# 1

# Production Engineering

By

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**Teaching Experience ( 12 Years)**

**GATE percentile 99.96**

## Analysis of Previous IES Papers

| | Production | Materials | Total Question |
|---|---|---|---|
| IES-2011 | 31 | 28 | 59 |
| IES-2010 | 33 | 19 | 52 |
| IES-2009 | 38 | 16 | 54 |
| IES-2008 | 25 | 15 | 40 |
| IES-2007 | 34 | 15 | 49 |
| IES-2006 | 23 | 13 | 36 |
| IES-2005 | 28 | 12 | 40 |
| Average | 30 | 17 | 47 |

No of questions asked

## Analysis of Previous GATE Papers

| | Production | Materials | Total Marks |
|---|---|---|---|
| GATE-2011 | 13 | 1 | 14 out of 100 |
| GATE-2010 | 13 | 1 | 14 out of 100 |
| GATE-2009 | 16 | 2 | 18 out of 100 |
| GATE-2008 | 26 | 0 | 26 out of 150 |
| GATE-2007 | 25 | 2 | 27 out of 150 |
| GATE-2006 | 25 | 1 | 26 out of 150 |
| GATE-2005 | 19 | 1 | 26 out of 150 |
| Average | 15.22 % | 0.9 % | 16.57 % |

No of Marks asked

## Why PPT and Video needed ?



**Discussed Questions are available at**

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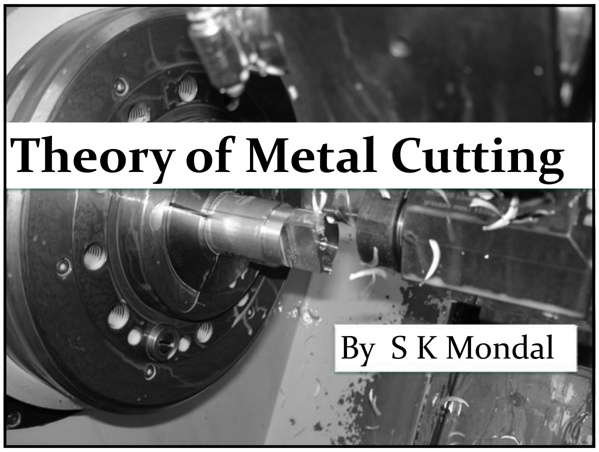


# Theory of Metal Cutting

By S K Mondal

## Classification of Manufacturing Process

- Shaping or forming
- Joining process
- Removal process
- Regenerative manufacturing

## Regenerative Manufacturing

- Production of solid products in layer by layer from raw materials in different forms.
- Very rapid, accurate used for Rapid prototyping and tooling.

## Basic Principle of Regenerative Manufacturing

Advantages:
- Process is Independent of Part Feature
- No Blanks are Requires
- Toolless process
- Easily Automation Possible

## Machining

- Machining is an essential process of finishing by which jobs are produced to the desired dimensions and surface finish by gradually removing the excess material from the preformed blank in the form of chips with the help of cutting tools moved past the work surface. Machining is a removal process.

## Machining aim to

- Fulfill its functional requirements
- Improve its performance
- Prolong its service.

## Drawback in Machining

- Loss of material in the form of chips.

## Machine tool

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

## Why even a battery operated pencil sharpener cannot be accepted as a machine tool?

- **Ans.** In spite of having all other major features of machine tools, the sharpener is of low value.

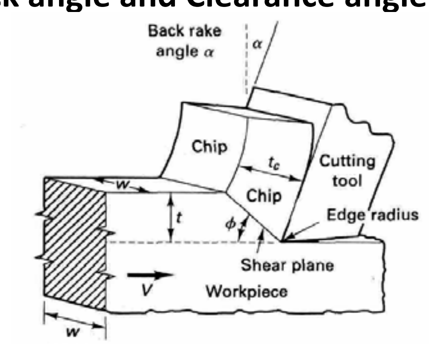
## IAS 2009 main

- Name four independent variables and three dependent variables in metal cutting.

[ 5 marks]

| Independent Variables | Dependent Variables |
|---|---|
| •Starting materials (tool/work)<br>•Tool geometry<br>•Cutting Velocity<br>•Lubrication | •Force or power requirements<br>•Maximum temperature in cutting<br>•Surface finish |

## Rack angle and Clearance angle



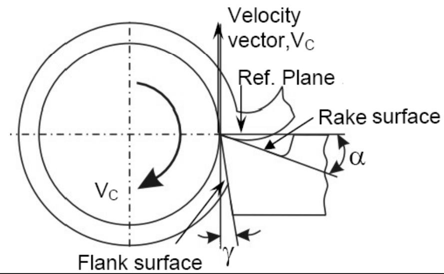

## Rack Surface and Flank

- The surface along which the chip moves upward is called 'Rack surface' of tool.
- The other surface which is relieved to avoid rubbing with the machined surface, is called 'Flank'.

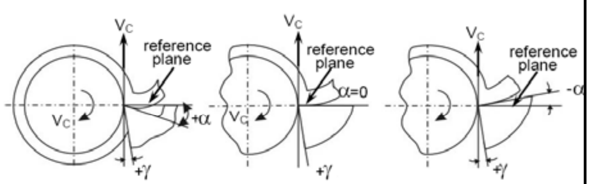
## Rake angle and Clearance Angle

- **Rake angle ($\alpha$) Angle of inclination of rake surface from reference plane i.e. normal to horizontal machined surface.**
- **Clearance angle ($\gamma$) :Angle of inclination of clearance or flank surface from the finished surface.**

## The nomenclature of different angle and surface in **turning**




## Discussion on Rack angle




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

## Positive rake

- Reduce cutting force
- Reduce cutting power

## Positive rake angles is recommended

- Machining low strength material
- Low power machine
- Long shaft of small diameter
- Set – up lacks strength and rigidity
- Low cutting speed

## Negative rake

- Increase edge strength
- Increases life of the tool
- Increases the cutting force
- High cutting speeds
- Requires ample power

## Negative rake angles is recommended

- Machining high strength alloy
- Heavy impact loads
- High speed cutting
- With rigid set- up

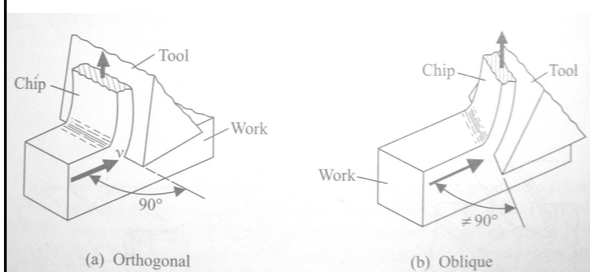
## Zero rake

- To simplify design and manufacturing of the form tools.
- Increases tool strength
- Avoids digging of the tool into the workpiece
- Brass is turned with zero rake angle

## Clearance angle

- Provided to avoid rubbing of the tool (flank) with the machined surface.
- Reduce tool wear
- Increase tool life.
- Must be positive (3° – 15°)

## Types of Machining




## Orthogonal Cutting

1. Cutting edge of the tool is perpendicular to the direction of cutting velocity.
2. The cutting edge is wider than the workpiece width and extends beyond the workpiece on either side. Also the width of the workpiece is much greater than the depth of cut.
3. The chip generated flows on the rake face of the tool with chip velocity perpendicular to the cutting edge.
4. The cutting forces act along two directions only.

## Geometry of single point turning tool

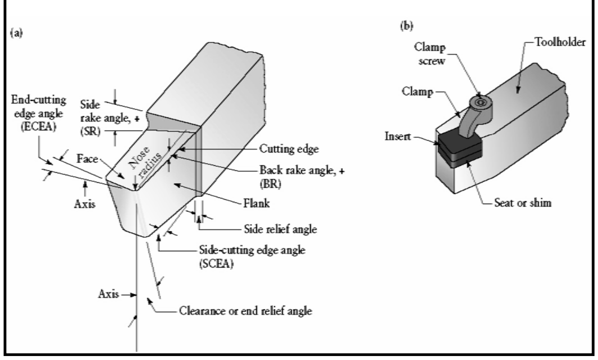
## Classification: (According to the number of major cutting edges (points) involved.)

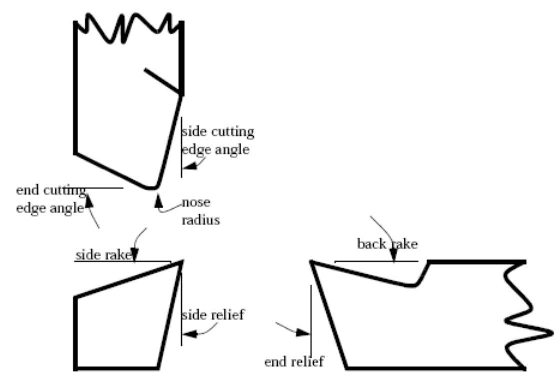
- **Single point:** turning, shaping, planning, slotting tools etc.
- **Double point:** drilling tools
- **Multipoint:** Milling, broaching, hobbing tools etc.

## System of Description of Tool Geometry

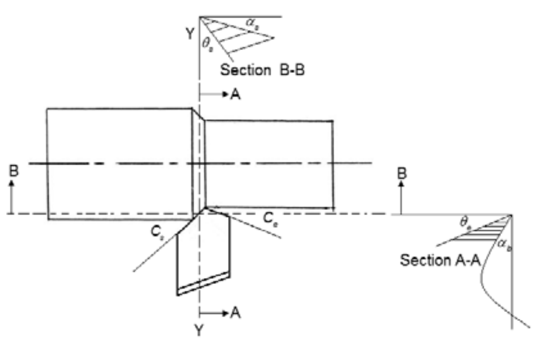
- **(I) Machine reference system: ASA or ANSI**
- **(II) Tool reference system: ORS and NRS**
- **(III) Work reference system: WRS**

## A Single point cutting tool

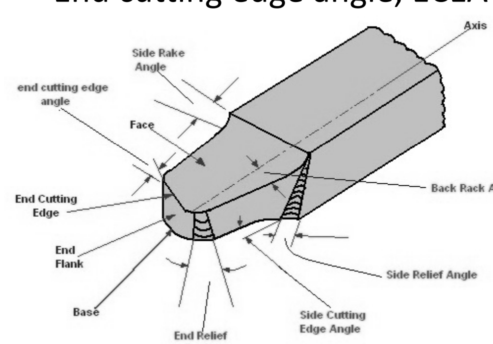



## ASA or ANSI system




## End cutting edge angle, ECEA

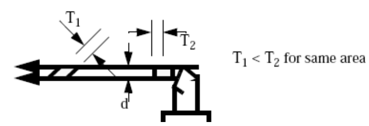


## Back Rake angle

- It is the angle between the face of the tool and the base of the shank or holder, and is usually measured in a plane through the side-cutting edge, and at right angles to the base
- It affects the ability of the tool to shear the work material and form the chip.

## **Side-rake angle (**axial rake)

- It is the angle between the face of the tool and the base of the shank or holder, and is usually measured in a plane perpendicular to the base, to the side-cutting edge
- Increase in the side rake angle reduces the chip thickness in turning.




## Side-relief angle

- It is the angle between the portion of the side flank immediately below the side-cutting edge, and a line drawn through this cutting edge perpendicular to the base.
- It is measured in a plane perpendicular to the side flank.

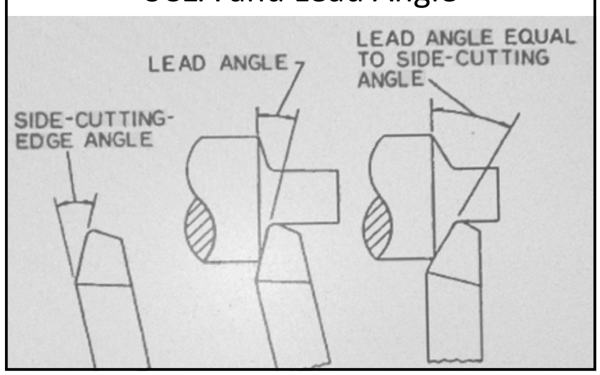
## End-relief angle

- It is the angle between the portion of the end flank immediately below the end cutting edge, and a line drawn through this cutting edge perpendicular to the base. It is usually measured in a plane perpendicular to the end flank.
- The End Relief Angle prevents friction on the flank of the tool.

## Side cutting edge angle, SCEA ($C_S$)

- It is the angle which prevents interference as the tool enters the work materials. (Normally 15 – 30° )
- Larger this angle, the greater the component of force tending to separate the work and the tool. (May induce Chatter)
- At its increased value it will have more of its length in action for a given depth of cut.
- At its increased value it produce thinner and wider chip that will distribute the cutting heat. (increase tool life)
- Zero SCEA is desirable when machining casting and forging with hard and scaly skins, because of the least amount of tool edge should be exposed to the destructive action of the skin.

## SCEA and Lead Angle



## Lip angle

- Lip angle or cutting angle depends on the on the rake and clearance angle provided on the tool and determine the strength of the cutting edge.
- A larger lip angle permits machining of harder metals, allow heavier depth of cut, increase tool life, better heat dissipation.
- Larger lip angle reduce cutting speed (Disadvantage)

## Nose radius

- It is curvature of the tool tip.
- It provides strengthening of the tool nose and better surface finish.
- But too large a nose radius will induce chatter.
- If nose radius increased cutting force and cutting power increased.

## Tool designation (ANSI) or ASA

To remember easily follow the rule

- rake, relief, cutting edge
- Side will come last
- finish with nose radius (inch)

$$\alpha_b - \alpha_s - \theta_e - \theta_s - C_e - C_s - R$$

## Orthogonal Rake System (ORS)

$$i - \alpha - \gamma - \gamma_1 - C_e - \lambda - R$$

- Inclination angle (i) – side rake ($\alpha$) – side relief ($\gamma$) – end relief ($\gamma_1$) – End cutting edge ($C_e$) – Approach ($\lambda$) – nose radius (mm)
- Approach angle ($\lambda$) = 90 - $C_S$
- [Sometimes $\lambda$ is called principal cutting edge angle (Orthogonal cutting)]
- For Pure orthogonal cutting, i = 0
- For Oblique cutting, i ≠ 0

## Inter conversion between ASA & ORS

$$\tan\alpha = \tan\alpha_s \sin\lambda + \tan\alpha_b \cos\lambda$$

$$\tan\alpha_b = \cos\lambda \tan\alpha + \sin\lambda \tan i$$

$$\tan\alpha_s = \sin\lambda \tan\alpha - \cos\lambda \tan i$$

$$\tan i = -\tan\alpha_s \cos\lambda + \tan\alpha_b \sin\lambda$$

## Critical correlations

When $\lambda = 90$ $\quad \alpha_s = \alpha$

When $i = 0$ $\quad \alpha_n = \alpha$

When $i = 0$ and $\lambda = 90$ $\quad \alpha_s = \alpha_n = \alpha$

(Pure orthogonal cutting)

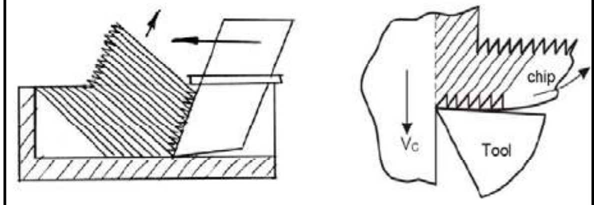
$\lambda$ is principal cutting edge angle
$i$ is inclination angle
$\alpha_s$ is side rake angle ($ASA$)
$\alpha$ is orthogonal rake angle ($ORS$)
$\alpha_n$ is normal rake angle (NRS)

## Cause of chip formation

**Yielding –in ductile material**

**Brittle fracture – in brittle material**

## Mechanism of chip formation in ductile material




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

(b) Chip formation by shear in lamella.

## Mechanism of chip formation in brittle material

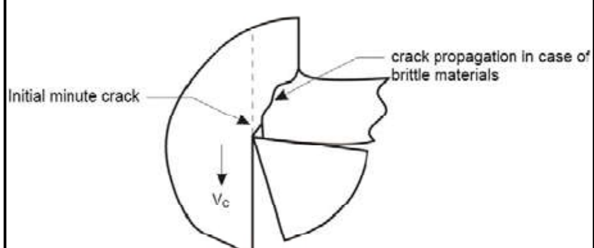



**Fig. Development and propagation of crack causing chip separation.**

## Types of chip

- Continuous chip
- Discontinuous chip
- Continuous chip with BUE
- Serrated chip

## Types of chip depends on

- Work material (ductile, brittle)
- Cutting tool geometry (rake angle, cutting angle etc.)
- Cutting velocity and feed rate.
- Types of cutting fluid and method of application.

## Conditions for forming Discontinuous chip

**of irregular size and shape**

work material brittle (grey cast iron)

**of regular size and shape**

work material – ductile but hard and work hardenable

feed – large

tool rake – negative

cutting fluid – absent or inadequate

## Conditions for forming Continuous chip without BUE

- work material – ductile
- Cutting velocity – high
- Feed- low
- Rake angle – positive and high
- Cutting fluid – both cooling and lubricating

## Conditions for forming Continuous chip with BUE

- Work material – ductile
- Cutting velocity – medium
- Feed – medium
- Cutting fluid - absent or in adequate.

## Built – up – Edge (BUE) formation

- In machining ductile material with long chip tool contact length, lot of stress and temperature develops in the secondary deformation zone at the chip tool interface.
- Under such high stress and temperature in between two clean surfaces of metals, strong bonding may locally take place due to adhesion similar to welding.
- Such bonding will be encouraged and accelerated if the chip tool materials have mutual affinity or solubility.
- The weld material starts forming as an embryo at the most favorable location and thus gradually grows.

Contd….

## Built – up – Edge (BUE) formation

- With the growth of the BUE, the force also gradually increased due to wedging action of the tool tip along with the BUE formed on it.
- Whenever the force exceeds the bonding force of the BUE, the BUE is broken or sheared off and taken away by the flowing chip. Then again starts forming and grow.
- This BUE changes its size during the cutting operation.
- It first increases, then decreases, and then again increases.
- Low cutting speed also contributes to the formation of BUE.

## Effects of BUE formation

**Harmful effect**

- It unfavourably changes the rake angle at the tool tip causing increase of cutting force i.e. power consumption.
- Induce vibration.
- Poor surface finish.

**Good effect**

- BUE protects the cutting edge of the tool i. e. **increases tool life.**

## Reduction or Elimination of BUE

**Increase**

↑ Cutting speed
↑ Rake angle
↑ Ambient work piece temperature.

**Reduce**

↓ Feed
↓ Depth of cut

**Use**

- Cutting fluid
- Change cutting tool material (as cermets).

## Serrated Chips

- Serrated chips also called segmented or non-homogeneous chips are semi-continuous chips with zones of low and high shear strain.
- Metals with low thermal conductivity and strength that decreases sharply with temperature, such as titanium exhibit this behaviour, the chips have sawtooth like appearance.

**When is forced chip breaking necessary and why ?**

When chips continuously form and come out very hot, sharp and at quite high speed

**Under the condition**

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

**For**

- Safety and convenience of the operator
- easy collection and disposal of chips

## Shear angle ($\phi$)

$$r = \frac{t}{t_c} = \frac{l_c}{l} = \frac{V_c}{V} = \frac{\sin\phi}{\cos(\phi-\alpha)} = \frac{1}{\varepsilon}$$

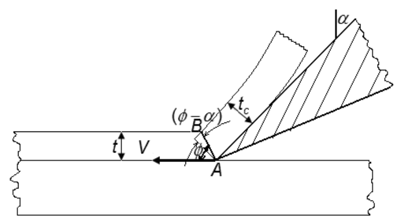
and

$$\tan\phi = \frac{r\cos\alpha}{1-r\sin\alpha}$$

Where $r<1$

| | |
|---|---|
| $r$ | is chip thickness ratio, or chip compression factor or cutting ratio |
| $\varepsilon$ | is chip reduction factor |
| $\phi$ | is shear angle |
| $\alpha$ | is rake angle |

## Proof




## For orthogonal cutting

$$\frac{1}{\gamma} = \varepsilon = e^{\mu\left(\frac{\pi}{2}-\alpha\right)}$$

From this expression we will get

(The value of $\varepsilon$ can be reduced by)

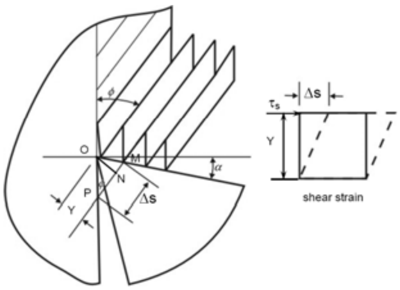
- using tool having large positive rake
- Reduce friction by using lubricant.

## Cutting shear strain ($\varepsilon$ )

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

$$= \frac{\cos\alpha}{\sin\phi\cos(\phi-\alpha)}$$

## Proof



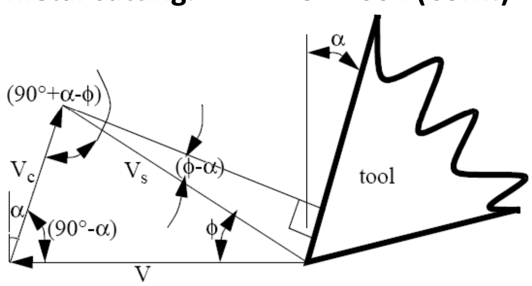

## Velocities in metal cutting

(i) The velocity of the tool relative to the work piece (V) called the cutting speed.

(ii) The velocity of the chip relative to the work, $V_s$ called the shear velocity.

(iii) The velocity of the chip up the face of the tool $V_c$, called chip velocity.

## Derive the expression for velocities in metal cutting. ESE-2004 (Conv.)




## Shear Strain Rate

(Note: it is not shear strain it is rate of shear strain i.e. flow)

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{V_s}{\text{thickness of shear zone } \left(t_s\right)}$$

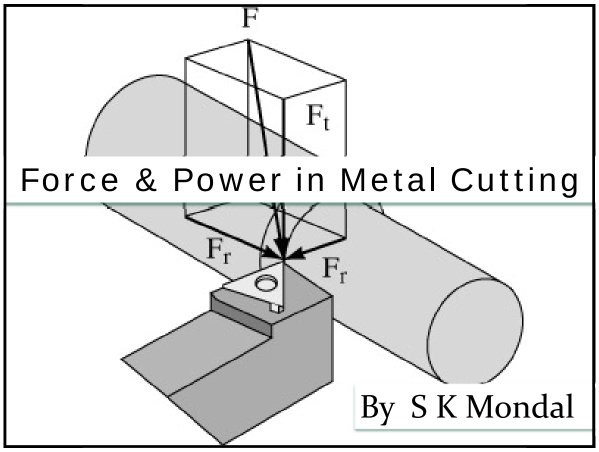
## Determination of Un-deformed chip thickness in Turning: (VIMP)

**For single point cutting tool**

$$t = f \sin\lambda$$

$$b = \frac{d}{\sin\lambda}$$

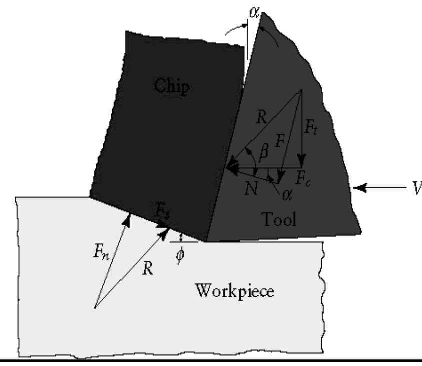
Where
t =Uncut chip thickness
f = feed
$\lambda$ = 90 – $C_s$ = approach angle
$C_s$ = side cutting edge angle




# Force & Power in Metal Cutting

By S K Mondal

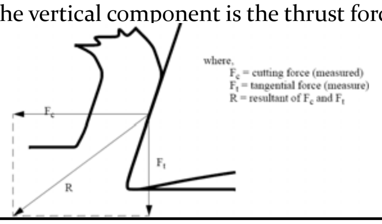
When a cut is made the forces acting on the metal chips are:




## $F_c$ and $F_t$

The two orthogonal components (horizontal and vertical) $F_c$ and $F_t$ of the resultant force R can be measured by using a **dynamometer**.

The horizontal component is the cutting force ($F_c$) and the vertical component is the thrust force ($F_t$)

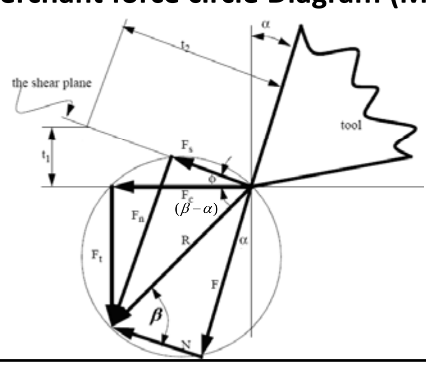



## The force relations (VIMP)

$$\boxed{\begin{aligned} F &= F_c \sin\alpha + F_t \cos\alpha \\ N &= F_c \cos\alpha - F_t \sin\alpha \\ F_n &= F_c \sin\phi + F_t \cos\phi \\ F_s &= F_c \cos\phi - F_t \sin\phi \end{aligned}}$$

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

## Merchant force circle Diagram (MCD)




## Merchant Analysis

### Assumption

- The work material behaves like an ideal plastic.
- The theory involves minimum energy principal.
- As, $\tau_s$ and $\beta$ are assumed to be constant, independent of $\phi$
- It is based on single shear plane theory.

## Limitations of Merchant's Theory

1. Merchant theory is valid only for orthogonal cutting.
2. By the ratio F/N, the Merchant theory gives apparent (not actual) co-efficient of friction.

## From Merchant Force Circle Diagram

$$\boxed{\phi = \frac{\pi}{4} + \frac{\alpha}{2} - \frac{\beta}{2}}$$

## Modified Merchant Theory

$\tau_s = \tau_{so} + k\sigma_s$ where, $\sigma_s$ is the normal stress on shear plane.

$$\left[\sigma_s = \frac{F_n}{A_s}\right]$$

and then $2\phi + \beta - \alpha = \cot^{-1}(k)$

## Theory of Lee and Shaffer

They applied the theory of plasticity for an ideal-rigid-plastic material. They also assumed that deformation occured on a thin-shear plane. They derive.

$$\phi = \frac{\pi}{4} + \alpha - \beta$$

## Other Relations

- **By *Stabler***

$$\phi = \frac{\pi}{4} + \frac{\alpha}{2} - \beta$$

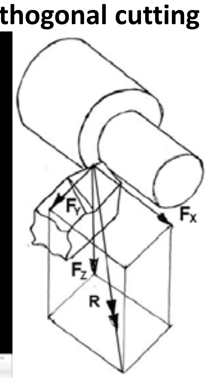
- **By dimensional analysis**

$$\frac{\varphi}{\beta} = k\left(\frac{\alpha}{\beta}\right)^{a}\left(\frac{f}{d}\right)^{b}$$

$$\frac{\varphi}{\beta} = k_1 (\cos\alpha)^{a_1}\left(\frac{f}{d}\right)^{b_1}$$

where, k, a, b, $k_1$, $a_1$ and $b_1$ are empirical constants to be established from the experimental data
f is feed and d is depth of cut.

## Compare turning with orthogonal cutting



- **$F_c$:** primary cutting force acting in the direction of the cutting velocity, largest force and accounts for 99% of the power required by the process.
- **$F_f$:** feed force acting in the direction of the tool feed. This force is about 50% of $F_c$, but accounts for only a small percentage of the power required because feed rates are usually small compared to cutting speeds.
- **$F_r$:** radial or thrust force acting perpendicular to the machined surface. This force is about 50% of $F_f$ and contributes very little to power requirements because velocity in the radial direction is negligible.

## Metal Removal Rate (MRR)

Metal removal rate (MRR) = $\mathbf{A_c.V = b\ t\ V}$

Where

$A_c$ = cross-section area of uncut chip

V = cutting speed = $\frac{\pi DN}{60}$

## Power Consumed During Cutting

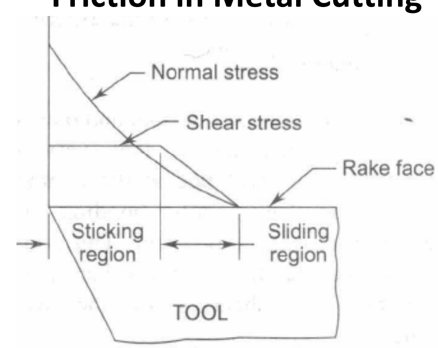
$$F_c \times V$$

Where

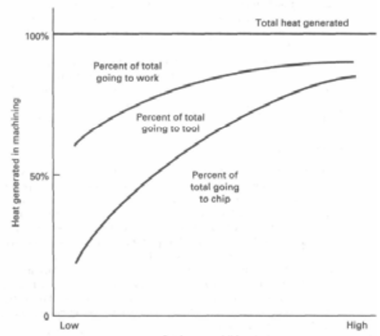
$F_c$ = cutting force

V = cutting speed = $\frac{\pi DN}{60}$

## Friction in Metal Cutting




## Heat and Temperature in Metal Cutting




## Determination of cutting temperature

**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, precise and reliable.

## Experimental Methods are

- **Calorimetric method**
- **Decolourising agent**
- **Tool-work thermocouple**
- **Moving thermocouple technique**
- **Embedded thermocouple technique**
- **Using compound tool**
- **Indirectly from Hardness and structural transformation**
- **Photo-cell technique**
- **Infra ray detection method**

## Dynamometers for measuring cutting forces

Measurement of cutting force(s) is based on three basic principles :

(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.

## Design requirements for 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 $P_Z$) does not affect measurement of the other forces (say $P_X$ and $P_Y$)

## Types of Dynamometers

The dynamometers being commonly used now-a-days for measuring machining forces desirably accurately and precisely (both static and dynamic characteristics) are

Either

**Strain gauge type**

Or

**piezoelectric type**

Strain gauge type dynamometers are inexpensive but less accurate and consistent, whereas, the piezoelectric type are highly accurate, reliable and consistent but very expensive for high material cost and stringent construction.

## Strain Gauge Dynamometers

The strain, ε induced by the force changes the electrical resistance, R, of the strain gauges which are firmly pasted on the surface of the tool-holding 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)