2

MECHANICS OF METAL CUTTING

Introduction; chip formation; orthogonal cutting; cutting forces in orthogonal cutting, theory of Ernst and Merchant; Theory of Lee and Shaffer, stress distribution on rake face; ploughing force; chip velocity; Machining with variable uncut chip thickness; oblique cutting; mechanics of turning process; Mechanics of milling process; Mechanics of drilling process; Question Bank.

2.1 INTRODUCTION

Mechanics of metal cutting consists of study of machining process and accurate estimation of dynamic cutting forces by the use of suitable analytical models. Different scientists have prepared different models and advanced their own theory and analysis of metal cutting action. There are certain basic concepts used by most of them. A wedge-shaped tool with a straight cutting edge is made to move relative to the workpiece and a layer of metal called chip is removed. The model of cutting process is shown in Fig. 2.1. The chip is formed by a continuous shearing action of workpiece and there is friction between the flowing chip and face of the tool.

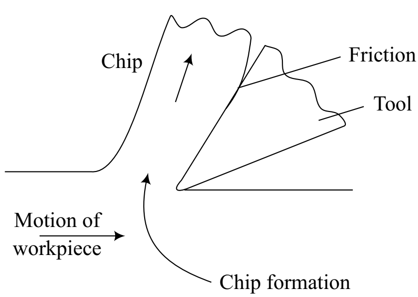


Fig. 2.1 Model of cutting process.

Different machining processes may be classified into two categories:

1. **Orthogonal cutting:** A special case of metal cutting, where the cutting edge of the fool is arranged perpendicular to the direction of relative work-tool motion is called orthogonal cutting. It represents a two-

1. Continuous chips
2. Continuous chips with built-up edge
3. Discontinuous chips
4. Segmented chips

2.2.1 Continuous Chip

A continuous ribbon-type chip is produced during cutting of ductile materials such as low carbon steel, copper, brass and aluminium alloys. The tool presses against the material which is deformed plastically. The material is subjected to both compression and shear. The chip slides over the tool rake face for some distance and then leaves the tool. Friction between the chip and tool may produce additional deformation of the chip material called secondary deformation. Similarly, the plastic zone ahead of tool edge is called the primary zone of deformation and the deformation zone on the rake face is called secondary zone of deformation, see figure 2.4.

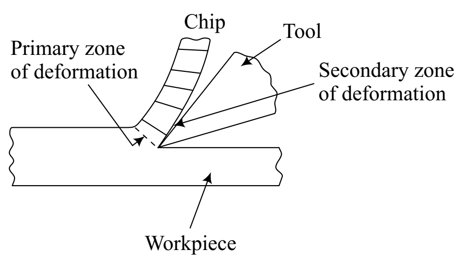


Fig. 2.4 Continuous chip.

Heat is generated in the two deformation zones. Heat is also generated due to sliding of chip on the rake face. The heat generated results in increase of temperature of tool-chip interface and that of tool.

The size of primary zone of deformation depends upon the following factors:

1. Rake angle of tool
2. Cutting speed
3. Properties of work material
4. Friction on rake face

1. Rake angle

The transition of work material into chip is gradual and the material suffers less overall deformation if rake angle of tool is large. The cutting forces are small. If rake angle is small or negative, the material suffers more severe deformation. The cutting forces are also large.

2. Cutting speed

The thickness of primary zone of deformation reduces and zone becomes narrower with the increase of cutting speed.

3. Work material

The size of the primary zone depends upon the following properties of work material.

1. Strength
2. Strain hardening
3. Strain rate
4. Heat conductivity

4. Friction on rake face

The size of both primary and secondary zones of deformation increases due to increase in friction between chip and tool rake face.

2.2.2 Continuous Chip with Built-up Edge

The chip slides under heavy pressure on the rake face. Also there is high temperature between the chip and tool. Due to high temperature and pressure existing, the chip may stick to the rake face of the tool. The heat of chip is conducted to the tool at close contact area. The chip becomes stronger and more of deforming work material is attracted. The size of built-up edge (*BUE*) goes on increasing till a "critical size" is reached when it breaks. The broken portion of *BUE* gets embedded into the machined surface or gets attached to the under side of the flowing chip. The building up and breaking of *BUE* is cyclic and there is a regular embedding of broken *BUE* into machined surface. The surface friction is affected.

With the increase of cutting speed, the temperature of cutting zone increases. The built-up edge is softened at high temperature and critical size of *BUE* reduces. At very high cutting speeds, the *BUE* disappears completely.

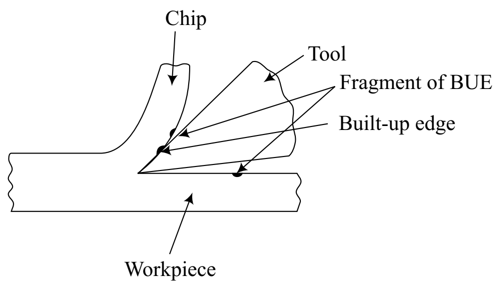


Fig. 2.5 Continuous chip with *BUE*.

2.2.3 Discontinuous Chip

Discontinuous chips are produced during machining of brittle materials such as cast iron and brasses. There is crack formation in the deforming zone ahead of cutting edge. The crack travels with further advancement of tool and results in formation of small lumps of chip. These lumps start moving up the rake face.

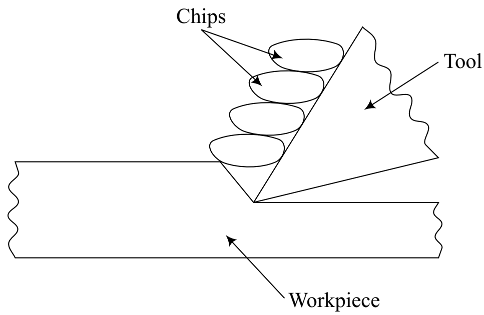


Fig. 2.6 Discontinuous chips.

The friction force obstructs the motion of the lump and crack propagates towards the surface. The fragment of chip gets detached. The heat generated in the cutting zone is mostly carried by the chip and tool life increases due to its lower temperature.

2.2.4 Segmented Chip

During machining of most engineering materials, segmented chips are produced which are a combination of continuous chips and discontinuous chips. The shape of these chips depends upon rake angle, cutting speed and material properties.

2.3 ORTHOGONAL CUTTING

The cutting edge of the tool is perpendicular to the direction of cutting speed. See Fig. 2.7.

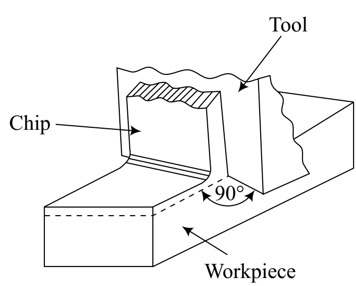


Fig. 2.7 Orthogonal cutting.

2.3.1 Shear Plane

The work material deforms plastically ahead of cutting tool edge. It slides on the rake face of tool and forms a chip. The region between the start of the chip and undeformed (elastically deformed) workpiece is called zone of plastic deformation.

The size of zone of plastic deformation depends upon cutting parameters. The size of this zone decreases with the increase of cutting speed. In the analysis of thin zones, it is assumed that the work material shears across a plane and forms the chip. This plane is called shear plane.

2.3.2 Shear Plane Angle

The angle between the cutting velocity vector and shear plane is called angle of shear plane ϕ. The chip is formed by plastic deformation of work material and material flow is continuous.

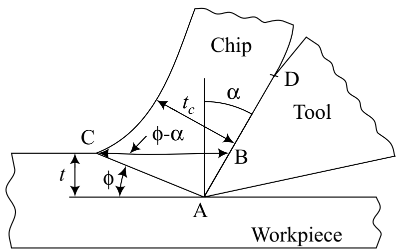


Fig. 2.8 Shear plane angle.

From equation of continuity,

$$t.b.v = t_c.b_c.v_c \qquad ...(1)$$

where,
t = deprth of cut.
b = width of cut
v = cutting velocity
t_c = chip thickness
b_c = width of chip
v_c = chip velocity

In most cutting processes, $b \approx b_c$

$$\therefore \quad tv = t_c v_c \qquad ...(2)$$

The chip thickness ratio,

$$r_t = \frac{t}{t_c} = \frac{v_c}{v} = \frac{L_c}{L} \qquad ...(3)$$

where,
L = uncut chip length
L_c = length of chip formed.

From Fig. 2.8, the length of shear plane,

$$AC = \frac{t}{\sin\phi} = \frac{t_c}{\cos(\phi - \alpha)} \qquad ...(4)$$

where, α = rake angle of tool.

$$\therefore \qquad r_t = \frac{t}{t_c} = \frac{\sin\phi}{\cos(\phi - \alpha)} \qquad \text{...(5)}$$

$$\therefore \qquad \tan\phi = \frac{r_t \cos\alpha}{1 - r_t \sin\alpha} \qquad \text{...(6)}$$

The shear angle ϕ can be experimentally found out from r_t and rake angle α.

A pipe of ductile material is turned with the help of tool with side rake angle (condition for orthogonal cutting). Measure L and L_c and calculate r_t. Measure rake angle α.

The tool should have only back rake angle and side zero rake angle for orthogonal cutting.

Example 2.1 The end of a pipe was orthogonally cut with a tool of 20° rake angle. The chip length was measured as 85 mm whereas uncut chip length was 202 mm. Determine shear plane angle and chip thickness if depth of cut was 0.5 mm.

Solution: Assume, the chip width b_c = width of uncut chip, b

Chip length L_c = 85 mm

Length of uncut chip L = 202 mm

$$\therefore \qquad \text{Chip thickness ratio } r_t = \frac{L_c}{L} = \frac{85}{202} = 0.42$$

Now,

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

$$= \frac{0.42 \cos 20°}{1 - 0.42 \sin 20°}$$

$\therefore$ Shear plane angle, ϕ = **27.4°** **Ans.**

$$\text{Chip thickness, } t_c = \frac{t}{r_t} = \frac{0.5}{0.42} = \mathbf{1.19\ mm} \quad \textbf{Ans.}$$

Example 2.2 A specimen of 100 mm length along the stroke of a shaper is machined with 15° rake angle tool. Determine the shear plane angle and chip thickness if uncut chip thickness is 1.5 mm and chip length obtained is 40 mm.

Solution: Assuming that there is no change in the width of chip during machining,

$$t \times L = t_c \times L_c.$$

$$\therefore \quad \text{Chip thickness ratio,} \qquad r_t = \frac{t}{t_c} = \frac{L_c}{L} = \frac{40}{100} = 0.4.$$

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

$$= \frac{0.4 \cos 15°}{1 - 0.4 \sin 15°}$$

Shear plane angle,

$$\phi = 25.8°$$

Chip thickness, $$t_c = \frac{t}{r_t} = \frac{1.5}{0.4} = \mathbf{3.75\ mm} \quad \textbf{Ans.}$$

2.4 CUTTING FORCES IN ORTHOGONAL CUTTING

In orthogonal cutting the resultant force $\vec{R}$ applied by the tool to the chip lies in a plane normal to the tool cutting edge. This can be determined experimentally by measuring its orthogonal components in the direction of cutting (known as cutting force F_h) and other normal to the direction of cutting (known as thrust force F_v) with the help of dynamometers. The magnitude of resultant force may be found out as follows

$$R = \sqrt{F_h^2 + F_v^2}$$

The component of R in the direction of width b is zero.

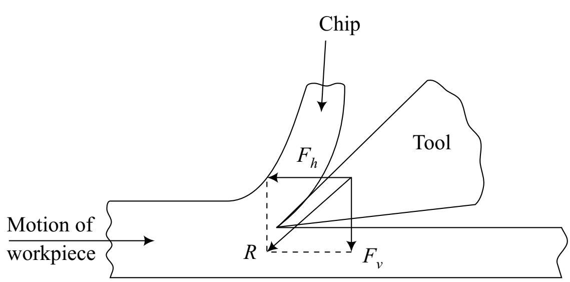


Fig. 2.9 Orthogonal component of cutting force.

The geometrical relationships of components of resultant force in other directions can be found out with the help of Fig. 2.10 which shows the following angles and directions.

Shear plane angle = ϕ

Angle of friction = β

Tool rake angle = α.

The following pairs of components are shown in selected directions.

1. F_h = Horizontal force component along cutting velocity vector.
   F_V = Vertical force component normal to cutting velocity vector.
2. F_s = Force component parallel to shear plane (AC)
   F_p = Force component normal to shear plane (AC)
3. F_t = Force component parallel to tool rake face.
   F_n = Force component normal to tool rake face.

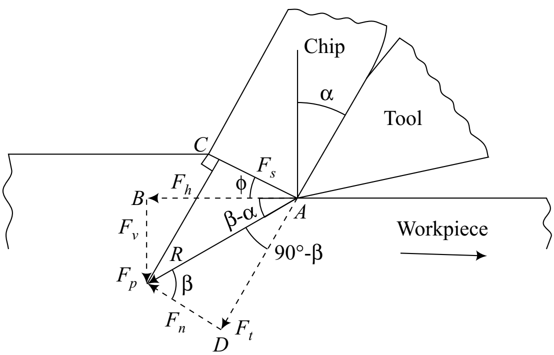


Fig. 2.10 Cutting forces.

$$\therefore \qquad R = \sqrt{F_h^2 + F_v^2}$$

$$R = \sqrt{F_s^2 + F_p^2}$$

$$R = \sqrt{F_t^2 + F_n^2}$$

If average coefficient of friction between the chip and tool is μ.

$$\therefore \qquad \mu = \tan\beta = \frac{F_t}{F_n} \qquad ...(1)$$

Also $$\tan(\beta - \alpha) = \frac{F_v}{F_h} \qquad ...(2)$$

Equations (1) and (2) can be used to find friction angle β.

Expressing different force components in term of R, φ, β and α,

$$\left.\begin{aligned} F_s &= R\cos(\phi + \beta - \alpha) \\ F_P &= R\sin(\phi + \beta - \alpha) \end{aligned}\right\}$$

$$\left.\begin{aligned} F_h &= R\cos(\beta - \alpha) \\ F_v &= R\sin(\beta - \alpha) \end{aligned}\right\}$$

$$\left.\begin{aligned} F_n &= R\cos\beta \\ F_t &= R\sin\beta) \end{aligned}\right\}$$

2.5 THEORY OF ERNST AND MERCHANT

Merchant's model for orthogonal cutting is based on the assumption that shear plane angle ϕ should minimize the work done during cutting.

Following assumptions are made

1. The tool edge is sharp.
2. The shear plane is thin.
3. The deformation is in two dimensions only.
4. The normal and shear stresses are distributed uniformly on the shear plane.
5. The work material is rigid and perfectly plastic.

From Fig. 2.10, following relations were obtained:

$$F_h = R\cos(\beta - \alpha)$$

$$F_s = R\cos(\phi + \beta - \alpha)$$

Let yield stress of material in shear = k

$$F_s = \text{Area} \times k$$

$$= (\text{AC}) \times b \times k$$

$$= \frac{t \times b}{\sin\phi} k.$$

$$\therefore \qquad R = \frac{F_s}{\cos(\phi + \beta - \alpha)} = \frac{t \times b \times k}{\sin\phi\cos(\phi + \beta - \alpha)}$$

$$\therefore \qquad F_h = \frac{t \times b \times k\cos(\beta - \alpha)}{\sin\phi\cos(\phi + \beta - \alpha)} \qquad \text{...(1)}$$

The energy consumption during machining.

$$P_m = F_h.v$$

Assume that ϕ and β are not functions of cutting velocity v.

$$\therefore \qquad \frac{dP_m}{d\phi} = \frac{dF_h}{d\phi} = 0$$

Differentiating equation (1) w.r.t ϕ and putting equal to zero for minimi-zation of F_h.

$$\therefore \quad \frac{t \times b \times \cos(\beta - \alpha)[\cos\phi\,(\phi + \beta - \alpha) - \sin\phi \sin(\phi + \beta - \alpha)]}{\sin^2\phi \cos^2(\phi + \beta - \alpha)}$$

$$\sin\phi \neq 0 \quad \text{and} \quad \cos(\phi + \beta - \alpha) \neq 0$$

$$\therefore \quad \cos(\phi + \beta - \alpha) = 0$$

$$\cos(\beta - \alpha) \neq 0$$

$$\therefore \quad \cos(2\phi + \beta - \alpha) = 0$$

Hence, optimum value,

$$\phi = \frac{\pi}{4} - \frac{(\beta - \alpha)}{2}.$$

Example 2.3 Determine the shear plane angle, cutting force component and resultant force on the tool for orthogonal cutting of a material with yield stress of 250 N/mm^2. Following are the machining parameters.

Tool rake angle = 15°
Uncut chip thickness = 0.25 mm
Chip width = 2 mm
Chip thickness ratio = 0.46
Angle of friction = 40°

Solution:

$$\tan\phi = \frac{r_t \cos\alpha}{(1 - r_t \sin\alpha)}$$

$$= \frac{0.46 \cos 15°}{(1 - 0.46 \sin 15°)}$$

$$\therefore \quad \phi = 29.57°$$

Shear force along the shear plane,

$$F_s = \frac{t.b.K}{\sin\phi} = \frac{0.25 \times 2 \times 250}{\sin 29.57°}$$

$$= 279.04 \text{ N}$$

The resultant force on cutting tool,

$$R = \frac{F_s}{\cos(\phi + \beta - \alpha)} = \frac{279.04}{\cos(29.57 + 40° - 15°)}$$

$$= \frac{279.04}{\cos 54.57°} = 426.3 \text{ N}.$$

The cutting force component,

$$F_h = R\cos(\beta - \alpha)$$

$$= 426.3\cos(40° - 15°) = 426.3\cos 25°$$

$$= \mathbf{393.85\ N} \quad \textbf{Ans.}$$

Example 2.4 Determine the shear plane angle, resultant force on the tool and cutting force component for orthogonal cutting operation of a material with shear yield strength of 200 N/mm^2. The machining data is as follows:

Uncut chip length = 100 mm

Length of cut length = 50 mm

Rake angle of tool = 10°

Width of cut = 1.5 mm

Uncut chip thickness = 0.2 mm

Coefficient of friction = 0.8

Solution: Chip thickness ratio, $r_t = \dfrac{L_c}{L} = \dfrac{50}{100} = 0.5$

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

$$= \frac{0.5\cos 10°}{1 - 0.5\sin 10°}$$

$\therefore$ Shear plane angle,

$$\phi = 28.34°.$$

Shear force along shear plane,

$$F_s = \frac{tbK}{\sin\phi} = \frac{0.2 \times 1.5 \times 200}{\sin 28.34°}$$

Resultant force on cutting tool,

$$R = \frac{tbK}{\sin\phi . \cos(\phi + \beta - \alpha)}$$

$$\tan\beta = \mu = 0.8$$

$$\therefore \quad \beta = 38.66°$$

$$\therefore \quad R = \frac{126.3}{\cos(28.34° + 38.66° - 10°)} = \frac{126.3}{\cos 57°}$$

$$= \mathbf{232\ N} \quad \textbf{Ans.}$$

Cutting force component

$$F_h = R\cos(\beta - \alpha) = 232\cos(38.66° - 10°)$$

$$= \mathbf{203.58\ N} \quad \textbf{Ans.}$$

2.6 THEORY OF LEE AND SHAFFER

The theory of Lee and Shaffer is based on slip line field theory and applies simplified plasticity analysis to the problem of orthogonal metal cutting. The following assumptions are made on the behaviour of work material under stress.

1. The material is rigid plastic. The stress-strain curve is shown in Fig. 2.11.
2. The behaviour of material is independent of rate of deformation.
3. The effect of temperature increase during deformation are negligible.
4. The inertia effects resulting from acceleration of material during deformation are negligible.

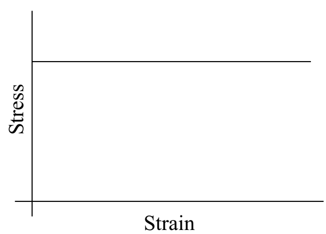


Fig. 2.11 Stress-stain curve for a rigid-plastic material.

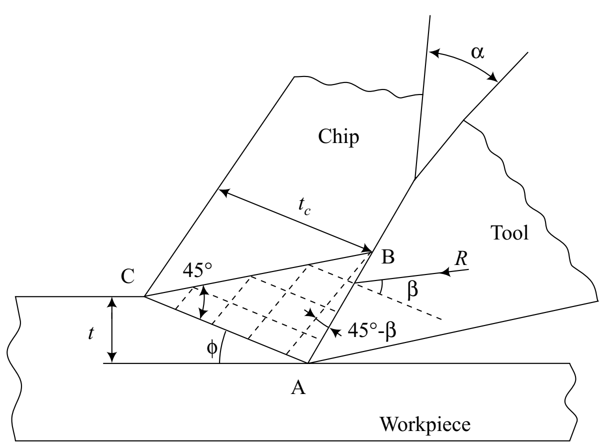


Fig. 2.12 Slip-line field for orthogonal cutting.

The slip-line field for orthogonal cutting is shown in Fig. 2.12.

R = resultant tool force

β = mean friction angle on tool face

ϕ = shear plane angle

α = rake angle

t = undeformed chip thickness

t_c = chip thickness

Triangle ABC contains the zone of deformation. The plane CB is stress free and slip lines meet CB at 45°. AC is the shear plane and there is velocity discontinuity along AC. A set of slip lines are parallel to AC and other set perpendicular to AC and inclined at an angle (45° – β) with the tool rake face.

From Fig. 2.12, $\angle CAB = 45° + \beta$

$$\therefore \quad \phi + \angle \mathrm{CAB} = 90° + \alpha$$

$$\phi = 45° - (\beta - \alpha).$$

or,
$$\phi + \beta - \alpha = 45° \qquad ...(1)$$

Equation (1) is the required shear-angle solution.

Case 1: Zero rake angle

If $\beta = 45°$ and $\alpha = 0°$, $\phi = 0°$

High friction and low rake angle leads to formation of built-up edge.

Case 2: Negative rake angle

If $\beta = 35°$ and $\alpha = -10°$, $\phi = 0°$.

This solution is again impracticable.

2.7 STRESS DISTRIBUTION ON RAKE FACE

In the analysis of orthogonal cutting as per theory of Lee and Shaffer, shear and normal stresses are uniformly distributed in the plastic region and also there is uniform distribution of stress on the rake face. However, it is found that this assumption is not true. Both the stresses are found experimentally to vary along the contact length.

Photo-elastic apparatus was used and stress distribution pattern on the rake face were determined by the analysis of fringe patterns observed. The forces were measured by dynamometers. The distribution of normal and shear stresses on the rake face found out experimentally are shown in Fig. 2.13.

2.7.1 Idealized Stress Distribution

Idealized stress distribution of normal stress (CB) along the rake face is shown by an exponential curve in Fig. 2.14. The shear stress is shown constant upto a portion of contact length from tool tip. This zone is called "**sticking zone**". The shear stress exponentially decreases to zero beyond sticking zone. This constant stress zone is called "slipping zone" and Coulomb's laws of friction are applicable.

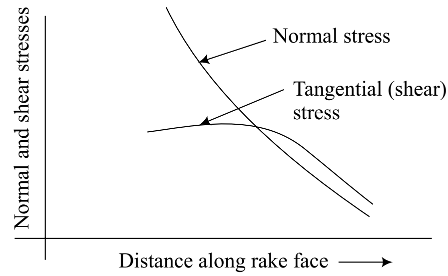


Fig. 2.13 Normal and shear stress distribution on rake face.

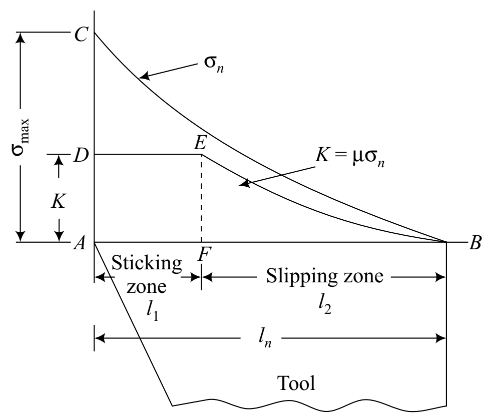


Fig. 2.14 Idealized stress distribution on rake face.

2.7.2 Stress Relationships

The distribution function of normal stress

$$\sigma_n = Ax^m$$

where, A = constant

m = constant

x = distance from end of chip-tool contact.

If σ_n is the normal stress on the rake face at a distance x from the end of contact length.

$$\sigma_n = \sigma_{\max}\left(\frac{x}{l_n}\right)^m$$

where, $\sigma_{\max}$ = max. normal stress at the cutting edge

l_n = natural contact length between tool and chip.

Average coefficient of friction,

$$\mu = \tan\beta = \frac{F_t}{F_n} = \frac{(F_{t_1} + F_{t_2})}{F_n}$$

Substituting the values of F_{t_1}, F_{t_2} and F_n,

$$\mu = \frac{K.(l_n - l_2)(m+1) + \mu\sigma_{\max}(l_2)^{m+1}}{\sigma_{\max}(l_n)^{m+1}}$$

2.8 PLOUGHING FORCE

The resultant tool force in metal cutting is distributed over the areas of the tool that contact the chip and workpiece. No cutting tool is perfectly sharp and the cutting edge can be represented by a cylindrical surface joining the tool flank and the tool face. For a freshly ground high-speed steel tool, the radius of the edge varies from 0.005 to 0.03 mm. Deformation of tool material occurs in this region due to high stresses on the cutting edge. There is contact between the tool and the new workpiece surface over a small area of tool flank. A frictional force may act in the tool flank region. This force does not contribute to the removal of the chip. This force is called ploughing force.

The total resultant tool force,

$$R = F_c + F_p$$

where, F_c = force required to remove the chip

F_p = ploughing force acting on the tool edge and work-tool interface region.

The specific cutting energy increases especially at low values of undeformed chip thickness.

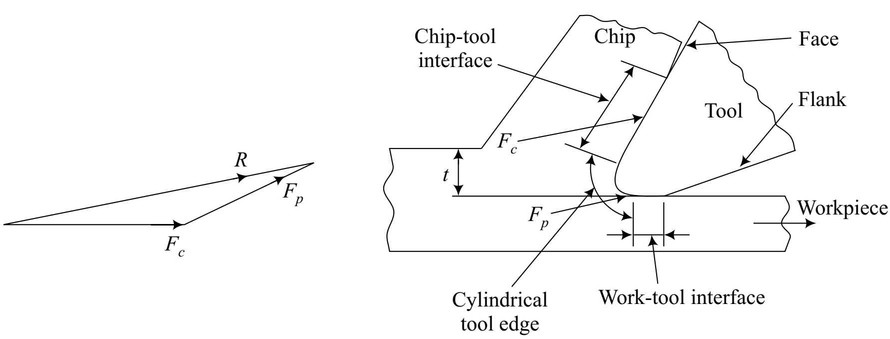


Fig. 2.15 Contact regions in a cutting tool.

2.9 CHIP VELOCITY

The chip velocity along the tool rake face, V_c is the vector sum of velocity of uncut chip V and the velocity discontinuity along the shear plane.

$$\vec{V}_c = \vec{V}_t + \vec{V}_s$$

The velocity of the uncut chip is the velocity of workpiece with respect to cutting tool. The surface layer shears across the shear plane AC and becomes a part of the chip. Therefore, surface layer suffers a velocity discontinuity parallel to shear plane as shown in Fig. 2.16.

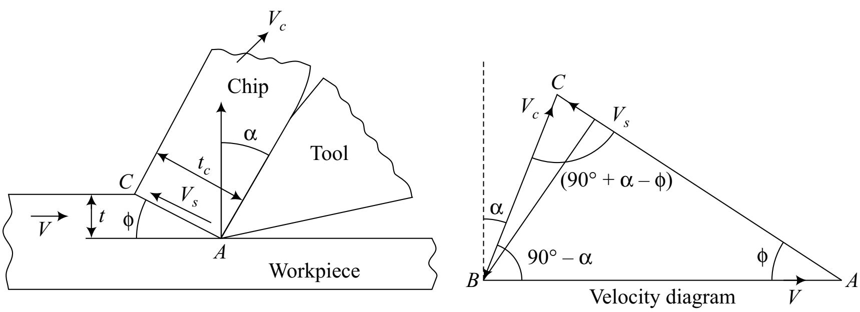


Fig. 2.16 Velocity relationship in orthogonal cutting.

From velocity triangle BAC, using Lami's theorem,

$$\frac{V}{\sin(90° + \alpha - \phi)} = \frac{V_s}{\sin(90° - \alpha)} = \frac{V_c}{\sin\phi}$$

The chip velocity,

$$V_c = \frac{V \sin\phi}{\sin(90° + \alpha - \phi)} = \frac{V \sin\phi}{\cos(\phi - \alpha)}$$

The shear velocity,

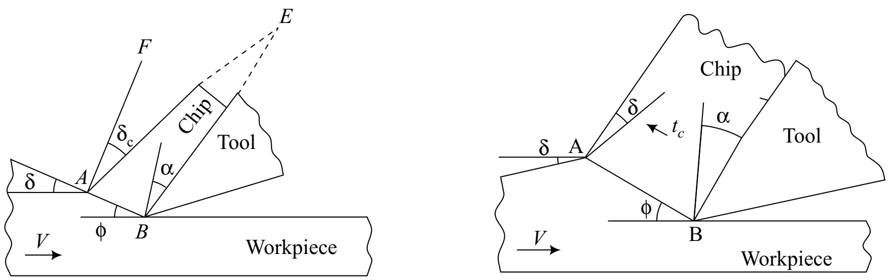
$$V_s = \frac{V \sin(90° - \alpha)}{\sin(90° + \alpha - \phi)} = \frac{V \cos\alpha}{\cos(\phi - \alpha)}.$$

2.10 MACHINING WITH VARIABLE UNCUT CHIP THICKNESS

In most machining processes such as milling, grinding, gear cutting, etc., the chip thickness varies during cutting. The uncut chip thickness may change from maximum to zero or zero to maximum. The vibration and chatter of machine tools also lead to chip thickness variation.

The following two cases are shown in Fig. 2.17.

1. The workpiece with positive surface slope. The uncut chip thickness varies from maximum to zero.



(a) Positive slope (b) Negative slope

Fig. 2.17 Variable uncut chip thickness.

2. The workpiece with negative surface slope. The thickness of uncut chip varies from zero to maximum.

Following relationship may be used to find shear plane angle ϕ in case of variable or unsteady chip thickness cutting. The instantaneous shear plane angle.

$$\phi = \phi_0 + c\delta$$

where, ϕ_0 = shear plane angle when slope of work surface is zero, i.e., $\delta = 0$

δ = slope of workpiece surface ahead of tool edge.

c = constant

= 0.50 Merchant

= 1.00 Shaw and Sanghoni

= 0.75 Wallace and Andrew

= 0.20 Oxleg

= 1.00 Kebayashi and Shabaik.

In most cases, c can be taken to unity. From so many values of c by various authors, it can be suggested that it is not a constant and may be a function of α, δ and ϕ_0.

2.11 OBLIQUE CUTTING

The rake and other tool angles required for ideal orthogonal cutting cannot be achieved due to practical considerations. Therefore, most machining processes approach oblique cutting with orthogonal cutting as a particular case.

2.11.1 Chip Flow Direction

The angle between the normal to the cutting edge and chip velocity vector is called chip flow angle. In orthogonal cutting, chip flows in a direction normal to the cutting edge and chip flow angle is zero.

$$\text{Chip width ratio, } r_b = \frac{b}{b_c}$$

$$\therefore \qquad r_t = \frac{1}{r_b . r_L}$$

2.11.4 Velocity Relationships

The velocity diagram for oblique cutting is shown in Fig. 2.19.

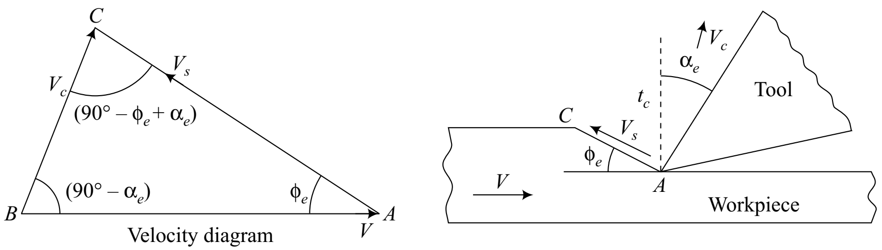


Fig. 2.19 Velocity relationship.

V = uncut chip velocity
V_c = chip velocity
V_s = shear velocity
ϕ_e = effective shear plane angle
α_e = effective rake angle

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

From properties of triangle ABC,

$$\frac{V_c}{V} = \frac{\sin \phi_e}{\cos(\phi_e - \alpha_e)}$$

$$\frac{V_s}{V} = \frac{\cos \phi_e}{\cos(\phi_e - \alpha_e)}$$

Expressing the relationship in terms of chip flow angle ψ, angle of obliquity I and normal rake angle α_n,

$$\frac{V_c}{V} = \frac{\sin \phi_n \cos I}{\cos(\phi_n - \alpha_n) . \cos \psi}$$

and,
$$\frac{V_s}{V} = \frac{\cos I \cos \alpha_n}{\cos \psi \cos(\phi_n - \alpha_n)}.$$

2.11.5 Shear Plane Angle

The angle between shear velocity vector, V_s and the cutting edge is called shear plane angle. Similar to rake angle, shear angle can be measured in different planes. Refer to Fig. 2.19.

$$\tan \phi_e = \frac{V_c/V \cos \phi_c}{1 - V_c/V \sin \alpha_e}$$

Normal shear angle is measured in a plane normal to cutting edge.

$$\tan \phi_n = \frac{\left(\dfrac{t}{t_c}\right) \cos \alpha_n}{1 - \left(\dfrac{t}{t_c}\right) \sin \alpha_n}$$

2.12 MECHANICS OF TURNING PROCESS

A turning tool has complex geometry with the following important angles which affect the chip flow direction.

1. Rake angle (α)
2. Back rake angle (α_b)
3. Side rake angle (α_s)
4. Side cutting edge angle (γ_s)
5. End cutting edge angle (γ_e)
6. Nose radius

The chip flow direction becomes complex due to the presence of nose radius and for mathematical analysis, the presence of nose radius is neglected.

The top view of a turning tool is shown in Fig. 2.20, where

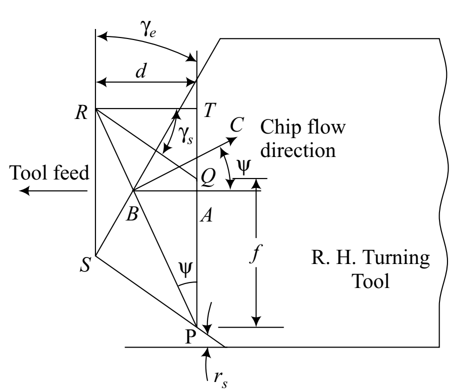


Fig. 2.20 Chip flow direction in turning.

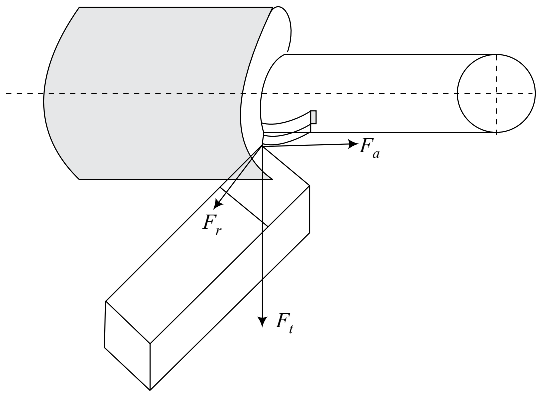


Fig. 2.21 Forces in turning.

where, F_t = tangential force component [N].
V = cutting velocity [m/min].

The cutting force components can be expressed by the following equations.

$$F_t = R_1 f^{m_1} d^{n_1} \text{ [N]}$$

$$F_a = R_2 f^{m_2} d^{n_2} \text{ [N]}$$

$$F_r = R_3 f^{m_3} d^{n_3} \text{ [N]}$$

where, f = feed
d = depth of cut
R_1, R_2, R_3 = material coefficients
m_1, m_2, m_3 and n_1, n_2, n_3 are exponents.

Various values of coefficients and exponents are given in Table 2.1.

Table 2.1 Coefficients and exponents for turning forces

Material	*Coefficients*			*Exponents*					
	R_1	R_2	R_3	m_1	m_2	m_3	n_1	n_2	n_3
0.2% carbon steel	1590	337	397	0.85	0.8	0.67	0.98	1.46	0.47
Brass	1210	220	558	0.81	0.91	0.97	0.96	1.43	0.38
18-8 stainless steel	1930	368	876	0.85	0.48	0.71	0.96	1.26	0.69

2.12.3 Specific Energy

Specific energy is the power consumption per unit volume of material removed.

$$P_s = \frac{F_t}{(f.d)}$$

The metal removal rate,

$$Z_w = f.d.V. \times \frac{1000}{60} \ [\text{mm}^3/\text{s}]$$

where, f = feed (mm)

d = depth of cut [mm]

V = cutting speed [m/min]

Power consumption,

$$P = F_t \times \frac{V}{60} \ [\text{W}]$$

$$P_s = \frac{F_t}{1000 \times f \times d} \ [\text{kW/cm}^3/\text{sec}].$$

Example 2.5 Calculate the specific energy and unit power in a turning process. The machining data are:

Diameter of workpiece = 50 mm

Cutting speed = 40 m/min

Feed = 0.24 mm/sec

Depth of cut = 1.8 mm

Tangential component of force = 800 N

Axial component of force = 290 N

Solution: Metal removal rate,

$$Z_w = fd\frac{V}{60} \ [\text{cm}^3/\text{s}]$$

$$= \frac{0.24}{10} \times \frac{1.8}{10} \times \frac{40 \times 100}{60} = 0.288 \ \text{cm}^3/\text{sec}.$$

Power consumed,

$$P = \frac{F_t \times V}{60} \ [\text{W}]$$

$$= 800 \times \frac{40}{60} \ [\text{W}].$$

Assume that power consumed by feed force is negligible.

Unit power, $$P_s = \frac{P}{Z_w} = \frac{800 \times 40}{60 \times 0.288} = 1.5 \text{ kW/cm}^3\text{/sec}$$

2.13 MECHANICS OF MILLING PROCESS

Slab milling and end milling processes are the most versatile milling processes for producing flat and formed surfaces. The cutter can move in both directions and the processes are called up-milling and down-milling. The average chip thickness is higher in down-milling as compound to up-milling. The power consumption is less in down-milling.

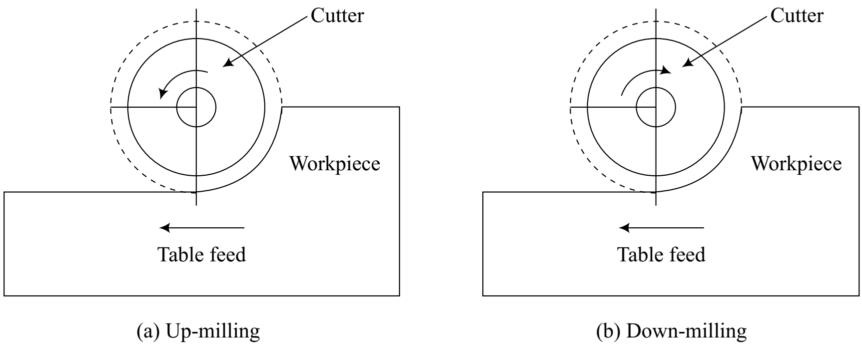


Fig. 2.22 Types of milling processes.

2.13.1 Chip Thickness in Slab Milling

The two positions of milling cutter are shown as C and C' during the distance travelled equal to feed per tooth, f_t.

The uncut chip thickness,

$$t = f_t \sin \theta$$

where, θ = angle of a radius with the vertical.

α = contact angle of cutter with workpiece.

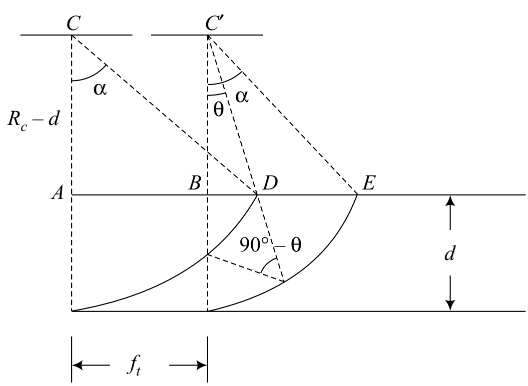


Fig. 2.23 Chip thickness in slab milling.