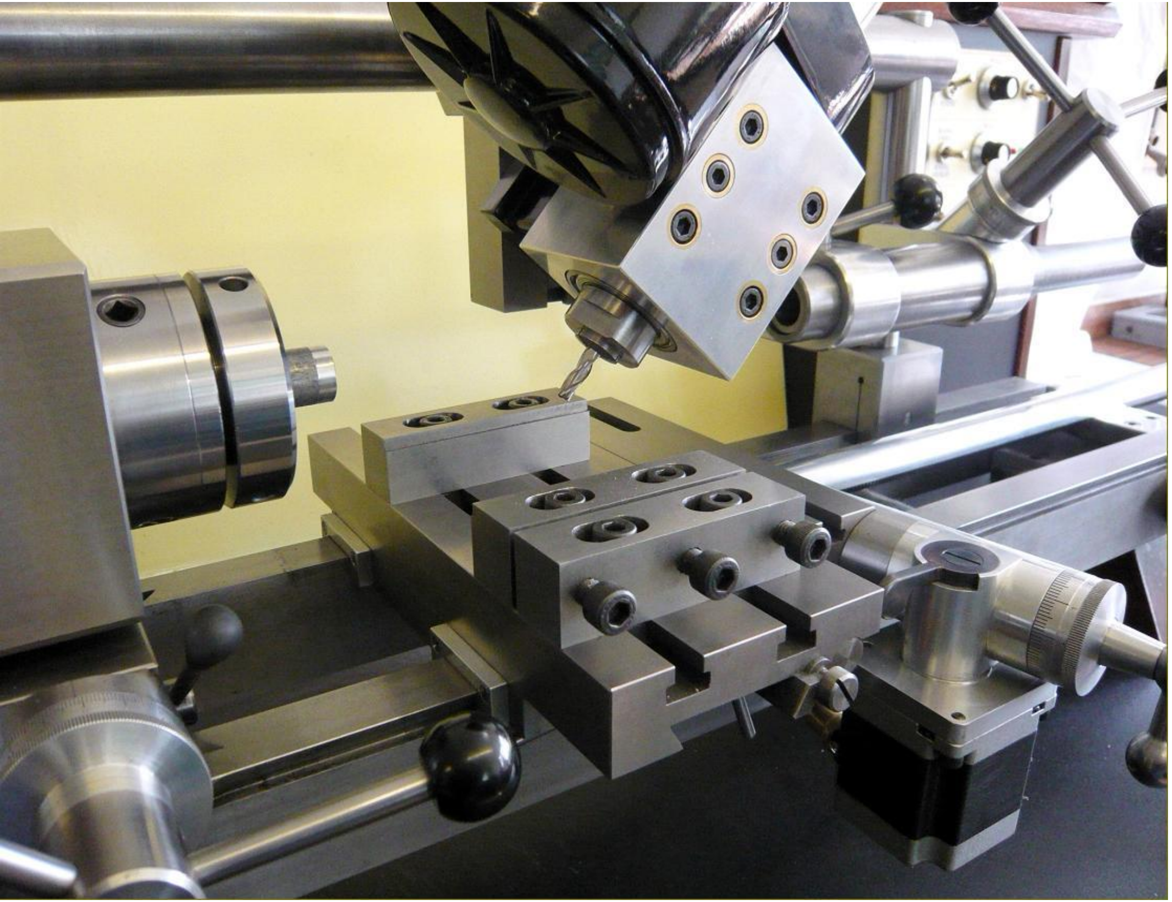


ME303 MACHINE TOOLS AND DIGITAL MANUFACTURING

SYLLABUS:

UNIT	DETAILS
I	Introduction to metal cutting: Tool nomenclature – Attributes of each tool nomenclature – Attributes of feed and tool nomenclature on surface roughness obtainable. Orthogonal and oblique cutting - Mechanism of metal removal... Primary and secondary deformation shear zones. Mechanism of chip formation – Types of chips, need and types of chip breakers – Merchant's theory... Analysis of cutting forces in orthogonal cutting– Work done, power required (simple problems) Friction forces in metal cutting – development of cutting tool materials Thermal aspects of machining -Tool wear and wear mechanisms Factors affecting tool life– Economics of machining (simple problems) Cutting fluids.

II	General purpose machine tools – Principle and operation of lathe – Types of lathes and size specification. Work holding parts of lathes and their functions – Main operations, Taper turning and thread cutting – Attachments, Feeding mechanisms, Apron mechanisms. Drilling Machines – Types – Work holding devices, Tool holding devices – Drill machine operations, Drilling machine tools – Twist drill nomenclature- cutting forces in drilling.

III	Reciprocating machines: Shaping machines – Types – Size, Principal parts – Mechanism. Work holding devices – Operations performed – Tools Cutting speed, feed and depth of cut – Machining time. Slotting machines – Types – Size – Principal parts – Mechanism , Work holding devices Operations performed – Tools – Cutting speed, feed and depth of cut Planing machines – Types – Size – Principal parts – Mechanism, Work holding devices Operations performed – Tools – Cutting speed, feed and depth of cut – Machining time- Surface roughness obtainable.

IV	Milling machines – Types – Principal parts – Milling mechanism. Work holding devices – Milling machine attachments, Types of milling cutters – Elements of plain milling cutters.. Nomenclature - Cutting forces in milling – Milling cutter materials, Up milling, down milling and face milling operations. Calculation of machining time. Indexing – Simple indexing – Differential indexing.

V	Grinding machines – Classification – Operations – Surface, cylindrical and Centre less grinding Grinding mechanisms – Grinding wheels: Specification – types of abrasives, grain size Types of bond, grade, structure – Marking system of grinding wheels, Selection of grinding wheels Glazing and loading of wheels – Dressing and Truing of grinding wheels, surface roughness obtainable Superfinishing operations: Lapping operation– Types of hand lapping, Lapping machines – Types of honing –Methods of honing. Types of honing stones – Honing conditions – Cutting fluids – Types of broaches – Force required for broaching – Surface roughness obtainable in lapping, honing and broaching operations. Semi-automatic machine tools – Turret and capstan lathes. Automatic machine tools – Single and multi-spindle machines

VI	Definition of digital manufacturing – Features and development of digital manufacturing. Theory system of digital manufacturing science: Operation Mode and Architecture of Digital Manufacturing System Operation reference mode of digital manufacturing system – Architecture of digital manufacturing system Modeling theory and method of digital manufacturing science Critical modeling theories and technologies of digital manufacturing science (Theory system of digital manufacturing science – Basics only)

COURSE OUTCOMES:

SL NO	DESCRIPTION	Bloom's Taxonomy Level
CME303.1	Students evaluate the mechanism of orthogonal and oblique cutting and analysing the cutting forces developed.	Evaluate (level 5)
CME303.2	Select appropriate process parameters in a machine tool while machining a job.	Evaluate (level 5)
CME303.3	Students able to understand and apply operational principles of machine tools.	Apply (level 3)
CME303.4	Students able to select different super finishing operations.	Understand (level 2)
CME303.5	Students understand and apply the principles of digital manufacturing.	Undestand (level 2)

WHAT IS A MACHINE?....

Mechanical engineering domain, **Machine** is defined as an assembly of mechanisms that are clustered to perform certain operations by utilizing electrical, mechanical, hydraulic, and/or pneumatic power.

- **<u>Introduction:</u>**
  - Manufacturing processes can be broadly classified as follows:

(a)Shaping or **forming** Manufacturing a solid product of definite size and shape from a given material taken in three possible states:

- ❑ in solid state – e.g., forging rolling, extrusion, drawing etc.
- ❑ in liquid or semi-liquid state – e.g., casting, injection moulding etc.
- ❑ in powder form – e.g., powder metallurgical process.

(b)Joining process: Welding, brazing, soldering etc.

(c)Removal process: Machining (Traditional or Non-traditional), Grinding etc.

NEED OF MACHINE TOOLS

- More production
- More Precision
- Changes in Manufacturing process
- Lead to the Development of High speed
- Special purpose lathes

Why MACHINE TOOLS not MACHINES???

- It must be power driven (human operated machines are not machine tools).
- It must be non-portable (portability irrespective of size).
- It must have sufficient value (value in terms of capability and performance, not on the basis of cost).
- It can perform more than one type of machining or metal cutting operations.
- It utilizes a cutting tool to shear off excess materials from workpiece.

METAL CUTTING

- Metal cutting/Machining – process of removing unwanted material from a block by the use of a tool, in the form of chips.
- Objective:
  - To form objects of desired shape, size and surface finish
  - fulfill its basic functional requirements
  - provide better or improved performance
  - render long service life

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

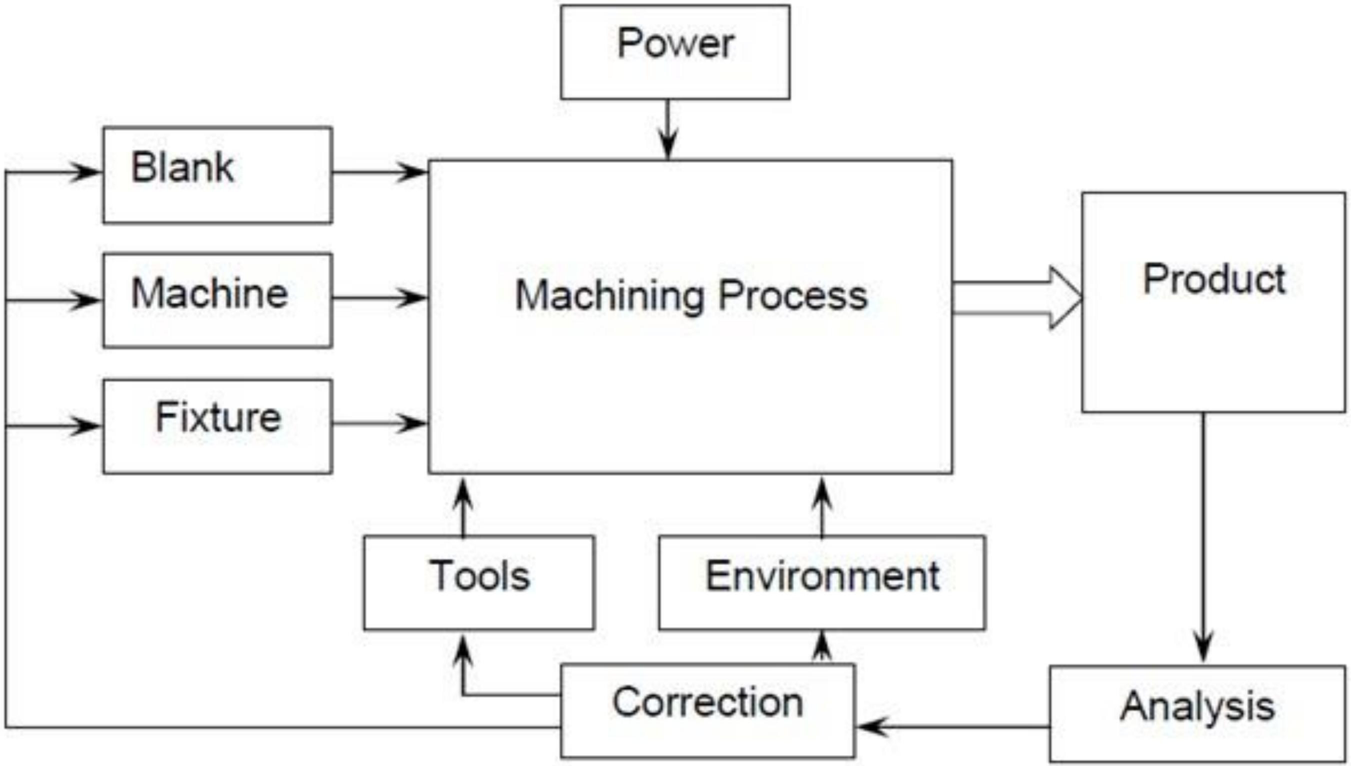


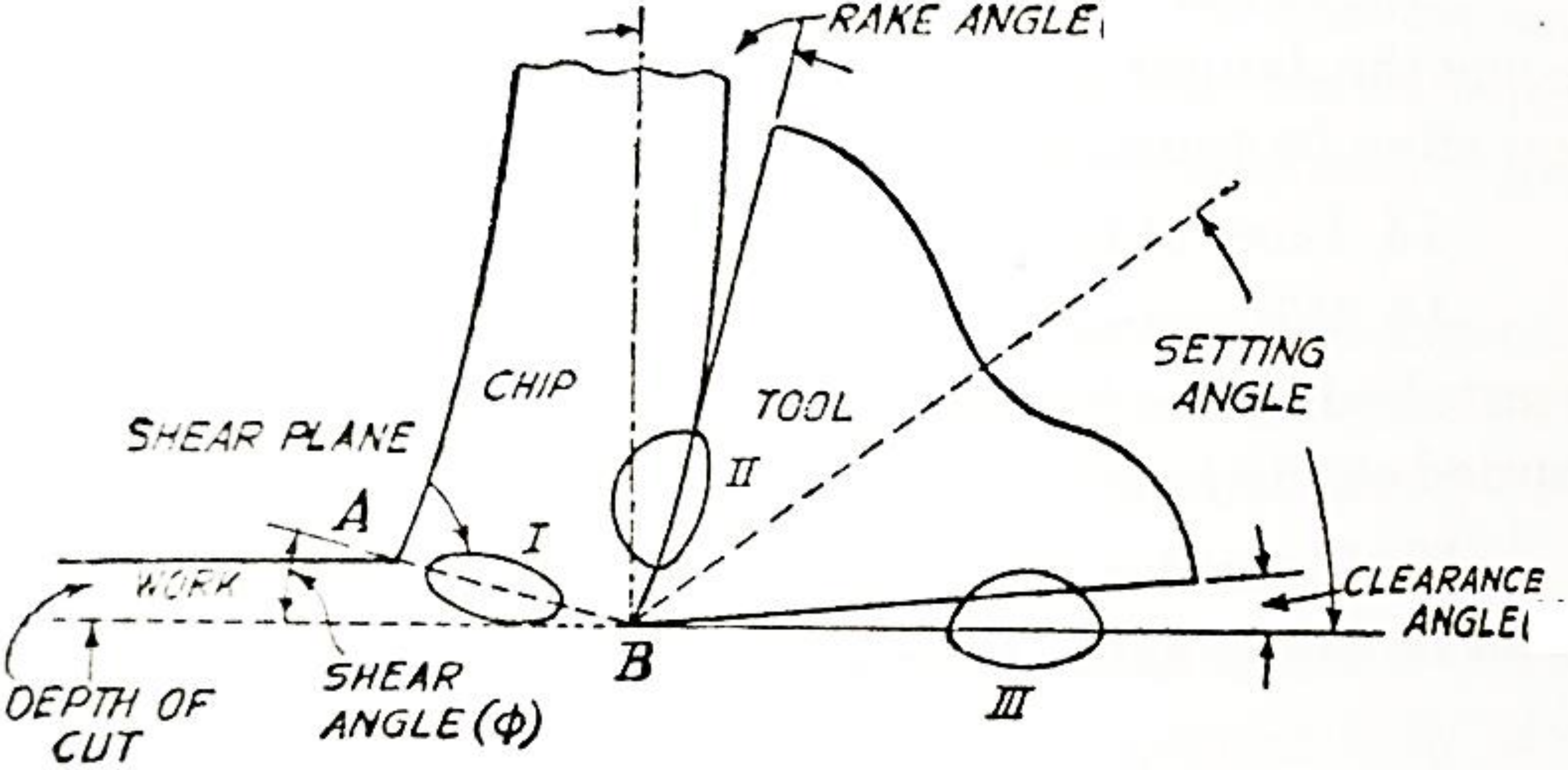
Fig. *Requirements for machining*

Elements of Cutting Process

- Any cutting process involves:
  - Work-piece (material)
  - Tool
  - Chips
  - Cutting Conditions

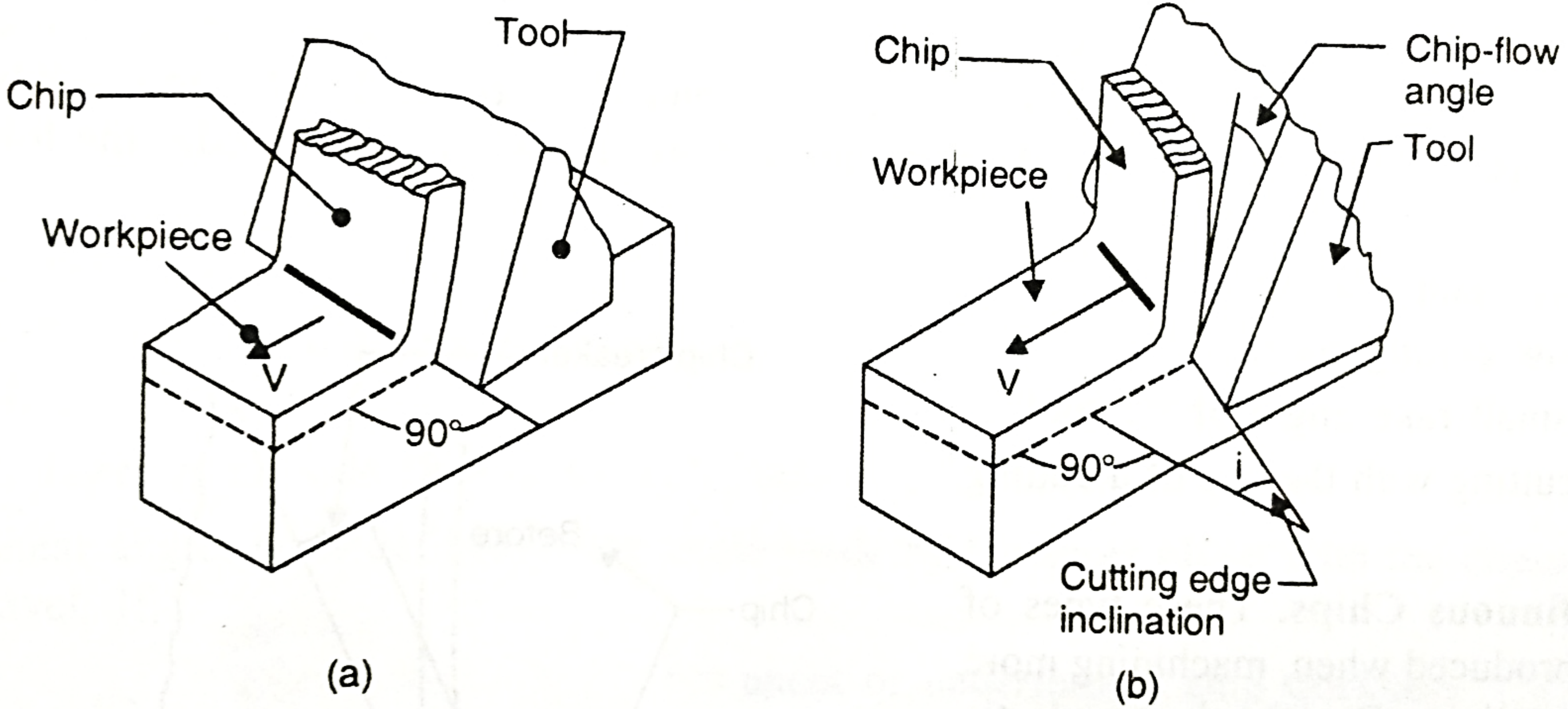
CUTTING TOOLS

- Cutting tools may be classified according to the number of major cutting edges (points) involved as follows:
  - **Single point:** e.g., turning tools, shaping, planning and slotting tools and boring tools
  - **Double (two) point:** e.g., drills
  - **Multipoint (more than two)**: e.g., milling cutters, broaching tools, hobs, gear shaping cutters etc.

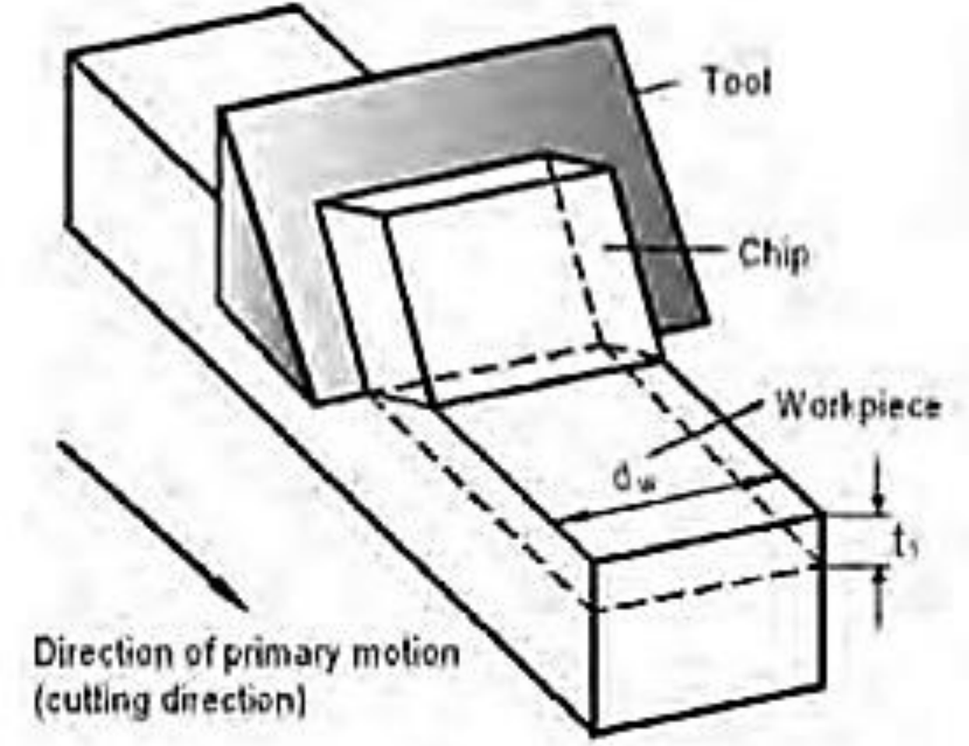

RAKE ANGLE
CHIP
TOOL
SHEAR PLANE
SETTING
ANGLE
A
I
II
WORK
CLEARANCE
ANGLE
B
III
SHEAR
ANGLE (ϕ)
DEPTH OF
CUT

Types of metal cutting

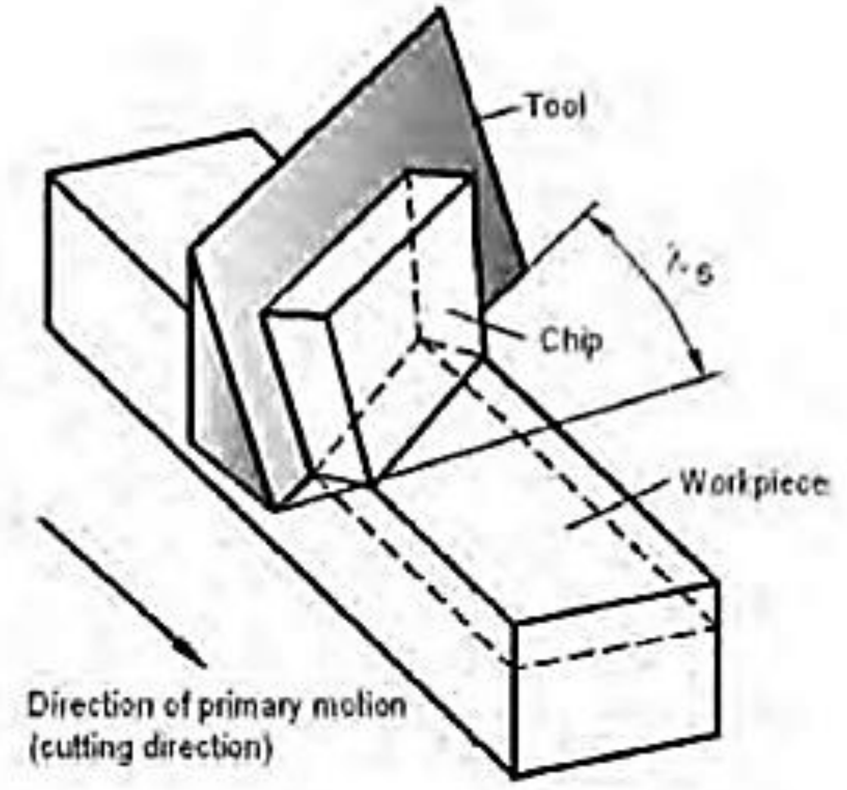
1. Orthogonal cutting/two dimensional cutting (Fig a)
   - Cutting edge of the tool is at right angles (90 degrees) to the direction of relative motion b/w tool and the workpiece.
   - E.g.: turning at the open end of a tube, planing a rib with a tool wider than the rib.
   - Simple process (used as the basis for metal cutting study)
2. Oblique cutting/three dimensional cutting (Fig b)
   - Cutting edge of the tool is at at an angle (not perpendicular) to the direction of relative motion b/w tool and the workpiece.
   - E.g.: Most actual cutting operations - turning



Tool
Chip
Workpiece
V
90°
(a)
Chip
Chip-flow angle
Tool
Workpiece
V
90°
i
Cutting edge inclination
(b)



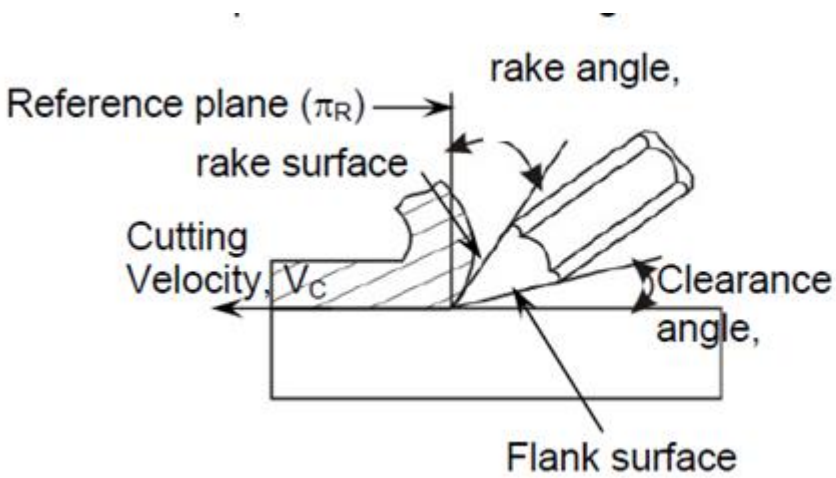
Orthogonal Cutting

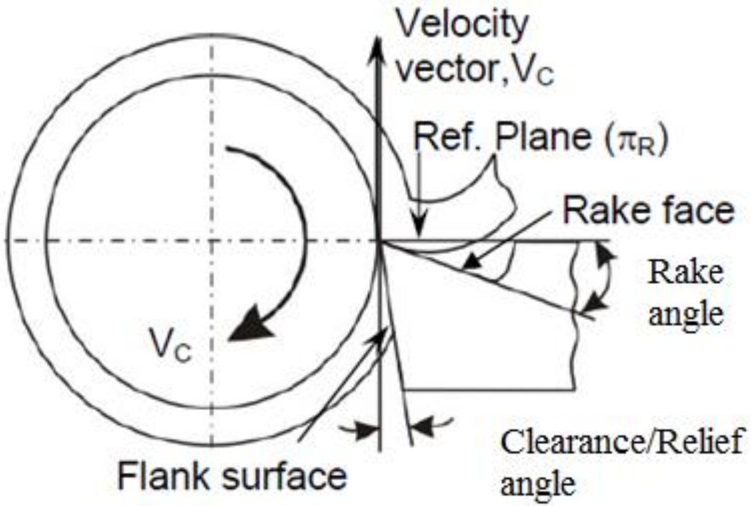


Oblique Cutting

Orthogonal Cutting	Oblique Cutting
The cutting angle of tool make right angle to the direction of motion.	The cutting angle of tool foes not make right angle to the direction of motion.
The chip flow in the direction normal to the cutting edge.	The chips make an angle with the normal to the cutting edge.
In orthogonal cutting only two components of force considered cutting force and thrust force which can be represent by 2D coordinate system.	In oblique cutting three component of force are considered, cutting force, thrust force and radial force which cannot represent by 2D coordinate. It used 3D coordinate to represent the forces acting during cutting, so it is known as 3D cutting.
This tool has lesser cutting life compare to oblique cutting.	This tool has higher cutting life.
The shear force act per unit area is high which increase the heat developed per unit area.	The shear force per unit area is low, which decreases heat develop per unit area hence increases tool life.
The chips flow over the tool.	The chips flow along the sideways.

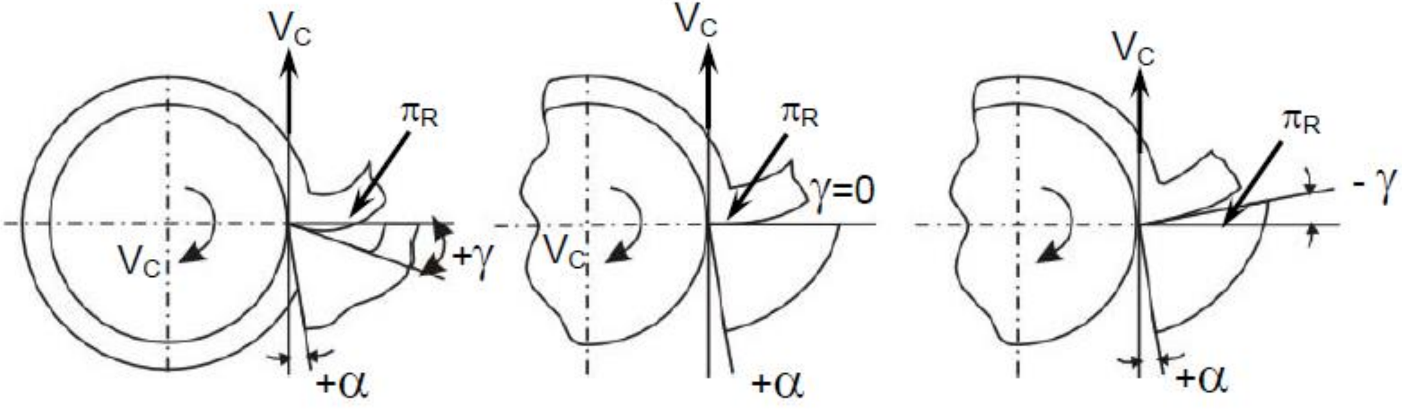
Concepts of Rake and Relief Angles





Rake and Clearance/Relief angle

- Rake angle : Angle of inclination of rake surface from reference plane
  - Relative advantages of such rake angles are:
    1. ***Positive rake – helps reduce cutting force and thus cutting power requirement.***
    2. ***Negative rake – to increase edge-strength and life of the tool***
    3. ***Zero rake – to simplify design and manufacture of the form tools.***
- Clearance angle : Angle of inclination of clearance or flank surface from the finished surface
  - Clearance angle is essentially provided to avoid rubbing of the tool (flank) with the machined surface which causes loss of energy and damages of both the tool and the job surface. Hence, clearance angle is a must and must be positive ($3^o \sim 15^o$ depending upon tool-work materials and type of the machining operations like turning, drilling, boring etc.)



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

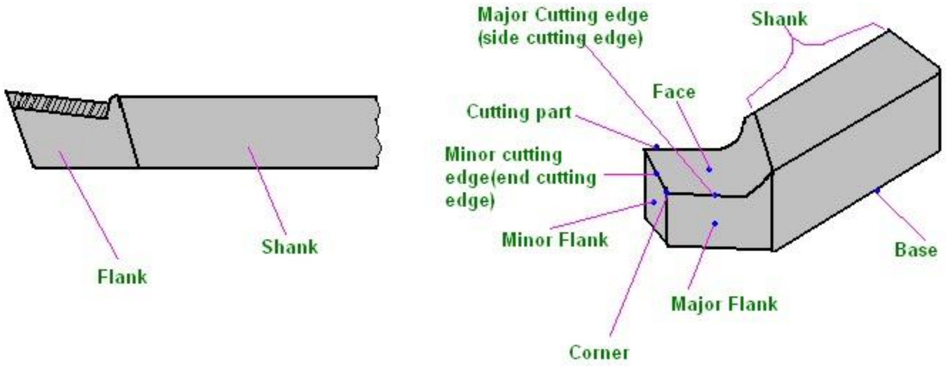
Systems for description of tool geometry

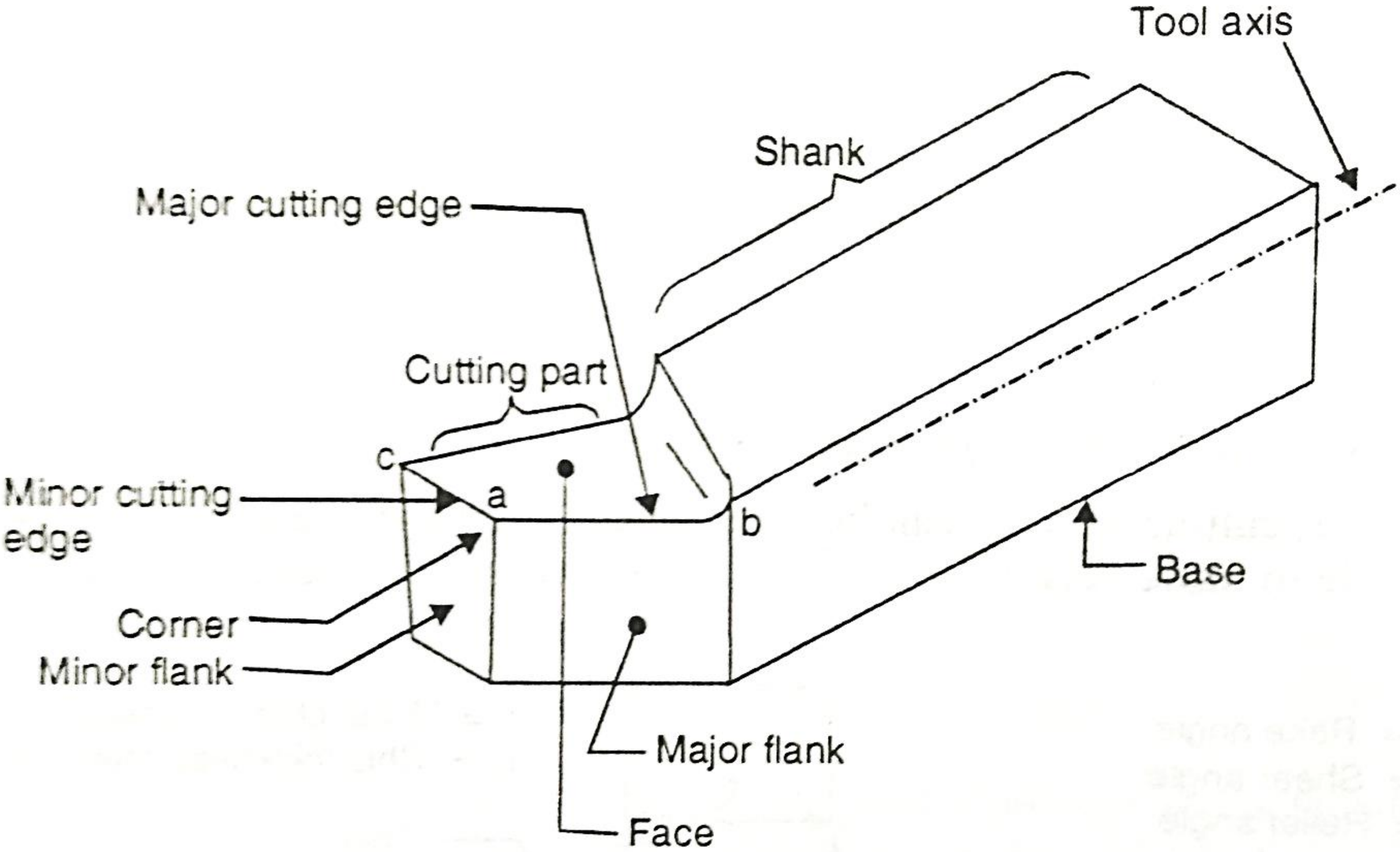
- Tool-in-Hand System
- Machine Reference System – ASA system
- Tool Reference Systems
    - **Orthogonal Rake System – ORS (ASSIGNMENT)**
    - Normal Rake System – NRS
- Work Reference System – WRS

TOOL IN HAND

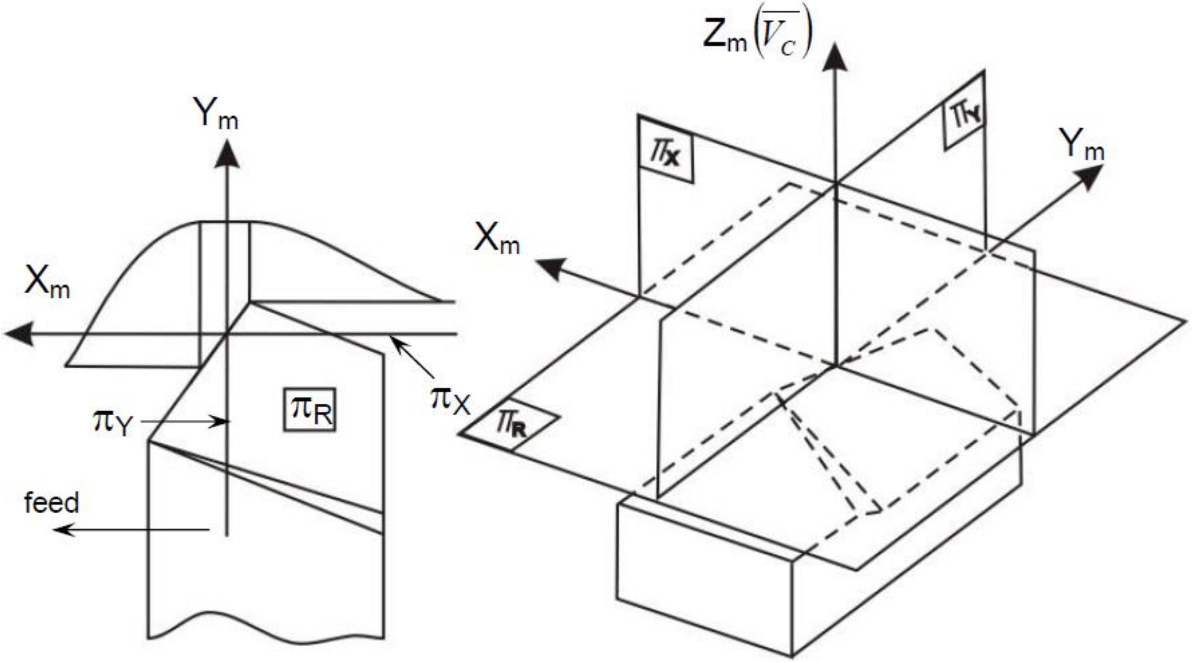
- where only the salient features of the cutting tool point are identified or visualized as shown in Fig. below. There is no quantitative information, i.e., value of the angles.

Nomenclature of single point cutting tool:

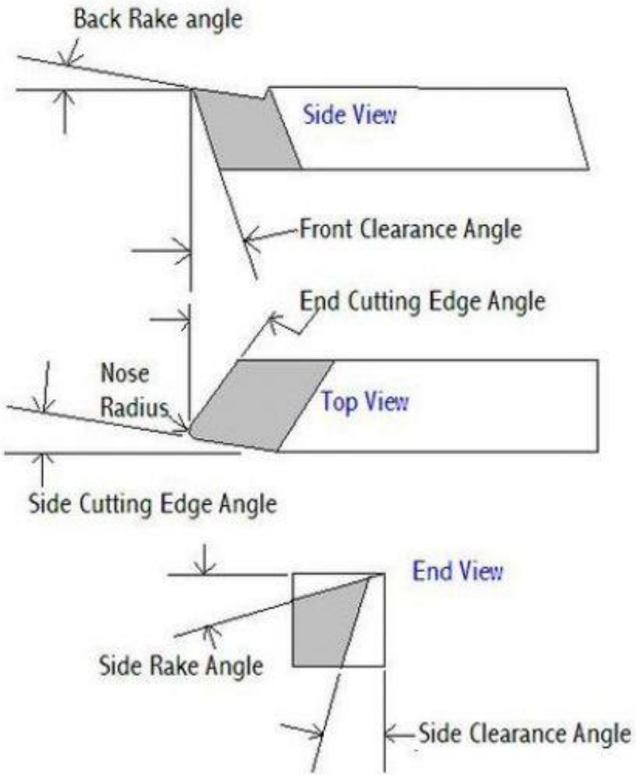



Tool axis
Shank
Major cutting edge
Cutting part
c
a
b
Minor cutting edge
Corner
Minor flank
Base
Major flank
Face

ASA (American Standards Association) System



Tool Bit Geometry



ASA System – Tool Angles

- Side cutting edge angle (SCEA)
    - Angle b/w the **side/major cutting edge** and the side of the tool shank
    - Also called lead angle
    - Protects the tip of the tool at the start of the cut
    - Vary from 0-90 degrees
    - Increased values – gives good tool life, but large values causes tool chatter
    - Typical values- 15-30 degrees
    - To produce a shoulder (necking tool), 90 degree SCEA used.

- End Cutting Edge Angle (ECEA)
    - Provides **relief to the trailing edge (minor cutting edge)** to prevent rubbing or drag b/w the machined surface and the non cutting part of the cutting edge.
    - Too large an angle takes away material supporting the tool tip and conducting the heat, making it fragile.
    - Ranges from 8-15 degrees
    - End cutting tools like necking tools have no ECEA (ECEA= 0)
- Side relief and End relief angles (SRA & ERA)
    - Provided so that the **flank** (major flank for SRA and minor flank for ERA) of the tool clears the workpiece and no rubbing occurs
    - Ranges from 5-15 degrees
    - Makes it easier to penetrate and cut the workpiece more efficiently, thus reducing the cutting forces and power required.
    - Small relief angles necessary to give strength to cutting edge to cut hard materials
    - Too large – weakens the cutting edge, and results in poor heat conduction away.

- Back Rake and Side Rake Angles
  - Affects the cutting angle and the shear angle.
  - Large rake angle (positive):
    - » Smaller the cutting angle (larger the shear angle); lower cutting force and power required
  - Small rake angles ensures tool strength
  - Practically is a compromise b/w the two.
- Generally,
  - Hard materials – small rake angles
  - Soft ductile materials – large rake angles (exception is brass- small angles used to prevent digging)

- Negative rake angles used for carbide inserts (brittle). Positive rake angle directs the cutting force on the tool to the cutting edge.

- Nose radius:
  - Required for long tool life and good surface finish
  - Too Small (Sharp tip) – high stress, short tool life and leaves grooves in the path of cut.
  - Too large – result in tool chatter.

TOOL SIGNATURE/DESIGNATION (ASA SYSTEM)

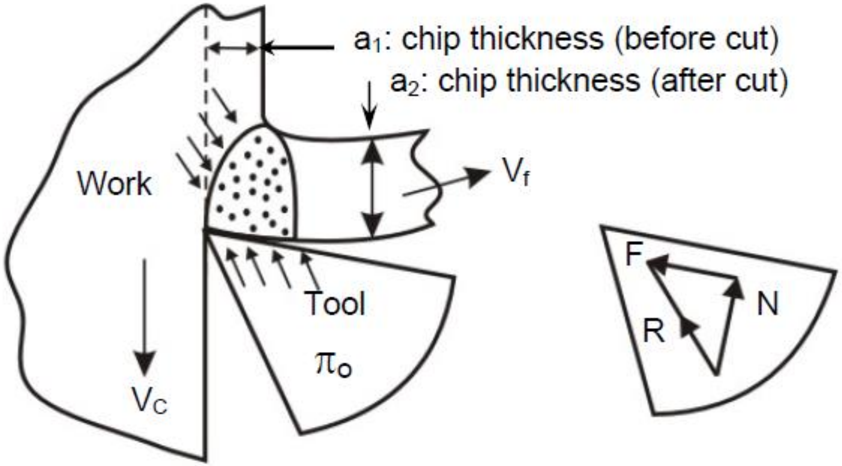
- Order of geometry specification:
    - Back Rake, Side Rake, End relief, Side relief, End cutting edge angle, side cutting edge angle and nose radius.
    - E.g.: 8-14-6-6-6-15-1/8

Mechanisms of chip formation

- The basic two mechanisms involved in chip formation are:
  1. **Yielding** – generally for *DUCTILE MATERIALS*
  2. **Brittle fracture** – generally for *BRITTLE MATERIALS*

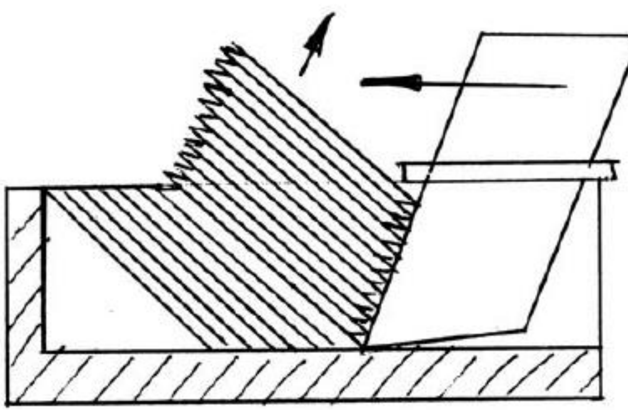
Mechanism of chip formation in machining ductile materials – YIELDING

- During continuous machining the uncut layer of the work material just ahead of the cutting tool (edge) is subjected to almost all sided compression

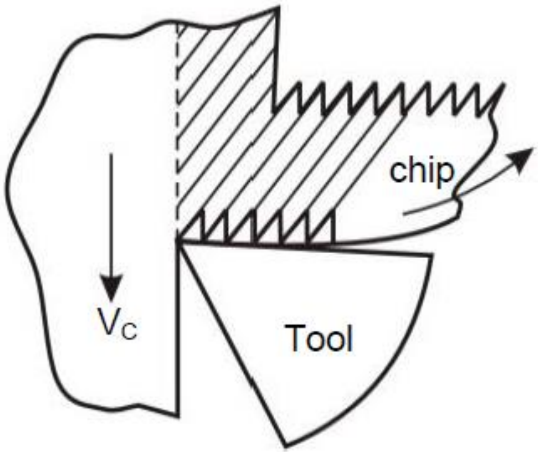


- Due to such compression, shear stress develops, within that compressed region, in different magnitude, in different directions and rapidly increases in magnitude.
- Whenever and wherever the value of the shear stress reaches or exceeds the shear strength of that work material in the deformation region, yielding or slip takes place resulting shear deformation in that region along the plane of maximum shear stress
- But the forces causing the shear stresses in the region of the chip quickly diminishes and finally disappears while that region moves along the tool rake surface towards and then goes beyond the point of chip-tool engagement
- As a result the slip or shear stops propagating long before total separation takes place. In the mean time the succeeding portion of the chip starts undergoing compression followed by yielding and shear. This phenomenon repeats rapidly resulting in formation and removal of chips in thin layer by layer

- This phenomenon has been explained in a simple way by Pispannen [1] using a card analogy as shown in Fig.

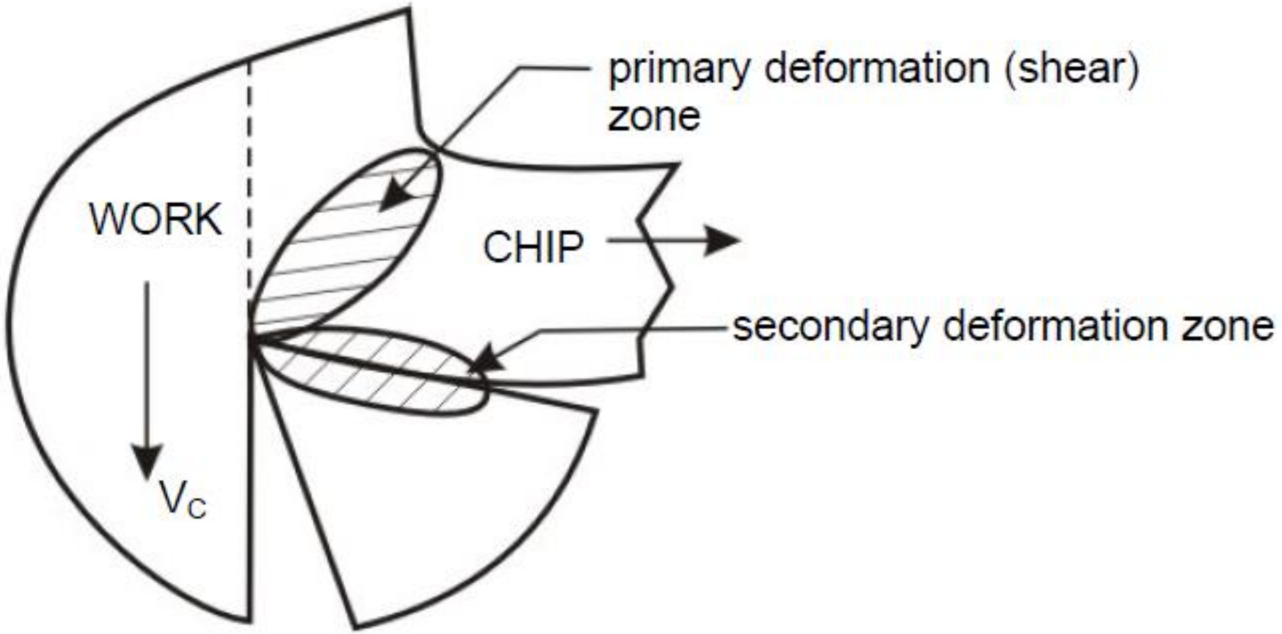


(a) Shifting of the postcards by partial sliding against each other



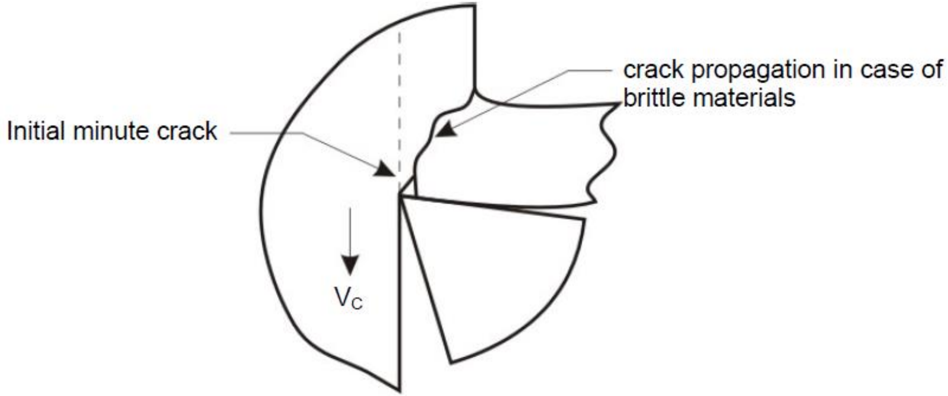
(b) Chip formation by shear in lamella.

- The lower surface becomes smooth due to further plastic deformation due to intensive rubbing with the tool rake surface at high pressure and temperature.



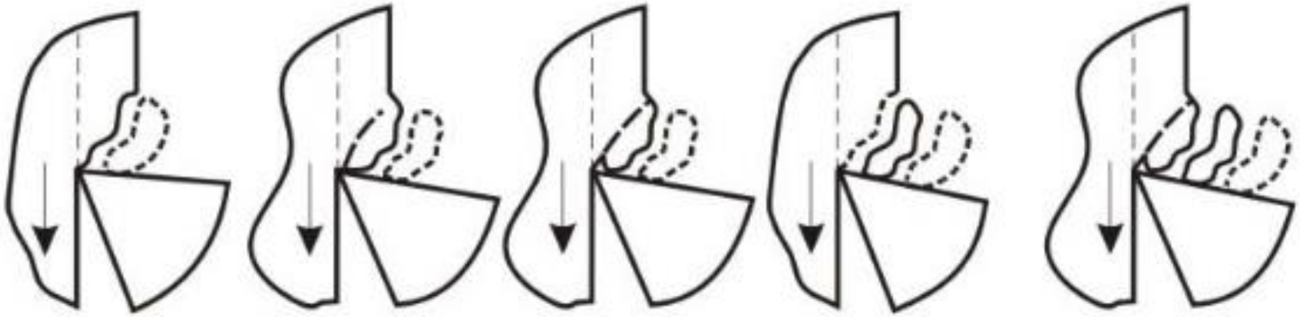
Mechanism of chip formation in machining brittle materials - BRITTLE FRACTURE

- During machining, first a small crack develops at the tool tip as shown in Fig due to wedging action of the cutting edge.



- At the sharp crack-tip stress concentration takes place.
- In case of ductile materials immediately yielding takes place at the crack-tip and reduces the effect of stress concentration and prevents its propagation as crack.
- But in case of brittle materials the initiated crack quickly propagates, under stressing action, and total separation takes place from the parent workpiece through the minimum resistance path as indicated in Fig in above slide

- Machining of brittle material produces discontinuous chips and mostly of irregular size and shape. The process of forming such chips is schematically shown in Fig below



(a) separation (b) swelling (c) further swelling (d) separation (e) swelling again

Types of Chips

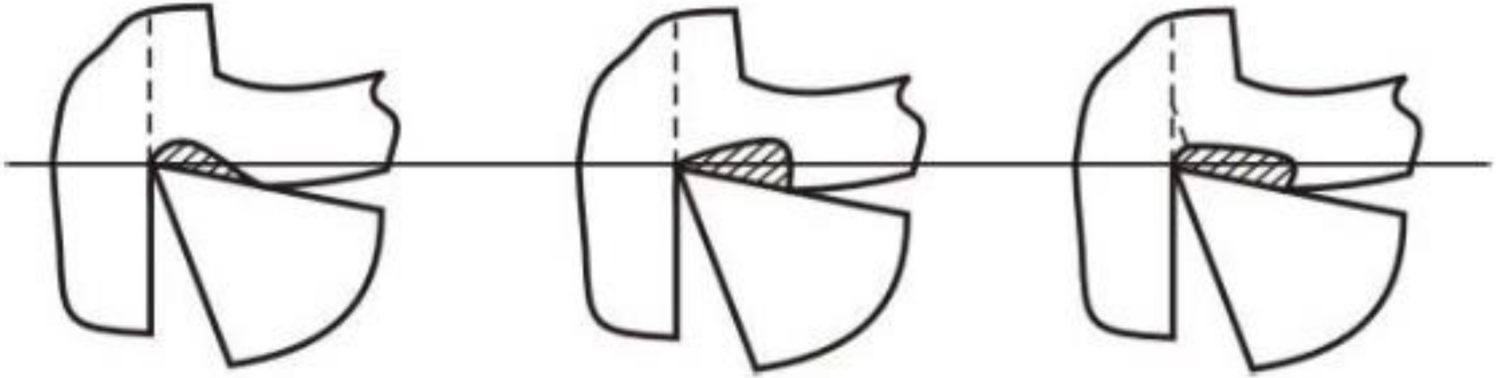
- 4 types:
  1. Discontinuous/Segmental chips
  2. Continuous chips
  3. Continuous chips with BUE (Built up Edge)
  4. Non-homogeneous chips

- Discontinuous/Segmental chips
    - **Consists of separate plastically deformed segments**
  - Produced during machining of brittle materials like cast iron, bronze etc.
  - Adv:
    - Easy to handle
    - Low power consumption
    - Reasonable tool life
    - Fair surface finish
  - Produced in machining ductile materials under the following conditions:
      - » High depth of cut
      - » Low speed
      - » Small rake angle
    - **NOT DESIRABLE FOR DUCTILE MATERIALS (poor surface finish and tool life)**

- Continuous chips
    - **Metal continuously deforms without fracture and flows over the rake face in the form of a ribbon**
  - Produced in machining ductile materials under the normal cutting speeds.
  - Produced under:
    - Small depth of cuts
    - Normal to high cutting speeds
    - Large rake angles
    - Reduced friction along chip tool interface.
  - Most desirable chip – indicates stable cutting, results in generally good surface finish
  - Disadv:
    - Difficult to handle and dispose off..
    - Chips coil in a helix (CHIP CURL), around the work and tool and may cause injury to the operator when it breaks loose.
    - Chip breakers are necessary
    - More frictional heat is generated due to longer durations of chip contact with rake face.

- <u>Continuous chips with BUE</u>
  - Produced in machining ductile materials under conditions of:
    - High local temperature and extreme pressures in the cutting zone
    - High friction at the tool-chip interface
    - Low cutting speed.
  - Causes work material to adhere/weld to the cutting edge of the tool, forming the BUE (further increasing friction)
  - Successive layers of work material are added onto the BUE, till it becomes unstable and breaks off. (some deposited on the work piece; some carried by the chip)
  - Causes:
    - **Vibration - Larger power consumption**
    - **Poor Surface Finish - Higher tool wear**
  - Can be avoided by:
    - Increasing the cutting speed
    - Increasing the rake angle
    - Use of cutting fluids

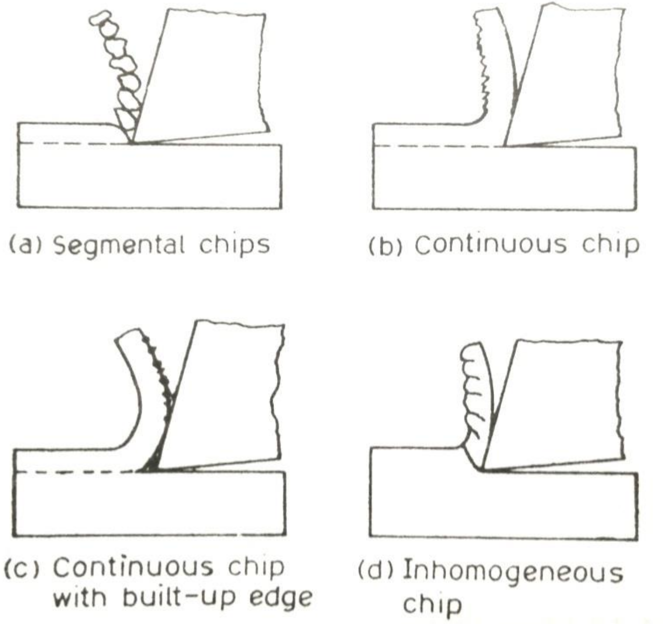
Types of BUE

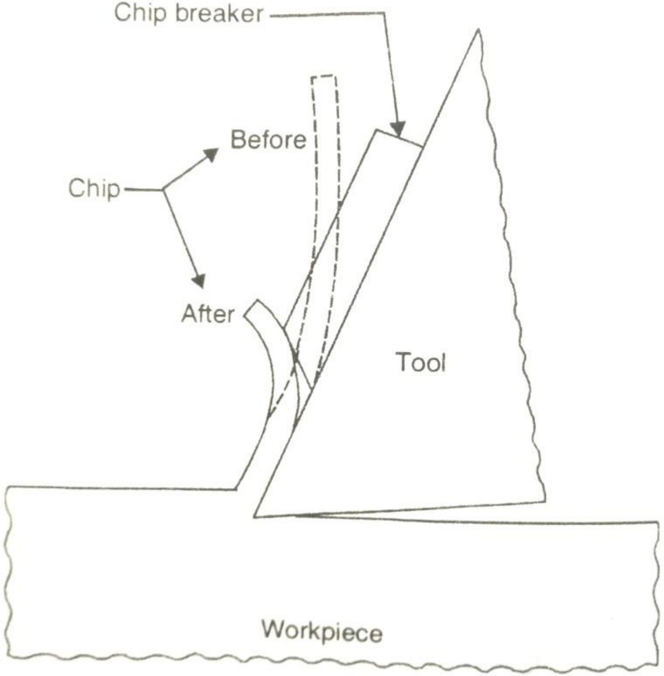


(a) positive wedge (b) negative wedge (c) flat type

- <u>Non-homogeneous chips</u>
  - Characterized by notches on the free side of the chip.
  - Observed in:
    - materials in which yield strength decreases with temperature.
    - Materials having poor thermal conductivity.
  - E.g. : Some steels and Ti Alloys at medium cutting speed.

  - During the chip formation by slip along the shear plane, the temperature also rises. This results in lowering of yield strength and causes further strain.
  - As the cutting is continued, a new shear plane will develop at some distance and the deformation shifts to this point.


(a) Segmental chips
(b) Continuous chip
(c) Continuous chip with built-up edge
(d) Inhomogeneous chip


Chip breaker
Before
Chip
After
Tool
Workpiece

CHIP CURL

- Chips will develop a curvature (*chip curl*) as they leave the workpiece surface.

- Factors affecting the chip curl conditions are:

1. Distribution of stresses in the primary and secondary shear zones.
2. Work-hardening characteristics of the workpiece material
3. Geometry of the cutting tool
4. Thermal effects
5. Cutting fluids

Cutting Ratio/Chip Thickness Ratio (r)

- Denoted as ‘r’
- Also called **<u>chip compression factor</u>**

Considering an ideal 2D cutting operation

$$\mathbf{r = t/t_c}$$

where,

t = uncut or un-deformed chip thickness

t_c = chip thickness after metal is cut

$$1/r = t_c/t = \zeta$$

ζ = chip reduction coefficient/factor

Let in the 2D cutting operation,

α = rake angle

θ = clearance angle

Φ = shear angle

t = uncut of un-deformed chip thickness

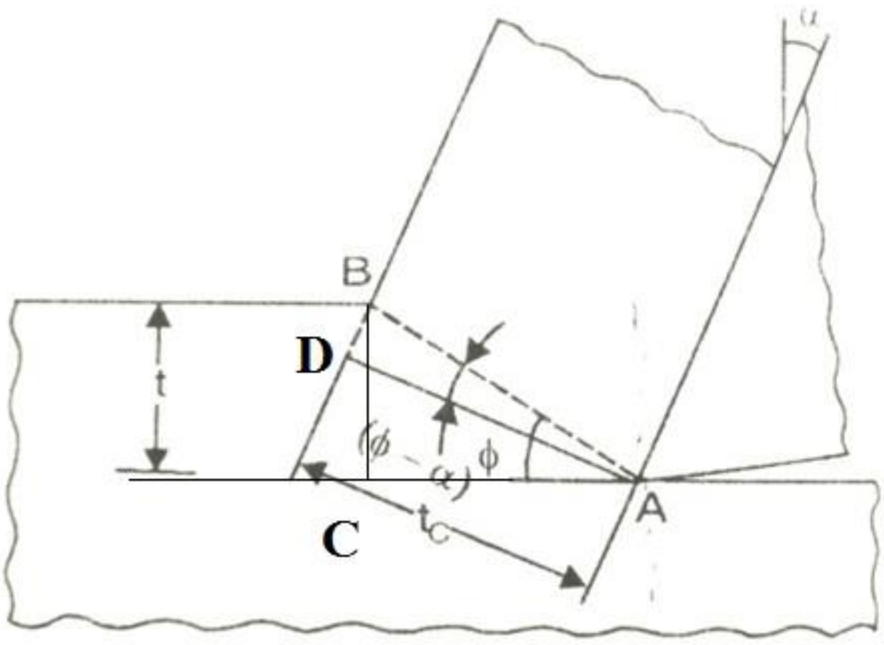
tc = chip thickness after metal is cut

v = velocity of the tool w.r.t workpiece

v_c = velocity of the chip along rake face of the tool

v_s = velocity of the chip along shear plane

Determination of Shear Angle (**Φ**)



We know:

$$r = t/t_c$$

From the above fig.

In triangle ABC ; $t = BC = AB \sin \Phi$

In triangle ADB; $t_c = AD = AB \cos(\Phi - \alpha)$

Hence, $r = \sin \Phi / \cos(\Phi - \alpha)$

$= \sin \Phi / \{\cos(\Phi)\cos(\alpha) + \sin(\Phi)\sin(\alpha)\}$

$$r\cos(\Phi)\cos(\alpha) + r\sin(\Phi)\sin(\alpha) = \sin \Phi$$

Dividing by cos(Φ):

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

Simplifying:

$$\tan\Phi - r\tan(\Phi)\sin(\alpha) = r\cos(\alpha)$$

$$\tan\Phi\,(1 - r\sin(\alpha)) = r\cos(\alpha)$$

$$\mathbf{\tan\Phi = r\cos(\alpha) / (1 - r\sin(\alpha))}$$

CHIP THICKNESS RATIO (r)

Mass of metal removed = Mass of chip

Hence, $$t b l \rho = t_c b_c l_c \rho_c$$

Where, l = length; b = width; t = thickness ; ρ = density
suffix c- chip

NOTE: Density and the width of the work and chip remain the same (in 2D cutting).
Hence,

$$\mathbf{t/t_c = l_c/l = r}$$

Similarly, From the continuity equation

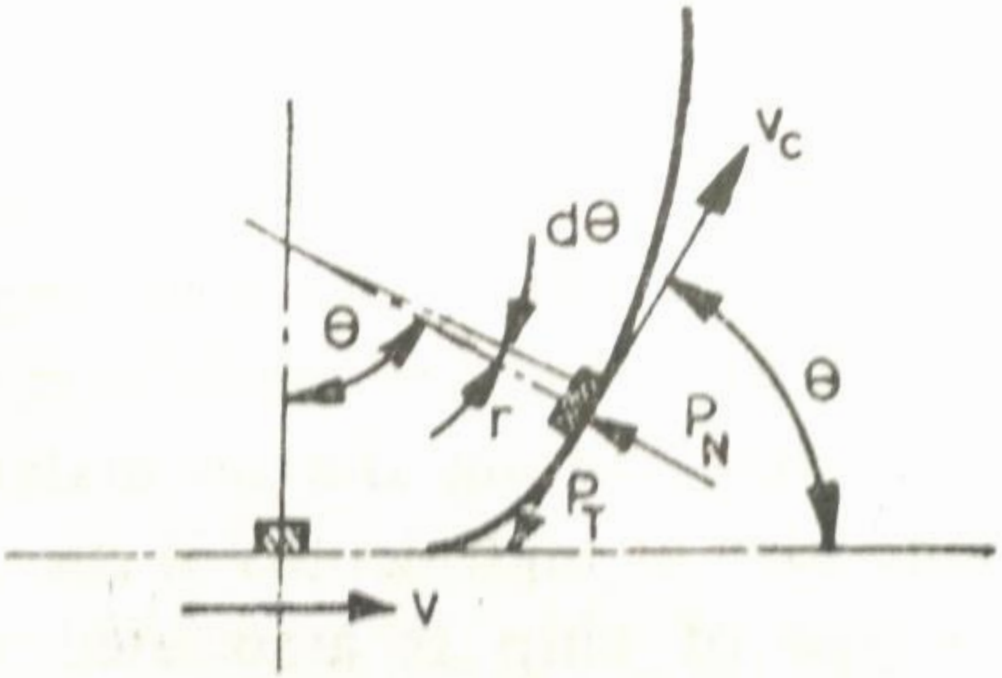
$$V\,tb = V_c\ t_c b_c$$

Hence,

$$t/t_c = V_c/V = r$$

The value of Vc/V can be determined mathematically, by finding the kinetic forces acting on the chip.

The forces acting on the chip are shown in the fig below. The chip is acted upon by the static normal force P_N and tangential force P_T



(b) Motion of chip particle

- Tangential Force (Pt) is balanced by the kinetic force m(dv/dt)
- Normal Force (Pn) balanced by the centrifugal force mv^2/r

$$Pt = -m(dv/dt) = \mu Pn$$

$$Pn = mv^2/r = mv\, d\theta/dt$$

Hence,

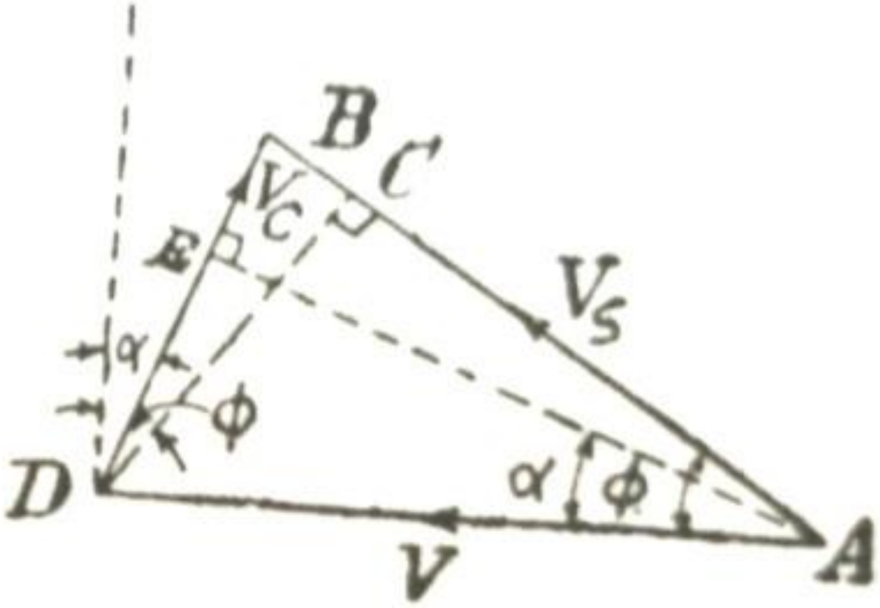
$$-m(dv/dt) = \mu mv\, d\theta/dt$$

$$dv/dt = -\mu v\, d\theta/dt$$

Integrating both sides within the limits of V and Vc:

$$\mathbf{r = Vc/V = e^{-\mu(\pi/2 - \alpha)}}$$

Velocity relations



- In triangle DCB; DC = $V_c \cos(\Phi-\alpha)$
- In triangle ACD; DC = $V\sin(\Phi)$
  - Hence, $V\sin(\Phi) = V_c \cos(\Phi-\alpha)$

$$\mathbf{V_c = V\sin(\Phi) / \cos(\Phi-\alpha)}$$

- Similarly:
- In triangle AED; AE = $V \cos(\alpha)$
- In triangle AEB; AE = $V_s \cos(\Phi-\alpha)$
  - Hence, $V_s \cos(\Phi-\alpha) = V \cos(\alpha)$

$$\mathbf{V_s = V \cos(\alpha) / \cos(\Phi-\alpha)}$$

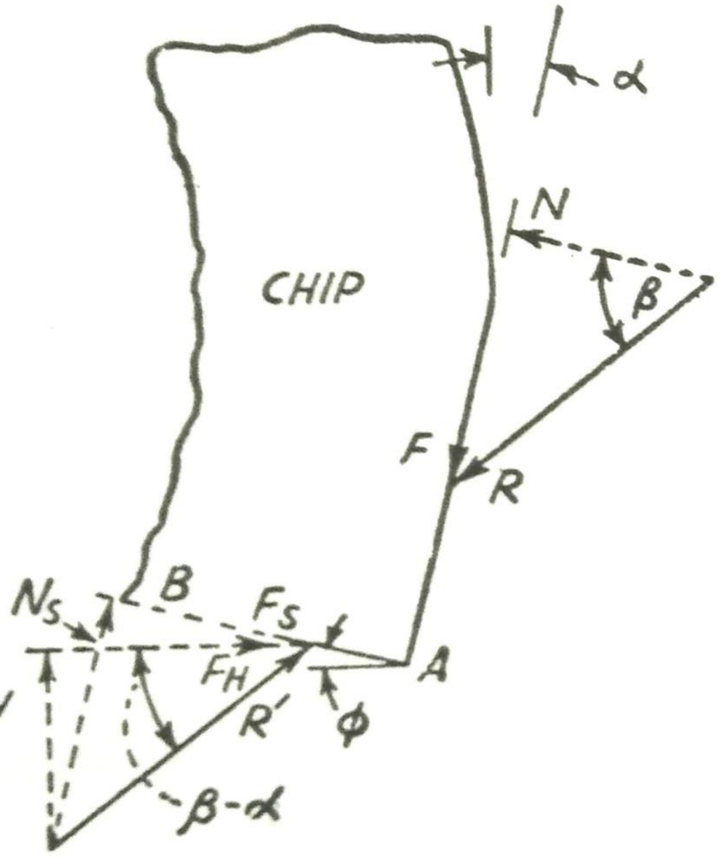
ORTHOGONAL CUTTING FORCES – **MERCHANT THEORY**

- Considering a 2D/Orthogonal Cutting operation.
- Assumptions:
  1. The tool is perfectly sharp and there is no contact along the clearance/flank face
  2. The cutting edge is a straight line, extending perpendicular to the direction of motion and generates a plane surface as the work moves past it.
  3. Width of the tool is greater than that of the workpiece.
  4. The depth of cut is constant
  5. The work moves relative to the tool with uniform velocity.
  6. The shear surface is a plane extending upwards from the cutting edge.
  7. The chip does not flow to either sides
  8. A continuous chip is produced with no BUE.

9. Plain strain conditions exists, (width of the chip remains equal to workpiece)
10. Chip is assumed to shear continuously across plane AB on which the shear stress reaches the value of the shear flow stress.

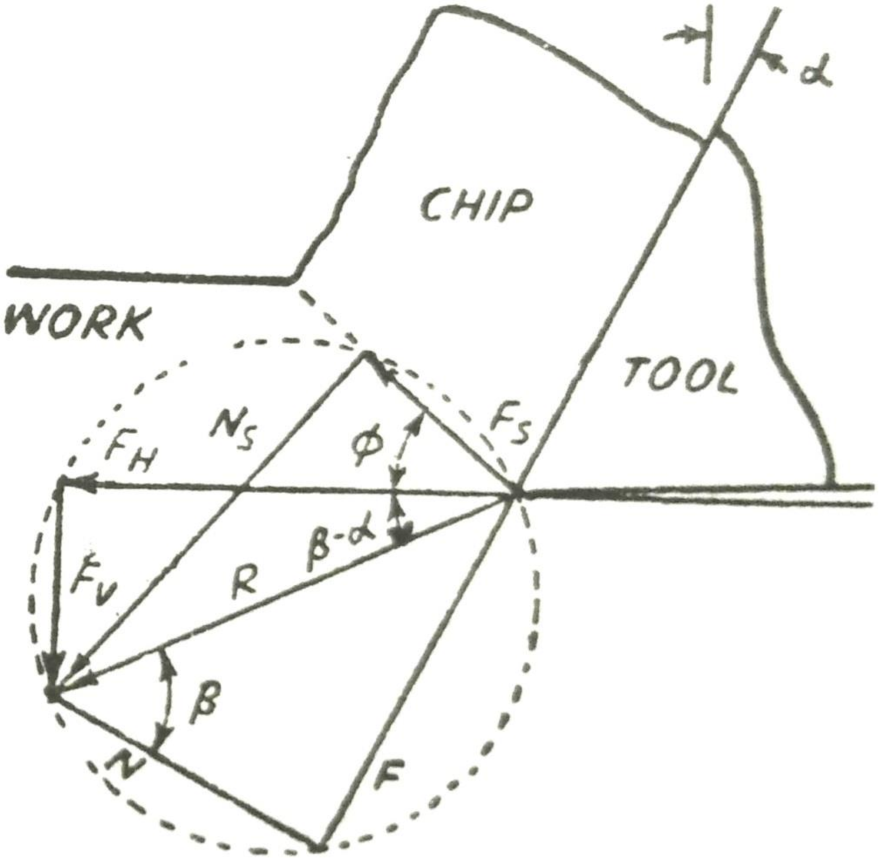
The forces acting on a metal chip during the cutting operation are:

- Fs – resistance to shear of the metal, acting along the shear plane (against the motion of the chip).
- Ns – backing up force on the chip provided by the workpiece, acting normal to the shear plane.
- N – normal to the cutting face of the tool (at the tool chip interface), provided by the tool
- F – frictional resistance of the tool acting on the chip. (downwards, against the motion of the chip)

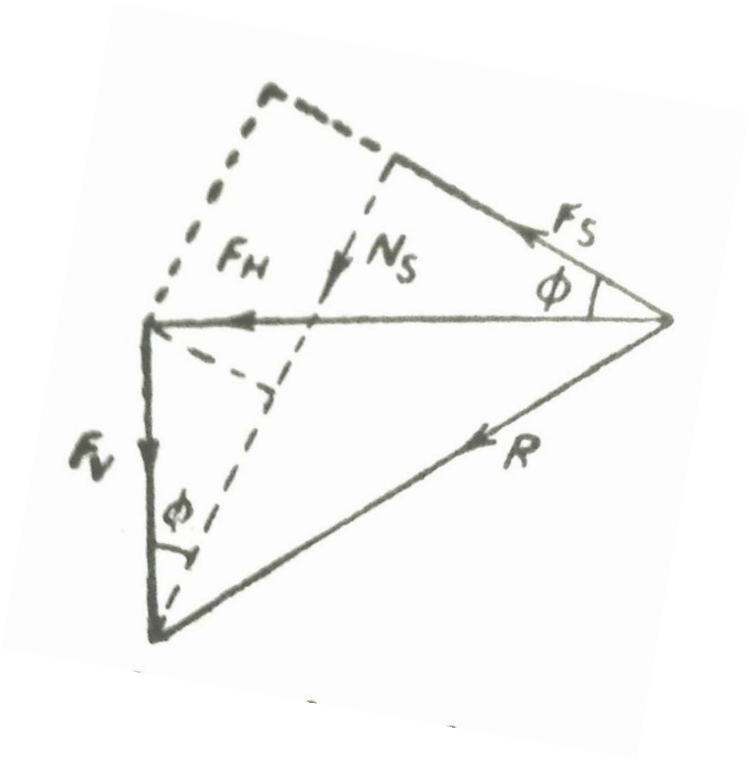

α
N
CHIP
β
F
R
B
Ns
Fs
A
FH
Fv
R'
φ
β-α

- All the above forces can be represented with the help of a circle know as '**Merchant Force Circle**'
- α- rake angle; β – angle of friction; Φ- shear angle
- R (b/w tool face and chip) and R' (b/w workpiece and chip) are the resultants.
- F_H and F_V are the horizontal and vertical forces.
- F_H is the cutting force & FV is the thrust force.
- Both F_H and F_V are measurable quantities (experimentally using a tool force dynamometer)

- R and R' must be equal for the equilibrium of the chip.



α
CHIP
WORK
TOOL
N_S
F_S
F_H
φ
β-α
F_V
R
β
N
F



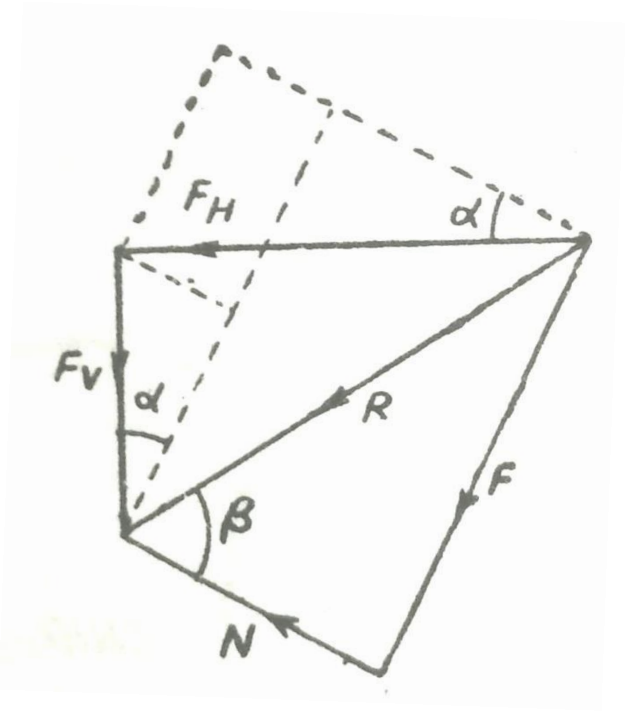
$F_S = F_H \cos\Phi - F_V \sin\Phi$

$N_S = F_H \sin\Phi + F_V \cos\Phi = F_S \tan(\Phi+\beta-\alpha)$

$R = F_H \sec(\beta-\alpha)$

$F_S = R \cos(\Phi+\beta-\alpha)$

$N_S = R \sin(\Phi+\beta-\alpha)$



$F = F_H \sin\alpha + F_V \cos\alpha$

$N = F_H \cos\alpha - F_V \sin\alpha$

Coefficient of friction (μ)

$$\mu = \tan\beta \qquad [\beta = \tan^{-1}\mu]$$

$$= F/N$$

$$= \frac{(F_H \sin\alpha + F_V \cos\alpha)}{F_H \cos\alpha - F_V \sin\alpha}$$

Dividing by cos α:

$$\mu = \frac{(F_H \tan\alpha + F_V)}{F_H - F_V \tan\alpha}$$

OR

$$\mu = \frac{\log(1/r)}{\pi/2 - \alpha}$$

Stresses & Strains

- The two stresses acting on the shear plane are:
  - Shear Stress τ_s = Shear force/Shear plane area
  - Normal stress σ_s = Normal force/Shear plane area

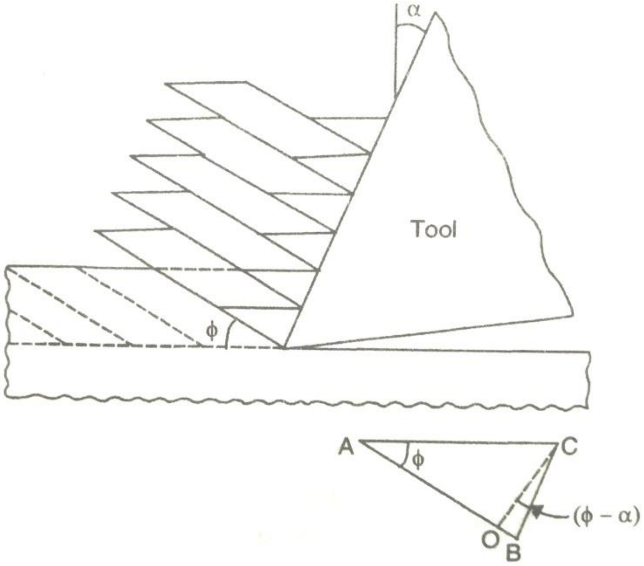
- Shear Plane area:
  - **$A_s = b\,(t/\sin\Phi)$**
- Hence:

$$\tau_s = F_s/A_s$$

$$\sigma_s = N_s/A_s$$

- Shear strain = distance sheared/thickness of the zone

From the Pispannens Card Model/Analogy:



Shear strain (s) = AB/OC

= (OA+OB)/OC

= (OA/OC) + (OB/OC)

= cot Φ + tan (Φ-α)

Shear strain rate (s·) = Vs/ ts

Note: ts – thickness of primary shear deformation zone = 1/10th of shear plane length (t/10sinΦ)

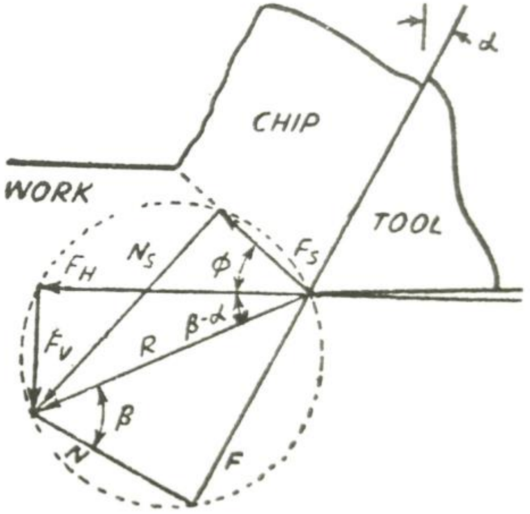
- <u>Factors affecting SHEAR ANGLE</u> **<u>– MERCHANT THEORY</u>**

- Ideally, shear angle should be such that the cutting forces are minimum or max shear stress occurs on the shear plane.
- We know,

$$F_S = R\cos(\Phi+\beta-\alpha)\ldots\ldots(1)$$

$$F_H = R\cos(\beta-\alpha)\ldots\ldots(2)$$

$$F_V = R\sin(\beta-\alpha)$$



From 2,

$$R = F_H\sec(\beta-\alpha)\ldots\ldots(3)$$

(3) In (1):

$$F_s = F_H \sec(\beta-\alpha)\cos(\Phi+\beta-\alpha)$$

We Know,

$$\tau_s = F_s/A_s$$

Hence,

$$\tau_s = [F_H \sec(\beta-\alpha)\cos(\Phi+\beta-\alpha).\sin\Phi]/bt$$

Assuming β to be independent of Φ, max shear stress,

$$\partial \tau_s / \partial \Phi = 0$$

We get:

$$\cos(\Phi+\beta-\alpha).\cos\Phi - \sin(\Phi+\beta-\alpha).\sin\Phi = 0$$

$$\cos(\Phi+\beta-\alpha).\cos\Phi = \sin(\Phi+\beta-\alpha).\sin\Phi$$

$$\tan(\Phi+\beta-\alpha) = \cot\Phi = \tan(90-\Phi)$$

Hence,

$$\mathbf{\Phi = (\pi/4) - \beta/2 + \alpha/2}$$

$$\mathbf{= (\pi/4) - (\beta - \alpha)/2}$$

This is called the **MERCHANT EQUATION**

METAL CUTTING PROCESS/PERFORMANCE PARAMETERS

- The different factors that affect the metal cutting operation are:

1. **Velocity (speed rate, feed rate):** Affects temp at tool point.
2. **Size/Depth of cut**
3. Tool geometry
4. Tool material
5. Nature of work-material: Ductile or Brittle
6. Cutting fluids

CUTTING POWER (P_c)

- It is the rate at which energy is consumed

$$\mathbf{P_c = F_H . V}$$

Where,

F_H = cutting force/horizontal force

V = cutting velocity (tool vel. w.r.t. workpiece)

$$V = [\pi DN/(60 \times 1000)] \text{ m/s}$$

Where,

D = diameter of the job/tool in mm

N = Velocity of the job/tool in rpm

If F_H is in N and V in m/sec

$$\mathbf{Pc = F_H . V / 1000 \text{ kW}}$$

$$F_H = Cd^x f^y V^z \text{, kgf}$$

Where,

F_H	= cutting force/horizontal force
V	= cutting velocity (tool vel. w.r.t. workpiece)
d	= depth of cut
f	= feed
C	= contant depending on material

Values of x, y, z = constants depending upon cutting conditions

Design power rating for the main drive motor

$$P_m = P_c \,/\, \eta_{mt}$$

where,

Pm = motor power

Pc = cutting power

η_{mt} = efficiency of the machine tool

NOTE:

Mean efficiencies (at full load) for machine tools are derived experimentally. (Lathe/Milling – 0.8 to 0.9)

METAL REMOVAL RATE (MRR)

- Volume of material removed/time - Expressed in mm^3/min
- Higher MRR does not indicate most economical process, since power consumed and cost factors must also be taken into account
- Hence, to compare two processes, the MRR per unit power consumed called SPECIFIC METAL REMOVAL RATE is used. (Unit- $mm^3/W/min$)
- For a single point cutting tool,

$$\mathbf{MRR = (1000.Ac.\ V)} \quad mm^3/min$$

where,

Ac = Cross sectional area of unreformed chip in mm^2

V = Cutting velocity in m/min

$$\textbf{MRR} = \mathbf{(1000.A_c.V)} \quad mm^3/min$$

$$= 1000.bt.V$$ (b-breadth of chip, t- thickness of chip)

For orthogonal turning,

$$MRR = 1000.df.V$$ ($\lambda = 90^o$, t=f; b=d)

$$= \pi DNdf$$ (N-rev/min; D-mean diameter in mm)

FRICTION

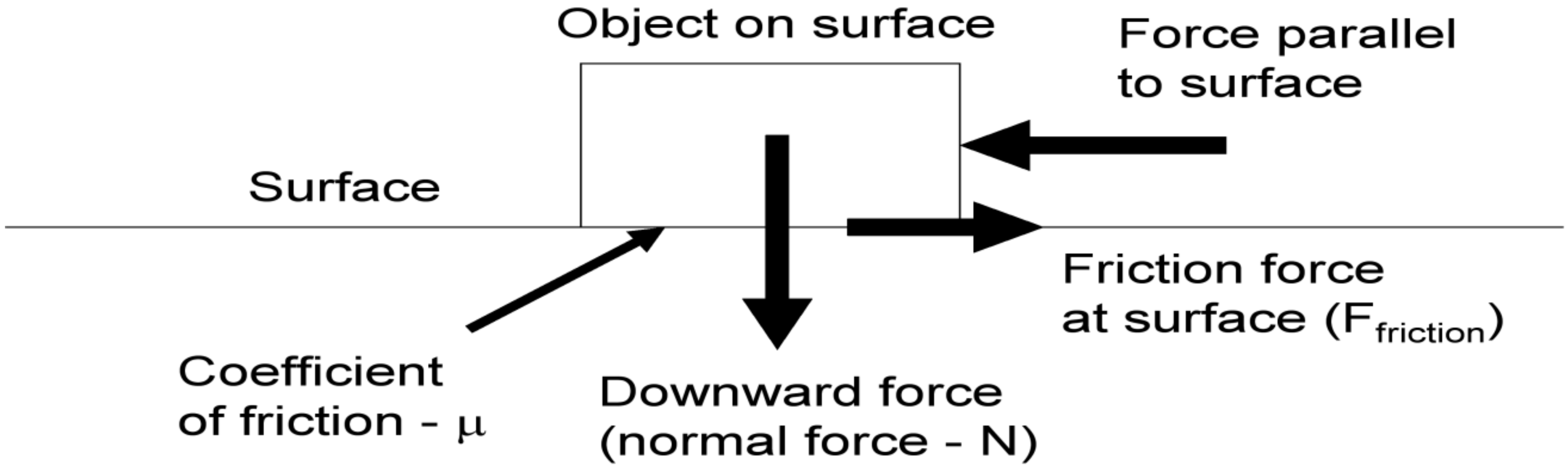
- One of the first people to investigate friction was Leonardo da Vinci
- Friction is the force resisting the relative motion of solid surfaces, fluid layers, and material elements sliding against each other
- <u>LAWS OF SLIDING FRICTION</u>
  - empirical relations
  - Three Laws of Friction
  - First two laws - Amontons Laws

First Law:

- The frictional force (F_f) is proportional to the normal load (N)
- μ is independent of normal load N
- Mathematically,

$$F_f = \mu \times N$$

- Where,
  - F_f – frictional force
  - N – total normal reaction/load at contact interface
  - μ - coefficient of friction



$$F_{friction}=\mu N$$

Figure 1 – Basic Definitions of the Coefficient of Friction

- Value of μ varies from 0.001 (lightly loaded rolling bearing) to greater than 10 (clean metals sliding against themselves in vacuum)
- Most common materials, μ ranges from 0.1 to 1.
- <u>NOTE: Polymers do not usually obey first law.</u>

- **Second Law**
  - Frictional force is independent of the apparent area of contact
  - Experiment – Normal load is held constant, apparent area of contact increased
  - μ is independent of apparent area of contact
  - NOTE: Second law – not obeyed by POLYMERS

- **<u>Third Law (Coulomb's Law)</u>**
- Found by Coulomb
  - Friction is independent of sliding velocity
  - Friction Force to initiate sliding more than that necessary to maintain it.
  - Hence,
    - μ_s (coefficient of static friction) > μ_d (coefficient of dynamic friction)
    - μ_d is nearly independent of sliding velocity
    - At very high speeds (tens or hundreds of m/s), μ_d falls with increasing velocity

Coefficient of Friction (μ)

- Independent of:
  - Normal Force
  - Apparent Area of contact
  - Nearly independent of sliding velocity

- Depends solely on the materials of the surfaces in contact.

Causes of Friction

- When two surfaces are loaded together they can adhere over some part of the contact and this adhesion is therefore one form of surface interaction causing friction.
- If no adhesion takes place then the only alternative interaction which results in a resistance to motion is one in which material must be deformed and displaced to accommodate the relative motion. We can consider two types of interaction

1. Asperity interlocking: motion cannot take place without deformation of the asperities (fig A)
2. Macro displacement : Here a hard sphere A loaded against a softer material B causes displacement of material B during motion. (fig B)

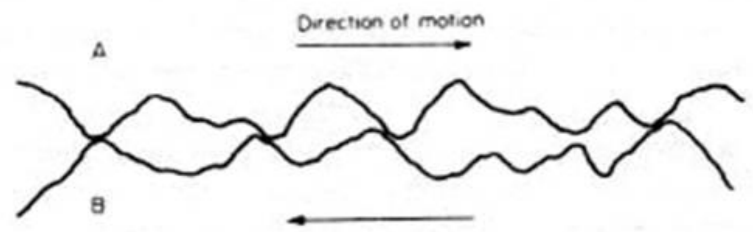


FIG A

FIG B

ADHESION THEORY OF FRICTION

- Bowden and Tabor explained the adhesion theory of friction - when metal surfaces are loaded against each other, they make contact only at the tips of the asperities.
- Because the real contact area is small the pressure over the contacting asperities is assumed high enough to cause them to deform plastically.
- This plastic flow of the contacts causes an increase in the area of contact until the real area of contact is just sufficient to support the load. Under these conditions for on ideal elastic-plastic material

$$\mathbf{W = A \cdot P_o \ldots\ldots (a)}$$

Where,

A is the real area of contact,

P_o is the yield pressure of the metal and

W is the normal load

- When the metals are in contact, cold welding takes place due to adhesion. So **S-** force per unit area of contact is necessary to shear the junction

$$F = A.S + P_e$$

- Where P_e is the force required to plough hard asperities through a softer surface.
- For most situations involving un-lubricated metals P_e is small compared to A.S and may be neglected.

- Therefore, $F = AS$

  $F = (W/ P_o) . S$….. From (a)

  $F/W = S/ P_o$

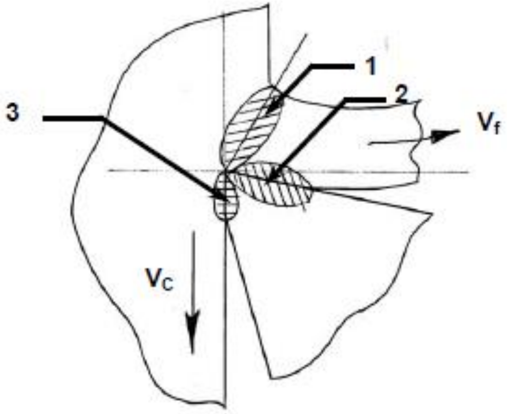
- Therefore $\mu = F/W = S/ P_o$

- Thus, this theory explains two laws of friction

- Almost all (90%-100%) of the mechanical energy consumed in a machining operation finally converted into the thermal energy
- Hence temp. is a major concern

Sources and causes of heat generation:

Since the heat generation is closely related to the plastic deformation and friction, we can specify three main sources of heat when cutting, as indicated in adjacent fig.



SOURCES

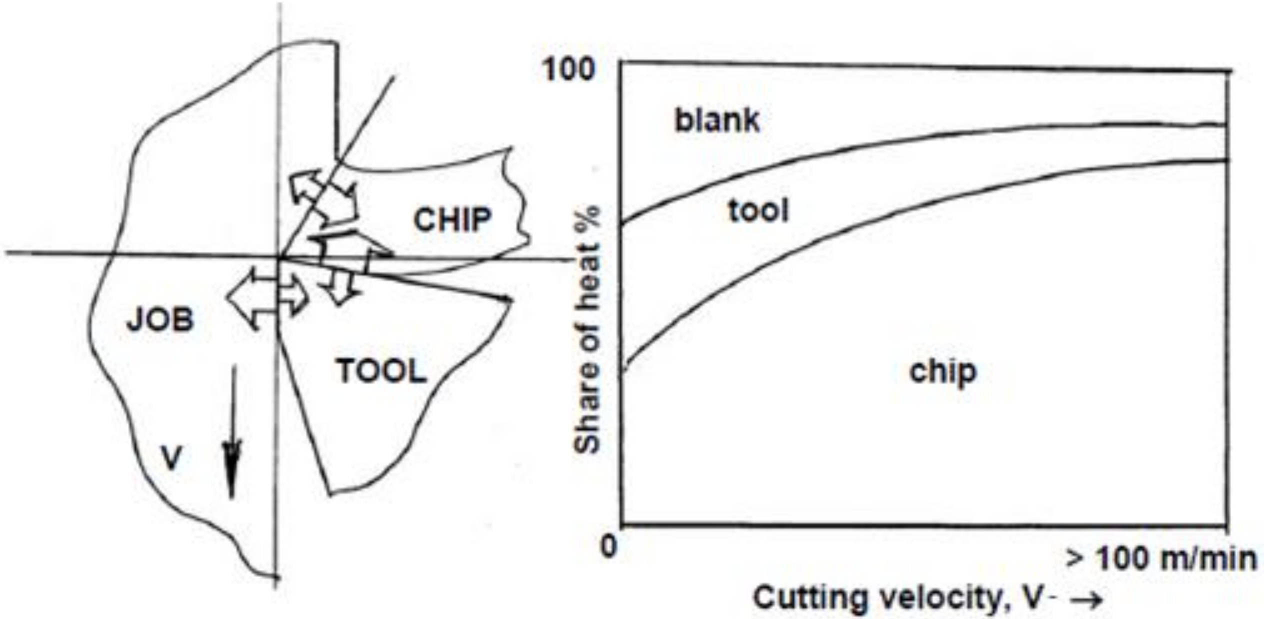
1. **Primary shear zone** (1) where the major part of the energy is converted into heat
2. **Secondary deformation zone** (2) at the chip – tool interface where further heat is generated due to rubbing and/or shear
3. **At the worn out flanks** (3) due to rubbing between the tool and the finishes surfaces

- The heat generated is shared by:
  - chip,
  - cutting tool and
  - the blank/workpiece.
- The discarded chip carries away about 60~80% of the total heat
- The workpiece acts as a heat sink drawing away 10~20% heat
- The cutting tool will also draw away ~10% heat

NOTE: If coolant is used in cutting, the heat drawn away by the chip can be as big as 90% of the total heat dissipated

- The proportion of sharing of the heat depends upon:
  - configuration, size and thermal conductivity of the tool – work material and
  - the cutting condition

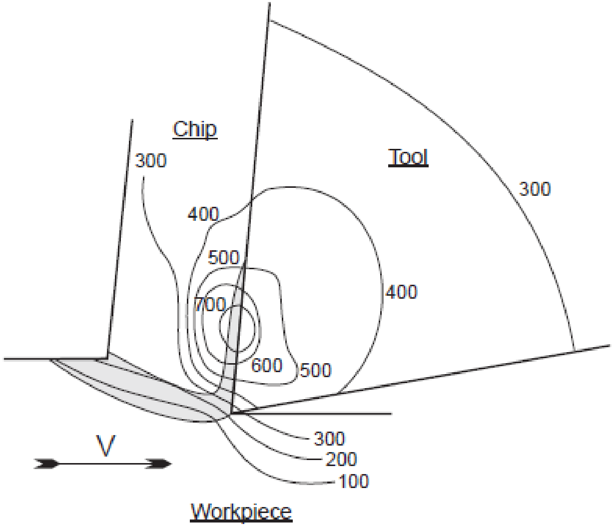
With the increase in cutting velocity, the chip tends to share a larger proportion of the heat generated.



TEMPERATURE DISTRIBUTION PATTERN

- Cutting temperature is not constant through the tool, chip and workpiece. The temperature field in the cutting zones is shown in the fig below

TEMP ISOTHERM

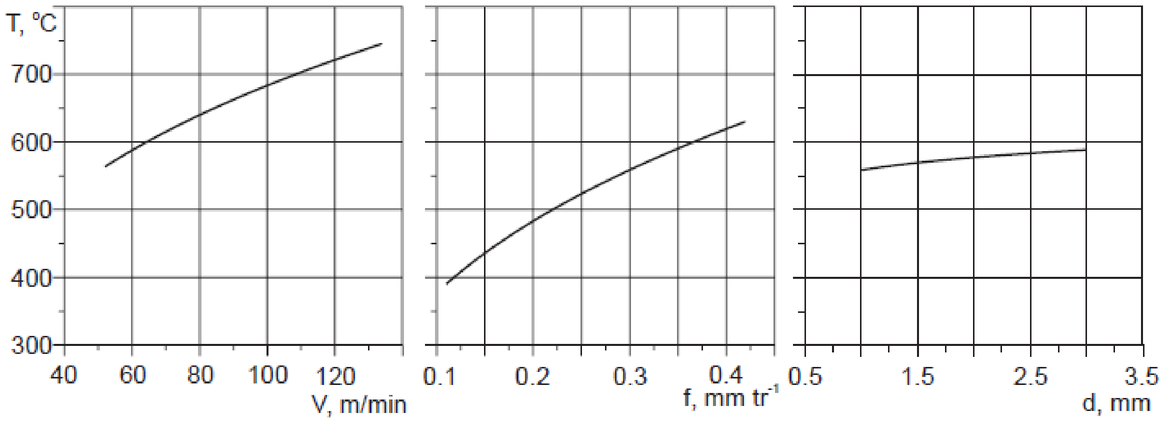


- It is observed, that the maximum temperature is developed not on the very cutting edge, but at the tool rake some distance away from the cutting edge

EFFECT OF MACHINING PARAMETERS ON CUTTING TEMPERATURE

1. Work material :
    1. ductility
    2. thermal properties
2. **Process parameters :**
    1. **cutting velocity (V)**
    2. **feed (f)**
    3. **depth of cut (d)**
3. Cutting tool material :
    1. Thermal properties
    2. wear resistance
    3. chemical stability
4. Tool geometry : rake angle (γ) , cutting edge angle (ϕ) , clearance angle (α) ,nose radius (r)
5. Cutting fluid : thermal and lubricating properties, method of application

- The diagrams below show the dependencies between the mean cutting temperature and process parameters cutting velocity (V), feed (f) & depth of cut (d)



Cutting temperature T as a function of cutting speed V, feed f, and depth of cut d

- It is seen that,
  1. As V increases, T also increases
  2. As f increases, T also increases
  3. The effect of d is seen to be negligible.

Effect of High Cutting Temperature on Tool and Workpiece/Job

- Cutting temperature effects (especially when high) are usually detrimental.
- Major part of the heat generated is carried away by chips, which are discarded.
- So attempts should be made such that max heat is carried away by the chips.
- The possible detrimental effects of the high cutting temperature on cutting tool are:
  1. Rapid Tool wear – reduced tool life
  2. Plastic deformation of cutting edges (if tool material has low hot hardness)
  3. Thermal flaking and fracturing of cutting edges (due to thermal shocks)
  4. BUE formation

- The possible detrimental effects of the high cutting temperature on work-piece are:
  1. Dimensional Inaccuracies of the job due to thermal distortion
  2. Surface damage due to oxidation (Poor surface finish)
  3. Induction of tensile residual stresses and surface/subsurface micro-cracks

NOTE:

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 which are very hard and hardenable like high manganese steel, Hadfield steel, Ni-hard, Nimonic etc

CUTTING TEMPERATURE CONTROL

- The temperature in metal cutting can be reduced by:
    1. application of cutting fluids (coolants).
    2. change in the cutting conditions by reduction of cutting speed and/or feed;
    3. selection of proper cutting tool geometry

TOOL TEMPERATURE MEASUREMENT

The temperatures which are of major interests are:

1. average shear zone temperature
2. average (and maximum) temperature at the chip-tool interface
3. temperature at the work-tool interface (tool flanks)
4. average cutting temperature

Cutting temperature can be determined by two ways :

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

ANALYTICAL METHOD

- **<u>Average shear zone temperature (Ts)</u>**
  - The cutting energy per unit time (power), i.e., $F_H.V$ gets used to cause primary shear and to overcome friction at the rake face as,

$$\mathbf{F_H.V = Fs.Vs + F.Vc}$$

where, Vs = slip velocity along the shear plane ; Vc = average chip – velocity

So,

$$\mathbf{Fs.Vs = F_H.V - F.Vc}$$

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

$$(Aq_1 \{F_H.V - F.V_c\})/J = C_v t b V_c (T_s - T_a)$$

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

Cv= volume specific heat of the chip

Ta = ambient temperature

tb = cross sectional area of uncut chip = feed (f) x depth of cut (d)

Generally A varies from 0.95 to 1.0 and q_1 from 0.7 to 0.9 in machining like turning.

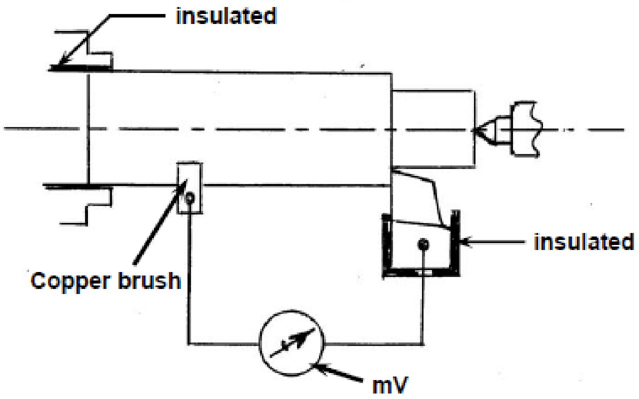
EXPERIMENTAL METHODS OF DETERMINATION OF CUTTING TEMPERATURE

- Generally used to find chip-tool interface temperature (highest – Max at the almost the middle of chip-tool contact length)
- The feasible experimental methods are :
  1. Calorimetric method – quite simple and low cost but inaccurate and gives only grand average value
  2. Decolourising agent – some paint or tape, which change colour with variation of temperature, is pasted on the tool or job near the cutting point; as such colour of the chip (steels) may also often indicate cutting temperature

3. Tool-work thermocouple – simple and inexpensive but gives only average value
4. Moving thermocouple technique
5. Embedded thermocouple technique
6. Using compound tool
7. Indirectly from Hardness and structural transformation
8. Photo-cell technique
9. Infrared ray detection method

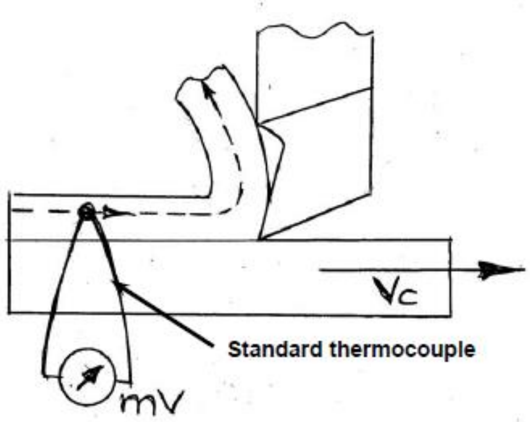
Tool-work thermocouple technique

- In a thermocouple two dissimilar but electrically conductive metals are connected at two junctions. Whenever one of the junctions is heated, the difference in temperature at the hot and cold junctions produce a proportional current which is detected and measured by a milli-voltmeter.
- In machining like turning, the tool and the job constitute the two dissimilar metals and the cutting zone functions as the hot junction.
- Then the average cutting temperature is evaluated from the mV reading, after thorough calibration for establishing the exact relation between mV and the cutting temperature.



Moving thermocouple technique

- This simple method, schematically shown in Fig. below, enables measure the gradual variation in the temperature of the flowing chip before, during and immediately after its formation.
- A bead of standard thermocouple like chrome-alumel is brazed on the side surface of the layer to be removed from the work surface and the temperature is attained in terms of mV.



TOOL MATERIALS

- Different types of materials are used for making tools. Each tool material finds its use under different applications.
- Some of the commonly used cutting tool materials are:
  - Carbon Steel
  - HSS (High Speed Steels)
  - Cemented carbides
  - Ceramics
  - CBN (cubic boron nitride)
  - PCD (poly crystalline diamond) and diamond coated tools

Characteristics of a good tool material

1. **Hot hardness:**
   - ability to withstand high temperatures without losing its cutting edge.
   - Important in high speed cutting
   - Increased by adding Cr, Mo, W and V (forms hard carbides)
   - Good wear resistance, but low toughness and mechanical shock resistance.
2. **Wear resistance:**
   - Ability to resist wear (may causes poor surface finish in its absence)
3. **Toughness:**
   - ability of a material to absorb energy and plastically deform without fracturing
   - Puts limitation to hardness of tool ; high hardness – brittle and weak
   - Important in the case of tools used for interrupted cuts.
4. **Mechanical and thermal shock resistance**

5. **Ability to maintain above properties at different temperatures occuring during machining**
6. **Low friction**
   - For improved tool life and better surface finish
7. **High thermal conductivity**
   - For quick removal of heat from the chip tool interface
8. **Readily obtainable**
9. **Favourable Cost**
   - Potential savings from its use (reduced labour, increased cutting speed(MRR), increased life) should outweigh its cost
10. **Easy to regrind/modify**

1. Plain High Carbon Tool Steel:

- C - 0.8-1.3%; Si - 0.1-0.4%; Mn - 0.1-0.4%; rest Fe
- Higher C content – increased wear resistance, but will make it brittle
- Two categories: a. Water hardening, b. Oil hardening
- **Characteristics:**
  - Low hot hardness - Will loose hardness above 200°C, will not regain it on cooling
  - Poor hardenability
  - Easy to machine
  - Keen cutting edge can be provided easily
  - High surface hardness with fairly tough core.
- **Use:**
  - Used in tool of small section which operate at relatively small speeds
  - Speed limited to 0.15m/s using large amounts of coolant
  - Used for manufacture of milling cutters, twist drills, turning tools etc. for wood, Mg, Al etc.

2. Low alloy carbon steels:

- Small amounts of Cr and Mo are used to increase hardenability of tools
- Upto 4% of W – used to improve wear resistance
- **Characteristics:**
  - Hot hardness same as that of carbon steels
  - Not suited for high speed operations
- **Use:**
  - Tools that require wear resistance
  - Drills, Taps and reamers

3. High Speed Steels (HSS)

- **Characteristics:**
  - Superior Hot hardness – can maintain hardness temp upto 600^{o} C (due to presence of W, Mo or Co), but soften rapidly after that.
  - Superior wear resistance
  - Can be used at higher cutting speed – limited to 0.75-1.8 m/s
- **Types:**

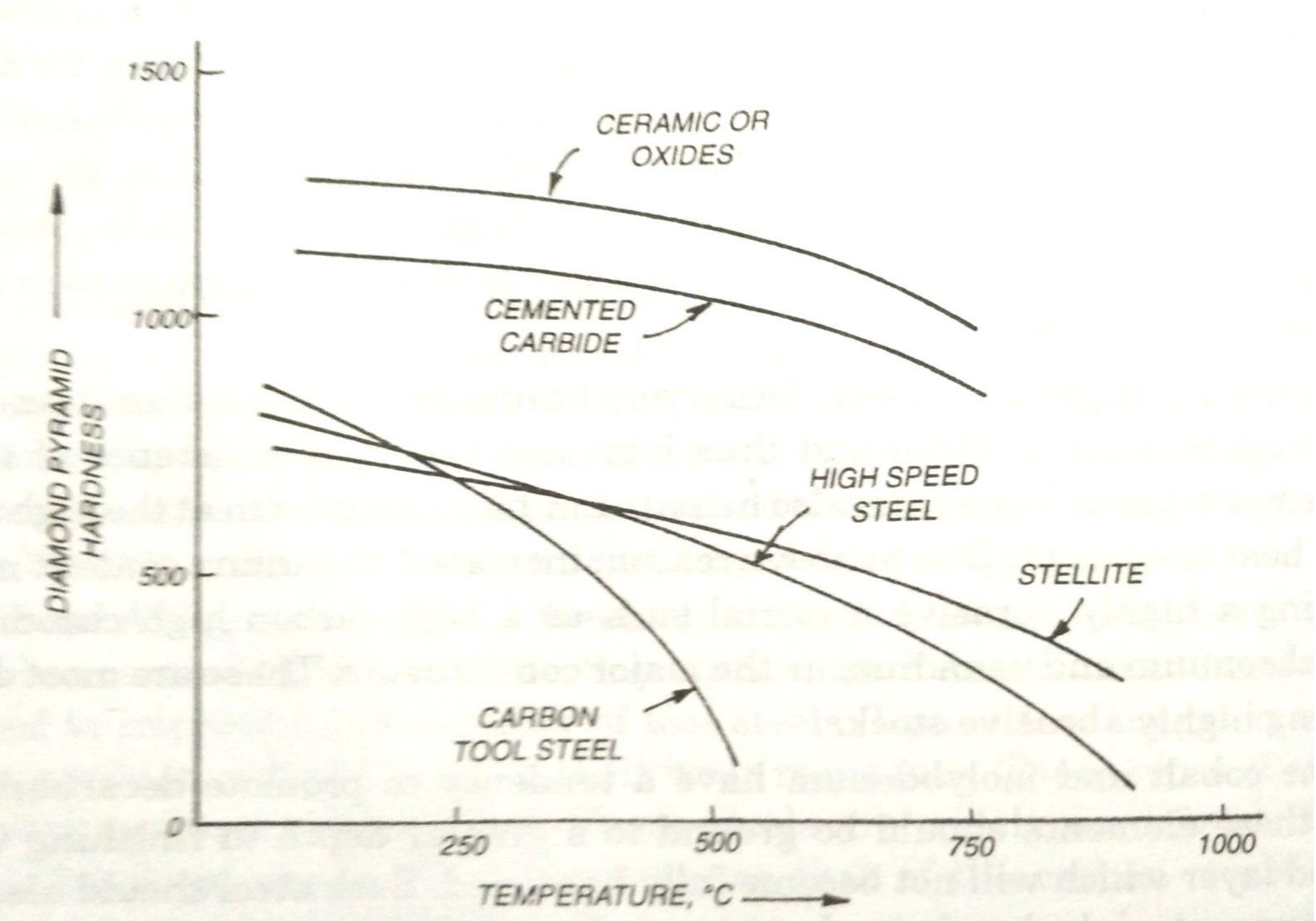
  a) Tungsten and Molybdenum Type: 3 types
     1. High tungsten (T-type)
     2. High Molybdenum (M-type)
     3. Tungsten-Molybdenum type

  b) Cobalt Type

Type	W	Cr	V	Mo	C	Fe
T type	18	4	1	-	0.7	Balance
M type	1.5	4	1	8.5	0.8	Balance
W-Mo type	6	4	1	5	0.8	Balance

- **HSS cont.**
  - All the above Tungsten and Molybdenum types of HSS contain about 0.025% Si and 0.25% Mn.
  - Co may be added (in 4,8 or 12% ratio) to any of the above types of HSS for increases hot hardness
  - W and Mo increase hot hardness by forming complex carbides of high hardness
  - Co forms an alloy going into the solid solution in the ferrite matrix and thus raising the recrystallization temp. (material can retain hardness gained through strain hardening at higher temp)
  - V forms very hard carbides and thus increases the wear resistance at high operating temp. (higher % used in tools used to machine highly abrasive material like High C-High Cr die steel)

- **HSS cont.**
  - Cr and Co have the tendency to promote retention of austenite, which has further tendency to transform into martensite at low temp when the tool is subjected to cold work as by grinding or in use of cutting. This will cause dev. of large internal stresses which frequently cause cracks to develop in tools, leading to premature breakdown of cutting edge.
  - Double tempering done to avoid this.
  - Heat treatment of HSS tools affects its properties.
  - HSS tools manufacture by – Powder metallurgy or electro slag refining process
  - HSS tools can also be coated with layers of refractory metal carbide or nitride by CVD.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1000
500
0
DIAMOND PYRAMID HARDNESS
CERAMIC OR OXIDES
CEMENTED CARBIDE
HIGH SPEED STEEL
STELLITE
CARBON TOOL STEEL
250
500
750
1000
TEMPERATURE, °C

4. <u>Stellites</u>:

- Non-ferrous alloys – high in Co
- 40-50% Co, 27-32% Cr, 14-29% W and 2-4% C
- They are cast alloys
- **<u>Characteristics</u>**
  - Cannot be heat treated.
  - Not as hard as Tool Steels at room temp, but retain hardness at higher temp. (harder than HSS above 500^{o} C)
  - Fragile in nature (weak in tension and hence tend to shatter under shock load or if not properly supported)
- **<u>Used:</u>**
  - For Rapid machining of hard metals.
  - For Making form tools
  - Used in tool or insert form

5. Cemented Carbides

- Fine crystals of WC (very hard) mixed with Co powder (binder), sintered onto tool bits.
- Manufactured by Powder metallurgy
- **Used:**
  - Machining cast irons, certain abrasive non ferrous alloys.
  - Not good for cutting steels (due to face wear; can be reduced by adding Ti and Ta carbides before sintering)
- **Grades:**
  - C-grade: WC with Co as binder (3-16%), greater Co content, greater shock resistance
  - S-grade: WC, TiC (0-10%), Tantalum carbide (0-16%) with cobalt binder; can be used to machine steels

    TiC – helps to reduce tendency of chip welding and increases hot hardness

    Tantalum carbide – helps improve crater wear resistance

5. Cemented Carbides cont.

- **Characteristics:**
  - High hardness over wide range of temp.
  - Very stiff (high Young's Modulus – nearly three times that of steel)
  - Very low thermal expansion
  - Relatively high thermal conductivity
  - Can be used for higher cutting speeds (3-4 m/s with mild steel)

6. Ceramics

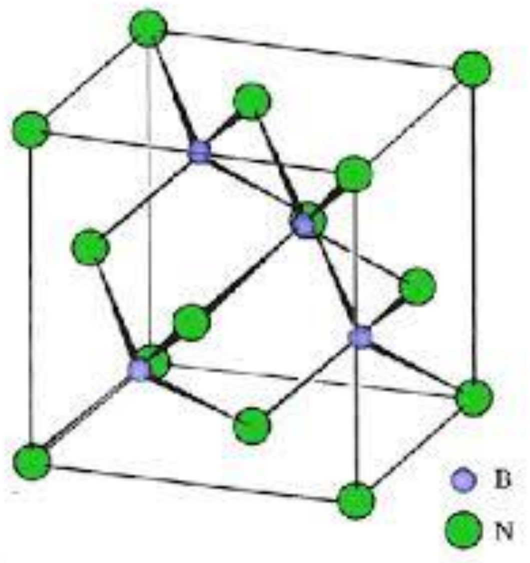
- Mainly consists of sintered oxides (Al_2O_3 mainly and other oxides)
- Sometimes Al_2O_3 may be as high as 97%.
- Sometimes, 80% Al_2O_3 with Ti, Mg and W oxides and carbides
- Prepared in the form of throw away inserts or clamped tips
- **Characteristics**
  - Can be used at very high speed (beyond carbide tools)
  - Resists BUE and produces good surface finish
  - Very hard and good resistance to wearing
  - High hot hardness – can maintain hardness upto 700^{o}C
  - Low friction at rake surface compared to carbide tools
  - Extremely brittle – limited to continuous cuts
  - Poor thermal conductors – high temperatures
  - **Cutting edges are usually chamfered and negative rakes of 15-20^o are provided**

7. Sialon

- Word Si Al ON, stands for Silicon Nitride based materials with aluminium and oxygen additions
- Produced by milling (grinding process) Si_3N_4, Aluminium Nitride, Alumina and Yttria (Y_2O_3). The mixture is dried, pressed is shape and sintered at 1800°C
- **Characteristics and Uses**
  - Tougher than Alumina (ceramics) and thus suited for interrupted cuts
  - Used to machine aerospace alloys and Ni based alloys
  - High cutting speeds of 200-300 m/min (3-5 m/s) can be used

8. Cubic Boron Nitride (cBN)

- It consists of atoms of nitrogen and boron, with special structural configuration similar to diamond.
- Available as indexable inserts
- **Characteristics:**
  - High Hardness (hardest material next to diamond)
  - High thermal conductivity
  - Chemically inert
- **Used:**
  - Machining hardened tool steel and high strength alloys
  - Grinding of HSS and stellites

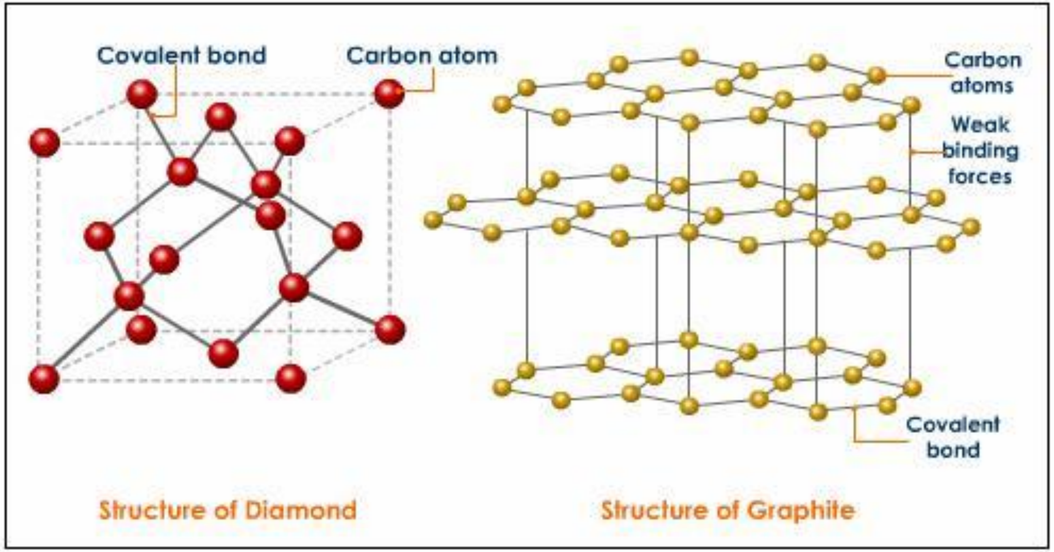


9. Diamond Tools

- It consists of atoms of carbon arranged in a variation of FCC structure called a DIAMOND LATTICE
- **Characteristics:**
  - High Hardness (hardest material)
  - High thermal conductivity (2 times that of steel)
  - Lowest thermal expansion (12% of steel)
  - Very low coefficient of friction
  - Very brittle
- **Used:**
  - Producing high surface finish on soft materials that are difficult to machine (Cu, Al etc.)
  - High cutting speeds can be used (nearly 150 m/min)

8. Diamond Tools cont.

- Diamonds commercially classified as:
  - Carbons (polycrystalline – Less dense and hard)
  - Ballas (polycrystalline – Less dense and hard)
  - Boarts (single crystals – less clear and fault free) – USED FOR CUTTING
  - Ornamental stones







TOOL FAILURE

- Cutting tools generally fail by :

i) **Mechanical breakage** due to excessive forces and shocks. Such kind of tool failure is random and catastrophic in nature and hence are extremely detrimental.

ii) **Quick dulling by plastic deformation** due to intensive stresses and temperature. This type of failure also occurs rapidly and are quite detrimental and unwanted.

iii) **Gradual wear** of the cutting tool at its flanks and rake surface

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

- But failure by gradual wear, which is inevitable, **cannot be prevented but can be slowed down only to enhance the service life of the tool**

TOOL WEAR MECHANISMS

There are different types of mechanisms responsible for wear.

1. **Adhesion**
2. **Abrasion**
3. **Diffusion & Dissolution**
4. **Chemical Reaction and Oxidation**
5. **Fatigue**

Depending on

- cutting conditions and
- tool-work materials combination,

the mechanism responsible for wear changes.

- At low cutting speeds, adhesive and abrasive wear tend to be dominant.
- Diffusion, dissolution, chemical reaction and oxidation are more relevant at high cutting speeds

1. ADHESION WEAR

- Adhesive wear occurs when one surface is sliding against another and fragments of one surface adhere to the other and then are pulled out of the original surface.
- The origin of adhesive wear is the strong adhesive forces that arise whenever atoms come into intimate contact
- The most up-to-date quantitative law for adhesive wear is the so-called modified Holm-Archard law given by

$$V = kLx/p$$

- Where V is the volume of wear per sliding distance, k is a probability constant, L is the load between surfaces, x is the distance slid and p is the hardness of the surface being worn.

1. ADHESION WEAR Cont.

- In metal cutting, adhesion may occur because the work material or the wear debris from the work material forms strong bonds (junction) with the tool under the high interfacial pressure and temperature.

- If the failure strength of the junction formed is larger than the local failure strength of one of the sliding surfaces, then, the junction will be detached from the surface with the lower failure strength. Tool wear will occur if the lowest failure strength happens to be on the tool

2. ABRASIVE WEAR

- Abrasive wear **occurs whenever a hard rough surface and/or a surface containing hard particles slides on top of a softer surface**.
- In tool wear, abrasive wear is the removal of tool material by hard, abrasive phases in work material.
- Depending on the morphology of the abrasive phases, both 2 and 3-body abrasion are possible


Abrasive wear
Two body abrasive wear
Three body abrasive wear
www.substech.com

3. DIFFUSION WEAR

- Solid-state diffusion takes place from regions of high atomic concentration to regions of low atomic concentration.
- *The diffusion rate increases exponentially with temperature.*
- Diffusion can occur in metal cutting due to the intimate contact at high temperatures in a very narrow reaction zone between the tool and the chip
- Diffusion wear mainly causes weakening of the surface structure of the tool

4. CHEMICAL REACTION

- Chemical reaction is not a wear mechanism.
- However, if chemical reaction occurs, it can affect tool wear tremendously when the tool material reacts with the work material or other chemicals to form compounds that are carried away in the chip stream or in the new generated surface of the workpiece.
- Chemical wear becomes predominant as cutting speed increases when machining highly reactive materials such as titanium

5. FATIGUE

- Will occur when two surfaces slides in contact with other under high pressure
- Asperities of the surfaces come into contact with each other
- Due to friction, one side of the asperity will be under tension and the other under compression.
- As sliding progresses, this loading changes cyclically causing fatigue failure and formation of wear debris.

TOOL WEAR

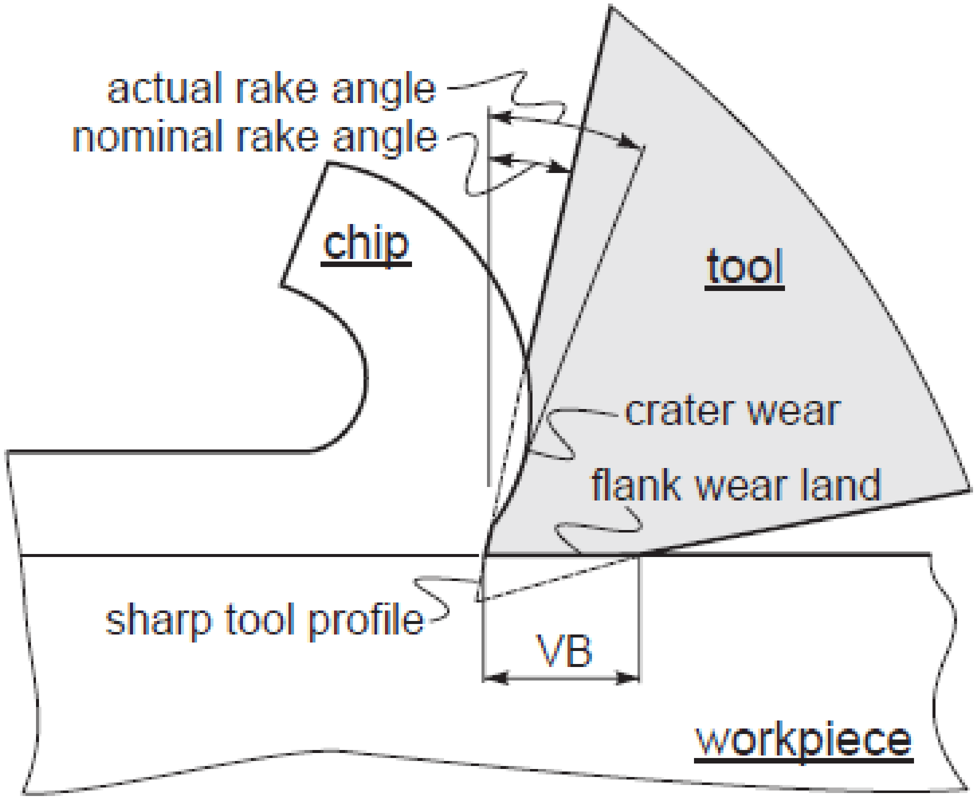
- Gradual wear occurs at two principal location on a cutting tool. Accordingly, two main types of tool wear can be distinguished,

1. Crater wear:

- consists of a concave section on the tool face formed by the action of the chip sliding on the surface.
- Crater wear affects the mechanics of the process increasing the actual rake angle of the cutting tool and consequently, making cutting easier.
- At the same time, the crater wear weakens the tool wedge and increases the possibility for tool breakage.
- In general, crater wear is of a relatively small concern.

2. Flank wear

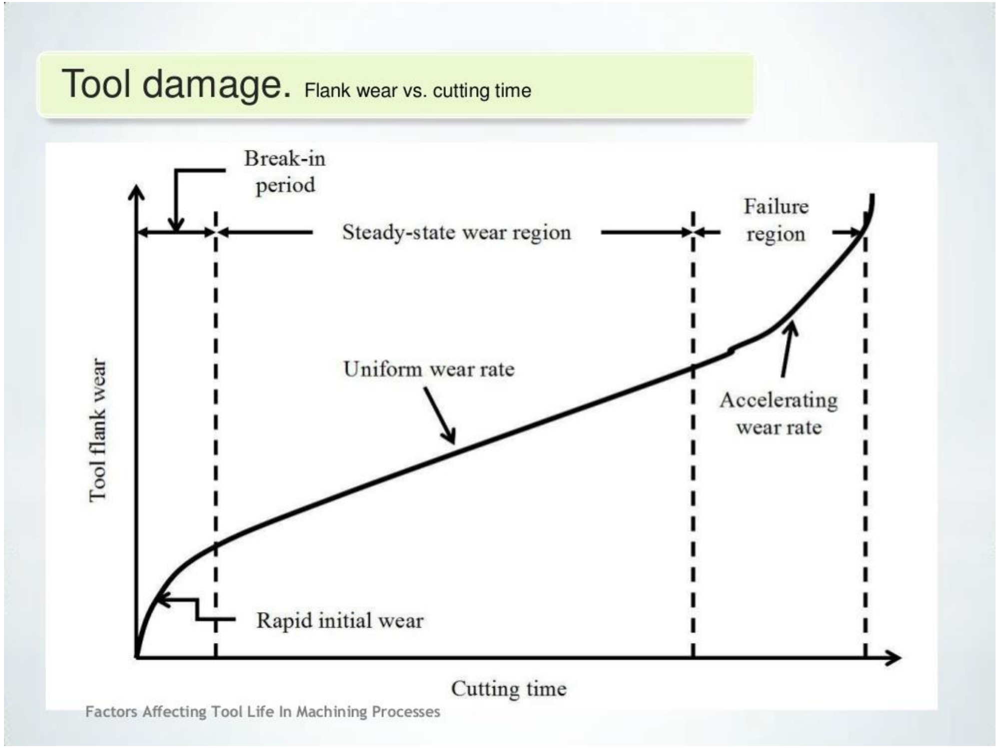
- Occurs on the tool flank as a result of friction between the machined surface of the workpiece and the tool flank.
- Flank wear appears in the form of so-called **WEAR LAND** and is measured by the width of this wear land, VB.
- Flank wear affects to the great extend the mechanics of cutting. Cutting forces increase significantly with flank wear.
- If the amount of flank wear exceeds some critical value (VB > 0.5~0.6 mm), the excessive cutting force may cause tool failure.


actual rake angle
nominal rake angle
chip
tool
crater wear
flank wear land
sharp tool profile
VB
workpiece

TOOL WEAR

The wear of tools takes place in 3 stages:

1. **Break in (rapid wear)**
2. **Steady-state wear (uniform wear rate)**
3. **Failure (acc. wear)**



Measurement of tool wear

The various methods are :

- by loss of tool material in volume or weight, in one life time – this method is crude and is generally applicable for critical tools like grinding wheels.
- using optical microscope fitted with micrometer – very common and effective method
- using scanning electron microscope (SEM) – used generally, for detailed study; both qualitative and quantitative
- Talysurf, specially for shallow crater wear

TOOL LIFE

- As a machining operation progresses, the cutting edge of the tool gradually wears out and at a certain stage it stops cutting metal efficiently (as per requirement).
- It has to be re-sharpened to make it cut.
- Tool life – useful cutting life of the tool from the start of cut until such a time when the tool no longer performs the designed function defined by the failure criteria. (expressed as time)

OR

- Tool life is defined as **the *length of cutting time* that the tool can be used satisfactorily**

TOOL LIFE cont.

The various possible indicators of end of tool life are:

1. **Failure of Tool**
2. **Extend of Tool wear**
3. **Poor surface finish**
4. **Dimensional instability**
5. **Sudden increase in cutting forces and power**
6. **Overheating and fuming**
7. **Presence of chatter etc.**

TOOL LIFE cont.

The various factors affecting cutting tool life are:

1. **Cutting Tool material**
2. **Workpiece material**
3. **Machining parameters**
4. **Cutting tool geometry**
5. **Cutting fluid**
6. **Nature of cutting (continuous or intermittent)**

Tool life is governed mainly by the level of the machining parameters i.e.,

1. **Cutting velocity (V)**
2. **Feed (f)**
3. **Depth of cut (d)**

Cutting velocity affects maximum and depth of cut minimum

TAYLORS EQUATION (for Tool life)

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

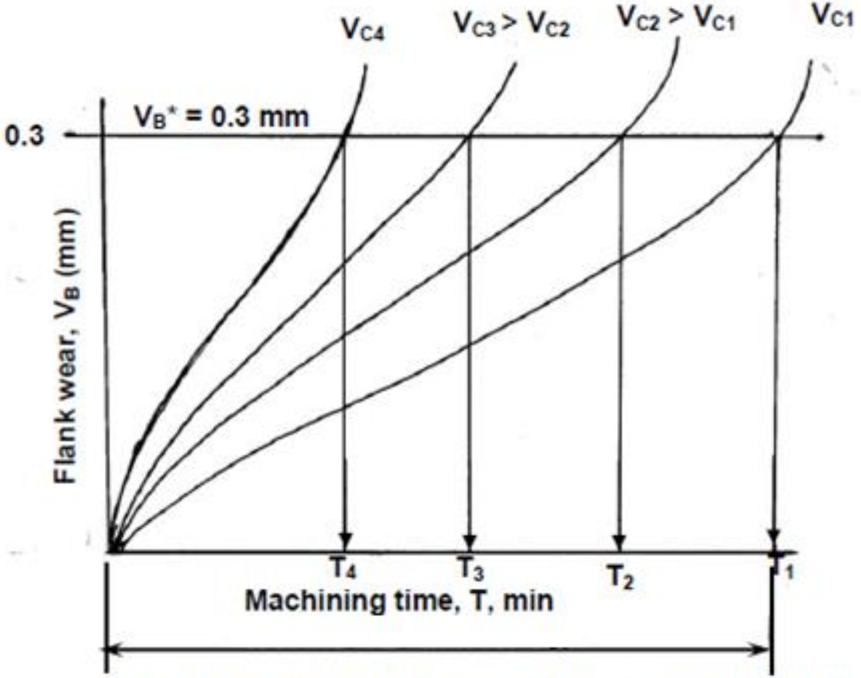
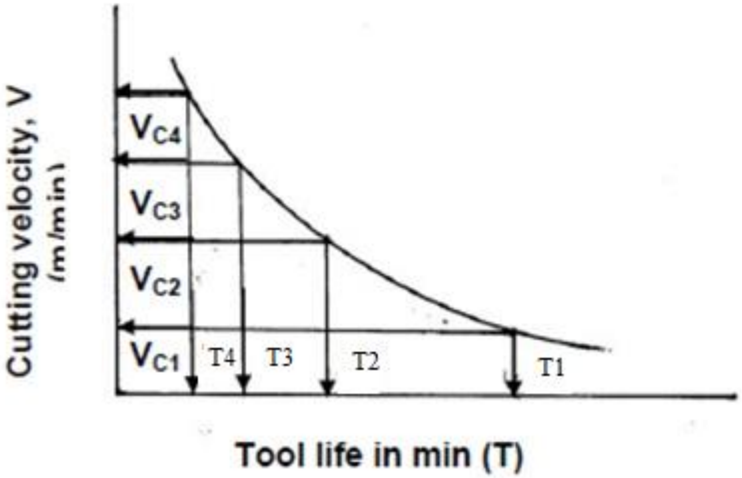
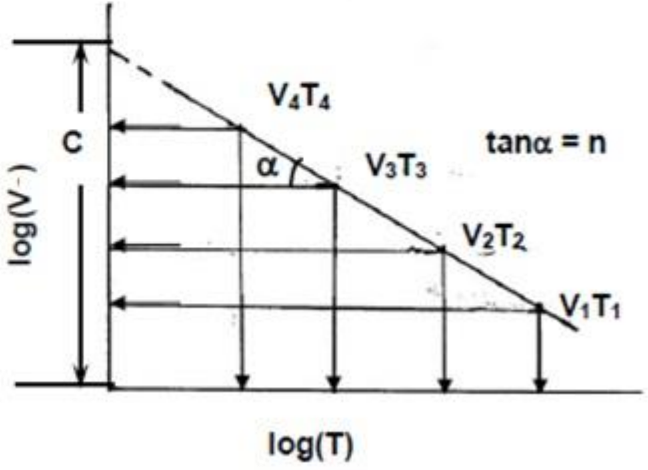


Fig. 3.2.3 Growth of flank wear and assessment of tool life

TAYLORS EQUATION (for Tool life)

- If the tool lives, T_1, T_2, T_3, T_4 etc. are plotted against the corresponding cutting velocities, V_1, V_2, V_3, V_4 etc. as shown in Fig. below, a smooth curve like a rectangular hyperbola is found to appear.
- When Taylor plotted the same figure taking both V and T in log-scale, a more distinct linear relationship appeared





TAYLORS EQUATION (for Tool life)

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

$$VT^n = C$$

- where, n is called, Taylor's tool life exponent.

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

Common Values for n

n = 0.1 to 0.15 for HSS tools

= 0.2 to 0.4 for Carbide tools

= 0.4 to 0.6 for Ceramic tools

Modified Taylor's Tool Life equation

- In Taylor's tool life equation, only the effect of variation of cutting velocity, V on tool life has been considered. But practically, the variation in feed (f) and depth of cut (d) also play role on tool life to some extent.
- Taking into account the effects of all those parameters, the Taylor's tool life equation has been modified as,

$$V(T^n f^x d^y) = C_T$$

where, T = tool life in min

C_T – a constant depending mainly upon the tool – work materials and the limiting value of V_B undertaken

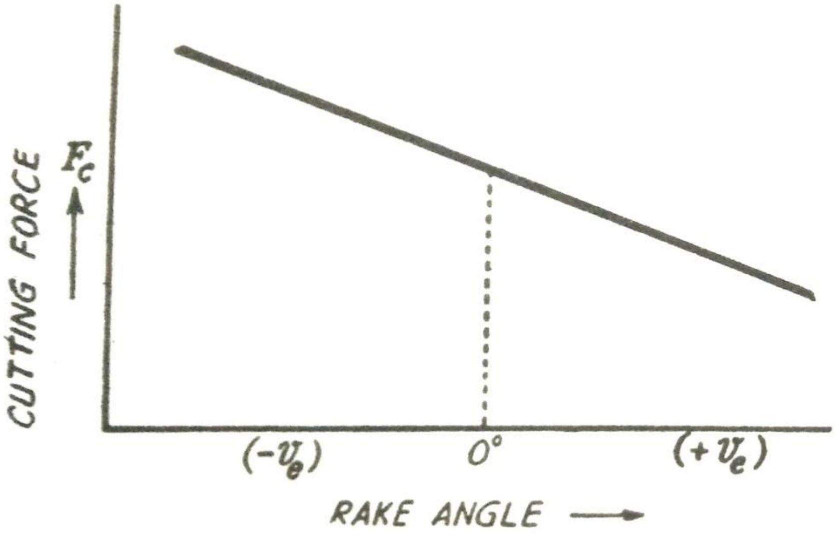
x, y and n – exponents so called tool life exponents depending upon the tool - work materials and the machining environment.

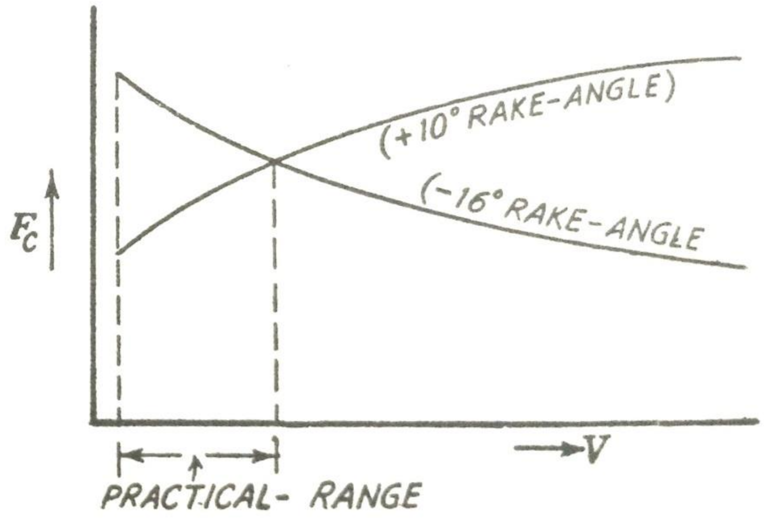
- Generally, x > y > n as V affects tool life maximum and d minimum

Effect of Rake Angle of Tool Life

- Back Rake:
  - Generally, when the back rake angle increases (positive), the cutting force decreases, thus improving the tool life. But, if too large – makes edge fragile.
  - When the back rake angles are negative, the cutting forces are larger. Subsequently, tool life is reduced.
- Side Rake:
  - Larger side rake angles produces chipping of cutting edge.
  - Smaller side rake generates greater heat or an excessive wear and deformation in tool

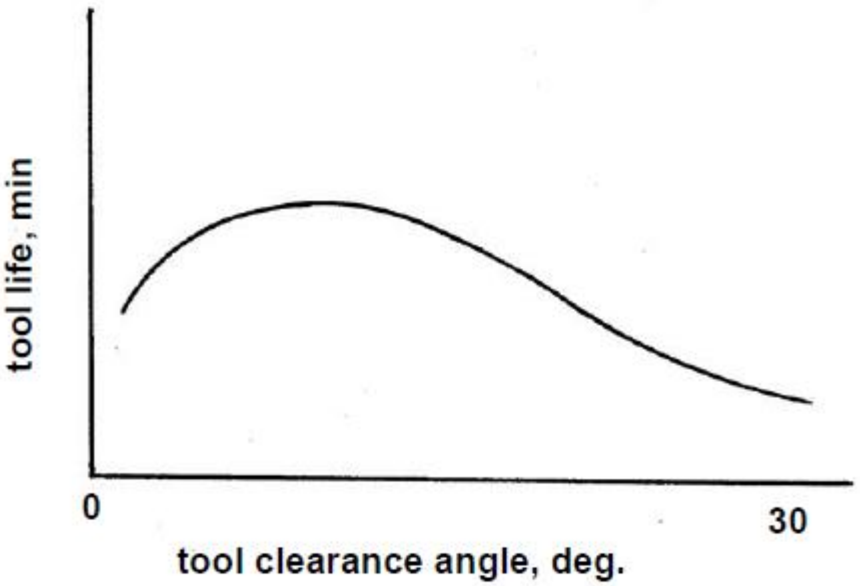
Effect of Rake Angle of Tool Life





Effect of Clearance Angle of Tool Life

- Fig. below schematically shows how clearance angle θ affects tool life.



Effect of Clearance Angle cont.

- Inadequate clearance angle reduces tool life and surface finish by tool - work rubbing,
- too large clearance reduces the tool strength and hence tool life.

CUTTING FLUIDS

- Work in two ways:
  - reduces cutting temperature directly by taking away the heat from the cutting zone and
  - also indirectly by reducing generation of heat by reducing cutting forces and friction.

Cutting Fluids - Purposes of application

1. Cooling of the job and the tool to reduce the detrimental effects of cutting temperature on the job and the tool
2. Lubrication at the chip–tool interface and the tool flanks to reduce cutting forces and friction and thus the amount of heat generation.
3. Cleaning the machining zone by washing away the chip – particles and debris which, if present, spoils the finished surface and accelerates damage of the cutting edges
4. Protection of the nascent finished surface – a thin layer of the cutting fluid sticks to the machined surface and thus prevents its harmful contamination by the gases like SO_2, O_2, present in the atmosphere.
5. The main aim of application of cutting fluid is to improve machinability through reduction of cutting forces and temperature, improvement by surface integrity and enhancement of tool life

Essential properties of cutting fluids

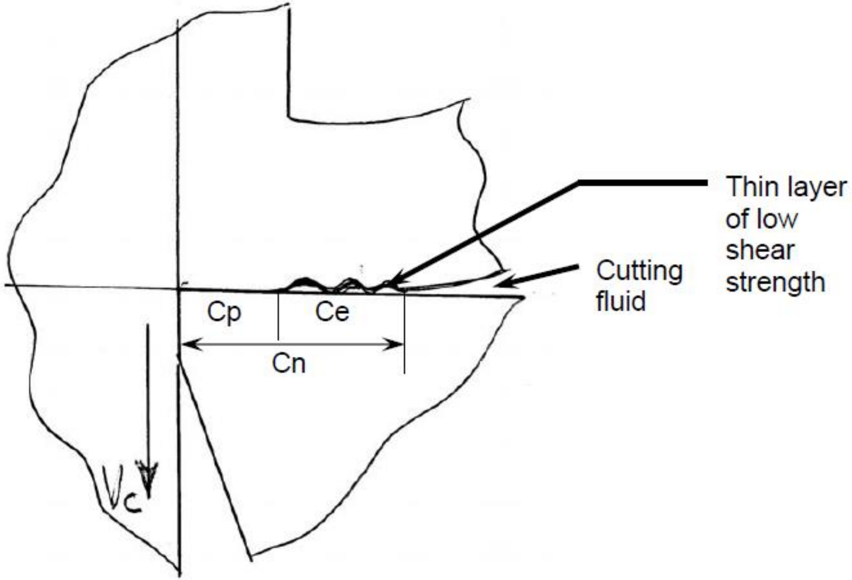
- Cutting fluid should fulfill its functional requirements without harming the Machine – Fixture – Tool – Work (M-F-T-W) system and the operators. Hence, cutting fluid should possess the following properties:
  1. For cooling :
     - high specific heat, thermal conductivity and film coefficient for heat transfer
     - spreading and wetting ability
  2. For lubrication :
     - high lubricity without gumming and foaming
     - wetting and spreading
     - high film boiling point
     - friction reduction at extreme pressure (EP) and temperature
  3. Chemical stability, non-corrosive to the materials of the M-F-T-W system

Essential properties of cutting fluids

4. Less volatile and high flash point
5. Non toxic in both liquid and gaseous stage
6. High resistance to bacterial growth
7. Odourless and also preferably colourless
8. Easily available and low cost.

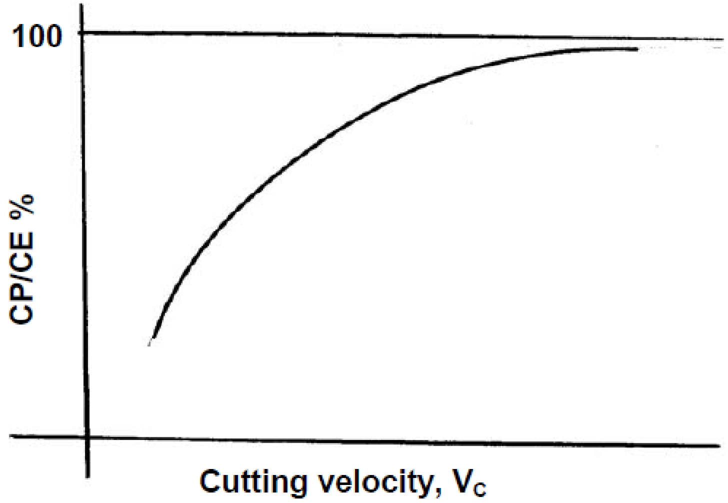
Principles of cutting fluid action

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



Principles of cutting fluid action

- The cutting fluid cannot penetrate or reach the plastic contact zone but enters in the elastic contact zone by capillary effect.
- With the increase in cutting velocity, the fraction of plastic contact zone gradually increases and covers almost the entire chip-tool contact zone as indicated in Fig. below



Principles of cutting fluid action

EPA (Extreme Pressure Additives)

- The chemicals like chloride, phosphate or sulphide present in the cutting fluid, under high pressure and temperature chemically reacts with the work material at the chip's under surface and forms a thin layer of the reaction product. The low shear strength of that reaction layer helps in reducing friction
- To form such solid lubricating layer under high pressure and temperature some extreme pressure additive (EPA) is deliberately added in reasonable amount in the mineral oil or soluble oil
- For extreme pressure, chloride, phosphate or sulphide type EPA is used depending upon the working temperature, i.e. moderate (200°C ~ 350°C), high (350°C ~ 500°C) and very high (500 °C ~ 800 °C) respectively

Types of Cutting Fluids

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

1. GASEOUS TYPE

- Machining of some materials like grey cast iron become inconvenient or difficult if any cutting fluid is employed in liquid form. In such case only air blast is recommended for **cooling and cleaning only.**
- Poor lubricating properties
- Some commonly used gaseous cutting fluids are:
  a. **Air** – effective coolant when used in sub-zero cooled state
  b. **CO_2** – has excellent heat extraction property (higher cost)
  c. **Ar**

Types of Cutting Fluids

2. LIQUID TYPE:

a. Water

- Due to its very high specific heat, water is considered as the best coolant and hence employed where cooling is most urgent
- Poor lubricating properties and have a tendency to cause rust and corrosion.

Types of Cutting Fluids

b. Oil Based cutting fluids

i. Soluble Oil/ Emulsions

- Non expensive
- Oil containing some emulsifying agent (soap) and additive like EPA, together called cutting compound, is mixed with water in a suitable ratio (1 ~ 2 in 20 ~ 50).
- Oil tends to reduce corrosion
- This milk like white emulsion, called soluble oil, is very common and widely used in machining and grinding

Types of Cutting Fluids

ii. Cutting oils (Mineral Oil + Straight fatty oil)

– Cutting oils are generally compounds of mineral oil to which are added desired type and amount of vegetable, animal or marine oils –called straight fatty oils (e.g. Lard oil) for improving spreading, wetting and lubricating properties.

– **NOTE:**

– Straight fatty oils like lard oil were not used directly due to their adverse effect on the health of the operator and due to it gummy characteristics

– As and when required some **EP additive (sulphur or chlorine) is also mixed** to reduce friction, adhesion and BUE formation in heavy cuts – **SULPHURISED OR CHLORINATED CUTTING OILS**

Types of Cutting Fluids

c. **Aqueous solutions/Chemical fluids**

– These are occasionally used fluids which are **water based** where some **organic and or inorganic materials are dissolved in water (alkali like sodium carbonate, potassium carbonate etc.)** to enable desired cutting fluid action.

– There are two types of such cutting fluid;

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

Types of Cutting Fluids

3. SOLID OR SEMI-SOLID LUBRICANT

- Either applied directly to the workpiece or as an constituent in the tool
- Reduce friction and thus cutting forces, temperature and tool wear

E.g.: Paste, waxes, soaps, graphite, Molybdenum-disulphide (MoS_2)

Types of Cutting Fluids

4. CRYOGENIC CUTTING FLUID

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

MACHINABILITY

- Is a term used to assess the ease with which a material could be machined
- Difficult to quantify machinability since a **large number of factors** are involved. The major factors are:
  1. **Cutting forces and power absorbed**
  2. **Tool wear and Tool life**
  3. **Surface finish**
  4. **Dimensional accuracy**
  5. **Machining cost**
- These factor are affected by **variables** like, **work material, tool material & geometry, cutting conditions, machine variables** etc.

MACHINABILITY

VARIABLES AFFECTING MACHINABILITY

1. **work material** - hardness, tensile strength, microstructure etc.
2. **tool material & geometry** – rake angle and nose radius have effect on surface finish and other parameters
3. **cutting conditions** – cutting speed, feed, use of cutting fluids etc.
4. **machine variables** – power, torque, accuracy, rigidity etc.

MACHINABILITY

ASSESSMENT OF MACHINABILITY

- The machinability of a material may be assessed by one or more of the following criteria:
  1. Long tool life at a given cutting speed
  2. Maximum material removal per tool re-sharpening
  3. Cutting force/power: Lowest cutting force on the tool or power consumption per unit vol. of material removed
  4. High Surface finish achieved under specific cutting conditions
  5. Good and uniform dimensional accuracy of successive parts
  6. Easily disposable chips

MACHINABILITY INDEX

- **Tool life** is the most important factor for assessing machinability.
- Since tool life is a direct function of cutting speed, a better machinable metal is one which permits higher cutting speed for a given tool life.
- **Machinability rating/index:**
  - Helps in comparing machinability of different materials
  - It is **relative measure**, comparing to a **index which is standardized**. **(Machinability index of free cutting steel is arbitrarily fixed as 100 %)**
- For other materials:

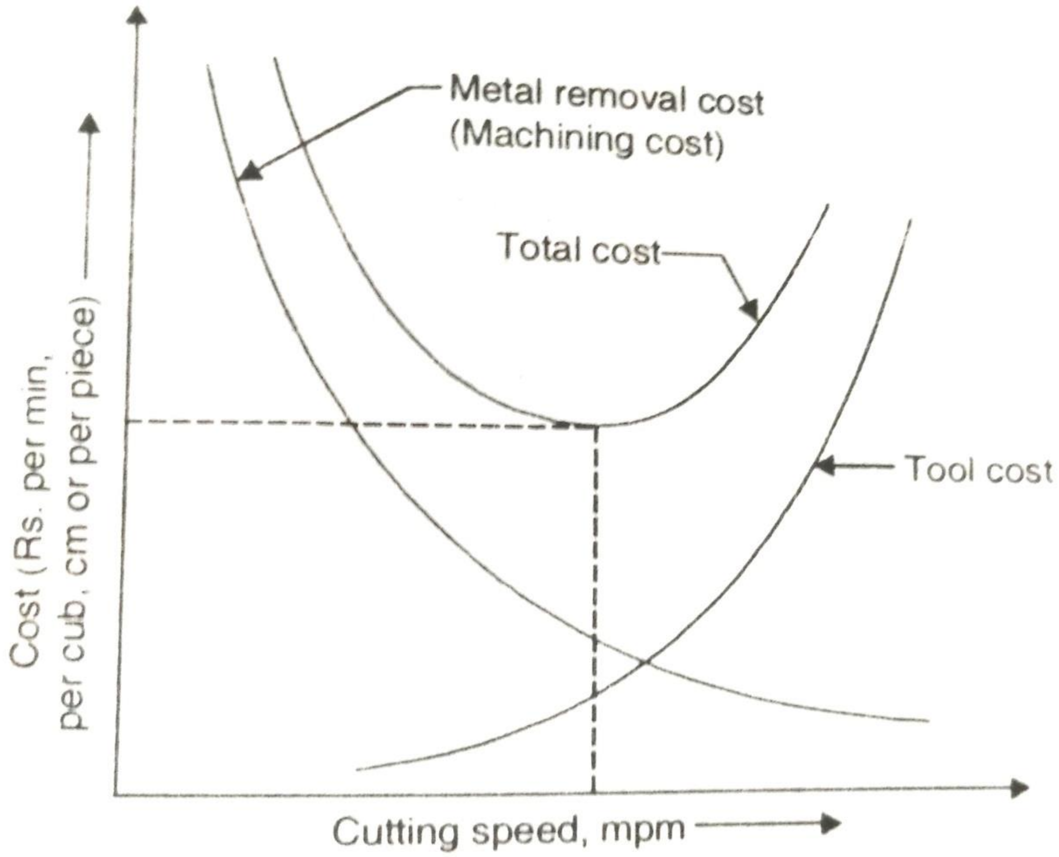
$$\text{Machinability index (\%)} = \frac{\text{Cutting speed of material for 20 min tool life}}{\text{Cutting speed of free cutting steel for 20 min tool life}} \times 100$$

MACHINABILITY INDEX

- **MI for some common materials:**
  - C-20 steel = 65
  - C-45 steel = 60
  - Stainless steel = 20
  - Copper = 70
  - Brass = 180
  - Aluminium alloys = 300-1500
  - Magnesium alloys = 600-2000

ECONOMICS OF MACHINING

- It is not sufficient to produce the desired component. The **production must be economical**.
- **Low cutting speeds**
  - tool life is higher, hence tooling cost is lower.
  - MRR will be low, hence cutting/machining cost will be high
  - Overall, total cost will be high.
- **High cutting speeds**
  - MRR will be high, hence cutting/machining cost will be low
  - tool life is shorter, hence tooling cost is higher.
  - Overall, total cost will be high


Metal removal cost
(Machining cost)
Total cost
Tool cost
Cost (Rs. per min, per cub, cm or per piece)
Cutting speed, mpm

ECONOMICS OF MACHINING

- At <u>some intermediate cutting speed, the total cost is minimum</u>. This cutting speed is called the <u>OPTIMUM/ECONOMIC CUTTING SPEED.</u>
- The tool life corresponding to this speed is the **<u>ECONOMICAL TOOL LIFE.</u>**
- **<u>To find optimum/economic cutting speed:</u>**

Total cost of cutting unit vol. of metal = **Machining cost** per unit vol. of metal cut + **Tooling cost** per unit vol. of metal cut

NOTE: **Tooling cost - cost of replacing or servicing the tool**

ECONOMICS OF MACHINING

- Let,

  Cm = machining cost per min (labour cost per min + overheads per min.)

  Ct = Tooling cost per service or replacement

NOTE: **Overheads** include power, cutting fluids, maintenance etc.

- Time required to machine unit vol. of metal (in min) = 1/MRR

  = 1/ (d.f.V)

  = C_1/V

Where, MRR in m^3/min, d & f in m and V in m/min

ECONOMICS OF MACHINING

- Hence,

Machining cost per unit vol. of metal cut = **$C_m C_1/V$…….(1)**

No. of Tool replacements/servicing in C_1/V min = C_1/TV

- Hence,

Tooling cost per unit vol. of metal cut = **$C_t C_1/TV$……..(2)**

We know, according to Taylor's Tool life eqn:

$$VT^n = C$$

ECONOMICS OF MACHINING

- Hence eqn (2):

Tooling cost per unit vol. of metal cut $= C_tC_1/[(C/V)^{1/n}V]$

$$= \frac{C_tC_1(V)^{(1-n)/n}}{C^{(1/n)}}$$

Therefore:

Total cost of cutting unit vol. of metal (Y) $= \dfrac{C_mC_1}{V} + \dfrac{C_tC_1(V)^{(1-n)/n}}{C^{(1/n)}}$

ECONOMICS OF MACHINING

For optimal value of V:

$$\partial Y/\partial V = 0$$

$$\text{i.e, } \left(-\frac{CmC_1}{V^2}\right) + \frac{(1-n)}{n}\frac{CtC_1}{C^{(1/n)}}(V)^{(1-2n)/n} = 0$$

$$\frac{(1-n)}{n}\frac{CtC_1}{C^{(1/n)}}(V)^{(1-2n)/n} = \frac{(CmC_1)}{V^2}$$

On simplification, optimal value of V for min. total cost;

$$Vo = C\,[(nCm/(1-n)Ct]^n$$

Metal cutting economics - Detailed Analysis

- Total cost = machining cost + tooling cost + (cost of setting up the machine + cost of loading, unloading and machine handling)

i.e., $\mathbf{Cp = Cm + Ct + Cs + C_L}$

Metal cutting economics - Detailed Analysis

- In the detailed analysis, we'll be considering **different costs per piece** manufactured.
- **Machining Cost (Cm)**

  Cm/piece = machining time per piece x (labour rate per unit time +overhead/burden rate per unit time)

$$Cm = Tm\ (Lm + Bm)$$

- **Setup Cost (Cs)**

  Includes cost for mounting the cutter and fixture and preparing the machine for cutting operation. This is fixed per piece. (Cs)

Metal cutting economics - Detailed Analysis

- **Tooling Cost (Ct)**

Ct /piece = (1/Z)(Cost in changing the tool + Cost for regrinding the tool + Depreciation of tool per grind)

$$Ct = (1/Z)\,[Tc\,(Lm + Bm) + Tg\,(Lg + Bg) + D]$$

where,

Z = no. of pieces machined per tool grind

Tc = time for tool change

Tg = time for tool grinding

Lg = labour rate per unit time for tool grinding

Bg = burden rate per unit time for tool grinder

D = depreciation of tool per grind

Metal cutting economics - Detailed Analysis

- **Loading Cost (C_L)**

C_L/piece = time for loading and unloading component, changing speed, feed rate etc. (Lm + Bm)

$$C_L = T_L(Lm + Bm)$$

For a metal machining, the following information is available:

Tool change time = 8 min

Tool regrind time = 5 min

Machine running cost = Rs. 5/hr

Tool depreciation per re-grind = 30 paise

$n = 0.25$

$C = 150$

Calculate the optimum cutting speed for min cost.

Answer

We know,

$$\mathbf{Vo = C\ [(nCm/(1\text{-}n)Ct]^{n}}$$

Cm (machining cost per min)= Rs.(5/60)

Ct = Cost for tool change + cost for tool grinding +Depreciation

= [8 x (5/60)] + [5 x (5/60)] + 0.30

= Rs. 1.38/-

Vo = $150\ [\ \{0.25x(5/60)\}/\{(1-0.25)x1.38\}]^{0.25}$

= 56.5 m/min

DYNAMOMETRY

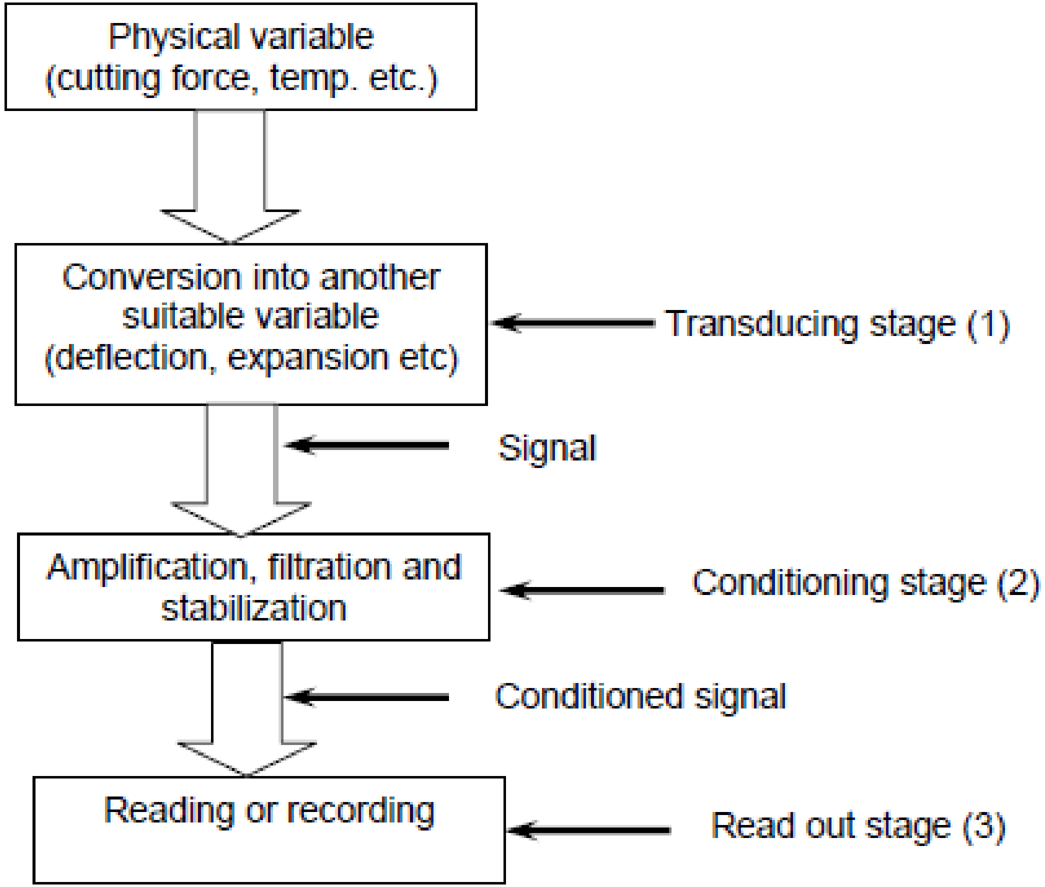
- Cutting force measurement - very important for a quantitative analysis of metal cutting operations
- **General principle of measurement**
  - The existence of some **physical variables like force, temperature etc.** and its magnitude or strength **cannot be detected or quantified directly but can be so through their effect(s) only**
  - These **effects, called signals**, often need proper conditioning for easy, accurate and reliable detection and measurement

E.g.: **a force which can neither be seen nor be gripped but can be detected and also quantified respectively by its effect(s) and the amount of those effects (on some material) like elastic deflection, deformation, pressure, strain etc.**

DYNAMOMETRY

- The measurement process is comprised of three stages:

1. **Stage – 1** : The target physical variable (say force) is converted proportionally into another suitable variable (say voltage) called signal, by **using appropriate sensor or transducer**.
2. **Stage – 2** : The feeble and noisy signal is amplified, filtered, rectified (if necessary) and stabilized for convenience and accuracy of measurement.
3. **Stage – 3** : where the conditioned signal (say voltage) is quantitatively determined and recorded by using some read out unit like galvanometer, oscilloscope, recorder or computer


Physical variable
(cutting force, temp. etc.)
Conversion into another
suitable variable
(deflection, expansion etc)
Transducing stage (1)
Signal
Amplification, filtration and
stabilization
Conditioning stage (2)
Conditioned signal
Reading or recording
Read out stage (3)

DYNAMOMETRY

- Dynamometers – apparatuses used for <u>measuring cutting tool forces.</u>
- ***<u>Main requirements of a dynamometer</u>***

1. **Sensitivity**
    - the dynamometer should be reasonably sensitive for precision measurement
2. **Rigidity**
    - The dynamometer need to be quite rigid to withstand the forces without causing much deflection which may affect the machining condition
3. **High frequency response**
    - such that the readings are not affected by vibration within a reasonably high range of frequency

DYNAMOMETRY

- ***Main requirements of a dynamometer***

4. **Stable**
   - Should be stable with respect to time, temperature and humidity
5. **Free from Cross sensitivity**
   - the dynamometer should be free from cross sensitivity such that one force (say Pz) does not affect measurement of the other forces (say Px and Py)
6. **Quick time response**
7. **Special requirements**
   - Size, Ruggedness etc.
   - Ability to record values of forces with time.