutting action leads to continual generation of heat and cooling as well as **shocks of cutting edge engagement.**

Heat-electric Wear:

The high temperature ǒ the formation of **thermal couple** between the work piece and the tool.

Due to the **heat related voltage** established between the work piece and tool, it may cause electric current between the two.

However, the mechanism of the heat-electric wear has not

Tool Failure:

A tool that no longer performs the desired functions is said to have failed and hence reached the end of its useful life. At such an end point the tool is not necessarily unable to cut the work piece but is merely unsatisfactory for the purpose required. The tool may be resharpened and used again.

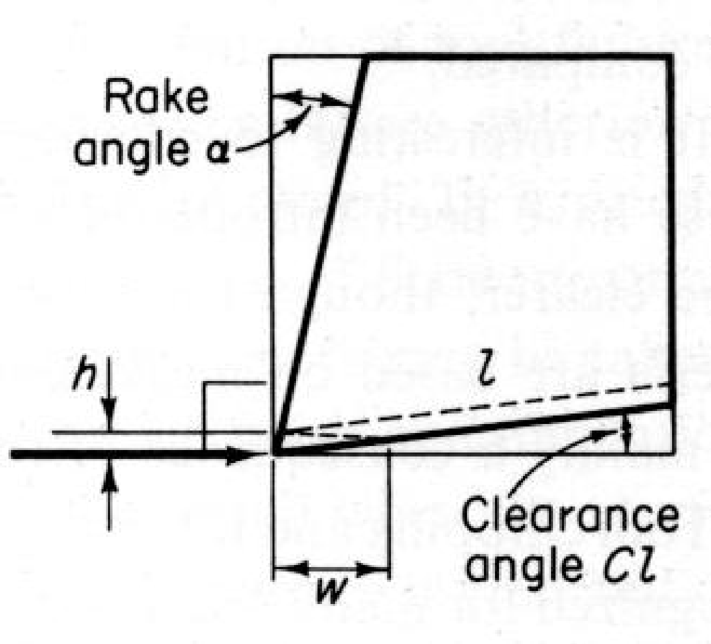
Tool Wear Criteria:

- It is the extent of or limiting value of the wear criteria before tool is declared as failed.

There are many choices of criteria being used in industry and research laboratory e.g. flank wear, crater wear, combination of both etc.

criterion

- Size of wear land (flank wea)



$$h\ 6\ \frac{w \tan Cl}{1\,0 \tan a \tan Cl}$$

$$W\ 6\ \frac{bw^{2} \tan Cl}{2(1\,0 \tan a \tan Cl)}$$

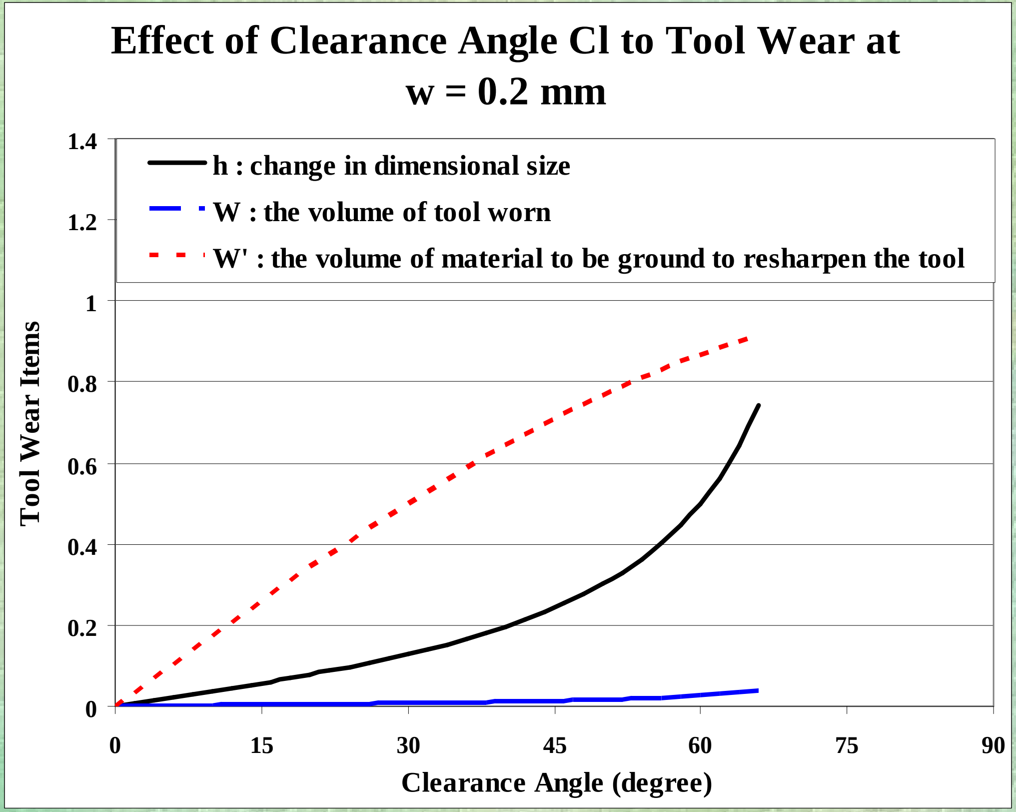
$$W'\,@lbw \sin Cl$$

h: change in dimensional size **w**: the wear-1and size,

W: the volume of tool worn **a**: is the rake angle

W': the volume of material to be ground to resharpen the tool

Tool Wear Criteria: Flank wear criterion



$$h\ 6\ \frac{w \tan Cl}{1\,0 \tan a \tan Cl}$$

$$W\ 6\ \frac{bw^2 \tan Cl}{2(1\,0 \tan a \tan Cl)}$$

$$W' @ lbw \sin Cl$$

h: change in dimensional size ***w***: the wear-1and size,
W: the volume of tool worn ***Cl***: the clearance angle
W': the volume of material to be ground to resharpen the tool

criterion

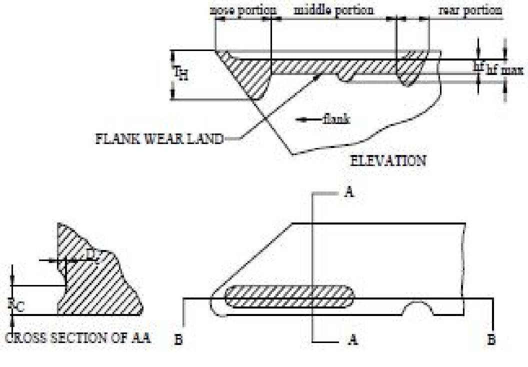
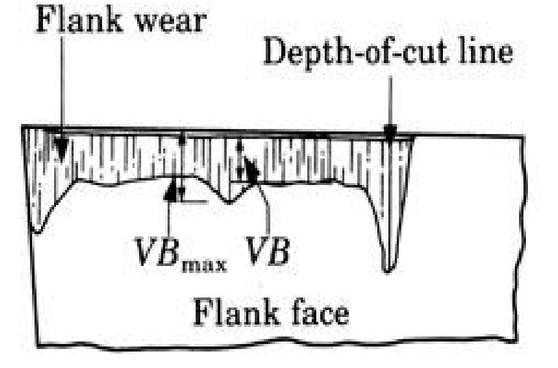
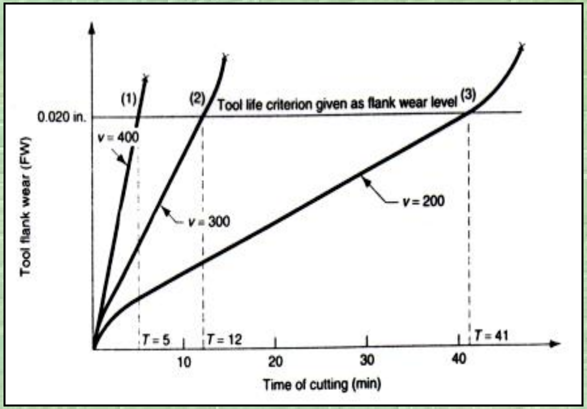


FIG WIDTH OF WEAR LAND AND MAXIMUM DEPTH OF CRATER

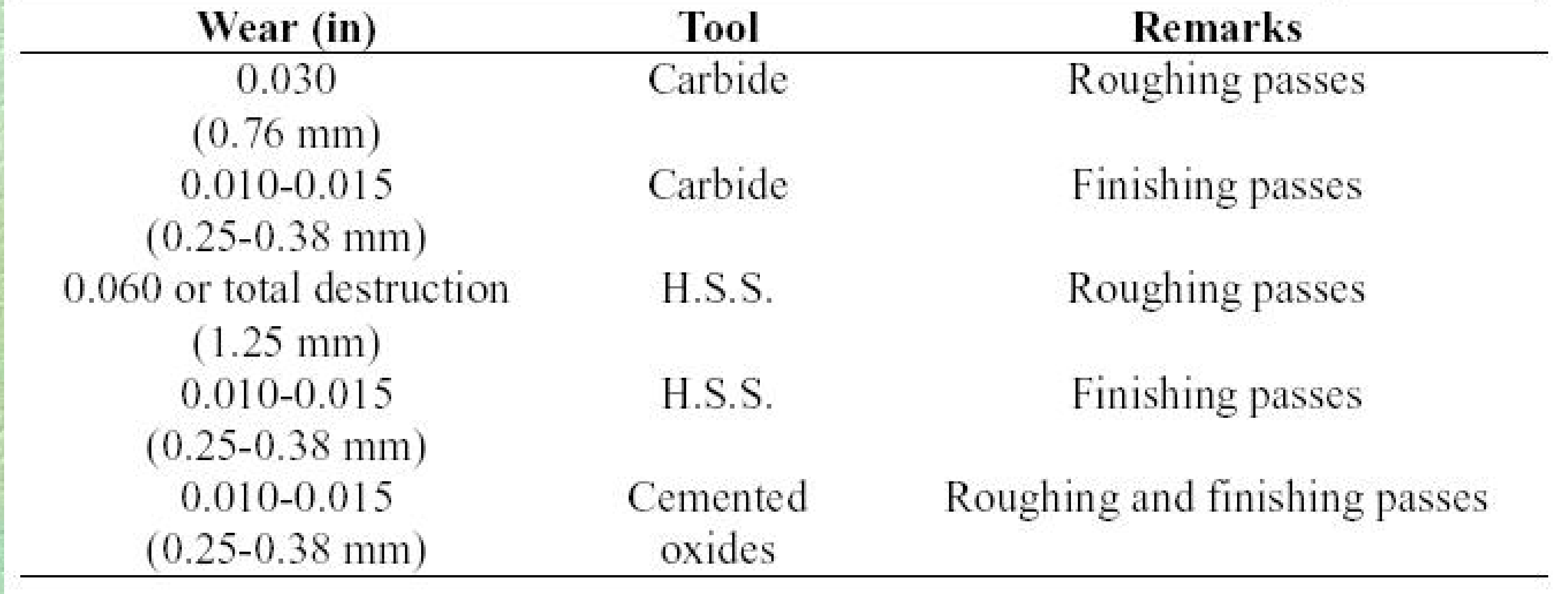




- Flank wear is not of uniform width. It is larger at or near the tow ends of the active portions of the side cutting edge.
- At the nose portion the chip flow is rather complicated and wearing conditions severe.
- At the rear portion of the flank wear land, groove or notch gets formed on account of accelerated wear. It has been suggested that accelerated wear is caused by abrasion and metal transfer, enhanced by chemical interaction with the surrounding atmosphere.
- The width of the wear land is maximum at the rear

criterion

Size of wear land (flank wear):



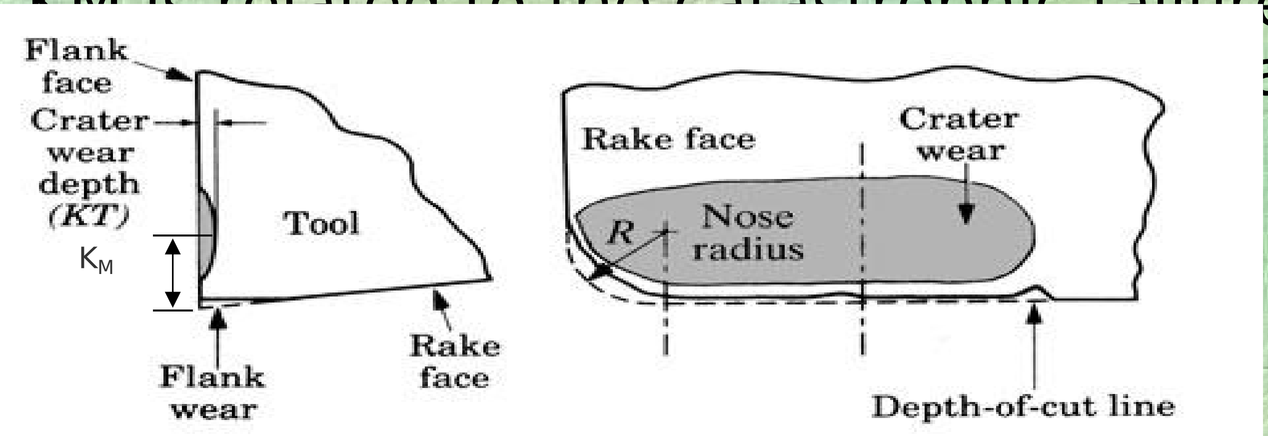
Wear (in)	Tool	Remarks
0.030 (0.76 mm)	Carbide	Roughing passes
0.010-0.015 (0.25-0.38 mm)	Carbide	Finishing passes
0.060 or total destruction (1.25 mm)	H.S.S.	Roughing passes
0.010-0.015 (0.25-0.38 mm)	H.S.S.	Finishing passes
0.010-0.015 (0.25-0.38 mm)	Cemented oxides	Roughing and finishing passes

Recommended wear land size for different tool material and operations

criterion

- The two parameters of interest in Crater wear are its maximum depth K_T and the distance K^L between the cutting edge and the location where maximum Crater depth occurs.
- It is obvious that the larger the depth of the Crater becomes weaker is the tool rendered. ISO recommends the following value of crater depth as the tool failure criterion:

  K_T = 0.06 + 0.3f, where f is the feed per revolutions,
- Optiz and Weber have suggested that the ratio of KT / KM is related to the catastrophic failure of the tool ay lie betw

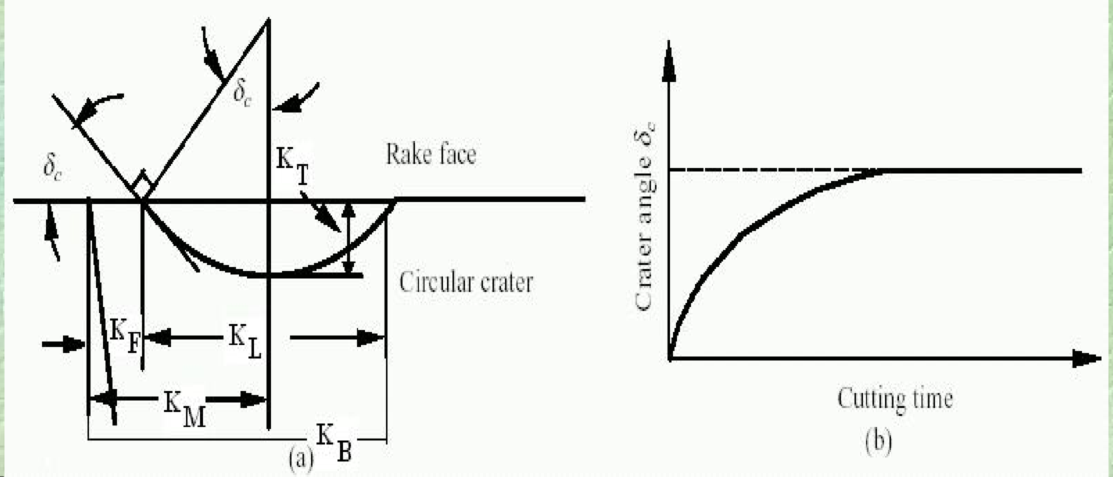


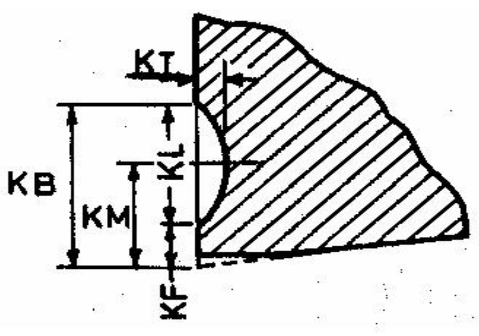
criterion

Crater wear:

- **Depth, KT**
- **Width, KL**
- **Crater angle, ○$_c$**
- **Crater wear index, KI**

$$KI \; 6 \; \frac{KT}{KF \;.\; KL/2}$$



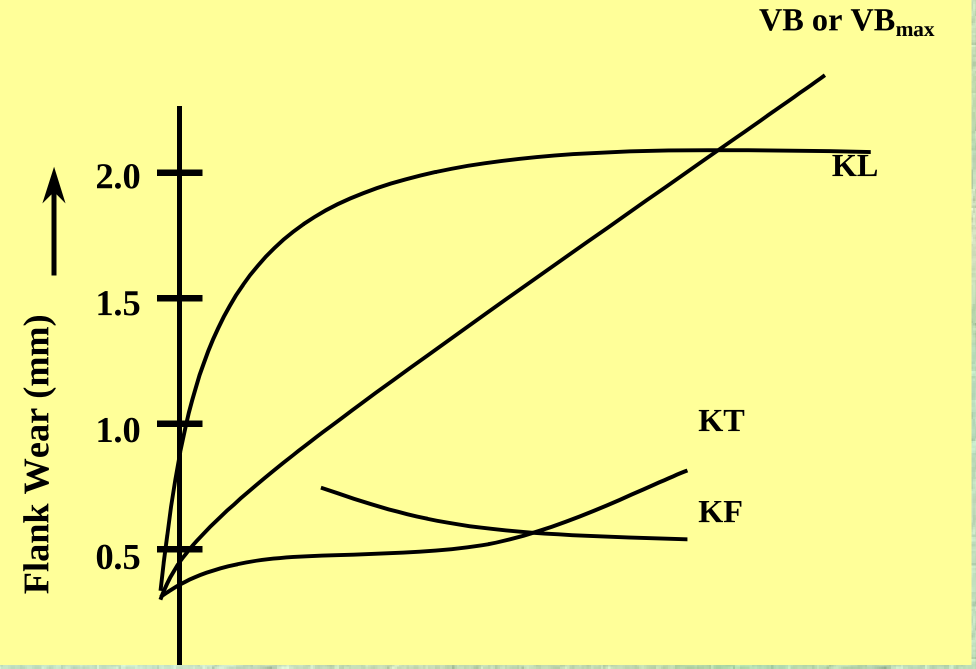


Crater wear is a more realistic tool-failure criterion when high speeds and feeds are used with the more ductile materials yielding continuous-chip formation
* Crater depth is a common criterion used in Europe
* From a practical point of view measurements of crater wear and crater depth are more cumbersome than the wear-land techniques.

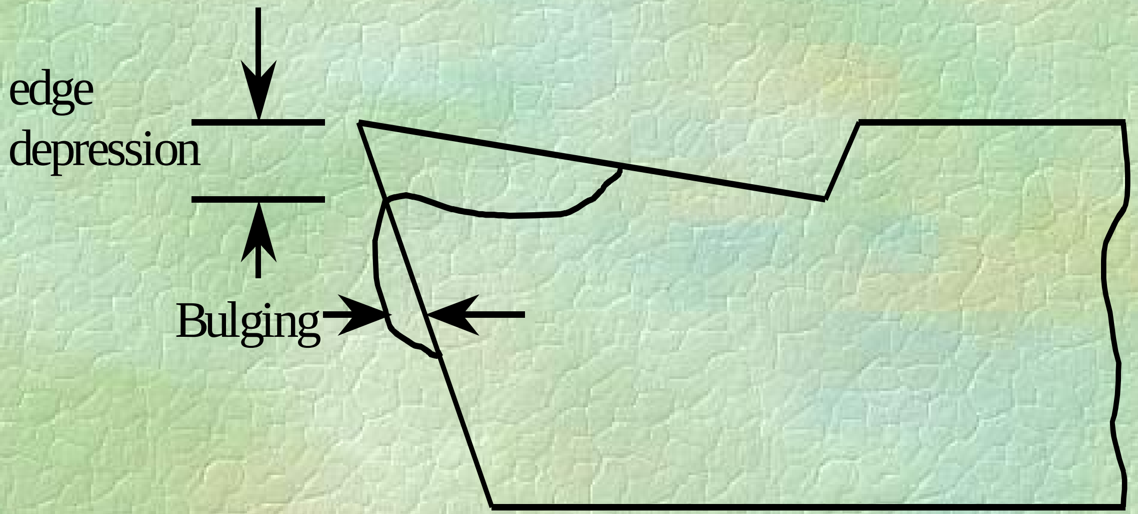
criterion

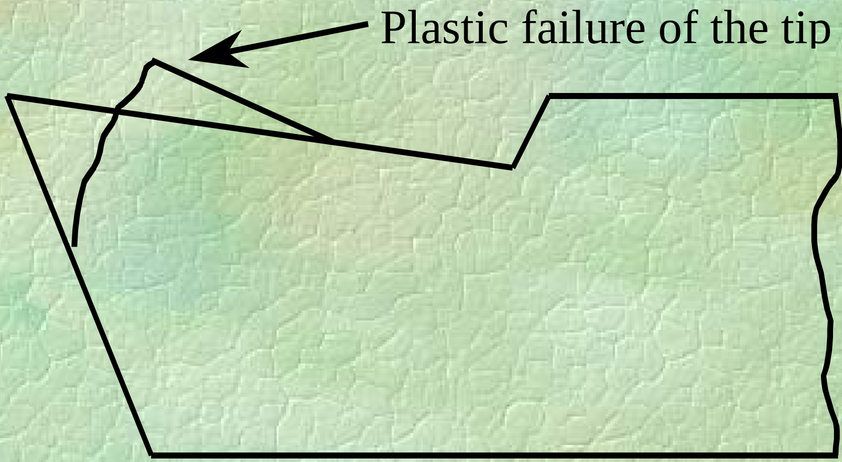
Combination of flank and crater wear: judged by the time to reach the point where rapid wear-growth starts.

- KI = 0.4 for carbide tools
- KI = 0.6 for HSS tools which occurs earlier
- VB = 1 mm



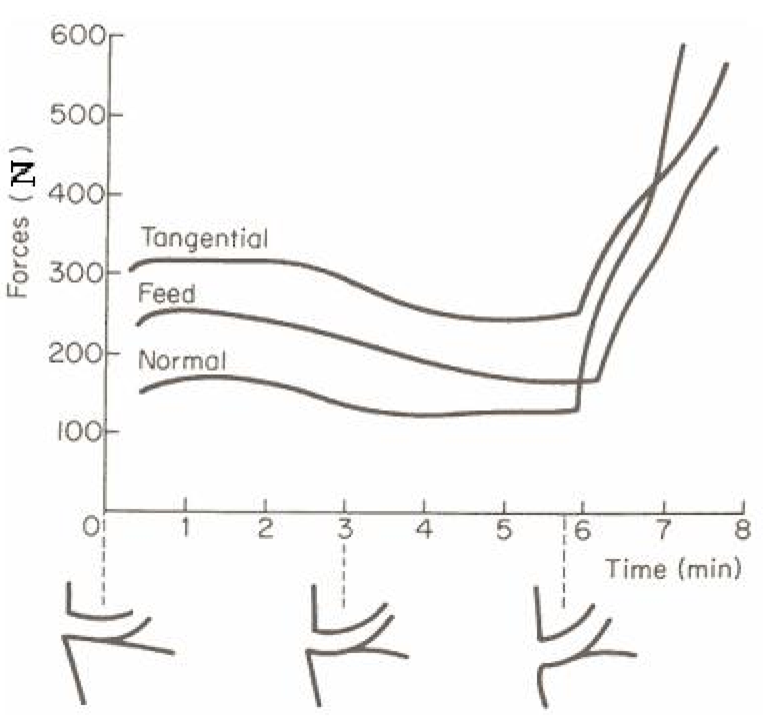
Loss of “Form Stability”





Other Wear Criteria:

- Surface-finish criterion:
  - Requires complicated and portable surface analyzers,
  - The scatter in the surface- finish values may require an increased number of observations.
- Dimensional-accuracy criterion:
  - May be a practical proposition,
  - Difficulties can arise when measuring awkward dimensions.
- Force/Power criterion:
  - A tool dynamometer, preferably coupled to a recorder is required



Variation of tool forces as the tool wears

Tool life:

- Tool life represents the useful life of the tool, expressed generally in time units from the start of a cut to some end point defined by failure criterion.
- A common method of forecasting tool wear is to use Taylor’s equation; his study on tool life was done in 1907.

Frederick W. Taylor 1856-1915

Taylor thought that there is an optimum cutting speed for best productivity. This is reasoned from the fact that at low cutting speeds, tools have higher life but productivity is low, and at higher speeds the reverse is true. This inspired him to check up the relationship of tool life and cutting speed. Based on the experimental work he proposed the formula for

Tool life: Taylor’s Equation

Taylor’s Empirical Equation: $VT\ n = C$

- Where, T = tool lifetime; usually in minutes
- V = cutting velocity, m/min
- C = constant; the cutting velocity for 1 minute of elapsed time before reaching the wear limit of the tool
- n = constant which is considered a characteristic of the tool material, called tool life index.
- Note: at $T = 1$ minute, C becomes equal to the cutting speed
- Each combination of work piece, tool material

values)

Sl No	Tool Materials	Values of "n"
1	**HSS**	0.08 - 0.2
2	**Cemented Carbide**	0.3 - 0.49
3	**Ceramic**	0.5 - 0.7

Sl No.	Work materials	Values of "C" for different Tool Materials		
		HSS	Carbide	Ceramic
1	Carbon steel	40 – 100	200 – 160	2500
2	Cast Iron	30 – 60	100 – 150	9000
3	Stainless Steel	20 – 35	120 – 200	
4	Titanium	10 – 20	100 – 150	
5	Tungste	120	400	

Variables Affecting Tool-Life:

- **Work Material** - physical, thermal and chemical properties.
- **Cutting Conditions** - e.g. speed, feed, depth of cut.
- **Tool Geometry** - e.g. rake angle, approach angle, inclination angle, helix angle, etc..
- **Tool Material** - H.S.S., Carbides, Ceramics, CBN, Diamonds.
- **Cutting Fluids**.

In addition, the **type** and **conditions** of machine tools used are also important.

Effect of Work Material:

- **Hardness**
- **Composition**
- **Microstructure (heat treatment)**
- **Work-hardening properties**

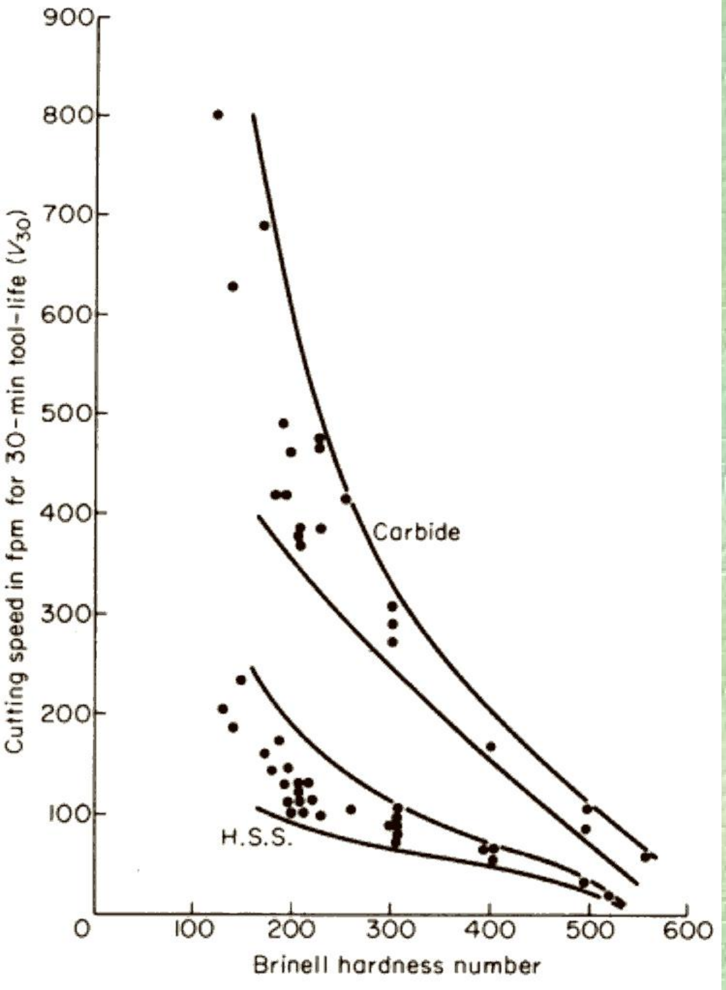
Easiest variable to measure and relate to tool life.

The harder the work material, the lower the tool life.

Effect of Work Material:

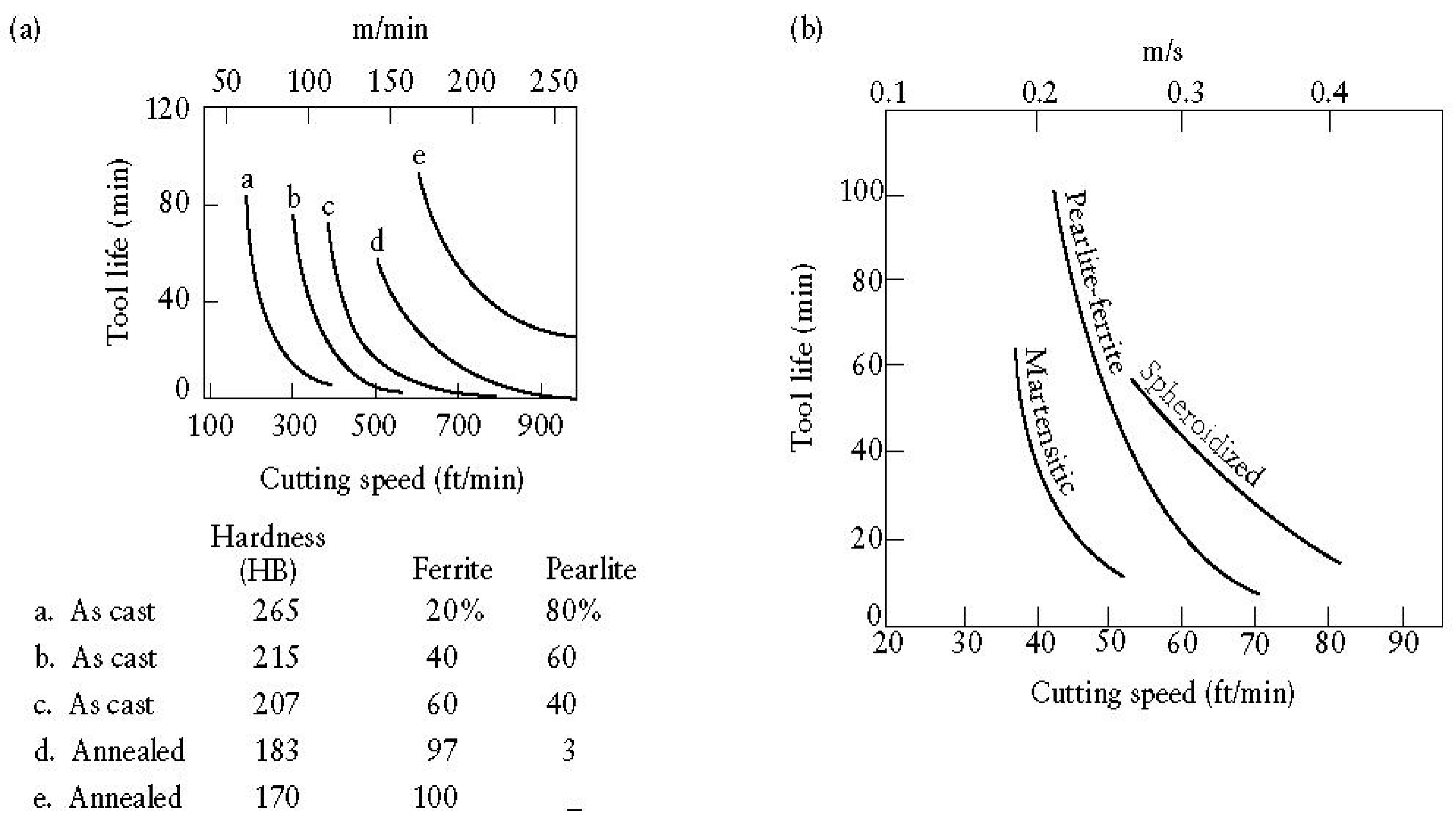
$$V_T \; 6 \, \frac{\text{Constant}}{(B.H.N.)^x}$$

- VT - the cutting speed for a fixed tool life T,
- B.H.N. - Brinell hardness number
- *x* - vary with tool material
- Constant – depends on both work and tool materials



Relation between cutting speed for a fixed tool life and Brinell hardness

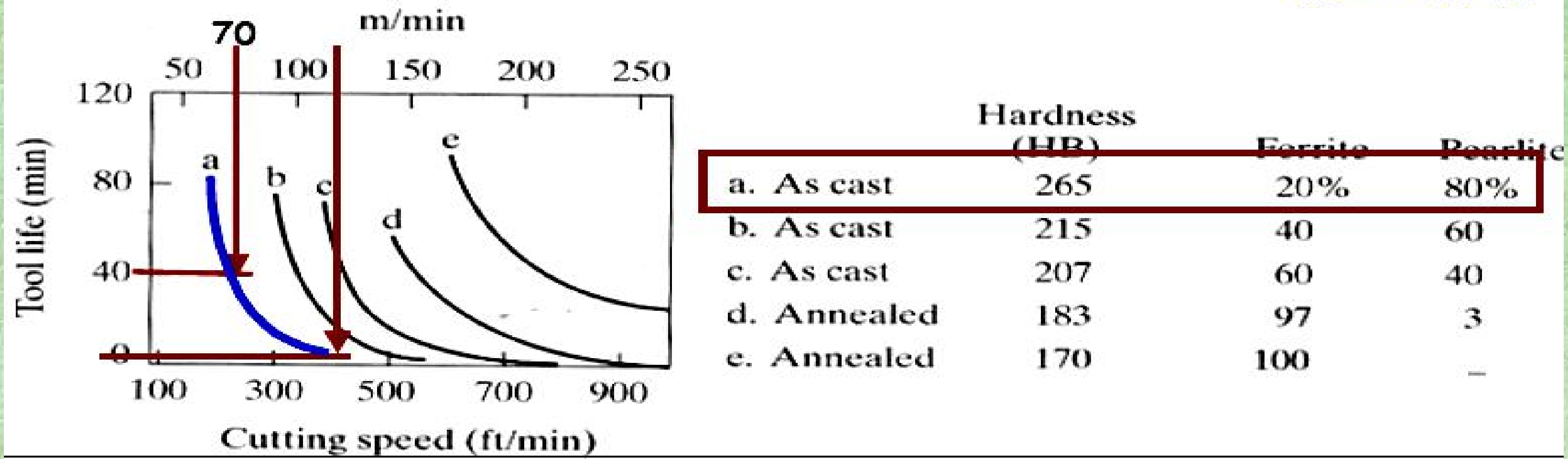
Effect of Work piece Microstructure on Tool Life in Turning:



	Hardness (HB)	Ferrite	Pearlite
a. As cast	265	20%	80%
b. As cast	215	40	60
c. As cast	207	60	40
d. Annealed	183	97	3
e. Annealed	170	100	–

FIGURE : Effect of work piece microstructure on tool life in turning. Tool life is given in terms of the time (in minutes) required to reach a flank wear land of a specified dimension. (a) ductile cast iron. (b) Steels, with identical hardness.

Effect of Work piece Microstructure speed & on Tool Life in Turning:



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a. As cast	265	20%	80%
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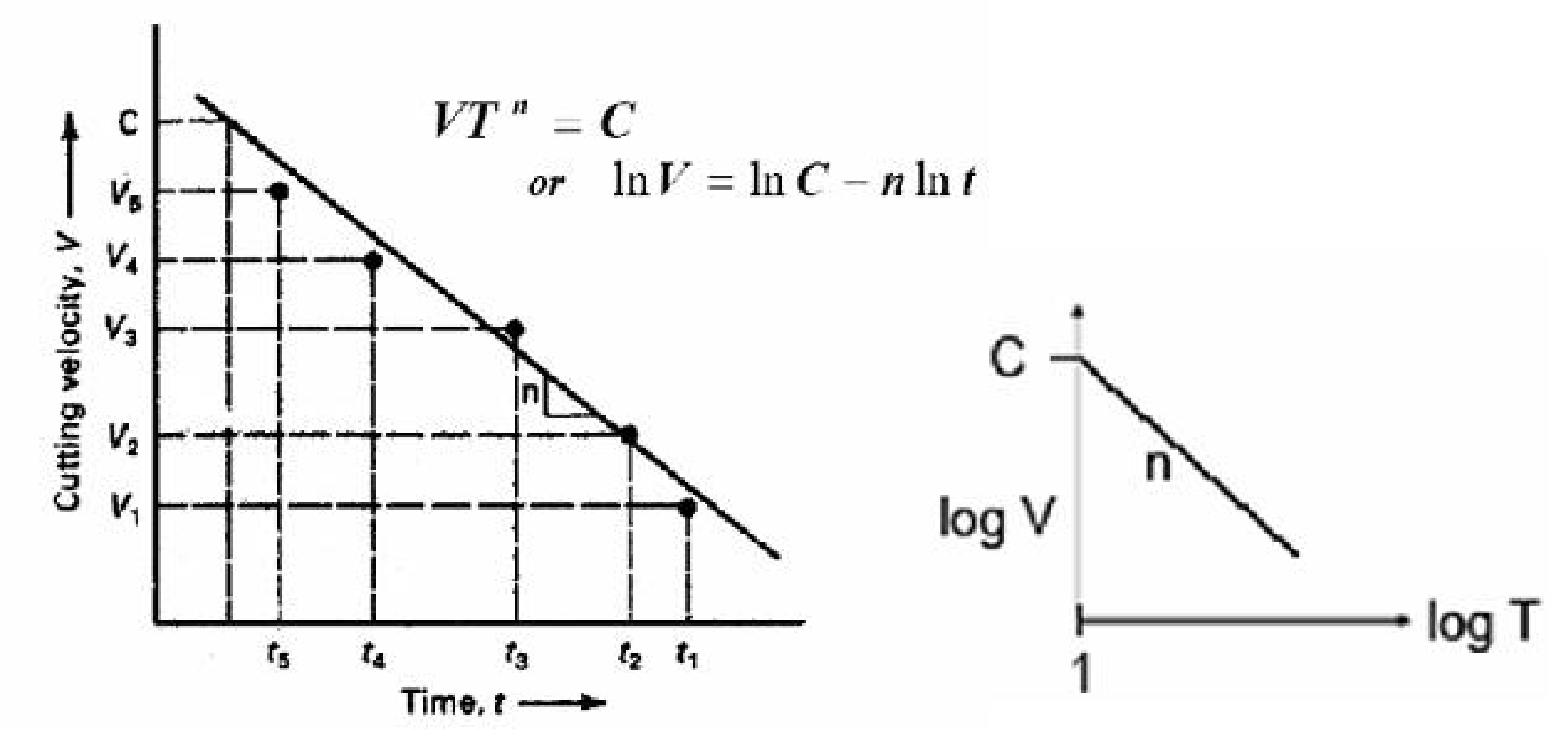
d. Annealed	183	97	3
e. Annealed	170	100	–

- The tool life curves above are obtained in cutting various ductile cast irons. Note the rapid decrease in tool life as the cutting speed increases and the strong influence of the condition of the work piece material microstructure on the tool life.
- **Effect of cutting speed upon material removal:** a material is being machined in the “a” condition – 265 HB; see the figure above
  - If the cutting speed is 70 m/min, tool life is about 40 min and the tool has “traveled” 70 m/min X 40 min = 2800 m before being replaced.
  - If the cutting speed is increased to 120 m/min, tool life is about 5 min and the tool “travels” 120 m/min X 5 min =

Effect of Work piece Microstructure & Speed on Tool Life in Turning:



Tool life curves are usually plotted on log-log paper or are plotted taking log of the equation, from which we can easily determine the exponent “n”.

Effect of Cutting Conditions:

- **Generalised Taylor Equation:**

$$T = \frac{K}{V^{\frac{1}{n}} f^{\frac{1}{n_1}} d^{\frac{1}{n_2}}}$$

- Where
  - T - the tool life (minutes),
  - V - the cutting speed (m/min),
  - f - the feed (mm/rev),
  - d - the depth of cut (mm),
  - K - a constant for a given **tool-work combination** and **tool geometry**,
  - $1/n$, $1/n_1$, $1/n_2$ – exponents of the speed, feed and depth of cut respectively

Effect of Cutting Conditions:

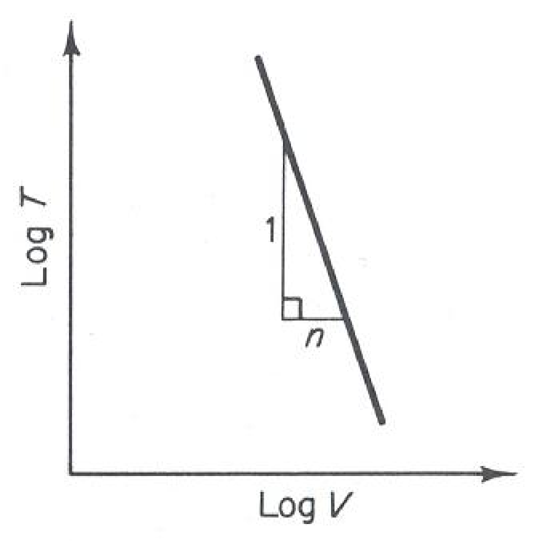
- The values of the exponents, $1/n$, l/n_1 and l/n_2 as well as K, will depend on **the failure criterion**.

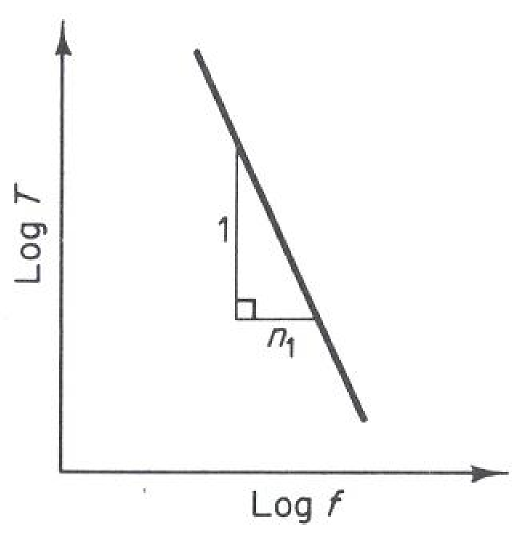
- These exponents will also vary with **different tool** and **work materials**.

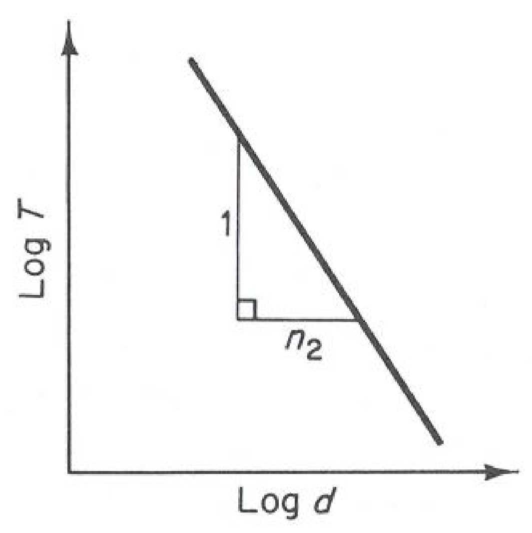
- These exponents describe **the effect of the variables on tool life**.

- It is usually found that **$1/n > l/n_1 > l/n_2$** so that **the cutting speed has the greatest influence** on the tool life, followed by **the feed** and **the depth of cut**.

Effect of Speed, Feed & Depth of cut on Tool Life:







Criterion:

1.Determination of the associated variables in turning operation

General function of the variables: $w = fn(t, V, f, d,$

- *w* wear land size (mm)
- *t* cutting time (min)
- *V* cutting speed (m/min)
- *f* feed per revolution (mm/r)
- *d* depth of cut

2. Set up different level of cutting speed *V*, feed *f*, and depth of cut *d*

3. Measure the wear land size *w* at a pre-determined the time interval and measure the time *t*

Criterion:

5. Use multi-variable regression analysis to curve-fit the wear land size with regard to other variables

$$w = C \cdot t^{a} \cdot V^{x} \cdot f^{y} \cdot d^{z}$$

re-arranging the above equation, we can have

$$t = \left[\frac{w}{C}\right]^{\frac{1}{a}} \frac{1}{V^{\frac{x}{a}}} \frac{1}{f^{\frac{y}{a}}} \frac{1}{d^{\frac{z}{a}}}$$

When the failure criteria is set, i.e. $w = w_c$, the tool-life equation can be written as:

$$T = \left[\frac{w_c}{C}\right]^{\frac{1}{a}} \frac{1}{V^{\frac{x}{a}}} \frac{1}{f^{\frac{y}{a}}} \frac{1}{d^{\frac{z}{a}}}$$

Cutting Conditions :

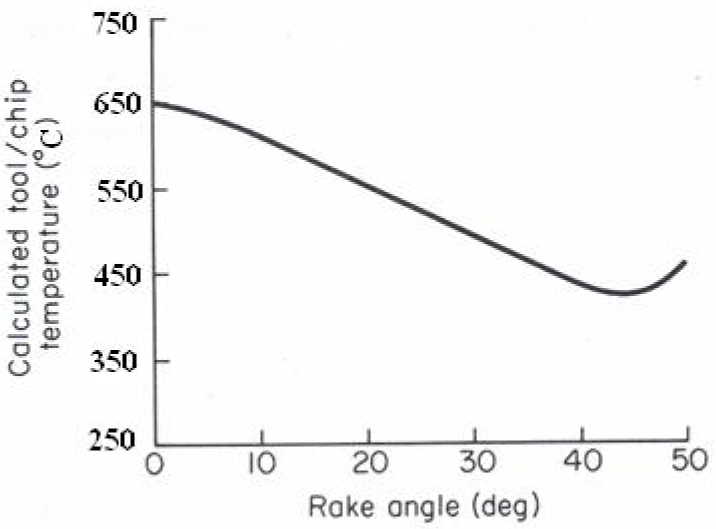
$$T = \frac{K}{V^{\frac{1}{n}} f^{\frac{1}{n_1}} d^{\frac{1}{n_2}}}$$

$$where \ \frac{1}{n} = \frac{x}{a}, \frac{1}{n_1} = \frac{y}{a}, \frac{1}{n_2} = \frac{z}{a} \ and \ K = \left[\frac{w_c}{C}\right]^{\frac{1}{a}}$$

For roughing, w_c is usually set to a larger value, and from the equation it can be found that larger w_c will result in longer tool-life.

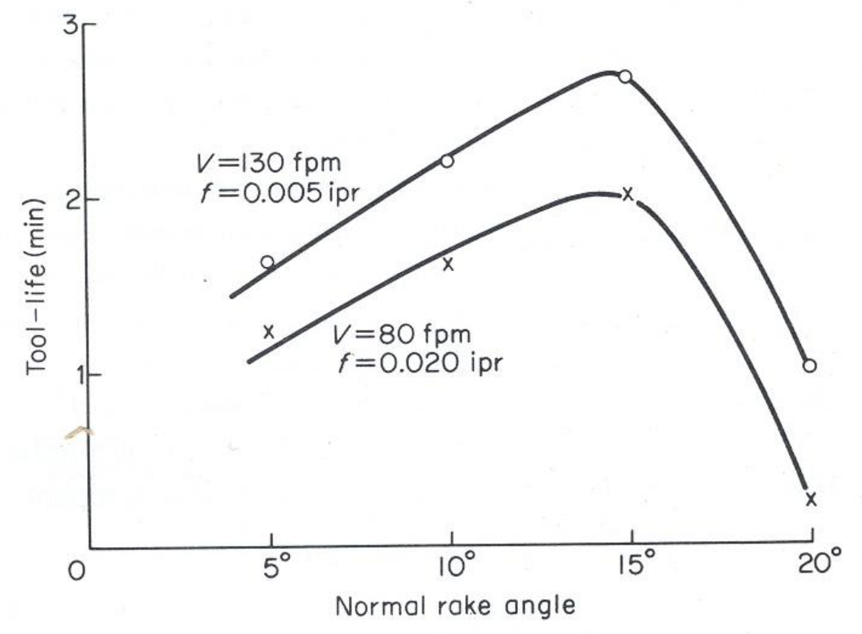
For finishing operation, w_c is usually set to a smaller value.

Effect of Tool Geometry on Tool Life:



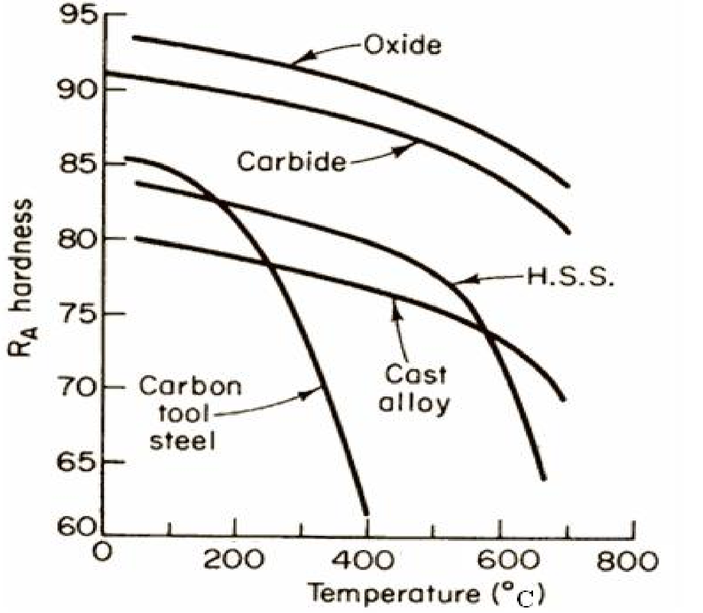
(a)

Effect of rake angle on the calculated tool-chip interface temperature in orthogonal cutting

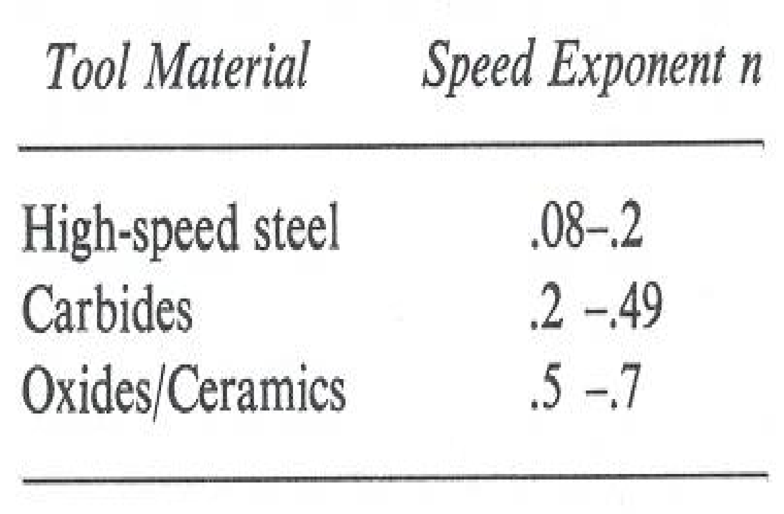


Effect of rake angle on tool life

Effects of Tool Materials on Tool Life:



Effect of temperature on the hardness of various tool materials



Tool Material	Speed Exponent n
High-speed steel	.08–.2
Carbides	.2 –.49
Oxides/Ceramics	.5 –.7

- Effect of temperature on hardness of tool hardness
- Approximate variation of speed exponent n for different tool materials
- **The smaller the value *n* (or the larger 1/*n*), the greater the effect of**

Cutting fluids:

Definition:

- Cutting fluids, sometimes referred to as lubricants or coolants, are liquids and gases applied to the tool and work piece to assist the cutting operation.

Functions of cutting fluids:

Primary Functions: To increase tool life by

- To cool the tool. To reduce temperature of tool, cutting zone & tool chip interface.
- To cool the work piece, cutting zone & tool work interface.
- To lubricate and reduce friction at interfaces and reduce power used to over come friction.

Secondary Functions:

- To improve surface finish.
- To protect the finished surface from corrosion.
- To wash the chips away from the tool.
- To reduce power used for cutting.

Cutting Fluids:

Properties of cutting fluids:

- High heat absorption capability. High specific heat.
- Good lubricating quality. Polar property.
- Good wettability.
- High flash point so as to eliminate the hazard of fire.
- Stability so as not to get oxidized in presence of air.
- Neutral so as not to react chemically.
- Odorless so as not to produce bad smell even when heated.
- Harmless to the skin of the operators.
- Non corrosive to the work or the machine.
- Transparency so that the cutting action of tool may be observed by the operators.

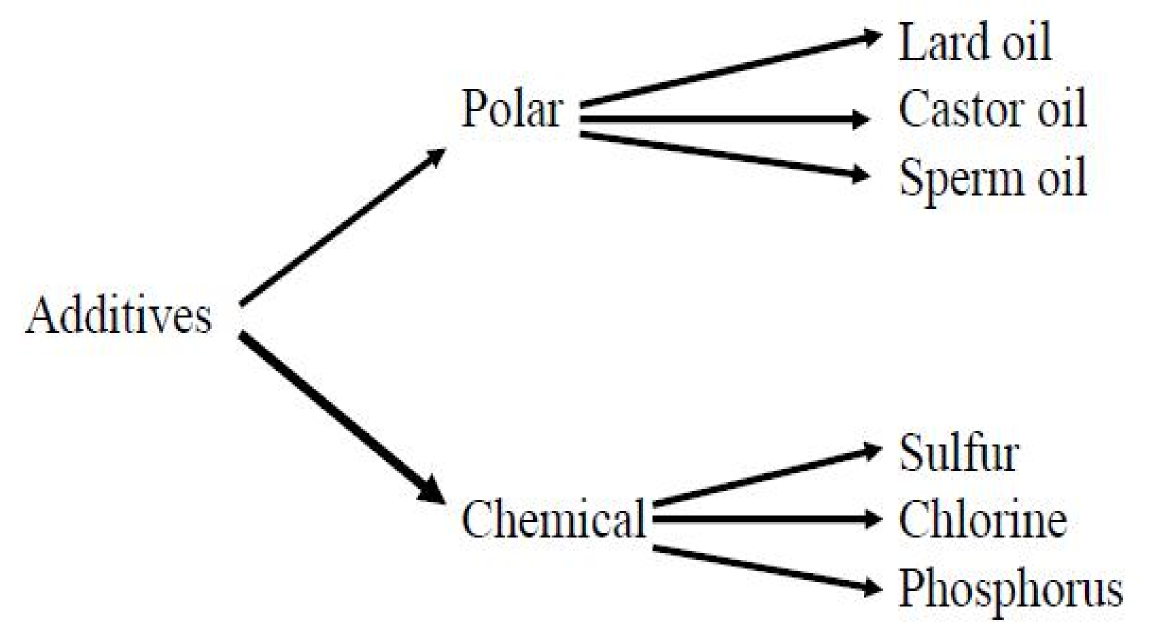
Types of cutting fluid:

- ***Water:*** Water provided good cooling effect but is not a good lubricant. Water is hardly used as cutting fluid because of its corrosiveness.
- ***Soluble oil or water miscible cutting fluids or Emulsions:*** These are also called water based cutting fluids. These comprises of mineral oil or fat mixtures and emulsifiers added to water. The emulsifier breaks the oil into minute particles and disperses them throughout water. These cutting fluids have excellent lubricating properties. It has milky appearance.
- ***Straight cutting oils:*** These oils have good lubricating but poor heat absorption properties and therefore are suitable only for low cutting speed.
- These are of three types:

  Mineral oil: Kerosene, low viscosity petroleum fraction.
  Fatty oil: Lard oil

  Combination of mineral and fatty oil
- ***Oils with adhesives:*** The benefits of mineral oils can be improved with the help of adhesives, which are generally compounds of sulphur or chlorine. Addition of sulphur or

Cutting Fluids:

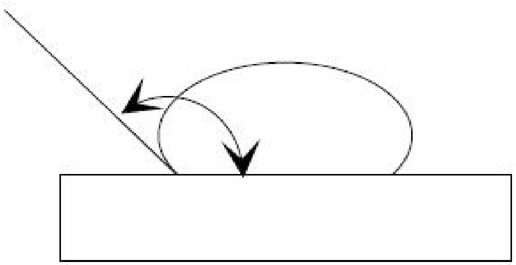


- Additives
  - Polar
    - Lard oil
    - Castor oil
    - Sperm oil
  - Chemical
    - Sulfur
    - Chlorine
    - Phosphorus

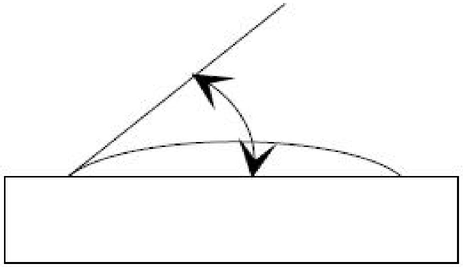
Polar additives:

Improve boundary lubrication property

Improve wetting effect

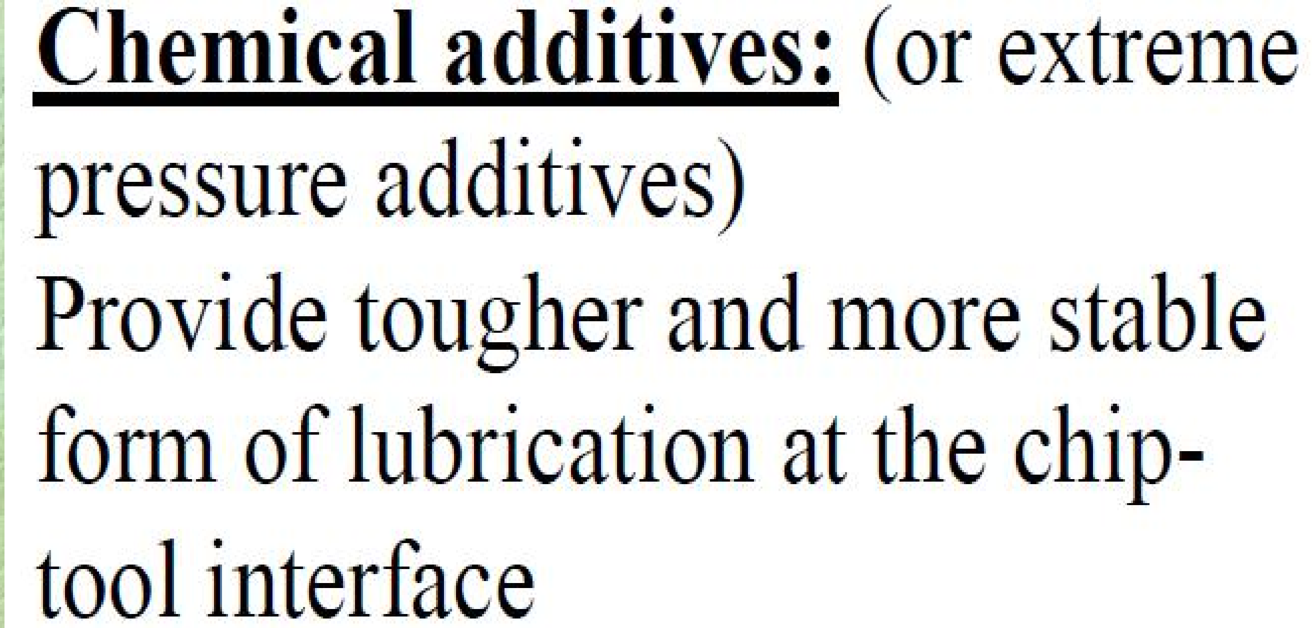


Poor wetting



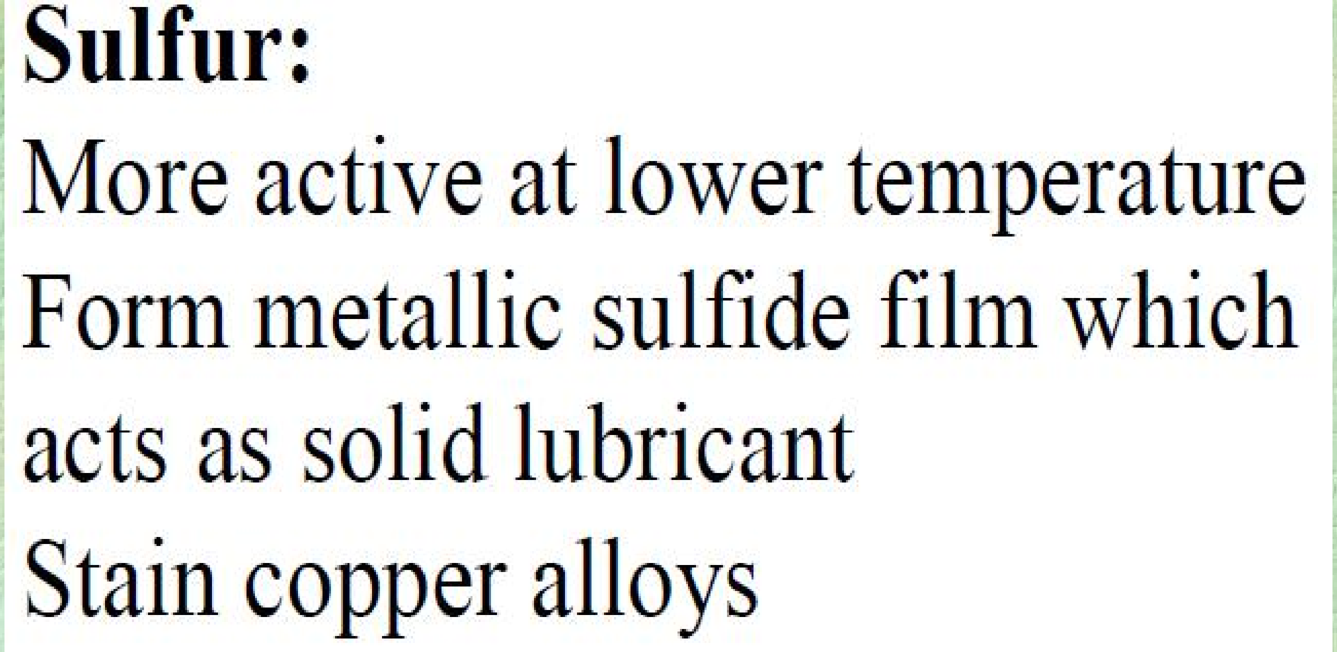
Better wetting

Cutting Fluids:



Chemical additives: (or extreme pressure additives)

Provide tougher and more stable form of lubrication at the chip-tool interface



Sulfur:

More active at lower temperature

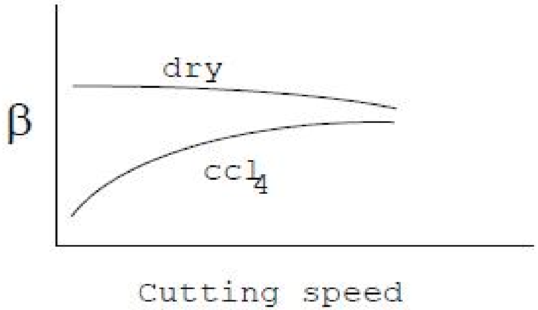
Form metallic sulfide film which acts as solid lubricant

Stain copper alloys

Cutting Fluids:

Chlorine:

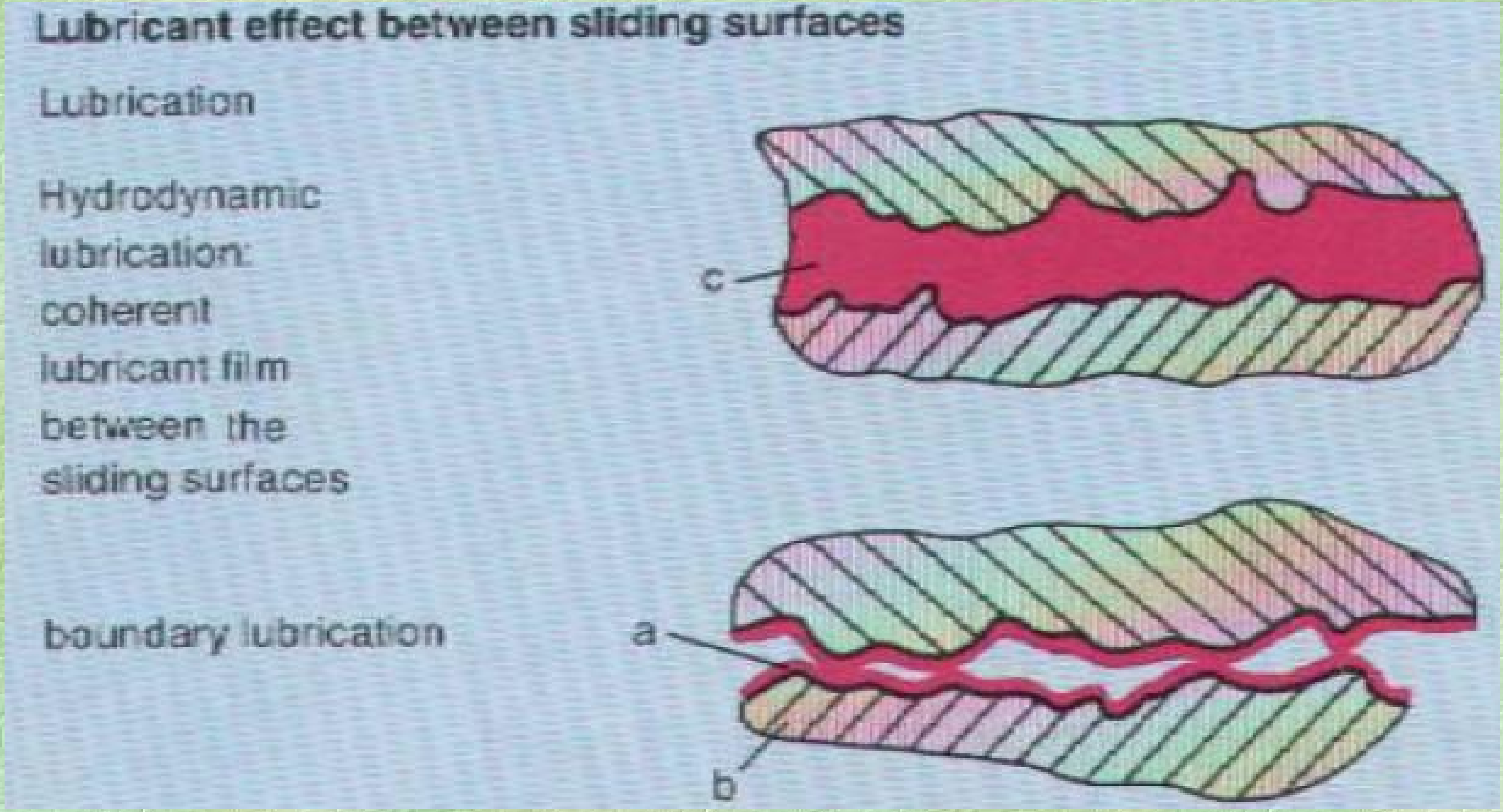
React chemically with workpiece and reduces the friction, therefore lowers power consumption.



Phosphorus:

Retain stability at lower temperature than other two chemical additives

Cutting Fluids:

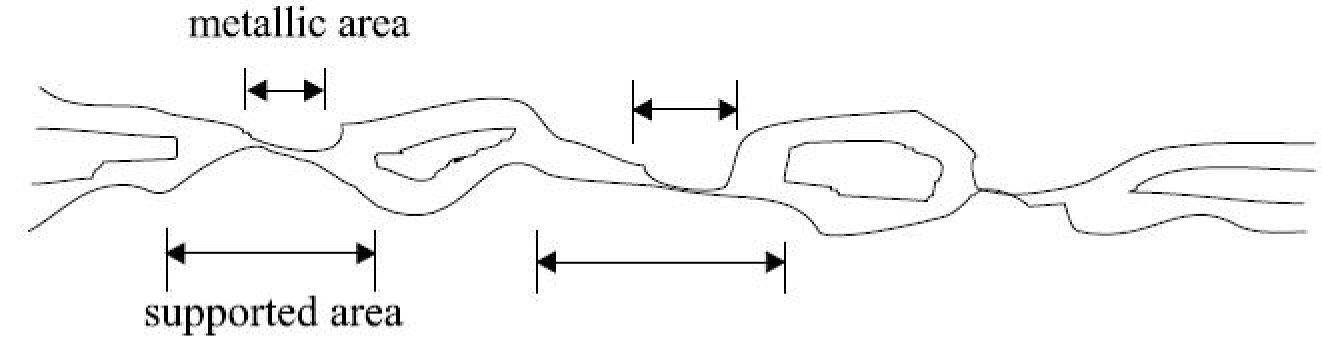


Lubricant effect between sliding surfaces

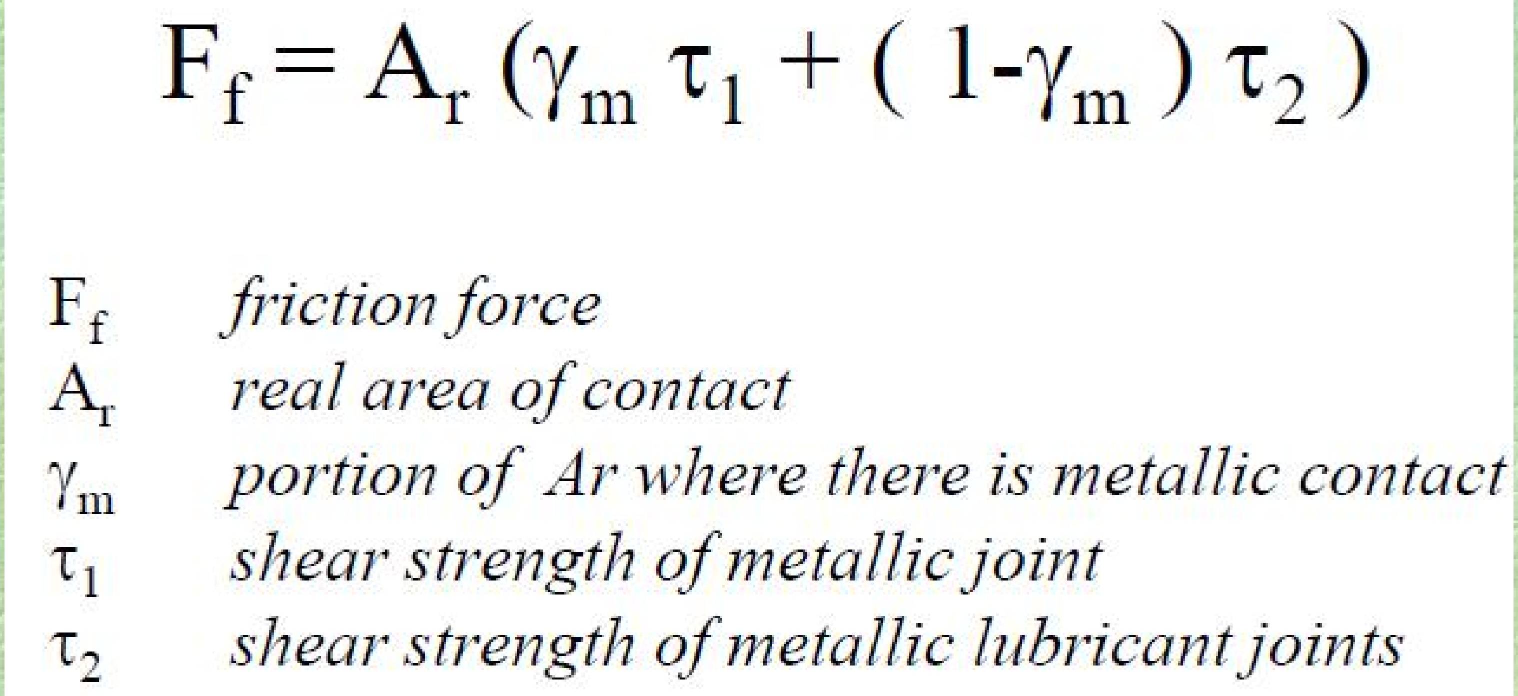
Lubrication

Hydrodynamic lubrication: coherent lubricant film between the sliding surfaces

boundary lubrication



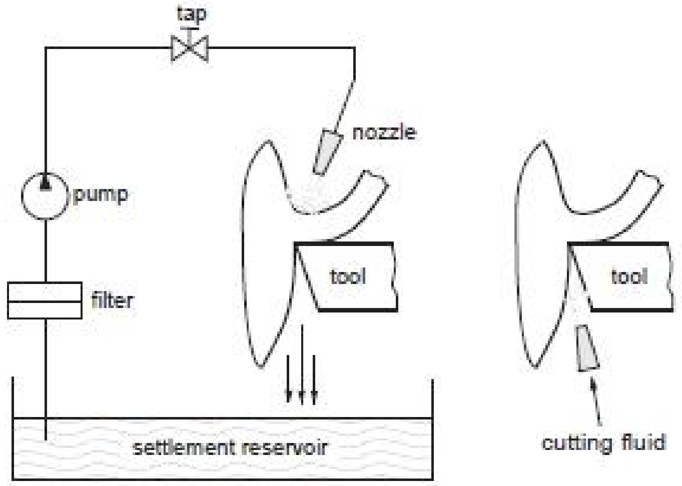
Cutting Fluids:



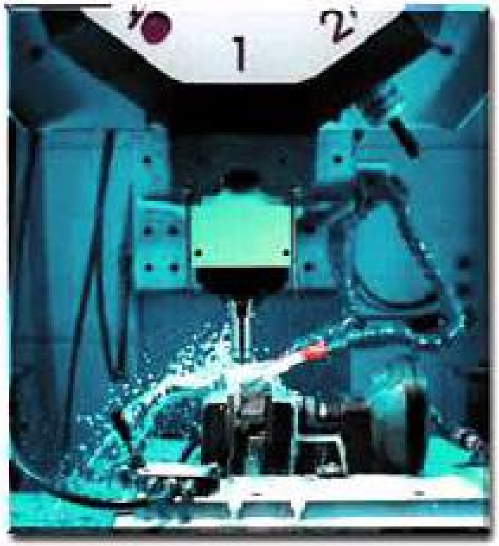
$$F_f = A_r\,(\gamma_m\,\tau_1 + (\,1-\gamma_m\,)\,\tau_2\,)$$

F_f	*friction force*
A_r	*real area of contact*
γ_m	*portion of Ar where there is metallic contact*
τ_1	*shear strength of metallic joint*
τ_2	*shear strength of metallic lubricant joints*

Cutting Fluids Application:



Cutting fluid application, (*Left*) Rake face flooding by means of a recirculating system, (*Right*) Flank face application of the cutting fluid

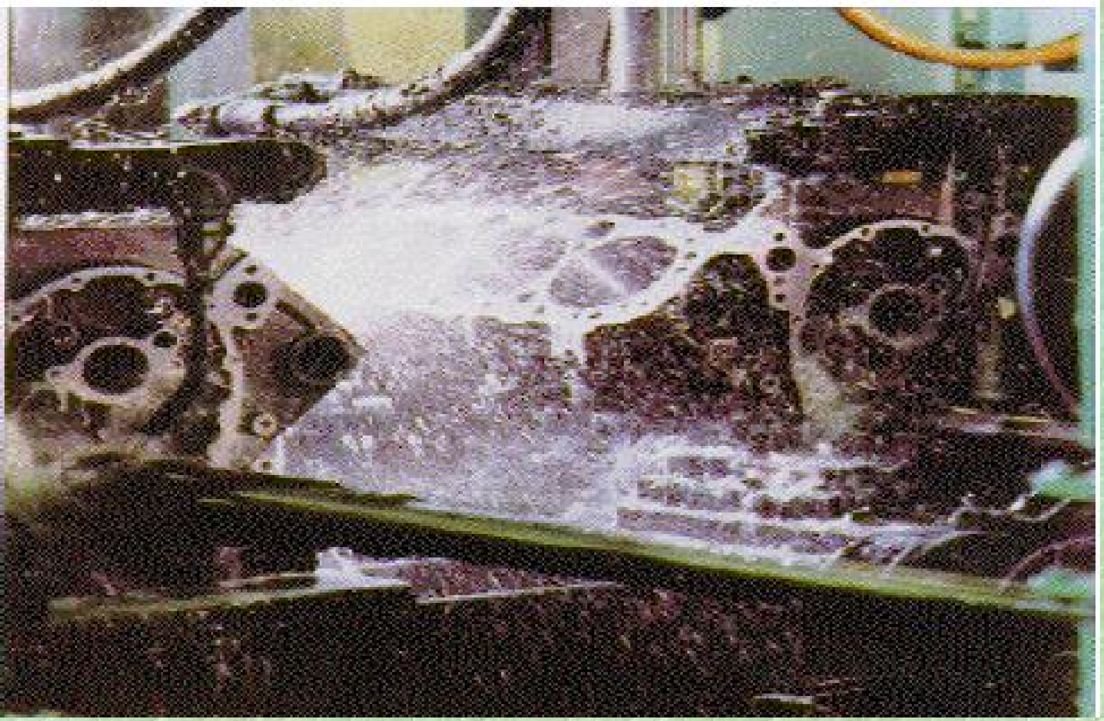


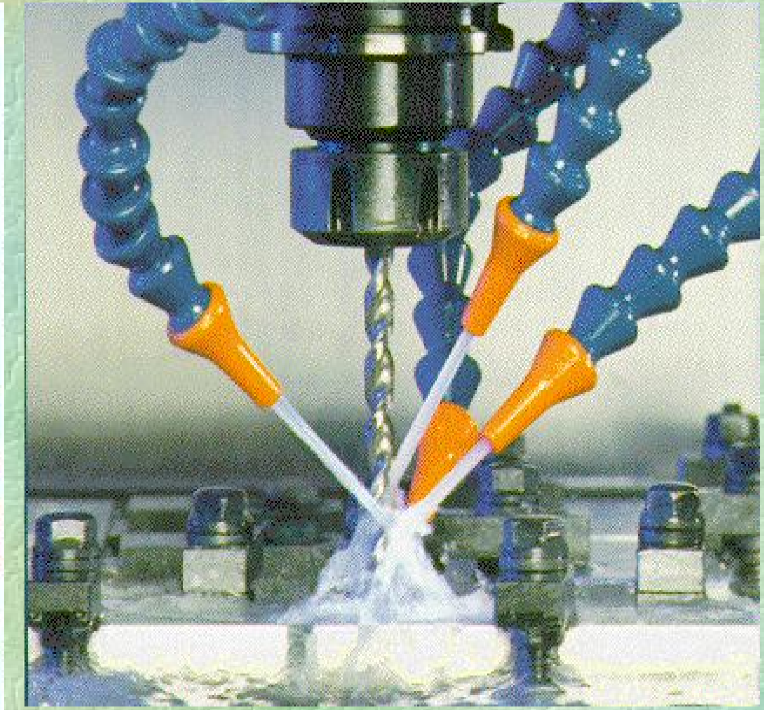
Application of flooding in milling

Application Of Cutting Fluids :

1. Manual Application
2. Flood Application :

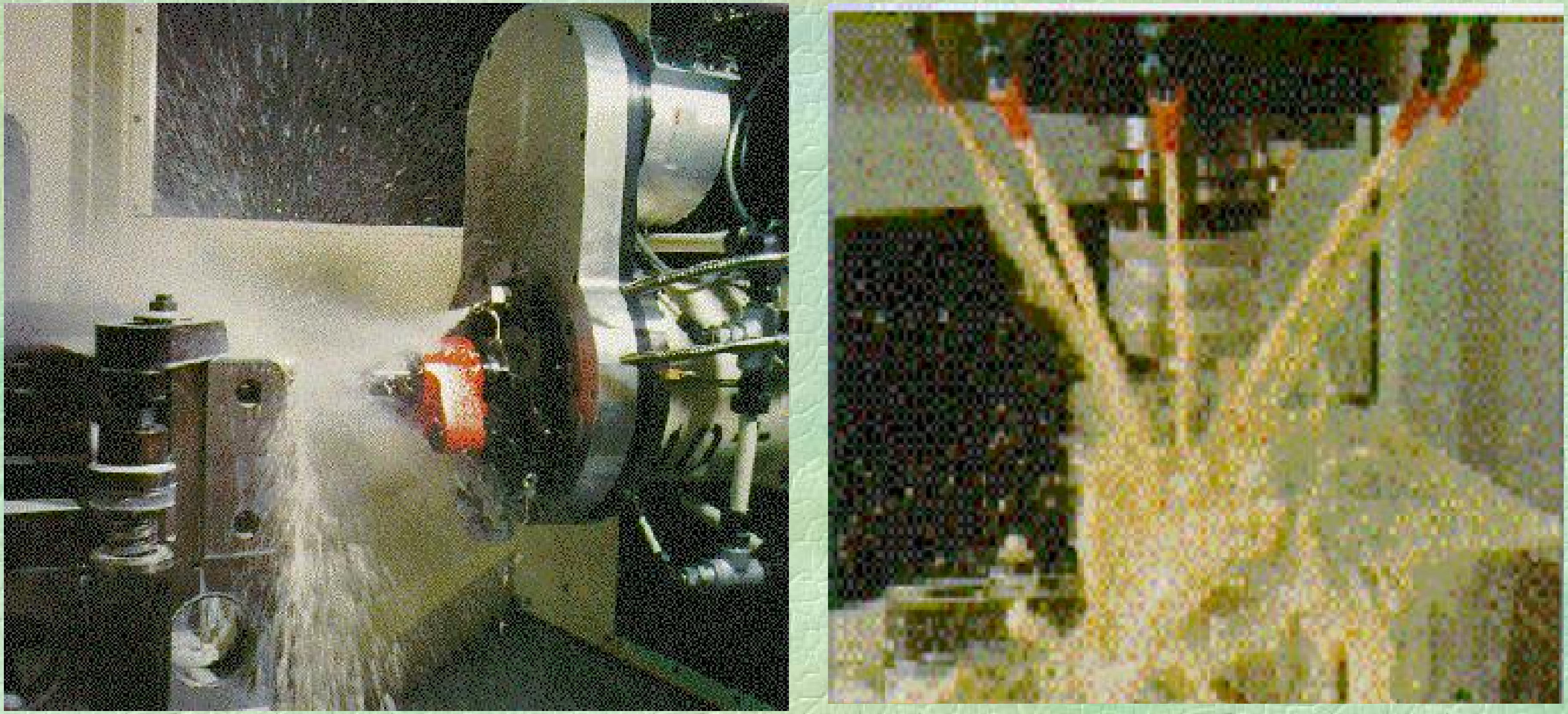
A flood of cutting fluid is applied on the workpiece





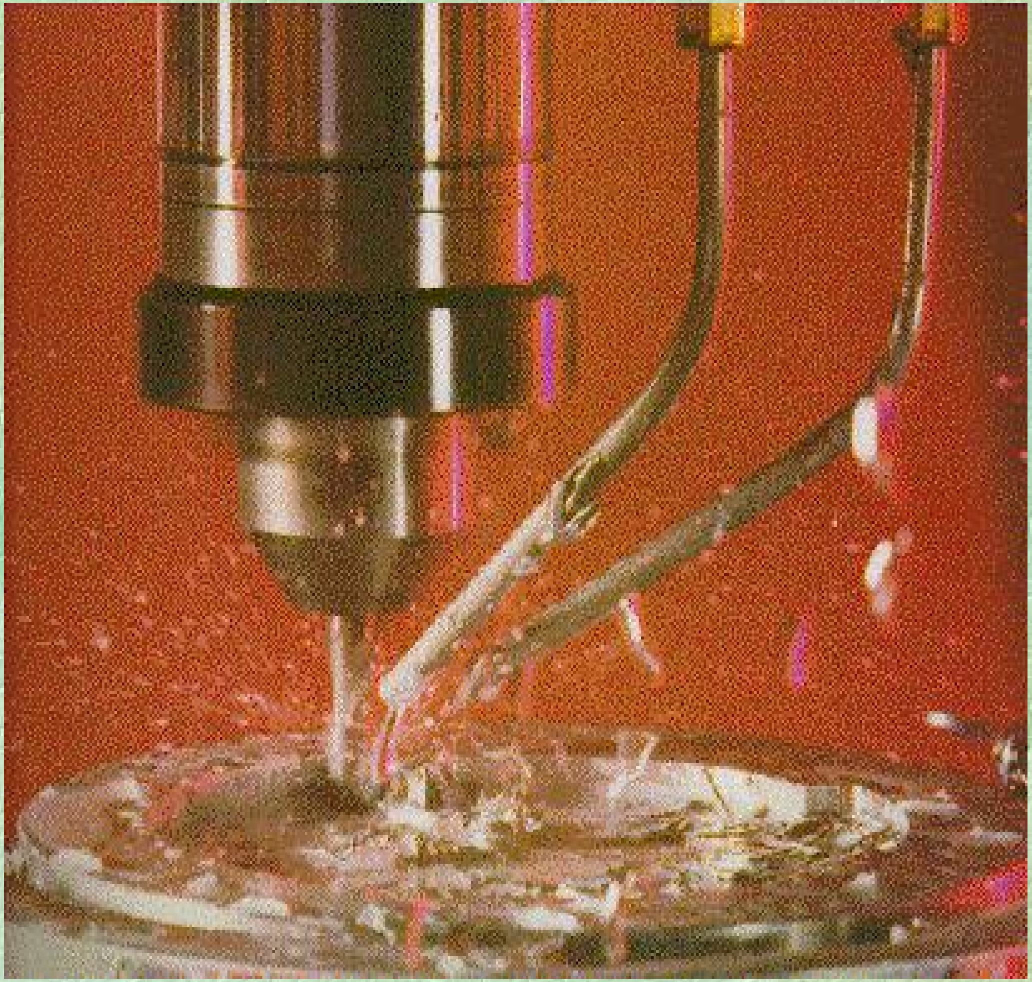
Cutting Fluids:

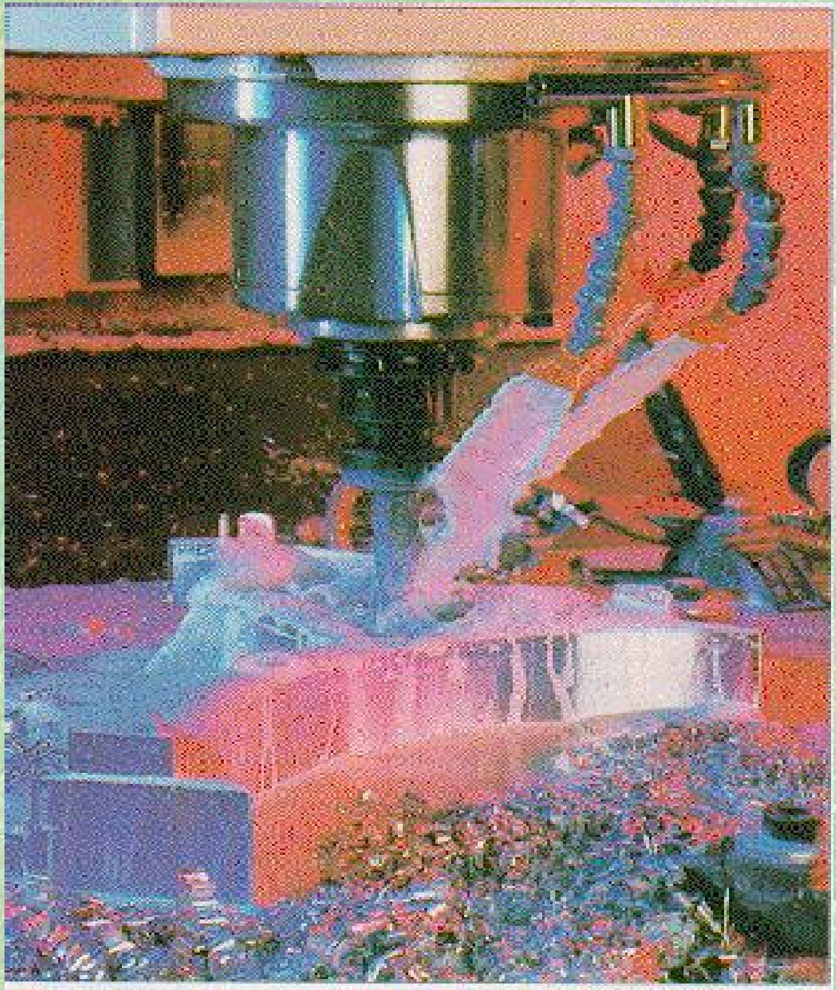
3. Jet Application :a jet of cutting fluid is applied on the workpiece directed at the cutting zone.



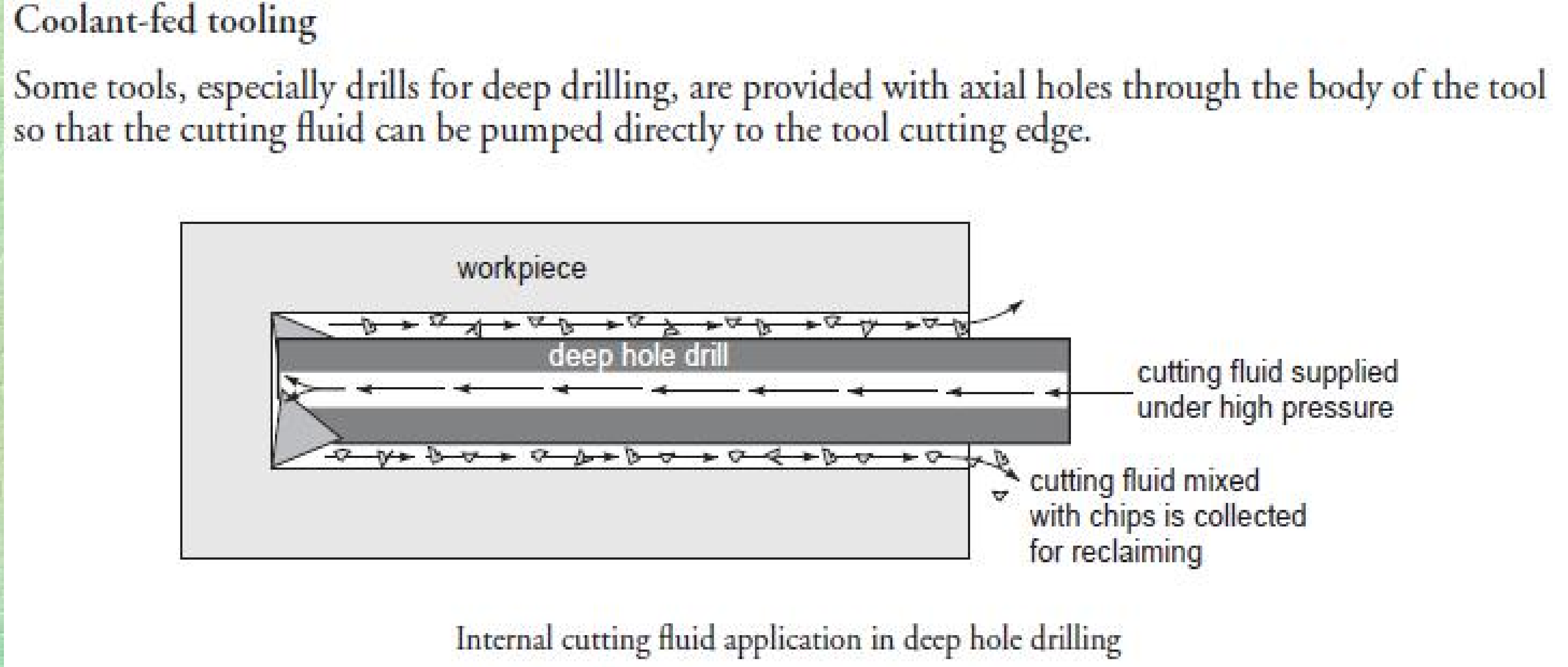
Cutting Fluids:

4. Mist Application :cutting fluid is atomized by a jet of air and the mist is directed at the cutting zone.





Cutting fluid applications:



Coolant-fed tooling

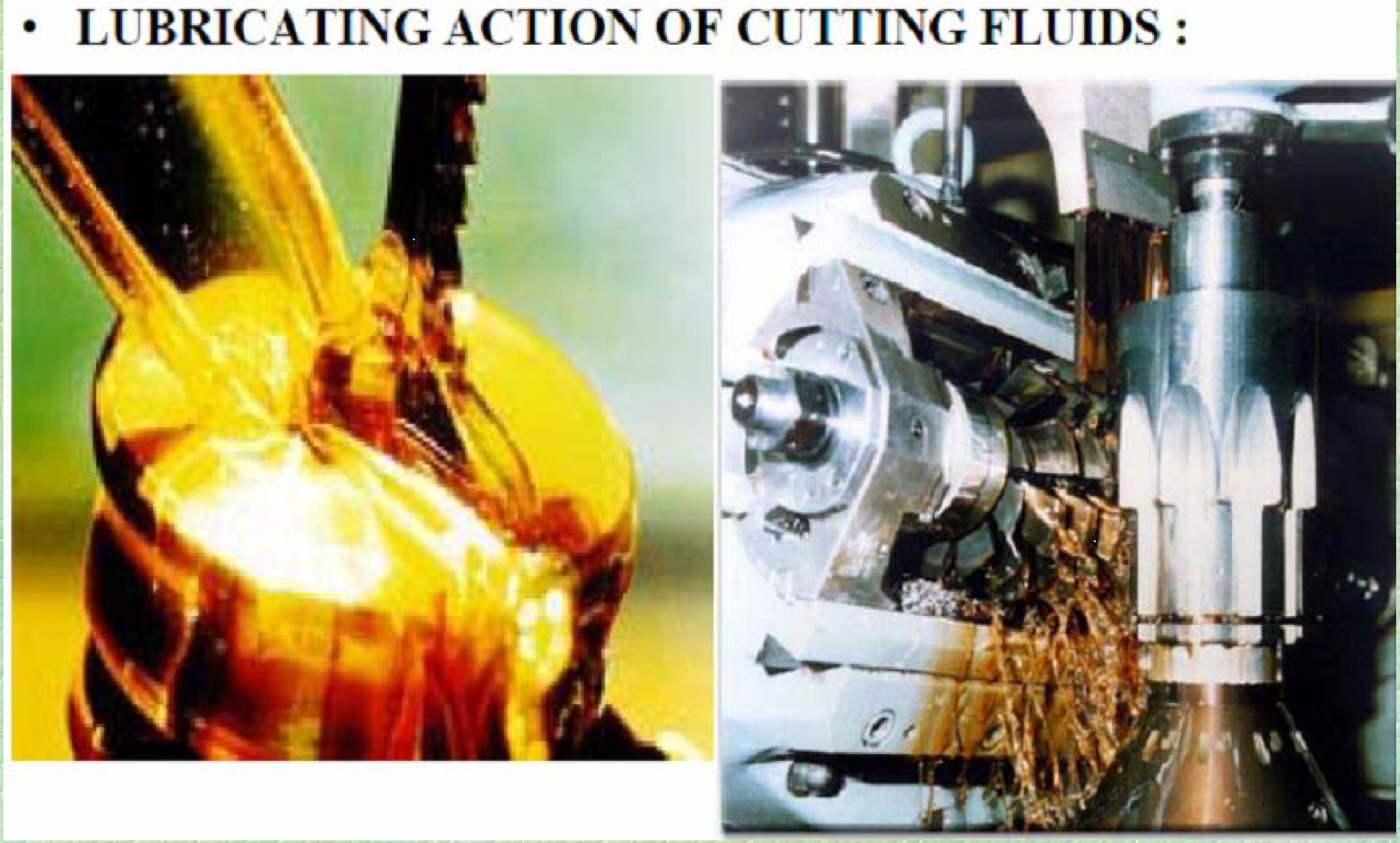
Some tools, especially drills for deep drilling, are provided with axial holes through the body of the tool so that the cutting fluid can be pumped directly to the tool cutting edge.

Internal cutting fluid application in deep hole drilling

Similar to this in grinding the cutting fluid is supplied at the center and then same is supplied to cutting zone through grinding wheel and this method is termed as Z – Z method. It will also through fluid out from non-contact portion of grinding wheel which is

Cutting fluid applications:

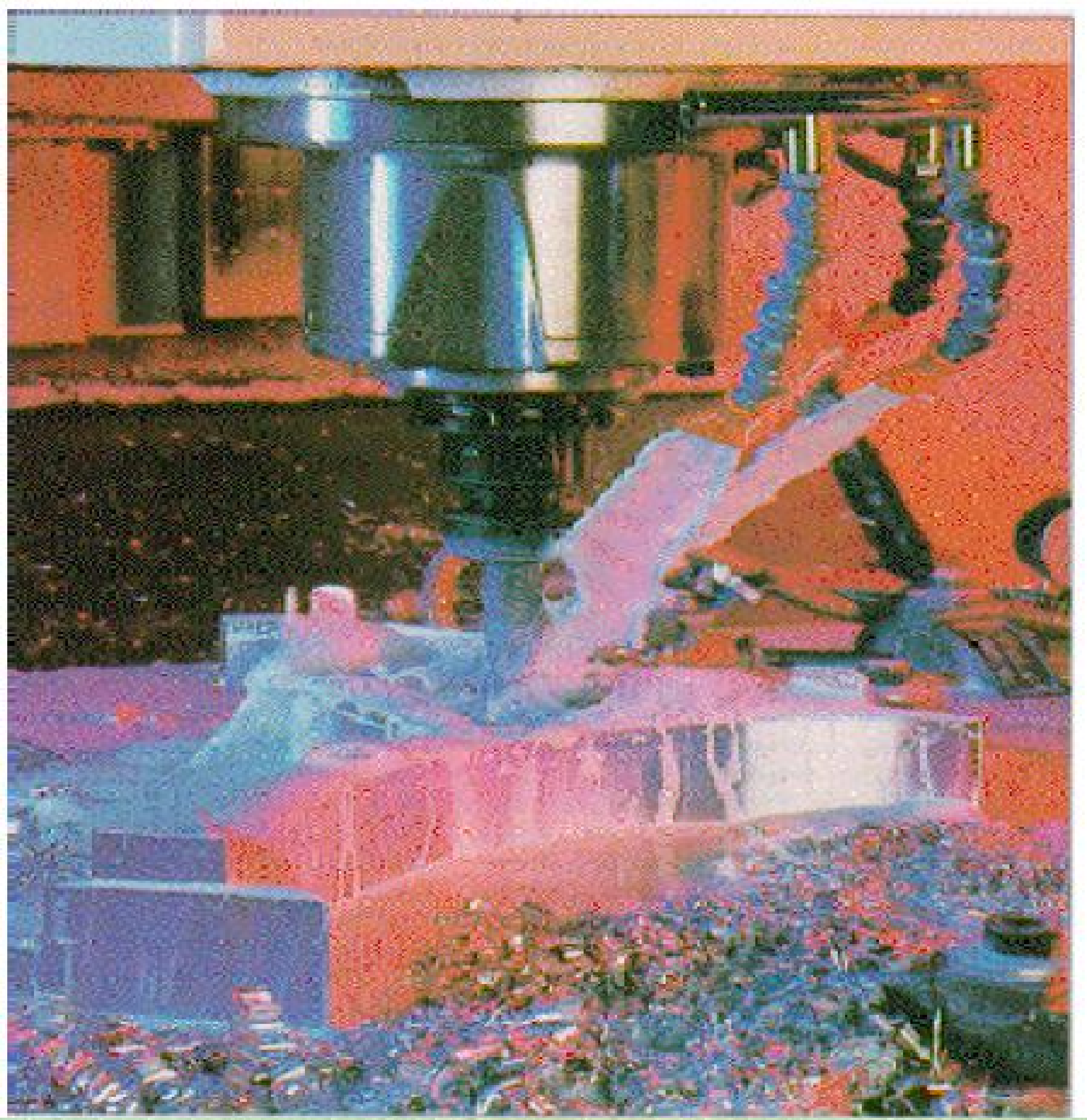
Cutting fluid applications:



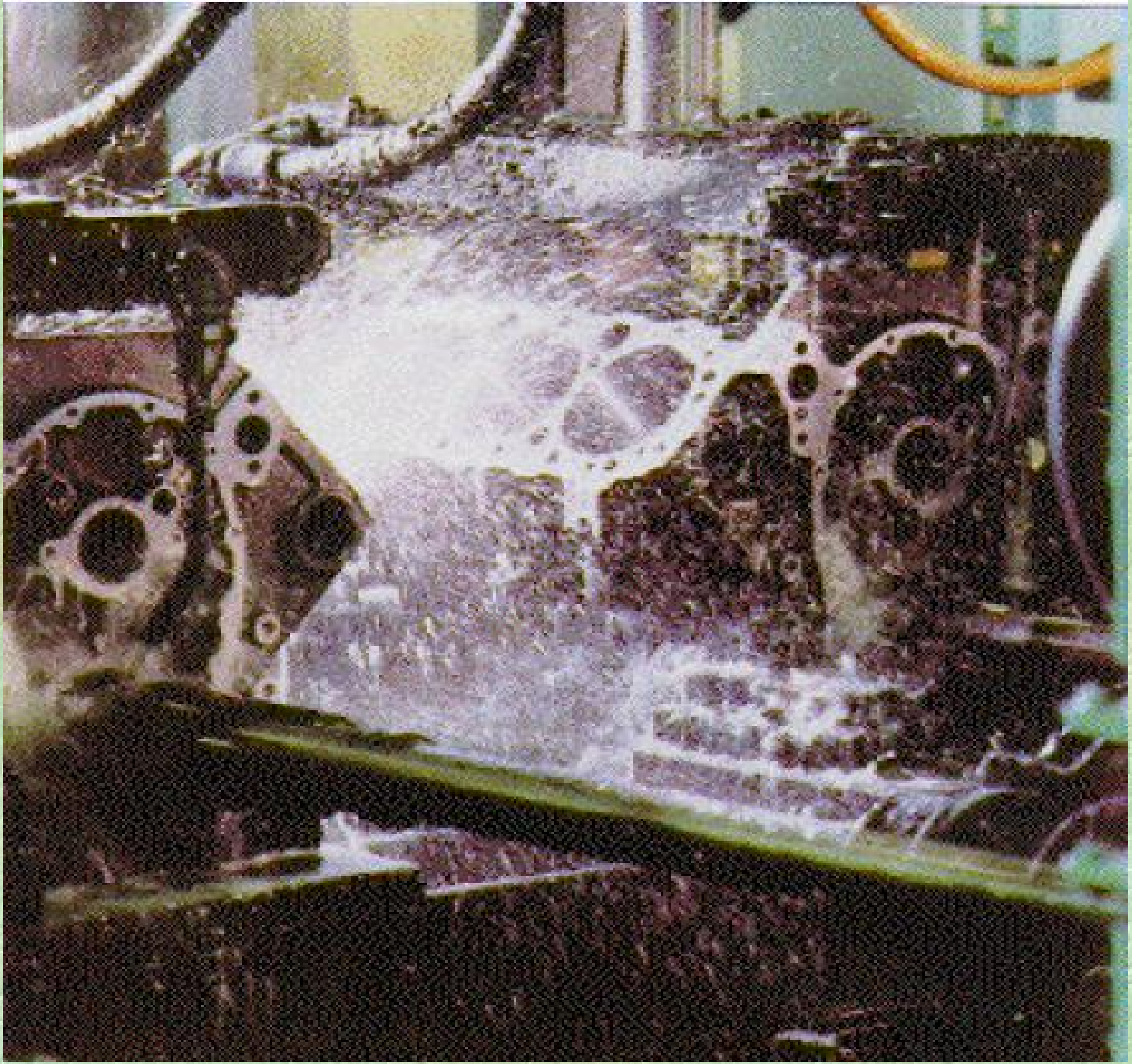
- **LUBRICATING ACTION OF CUTTING FLUIDS :**

Cutting fluid applications:

Cutting fluid applications:



Cutting fluid applications:



Cutting Fluids:

CUTTING FLUID SELECTION CRITERIA :

1. Process performance
2. Heat transfer performance
3. Lubrication performance
4. Chip flushing
5. Fluid mist generation
6. Fluid carry-off in chips
7. Corrosion inhibition
8. Fluid stability (for emulsions)

1. Cost Performance :
2. Environmental Performance
3. Health Hazard Performance

Environmental issues:

Cutting fluids become contaminated with garbage, small chips, bacteria, etc., over time.

Alternative ways of dealing with the problem of contamination are:

- Replace the cutting fluid at least twice per month,
- Machine without cutting fluids (dry cutting),
- Use a filtration system to continuously clean the cutting fluid.
- Disposed cutting fluids must be collected and reclaimed.

There are a number of methods of reclaiming:

- Cutting fluids removed from working area.
- Systems used range from simple settlement tanks to complex filtration and purification systems.
- Chips are emptied from the skips into a pulverizer and progress to centrifugal separators to become a scrap material.

work piece:

- While cutting without cutting fluid leaves surface of work piece with micro-cracks due to shearing action during previous cut. During next cut as tool advances in to work piece the micro-cracks present in work piece surface layer formed by previous cut get welded with further strain hardening causing increased cutting forces.

- Now cutting with cutting fluid results in penetration of cutting fluid in to micro-cracks present due to previous cut and when next cut is taken the cutting fluid present in the micro-cracks does not permit walls of cracks to get welded as it acts as inclusion and tool has to cut low shear strength layer due to micro-cracks forces resulting in with lower cutting forces as if work piece shear strength has reduced or

Economics of machining:

The efficiency of machine tools increases as cutting speeds increase, but tool life is reduced. The main objective of metal-cutting economics is to achieve the optimum conditions, that is, the minimum cost while considering the principal individual costs: machining

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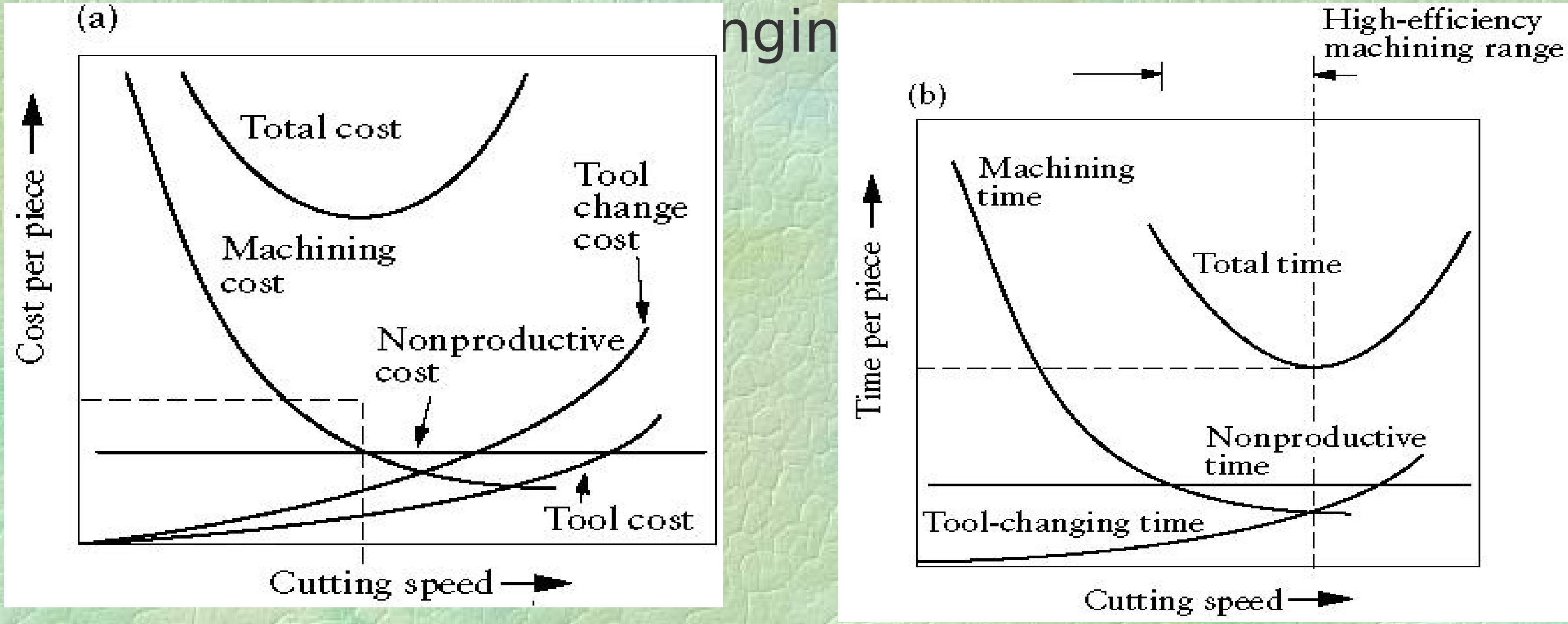

FIGURE :Graphs showing (a) cost per piece and (b) time per piece in machining. Note the optimum speeds for both cost and time. The range between the two optimum speeds is known as the *high-efficiency machining range*.

Economics of machining:

The two most important parameter in in economics of machining are the minimum cost per part and the maximum production rate. The total cost per piece consists of four items:

$$C_p = C_m + C_s + C_l + C_t$$

Where C_p is cost per piece, C_m is the machining cost, C_s is the cost of setting up for the machine for particular operation, C_l is the cost of loading, unloading, and machine handling, and C_t is the tooling cost, which includes tool changing, regrinding, and depreciation of the cutter. The machining cost is given by

$$C_m = T_m(L_m + B_m)$$

Where T_m is the machining time per piece, L_m is the labor cost of the operator per hour, B_m and is the burden rate, or overhead charge of the machine including depreciation, indirect labor etc.

Economics of machining:

The setup cost, C_s is a fixed amount per piece.

The loading, unloading, and machine handling cost, C_l is given by:

$$C_l = T_l(L_m + B_m)$$

Where T_l is the time required in loading and unloading the part, changing speed and feed etc.

The tooling cost, C_t is expressed as:

$$C_t = \frac{1}{N_p}\{T_c(L_m + B_m) + T_g(L_g + B_g) + D_c\}$$

Where N_p is the number of parts machined per tool grind; T_c is the time required to change the tool; T_g is the time required to grind the tool; L_g is the labor cost of the tool grinder operator per hour, B_g is the burden rate of tool grinder per hour; and D_c is the depreciation of the tool in rupees per grind.

Economics of machining:

The time needed to produce one part is
$$T_p = T_l + T_m + \frac{T_c}{N_p}$$

Where T_m has to be calculated for each particular operation.

For turning operation, the machining time is
$$T_m = \frac{L}{fN} = \frac{\pi LD}{fV}$$

From Taylor's tool life equation
$$T = \left(\frac{C}{V}\right)^{\frac{1}{n}}$$

The number of pieces per tool grind is
$$N_p = \frac{T}{T_m}$$

Therefore from the above equations:
$$N_p = \frac{fC^{1/n}}{\pi LDV^{(1/n)-1}}$$

Economics of machining:

$$C_p = C_m + C_s + C_l + C_t =$$

$$T_m(L_m + B_m) + T_l(L_m + B_m) + \frac{1}{N_p}\left[T_c(L_m + B_m) + T_g(L_g + B_g) + D_c\right]$$

$$= \frac{\pi LD}{fV}(L_m + B_m) + T_l(L_m + B_m) + \frac{\pi LDV^{(1/n)-1}}{fC^{1/n}}\left[T_c(L_m + B_m) + T_g(L_g + B_g) + D_c\right]$$

To find the optimum cutting speed and optimum tool life for minimum cost:

$$\frac{\partial C_p}{\partial V} = 0$$

Economics of machining:

Solving the above equation we get

The optimum cutting speed is given by

$$V_0 = \frac{C(L_m + B_m)^n}{\left\{\left[\left(1/n\right) - 1\right]\left[T_c(L_m + B_m) + T_g(L_g + B_g) + D_c\right]\right\}^n}$$

The optimum tool life T_0

$$T_0 = \left[\left(1/n\right) - 1\right]\frac{T_c(L_m + B_m) + T_g(L_g + B_g) + D_c}{L_m + B_m}$$

Economics of machining:

To find out the optimum tool life and optimum cutting speed for maximum production:

$$\frac{\partial T_p}{\partial V} = 0$$

Which gives

The optimum cutting speed

$$V_0 = \frac{C}{\left[\left(\frac{1}{n} - 1\right) T_c\right]^n}$$

and the optimum tool life, T_o is

$$T_0 = \left(\frac{1}{n} - 1\right) T_c$$

Machinability of metals:

One of the two common terms used in metal cutting,

- Seldom to be fully explained Š difficult to define,
- Expressed in terms of **physical quantities** (e.g. hardness) or **mathematical equations** (e.g. V_{60}),
- Can be vaguely defined as:

Machinability of metals:

- Machinability is used to refer to the ease with which a given work material can be machined under a given set of cutting conditions.
- It is of considerable economic importance for the production engineer to know in advance the machinability of a work material so that its processing can be efficiently planned.
- Because of complex nature of cutting operation, it is difficult to establish relationships that quantitatively define the machinability of a material.
- In manufacturing plants, tool life and surface finish are generally considered to be the most important factors in machinability.
- Although not used much any more, approximate, machinability ratings are used to get an idea about the machinability of any material.

Machinability of metals:

Mainly concerned with **assessing work materials**

It depends on several factors:

- **Tool material and geometry,**
- **Chemical composition of work material,**
- **Structure of the work material,**
- **Mechanical properties of tool and work material,**
- **Physical properties,**
- **Cutting conditions.**

Machinability of metals:

The judging criteria:

- **Tool life**
- **Intensity of cutting forces**
- **Quality of surface finish**
- **Form and size of chips**
- **Temperature of cutting.**

Machinability of metals:

Necessary and useful for **proper selection** and **manufacture of work materials** for machining purpose.

Commonly used machinability measure:

Equivalent cutting speed, *V_{60}* - Cutting speed f

$$\text{Relative machinability} = \frac{V_{60}\ \text{material}}{V_{60}\ \text{standard}} \quad (\%)$$

Machinability Ratings:

Specific cutting speed is defined as the cutting speed corresponding to the predetermined tool life.

Machinability ratings can be very easily understood with the help of a example.

For example if the tool life during a turning operation under standard condition (of feed, depth of cut, tool material and tool geometry) is found to be 60min at a cutting speed of 100 m/min, the specific cutting speed for 60 min tool life, V60 = 100 m/min.

Further if V^t_{60} is the specific cutting speed for 60 min tool life for a test material and V^s_{60} is the corresponding specific speed for a standard material,

The machinability ratings MR of the test material is given by

$$M_R = \frac{V^t_{60}}{V^s_{60}} \times 100\%$$

SAE 1212 is taken as standard material for testing machinability

Machinability Ratings:

Other machinability measure:

- **Production rate** - a high production rate represents good machinability**,**

- **Microstructure –** qualitatively accounts for the change in tool life and surface finish**,**

- **Machinability index = surface energy**
- **/the hardness *H***

  - ***Surface finish/chip formation***

  - ***Tool wear***

  - ***Cutting forces***

THANKS