i) Continuous chips without BUE form when,
- a) The work material is ductile
- b) Small uncut thickness of chip is taken
- c) High cutting speed is used
- d) Large rake angle of tool is used, and
- e) A suitable cutting fluid is used

ii) Continuous chips with BUE form when,
- a) Stronger adhesion between chips and tool face is present
- b) Low rake angle in cutting tool is present
- c) Large uncut thickness is taken

iii) Discontinuous chips are formed when,
- a) Work material is brittle (not necessarily hard)
- b) Large uncut thickness and depth of cut are taken
- c) Low cutting speed is used
- d) Small rake angle of tool is used

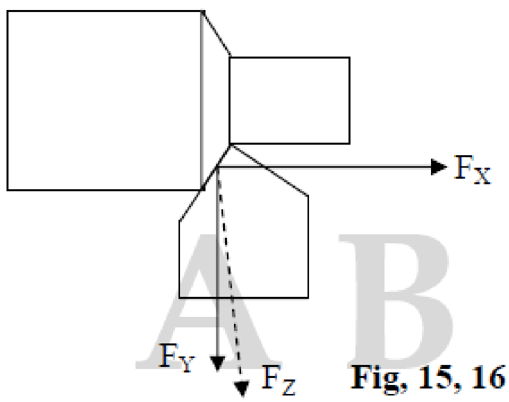
Discontinuous chips are also produced when ductile material is machined with low cutting speed and lubricant is not used. The excessive friction between the chip and tool face causes fracture of the chip into small segments. This results in poor surface finish on the workpiece and excessive wear on tool rake face. The basic difference between the continuous and discontinuous chips is that instead of shearing taking place ahead of the cutting edge of the tool continuously without fracture in chips, rupture occurs intermittently producing segments of chips. Brittle material fails by maximum normal stress, not by maximum shear stress.

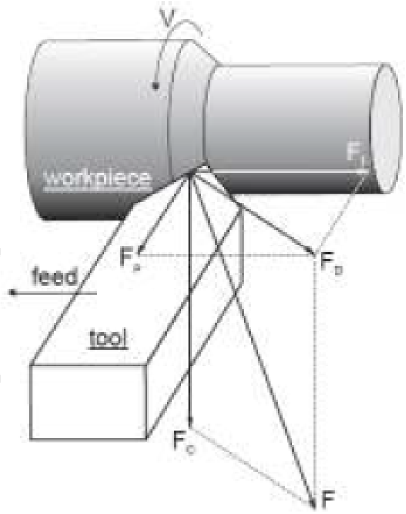
Cutting speed, feed and depth of cut:

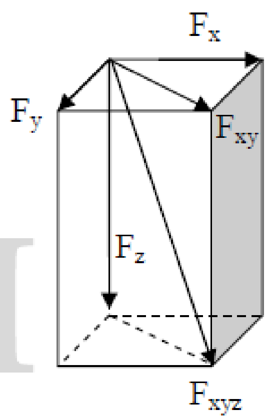
Cutting speed (V_c), is defined as the velocity with which the cutting tool moves through the workpiece. It is usually expressed in m/min. Feed commonly refers to the longitudinal feed or feed rate. It may be defined as the advancement of the tool through the workpiece per revolution of job or per stroke of tool or in unit time in longitudinal (X) direction, usually perpendicular to the V_c. It is usually expressed in mm/min or mm/rev. Depth of cut (d) is the normal distance between the unmachined surface and machined surface.

Cutting forces in Metal Cutting (turning)

The force system in the general case of conventional turning process is shown in Fig. 15. The resultant cutting force R (or F_{xyz}) is resolved into two components, i.e., the main cutting force or tangential force, acting in the direction of cutting velocity vector (F_z) and the thrust force or feed force (F_{xy} or F_D) acting in horizontal plane. The main cutting force constitutes about 70~80 % of the total force R. The thrust force F_{xy} is further resolved into two components, known as (longitudinal) feed force or axial thrust force (F_x), acting in the direction of feed in horizontal plane, and radial thrust force or radial force (F_y), acting in the direction perpendicular to F_x in horizontal plane . Thus, if the individual components are F_x, F_y and F_z, then R can be evaluated as: R = $F_x^{2} + F_y^{2} + F_z^{2}$, for a mutually perpendicular force system.







Fig, 15, 16

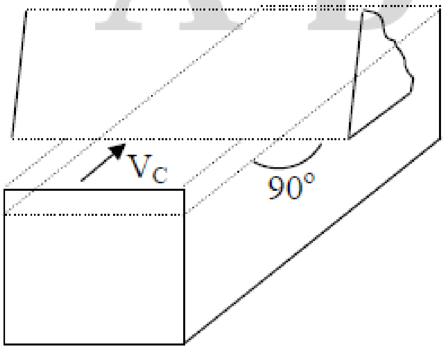
ORTHOGONAL CUTTING PROCESS

The metal cutting processes are of two types, (i) Orthogonal cutting process and (ii) Oblique cutting process.

Orthogonal cutting process:

Definition: 1) Principal cutting edge of the tool is perpendicular to the cutting velocity vector.
2) Chip flow angle is zero, i.e., the direction of chip flow velocity is normal to the principal cutting edge. In other words, chip flow direction lies in π_o. [Stabler's rule: $\psi = C\lambda$, C is a constant which may take a value between 0.9 to 0.98. Thus, $\psi \approx \lambda$.]

3) P_{xy}, i.e. resultant of P_x and P_y, is perpendicular to the principal cutting edge and P_{xy} is contained in π_o. This happens only when $\lambda = 0$.
4) A 3-D force system may be reduced to a 2-D rectangular force system by choosing λ and φ, in such a way that either P_x or P_y is made zero.
5) A restricted cutting does not ensure the cutting process to be an orthogonal cutting.



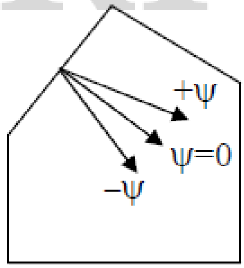


Fig. 17, 18

If in a 3-D force system P_x and P_y act in such a way that P_{xy} is contained in π_o, then the resultant of the entire force system R is also contained in π_o. This is called orthogonal system of first kind. This is ensured by satisfying the following conditions:

(i) $0 < \varphi < 90°$ (ii) $\lambda = 0$ and,
(iii) chip flow direction lies in π_o.
Here, $F_x = F_{xy} \sin\varphi$ and $F_y = F_{xy} \cos\varphi$
An orthogonal 2-D system of second kind can be obtained by choosing λ and φ in such a manner that either F_x or F_y can be made zero.

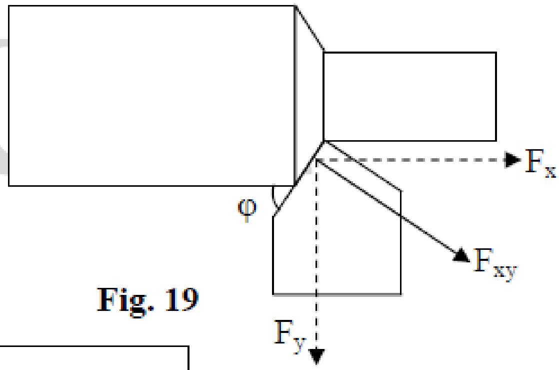
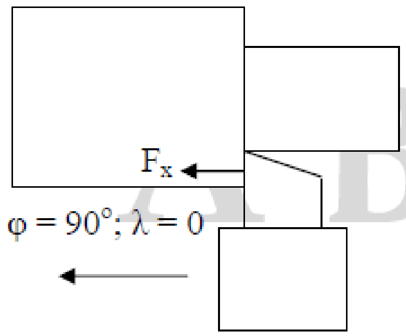


Fig. 19

For example: (a) Machining of thin walled tube by making $\varphi = 90°$ and $\lambda = 0$ ($F_y = 0$):



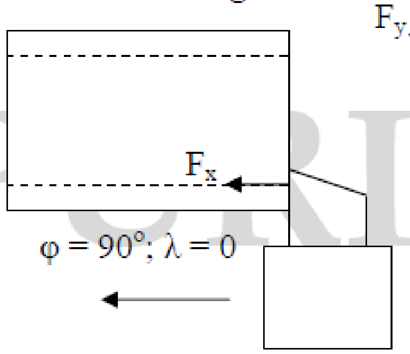


Fig. 20, 21

(b) A radial turning or parting off operation with $\varphi = 0$ and $\lambda = 0$ ($F_y = 0$):

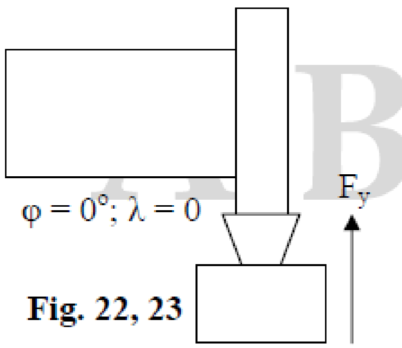
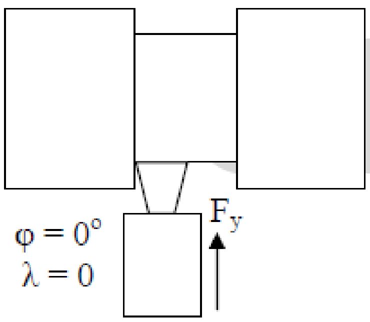


Fig. 22, 23



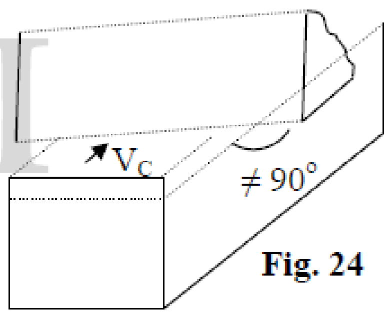


Fig. 24

When the length of the cutting edge is greater than the width of cut, i.e., cutting edge clears the width of workpiece on either ends, it is called free (orthogonal) cutting. In a cutting operation, where both the principal and auxiliary cutting edge become active, it is called non-free or restricted cutting.

Oblique Cutting:

Most of the metal cutting carried in workshop is through oblique cutting. In this case, the force system is 3-D and F_{xy} is not perpendicular to the principal cutting edge. Secondly, chip flow angle ψ has got a certain value and inclination angle $\lambda \neq 0$. However, the geometry of oblique cutting process is very complex and it is extremely difficult to analyze the system to determine cutting forces.

A Few Observations, Illustrations and Definitions

A) Let, a_1 = uncut chip thickness, mm; a_2 = cut chip thickness, mm
l_1 = length of uncut chip, mm; l_2 = corresponding length of cut chip, mm
b_1 = width of chip before cut, i.e., width of cut (b); b_2 = width of chip after cut, mm
f = longitudinal feed, mm/rev; d = t = depth of cut, mm;

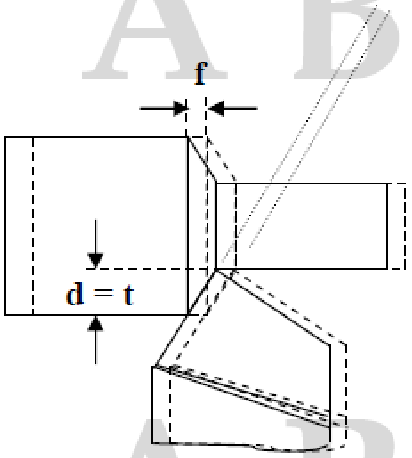
It has been observed that for a continuous chip (without BUE) formation, cut chip is thicker than uncut chip ($a_2 > a_1$), length of the cut chip is shorter than uncut chip ($l_2 < l_1$) and width of chip before and after cut is almost same ($b_1 \approx b_2$). Hence , it may be assumed that a plane strain condition exists during orthogonal cutting, i.e., no side-flow of chips occurs ($b = b_1 = b_2$). Chip thickness ratio (r) is the ratio of uncut chip thickness to cut chip thickness. It is also called cutting ratio.

Therefore, $r = \dfrac{a_1}{a_2}(<1) = \dfrac{OA}{OC} = \dfrac{OA}{OB}.\dfrac{OB}{OC} = \sin\beta.\sec(\beta-\gamma)$.

$OA \perp AB$; $OD \parallel AB$; $CE \perp OD$; $\angle GBD = \angle ECD = \angle COD = \gamma$
$OC \perp BC$; but, $\angle BOD = \beta$, Hence, $\angle BOC = \beta - \gamma$

Therefore, $r = \dfrac{\sin\beta}{\cos(\beta-\gamma)} = \dfrac{\sin\beta}{\cos\beta\cos\gamma + \sin\beta\sin\gamma} = \dfrac{\tan\beta}{\cos\gamma + \tan\beta\sin\gamma}$

$\Rightarrow \tan\beta = r\cos\gamma + r\tan\beta\sin\gamma$, $\quad \Rightarrow \tan\beta = \dfrac{r\cos\gamma}{1 - r\sin\gamma}$ .....(1)



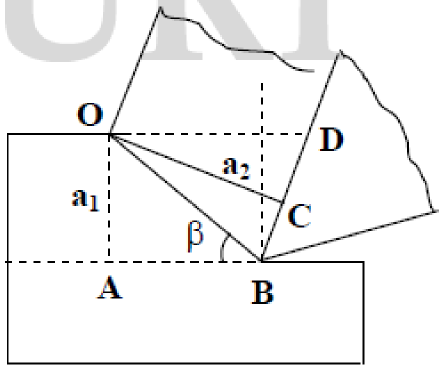


Fig. 25, 26, 27

B) Chip reduction coefficient $= k = \dfrac{1}{r}(>1)$ ...(2)

C) From Fig. 15, $d = t = b\sin\varphi$,
φ = plan approach angle ..(3)

D) From Fig. 15 and 16, $f = \dfrac{a_1}{\sin\phi}$;

$\Rightarrow a_1 = f\sin\varphi$ ..... (4)

E) From (3) and (4), $\Rightarrow f.t = f.d = a_1.b_1 = a_1 b$.(5)

F) **Cross sectional area** of uncut chip = $a_1 b_1 = A_1$
Cross sectional area of cut chip = $a_2 b_2 = A_2$
Cross sectional area of shear plane = $A_s = b_1 a_s = b_2 a_s$
a_s = thickness of chip along shear plane
$\therefore a_s \sin\beta = a_1$, and, $A_s \sin\beta = A_1$ (assuming plane strain condition i.e, $b_1 = b_2$) (6)

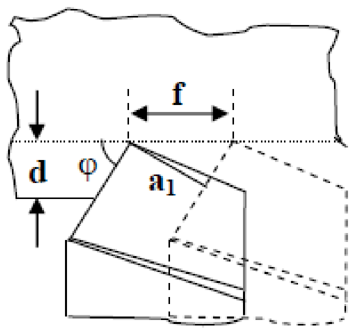


Fig. 27

G) **Volume of cut chip**: Considering volume of cut chip = volume of uncut chip,

$a_1 b\, l_1 = a_2 b\, l_2$ [$a_1 = t_1$ & $a_2 = t_2$]

$\Rightarrow \dfrac{l_1}{l_2} = \dfrac{a_2}{a_1} = \dfrac{1}{r}$ or, $r = \dfrac{a_1}{a_2} = \dfrac{l_2}{l_1}$ (7)

H) Mass of the cut chip:

If, w_2 be the mass of the cut chip of length l_2,
Then, $w_2 = \rho a_1 b l_1 = \rho a_2 b l_2$ (8)

I) Shear strain:

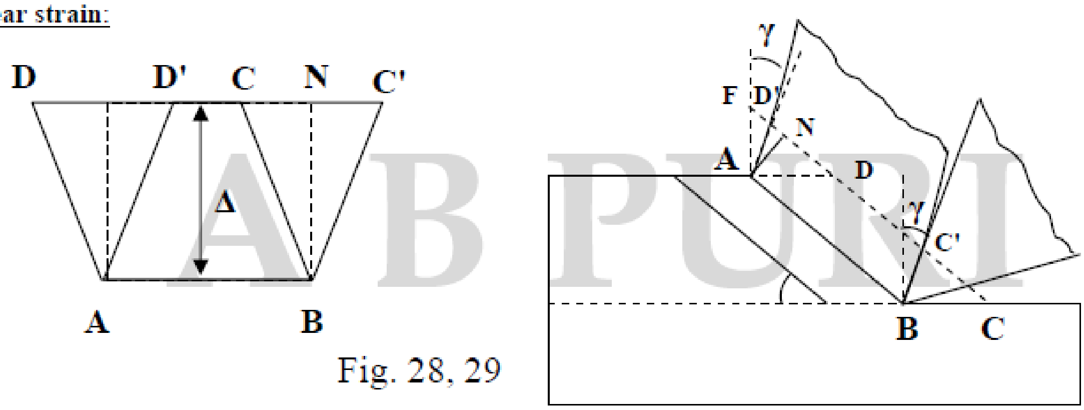


Fig. 28, 29

Parallelogram ABCD → ABC'D'; AB ∥ CD; CD is extended upto F, AN ⊥ DD'.
[ΔFAD ia right angled triangle. ∠BAD = ∠ADN = β = ∠FAN ; but, ∠FAD' = γ
Hence, ∠NAD' = β – γ]

Then, Shear strain $= \dfrac{DD'}{\Delta} = \dfrac{DN + ND'}{\Delta} = \dfrac{DN}{\Delta} + \dfrac{ND'}{\Delta}$

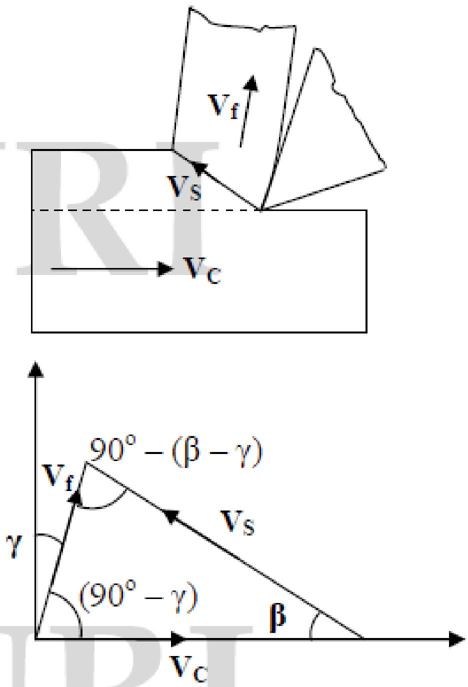
$= \cot\beta + \tan(\beta - \gamma)$

J. Velocity Relationship

Let, V_c = cutting velocity, V_f = chip flow (disposal) velocity, and V_s = shear velocity (in deforming metal) or sliding velocity. They are concurrent and coplaner.

$$\therefore \quad \frac{V_c}{\sin\{90^\circ - (\beta - \gamma)\}} = \frac{V_s}{\sin(90^\circ - \gamma)} = \frac{V_f}{\sin\beta}$$

$$\Rightarrow V_f = \frac{V_c.\sin\beta}{\cos(\beta - \gamma)} = r.V_c \qquad (10)$$



K. Volume rate of cut chip

= Volume rate of uncut chip

$\Rightarrow V_c.a_1b_1 = V_f.a_2b_2 \quad [b_1 = b_2]$

$\Rightarrow \dfrac{V_f}{V_c} = \dfrac{a_1}{a_2} = r; \qquad \Rightarrow V_f = r.\ V_c \qquad (11)$

L. Shear strain rate:

$$\varepsilon_s = \frac{DD'}{\Delta};\ \therefore\ \text{Rate of strain} = \dot{\varepsilon}_s = \frac{\varepsilon_s}{\Delta t} = \frac{DD'}{\Delta.\Delta t} = \frac{DD'}{\Delta t}.\frac{1}{\Delta} = V_s.\frac{1}{\Delta}$$

Fig. 30, 31

Δt = time interval and Δ = thickness of shear zone.

M. ORS ↔ ASA:

$$\begin{bmatrix} \tan\gamma_y \\ \tan\gamma_x \end{bmatrix} = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \tan\gamma \\ \tan\lambda \end{bmatrix}$$

$$\begin{bmatrix} \cot\alpha_y \\ \cot\alpha_x \end{bmatrix} = \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \cot\alpha \\ \tan\lambda \end{bmatrix}$$