From right angled triangle *BAC*.

$$AC = AB\cos(\beta-\alpha)$$

$$AC = V_C\cos(\beta-\alpha) \qquad \ldots(ii)$$

$\therefore$ From (*i*) and (*ii*)

$$V\sin B = V_C\cos(\beta-\alpha)$$

$$V_C = \frac{V\sin\beta}{\cos(\beta-\alpha)}$$

Again from right angle triangle *ODA*

$$OD = OA\cos\sigma$$

$$= V\cos\alpha \qquad \ldots(iii)$$

From right angled triangle *ODB*.

$$OD = V_S\cos(\beta-\alpha) \qquad \ldots(iv)$$

$\therefore$ From (*iii*) and (*iv*)

$$V\cos\alpha = V_S\cos(\beta-\alpha)$$

$$V_S = \frac{V\cos\alpha}{\cos(\beta-\alpha)}.$$

2.10.2. To Prove $V_C = rV$

We have proved that

$$V_C = \frac{V\,.\sin\beta}{\cos(\beta-\alpha)}$$

And it has also been proved in chapter one

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

where, r = chip thickness ratio

$$\therefore \qquad V_C = \frac{V\,.\sin\beta}{\cos(\beta-\alpha)} = V\,.\,r.$$

2.10.3. Effect of Cutting Variables on Cutting Forces

The cutting forces are direct functions of feed (*f*) and depth of cut (*d*) under conditions of other variables kept constant the following relations may be used for machining steel

$$F_z = C_1 d.f^{0.75}$$

$$F_y = C_2 d^{0.9} f^{0.75}$$

$$F_x = C_3 d^{1.2} f^{0.55}$$

For steel having ultimate strength 35 kg/mm^2 the values of C_1, C_2 and C_3 are as follows.

$$C_1 = 14$$

$$C_2 = 27$$

$$C_3 = 20$$

For machining cast iron (BHN = 150) the following relations may be used.

$$F_z = K_1 d.f^{0.78}$$

$$F_y = K_2 d^{0.9} f^{0.75}$$

$$F_x = K_3 d^{1.1} f^{0.65}$$

The values of constants K_1, K_2 and K_3 are follows :

$$K_1 = 80$$

$$K_2 = 59$$

$$K_3 = 28.$$

2.11. Improvement of Cutting Efficiency

It is desirable that the metal cutting should be economical.

Cutting efficiency can be improved by following factors.

(*i*) By reducing chip length by means of chip breakers.

(*ii*) By improving surface finish of the tool face by honing or chrome plating.

(*iii*) Increased depth of cut increases the cutting efficiency by a small amount.

(*iv*) By effective removal of heat produced during cutting.

2.12. Requirements Made to the Cutting Tool

A tool intended for high production machining should be amply strong and rigid, it should have optimum geometry, be keenly sharpened with a high class finish, producible in manufacture and convenient in use.

2.13. Cutting Tool Design

Proper cutting tool design is essential in order to achieve desired accuracy, and to increase tool life. The cutting tool should be of proper material and should be able to resist the forces acting on it. Proper tool geometry leads to increased tool life, desired functioning of tool and to increased strength of tool.

For more details see chapter 12.

2.14. Dynamometry

It is a method of measuring cutting force during metal cutting. Dynamometer is the instrument used for measuring the cutting force.

A dynamometer should possess the following two requirements :

(*i*) Sensitivity

(*ii*) Rigidity

A dynamometer is said to be sensitive if the measurements are accurate to within ± 1%. During use some deformation is associated with the operation of every dynamometer. A dynamometer should be rigid enough so that the cutting operation is not influenced by the accompanying deflections. The main stiffness criterion is the natural frequency of the dynamometer. All machine tools operated with vibrations. Large amplitude of vibrations are experienced during machining operations like milling, grinding, shaping etc. In order that the cutting force is not influenced by any vibrating motion of the dynamometer its frequency should be high (about 4 times as high) as compared to the exciting vibration. The dynamometer can be compared to a spring-mass system for purpose of analysis of vibrations. The natural frequency of such system is given by

$$\omega_n = \frac{1}{2\pi}\sqrt{\frac{K}{m}}$$

where ω_n = Natural frequency in cycles per second (CPS)

K = Spring stiffness (kgf/cm)

m = Mass (kg)

(*iii*) Size

(*iv*) Ruggedness

(*v*) Adaptability to several jobs.

A dynamometer should be stable with respect to the following :

(*i*) Time

(*ii*) Temperature

(*iii*) Humidity

Once a calibration is made the dynamometer should only have to be checked occasionally.

2.15. Types of Dynamometers

Various types of dynamometers are as follows :

(*i*) **Direct reading type.** These dynamometers use devices for the separation of force components which involve friction such as rollers, balls and sliding surfaces. However as friction conditions are usually variable due to dirt, temperature etc. such instruments are not commonly used.

(*ii*) Recording or indicating dynamometers. These dynamometers cost more than direct reading type. But these have the advantages of easy measurement and more life.

2.16. Force Measurement

A dynamometer should measure at least two force components in order to determine a two dimensional resultant cutting force. In a three dimensional cutting operation three force components are necessary while in drilling or tapping only a torque and a thrust are required.

Force measurement involves the measurement of a deflection with a suitable calibration between the force and deflection it produces. In most dynamometers the force is applied to some sort of spring and the deflection thus produced is measured.

Some of the devices used to measure small deflections in dynamometers are as follows :

(*i*) **Dial Indicator.** It can read deflections to about 25×10^{-4} mm. However dial indicators are subject to sticking and are not to be relied upon for absolutely static readings. A lever system is frequently use in conjunction with a dial indicator. A typical dynamometer has been explained in chapter 12.

(*ii*) **Hydraulic Dynamometer.** Hydraulic pressure cells are used in conjunction with pressure gauges to measure or record the force on a tool.

Fig. 2.9 shows basic principle of hydraulic dynamometer.

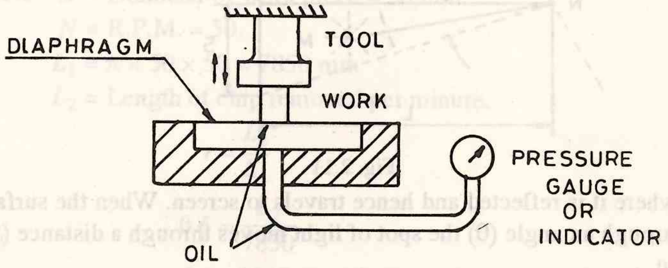


Fig. 2.9

(*iii*) **Pneumatic Dynamometer.** In such dynamometers the change in back pressure that occurs when a flat surface is brought into closer contact with a sharp edged orifice are some times used to measure deflections in tool dynamometers.

These dynamometers have the following advantages :

(*i*) Simple

(*ii*) Reliable if air supplied is clean with constant pressure of air.

However following drawbacks are observed in these dynamometers :

(*i*) There is a limited region over which they are linear.

(*ii*) They are generally bulky.

Basic principle of pneumatic dynamometer is shown in Fig. 2.10.

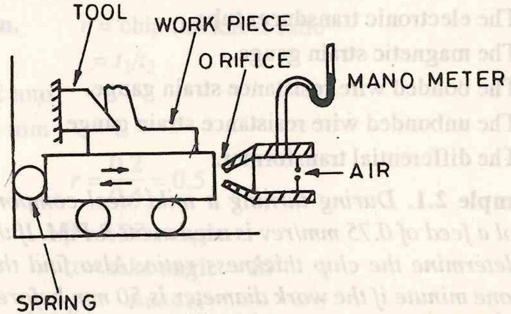


Fig. 2.10

(*iii*) **Optical Dynamometer.** These dynamometers use two methods :

(*a*) Interferometric method can be used to give very precise measurements using the wave length of light as a yard stick. But it is difficult to apply this method to the measurement of the dynamic deflections obtained in metal cutting.

(*b*) Optical lever principle to measure small deflections. Fig. 2.11 shows principle of optical lever principle. A narrow beam of light travels from M to N where it is reflected and hence travels to screen. When the surface N rotates through an angle (θ) the spot of light moves through a distance (*S*) on the screen.

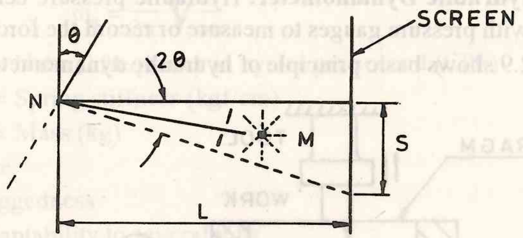


Fig. 2.11

$$\text{Tan } 2\theta = \frac{S}{L}$$

If angle θ is small

$$2\theta = \frac{S}{L}$$

$$S = 2\theta \times L$$

(*iv*) **Electric Dynamometers**

(*a*) Piezo electric crystals may be used as force measuring units.

(*b*) The electric transducers provide more convenient electrical units in the construction of dynamometers.

Electric transducers commonly used are as follows :

(*i*) The electronic transducer tube.

(*ii*) The magnetic strain gauge.

(*iii*) The bonded wire resistance strain gauge.

(*iv*) The unbonded wire resistance strain gauge.

(*v*) The differential transformer.

Example 2.1. *During turning a mild steel component with an orthogonal tool a feed of 0.75 mm/rev is used at 50 R.P.M. If the chip thickness is 1.5 mm determine the chip thickness ratio. Also find the length of chip removed in one minute if the work diameter is 50 mm before the cut is taken. Assume a continuous chip.*

Solution. r = Chip thickness ratio

$$r = \frac{t_1}{t_2}$$

where $t_1 = 0.75$ mm.

$t_2 = 1.5$ mm.

$$r = \frac{0.75}{1.5} = 0.5$$

L_1 = Length of chip before cutting

$= \pi DN$

where D = Diameter of work piece = 50 mm.

N = R.P.M. = 50.

$L_1 = \pi \times 50 \times 50 = 7850$ mm

L_2 = Length of chip removed per minute.

$$r = \frac{L_2}{L_1}$$

$$0.5 = \frac{L_2}{7850}$$

$L_2 = 3925$ mm. Ans.

Example 2.2. *In an orthogonal turning operation.*

Cutting speed = 80 m/min

Cutting force = 20 kg.

Feed force = 8 kg.

Back rake angle = 15°.

Feed = 0.2 mm/rev.

Chip thickness = 0.4 mm.

Determine the following :

(a) Shear angle.

(b) Work done in shear.

(c) Shear strain.

Solution. r = chip thickness ratio

$= t_1/t_2$

where $t_1 = 0.2$ mm

$t_2 = 0.4$ mm

$$r = \frac{0.2}{0.4} = 0.5$$

β = shear angle.

α = rake angle = 15°

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

$$\tan\beta = \frac{0.5\cos 15}{1 - 0.5\sin 15} = 0.55$$

$\beta = 28°$.

F_S = Shear force.

$= F_H \cos\beta - F_V \sin\beta$.

Now F_H = Cutting force = 20 kg.

F_v = Feed force = 8 kg.

$F_S = 20\cos 28 - 8\sin 28$

$= 13.84$ kg.

Now V = Cutting speed = 80 m/min.

$$V_S = \frac{V\cos\alpha}{\cos(\beta-\alpha)}$$

$$= \frac{80\cos 15}{\cos(28-15)} = 79 \text{ m/min.}$$

Work done in shear $= F_S . V_S = 13.84 \times 79$

$= 1093$ kg-m/min.

Shear strain $= \cot\beta + \tan(\beta - \alpha)$

$= \cot 28 + \tan(28 - 15)$

$= 1.65$.

Example 2.3. *Calculate the power consumed during cutting of a low carbon steel bar 40 mm diameter if cutting force is 150 kg at 200 R.P.M.*

Solution. F_H = Cutting force

$= 150$ kg

V = Cutting speed

$$= \frac{\pi DN}{1000} = \frac{\pi \times 40}{10000} \times 200$$

$= 25.12$ m/min.

Work done $= F_H \times V$

$= 150 \times 25.12$ kg m/min

$$\text{H.P.} = \frac{150 \times 25.12}{4500}$$

$= 0.83$. Ans.

Example 2.4. *Determine the time required to turn a brass component 50 mm diameter and 100 mm long at a cutting speed of 36 m/min. The feed is 0.4 m/revolution and only one cut is taken.*

Solution. D = Diameter of component.

$= 50$ mm

L = Length

$= 100$ mm

V = Cutting speed

$= 36$ m/min.

f = Feed = 0.4 mm/rev.

N = Spindle speed (R.P.M.)

$$V = \frac{\pi DN}{1000} \text{ m/min.}$$

$$36 = \frac{\pi . 50 . N}{10000}$$

$N = 229$ R.P.M.

T = Time required

$$= \frac{L}{f . N} = \frac{100}{0.4 \times 229} \text{ minutes.}$$

$$= \frac{100 \times 60}{0.4 \times 229} = 65 \text{ seconds. } \textbf{Ans.}$$

Example 2.5. *(a) In orthogonal cutting if the feed is 1.25 mm/rev, and chip thickness after cutting is 2 mm ; determine the following :*

(i) Chip thickness ratio.

(ii) Shear angle.

The tool bit has a rake angle of 10°

(b) If shear strength= 6000 kg/cm²

Width of cut = 10 mm

Cutting speed = 30 m/min.

Coefficient of friction = 0.9

Determine the following :

(i) Shearing force.

(ii) Friction angle.

(iii) Cutting force.

(iv) Horse power at the cutting tool.

Solution. (*a*) Let r = chip thickness ratio

$$= \frac{t_1}{t_2}$$

where t_1 = Chip thickness before cutting.

t_2 = Chip thickness after cutting.

Now $t_1 = 1.25$ mm.

$t_2 = 2$ mm.

$$r = \frac{1.25}{2} = 0.625$$

Let β = Shear angle

α = Rake angle = 10°

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

$$= \frac{0.625 \cos 10}{1 - 0.625 \sin 10}$$

$$= \frac{0.625 \times 0.9848}{1 - 0.625 - 0.1736} = 0.65$$

$$\beta = 33° \, 2'. \text{ Ans.}$$

(*b*) We know

$$F_S = \frac{f_S \, . \, A_1}{\sin \beta}$$

where F_S = Shearing force

F_S = Shear stress

A_1 = Area of chip

= Width of chip × Depth of cut

= 1 cm × 0.125 cm

$$\therefore \quad F_S = \frac{6000 \times (1 \times 0.125)}{\sin 33° \, 2'}$$

$$= \frac{6000 \times 0.125}{0.545} = 1376 \text{ kg.}$$

Let γ = Friction angle

μ = Coefficient of friction

$$\tan \gamma = \mu = 0.9$$

$$\gamma = 42°.$$

F_H = Cutting force

$$= \frac{F_S \, . \cos (\gamma - \alpha)}{\cos (\beta + \gamma - \alpha)}$$

$$= \frac{1376 \cos (42 - 10)}{\cos (33' - 2' + 42 - 10)}$$

$$= \frac{1376 \cos 32}{\cos 65° \, 2'} = 2778 \text{ kg.}$$

H.P. = Horse power at the tool

$$= \frac{F_H \times V}{4500}$$

where V = Cutting speed (metre/min)

$$\text{H.P.} = \frac{2778 \times 30}{4500} = 18.52 \text{ Ans.}$$

Example 2.6. *In orthogonal cutting of a material the feed force is 80 kg and cutting force is 150 kg. Calculate the following :*

(i) Compression and shear forces on shear plane.

(ii) Coefficient of friction of the chip on the tool face. Take chip thickness ratio as 0.3 and rake angle as 8°.

Solution. We have proved that

F_n = Compressive force on shear plane.

$$= F_V \cos \beta + F_H \sin \beta.$$

F_S = Shear force on shear plane

$$= F_H \cos \beta - F_V \sin \beta$$

Now F_H = 150 kg.

F_V = 80 kg.

$$\alpha = 8°$$

β = Shear angle.

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

$$= \frac{0.3 \cos 8}{1 - 0.3 \sin 8} = 0.3$$

$$\beta = 17°$$

$$\therefore \quad F_n = F_V \cos \beta + F_H \sin \beta$$

$$= 80 \cos 17 + 150 \sin 17$$

$$= 121 \text{ kg. Ans.}$$

$$F_S = F_H \cos \beta - F_V \sin \beta.$$

$$= 150 \cos 17 - 80 \sin 17$$

$$= 119.3 \text{ kg. Ans.}$$

μ = Coefficient of friction

$$\frac{F_H \tan \alpha + F_V}{P_H - F_V \tan \alpha} = \frac{150 \tan 8 + 80}{150 - 80 \tan 8}$$

$$= 0.73. \text{ Ans.}$$

Example 2.7. *In orthogonal turning process the feed is 0.25 mm/rev at 50 R.P.M. The thickness of the chip removed is 0.5 mm.*

(a) What is the chip thickness ratio ?

(b) If the work diameter is 50 mm before the cut is taken what is the approximate length of the chip removed in one minute. Assume a continuous chip.

Solution. r = Chip thickness ratio

$$= t_1/t_2$$

t_1 = Chip thickness before cutting

= 0.25 mm.

t_2 = Chip thickness

$$r = \frac{t_1}{t_2} = \frac{0.25}{0.5}$$

= 0.5 Ans.

Work diameter, $D = 50$ mm.

$= 5$ cm.

N = R.P.M.

$= 50.$

L_1 = Length of chip before cutting

$= \pi \,.\, D \,.\, N$

$= \pi \,.\, 5.50$

$= 785$ cm.

L_2 = Length of chip after cutting.

$$r = \frac{L_2}{L_1}$$

$$0.5 = \frac{L_2}{785}$$

$$L_2 = 0.5 \times 785$$

$= 392.5$ cm. **Ans.**

Example 2.8. *A medium carbon steel bar 40 mm diameter is turned on a lathe with a cutting tool having top rake angle 30° and with a cutting speed of 24 mpm (metre per minute). If the cutting force is 200 kg, feed force 80 kg and feed given to tool is 0.12 mm/rev. length of chip in one revolution = 70 mm, determine the following :*

(*a*) *Shear angle.*

(*b*) *Chip thickness.*

(*c*) *Velocity of chip along the tool face.*

Solution. F_H = *Cutting force.*

$= 200$ kg.

F_V = Feed force = 80 kg.

α = Rake angle = 30°

f = feed/revolution

$= 0.12$ mm/rev.

β = Shear angle.

$$\tan \beta = \frac{r \cos \alpha}{1 - r \sin \alpha} = \frac{r \cos 30}{1 - r \sin 30}$$

r = Chip thickness ratio.

$$= \frac{L_2}{L_1}$$

L_1 = Length of chip before cutting.

$= \pi D$

where D = Diameter of workpiece

$= \pi \times 40$ mm

L_2 = Length of chip after cutting

$= 70$ mm (given).

$$r = \frac{70}{\pi \times 40} = 0.55$$

$$\tan \beta = \frac{0.55 \cos 30}{1 - 0.55 \sin 30}$$

$\beta = 33° \, 6'$. **Ans.**

$$r = \frac{t_1}{t_2}$$

where t_1 = Chip thickness before cutting

= Feed.

t_2 = Chip thickness.

$$r = \frac{\text{Feed/rev.}}{\text{Chip thickness}}$$

$$\text{Chip thickness} = \frac{\text{Feed/rev.}}{r} = \frac{0.12}{0.55}$$

$= 0.218$ mm. **Ans.**

V_C = Velocity of chip along the tool face.

$$= \frac{V \sin \beta}{\cos (\beta - \alpha)} = V \times r$$

where V = Cutting speed.

$$\left[\text{As we have proved } r = \frac{\sin \beta}{\cos (\beta - \alpha)} \right]$$

$V_C = 24 \times 0.55 = 13.2$ mpm. **Ans.**

Example 2.9. *To turn a mild steel component the power required is 0.1/cm³/min. The maximum power available at the machine spindle is 5 H.P. If the cutting speed is 35 meter/min and feed rate is 0.25 mm/rev, determine the following :*

(*a*) *Maximum metal removal rate.*

(*b*) *Depth of cut.*

(*c*) *Cutting force.*

(*d*) *Normal pressure on chip.*

Solution. w = Maximum metal removal rate.

$$= \frac{5}{0.1} = 50 \text{ cm}^3\text{/min.}$$

F_H = Cutting force (kg)

V = Cutting speed (mpm)

$$\frac{F_H \times V}{4500} = \text{Horse power} = 5.$$

$$F_H = \frac{4500 \times 5}{35} = 643 \text{ kg.}$$

t = Depth of cut in cm.

f = Feed in cm.

= 0.025 cm/rev.

V = Cutting speed in cm.

$$w = t \times f \times V$$

$$50 = t \times 0.025 \times 35 \times 100.$$

$$t = \frac{50}{35 \times 100 \times 0.25}$$

$$= 0.55 \text{ cm} = 5.5 \text{ mm.}$$

Normal pressure on chip

$$= \frac{F_H}{\text{Chip Area}} = \frac{643}{\text{Feed} \times \text{Depth of cut}}$$

$$= \frac{643}{0.25 \times 5.5} = 468 \text{ kg/mm}^2\text{. Ans.}$$

Example 2.10. *Following observations were made from a metal cutting test carried out on a lathe.*

Cutting force = *180 kg.*
Feed = *5 cuts/mm.*
Depth of cut = *5 mm.*
Cutting speed = *30 mm.*

If overall efficiency of the machine is 70% determine

(a) Normal pressure on chip.

(b) Power required at the motor to turn the material.

Solution. F_H = Cutting force

= 180 kg.

Normal pressure on chip

$$= \frac{F_H}{\text{Cross sectional area of chip}}$$

$$= \frac{180}{5 \times 8.2} = 180 \text{ kg/mm}^2.$$

(Cross sectional area of chip

= Depth of cut × Feed per revolution)

Power required for cutting

$$= \frac{F_H \times V}{4500}$$

$$= \frac{183 \times 30}{4500} = 1.2$$

Power required at the motor

$$= \frac{1.2}{0.70} = 1.7 \text{ H.P. Ans.}$$

Example 2.11. *The power required by a lathe when running idle is 300 watts. The power input rises to 2400 watts when an alloy steel is machined on lathe at 120 r.p.m. If the depth of cut is 3.50 mm, feed is 0.2 mm/rev and cutting speed is 24 meter/min. Calculate the following :*

(a) Cutting force and torque at the spindle.

(b) H.P/cm^3/min required to cut the material.

Solution. Power required for cutting

= 2400 – 300 = 2100 Watts.

H.P. required for cutting

$$= \frac{2100}{735} = 2.87$$

T = Torque at the spindle.

N = r.p.m. = 120

$$\text{H.P.} = \frac{2\pi NT}{4500}$$

$$2.87 = \frac{2\pi \times 120 \times T}{4500}$$

$$T = \frac{2.87 \times 4300}{2\pi \times 120} = 17 \text{ kg m}$$

F_H = Cutting force.

V = Cutting speed in metre per minute

= 24 mpm

$$\text{H.P.} = \frac{F_H \times V}{4500}$$

$$2.87 = \frac{F_H \times 24}{4500}$$

$$F_H = \frac{2.87 \times 4500}{24} = 538 \text{ kg.}$$

w = Maximum metal removal rate

$= f \times t \times V$

where f = Feed = 0.2 mm/rev.

= 0.02 cm/rev.

t = Depth of cut.

= 3.5 mm = 0.35 cm

V = Cutting speed

= 24 metre/min.

= 2400 cm/min.

$$w = 0.02 \times 0.35 \times 2400$$
$$= 16.8 \text{ cm}^3\text{/min.}$$

$$\text{H.P./cm}^3\text{/min} = \frac{2.87}{16.8} = 0.17. \textbf{ Ans.}$$

Example 2.12. *During a metal cutting test under orthogonal conditions it was found that cutting force is 110 kg and feed force is 102 kg when cutting at 165 metre/mint. The rake angle of tool is 10° and shear plane angle was found to be at 19°. Determine the following :*

(i) Shear velocity.

(ii) Chip flow velocity.

(iii) Work done per minute in shearing the metal and work done against friction.

(iv) Show that the work in put is equal to the sum of work done in shearing and against friction.

Solution. Draw merchant circle diagram (Fig. 2.12).

$F_H = 110$ kg

$F_V = 102$ kg

α = Rate angle = 10°

β = Shear angle = 19°

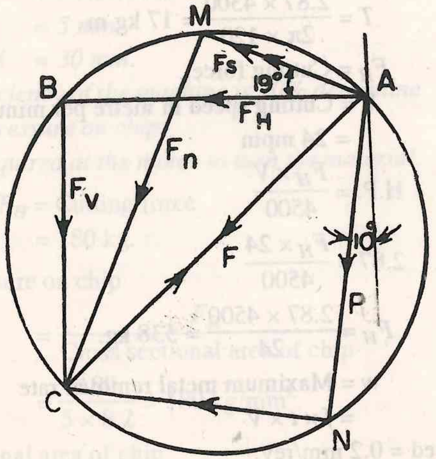


Fig. 2.12

Take $AB = F_H$ and $BC = F_V$ the two forces being at right angles. Draw a circle with AC diameter.

From the diagram

$F_S = 70$ kg

$P = 124$ kg

Now $V = 165$ m/min.

Draw the velocity diagram (Fig. 2.13).

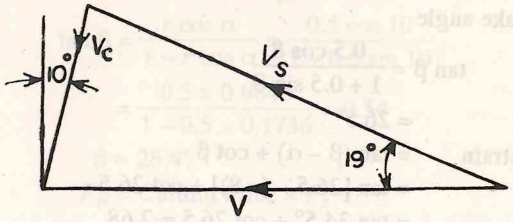


Fig. 2.13.

From the diagram

Shear velocity,

$$V_S = 162 \text{ m/min.}$$

Chip flow velocity,

$$V_C = 58 \text{ m/min}$$

(*W*) Work input $F_H \times V = 110 \times 165$

$$= 18{,}150 \text{ kg-m/min}$$

Work done in shearing the metal (W_1)

$$= F_S \times V_H$$
$$= 70 \times 162 = 11{,}340 \text{ kg-m}$$

Work done against friction (W_2)

$$= P \times V_C$$
$$= 124 \times 58 = 71{,}292 \text{ kg-m.}$$

$$W_1 + W_2 = 11340 + 7192$$
$$= 18{,}532 \text{ kg-m. } \textbf{Ans.}$$

It shows that within limits of accuracy the work input is equal to the work done in shearing and work done against friction.

Example 2.13. *In orthogonal cutting of a mild steel tube of 150 mm diameter and 2 mm thick the cutting force was observed to be 130 kg and feed force 35 kg and chip thickness 0.3 mm. The orthogonal cut was taken at 60 mpm with a feed of 0.14 mm/rev. If the back rake angle of the cutting tool was – 8°, calculate the following.*

(a) Shear strain,

(b) Strain energy per unit volume.

Solution. Feed = 0.15 mm/rev.

Chip thickness = 0.3 mm

r = Chip thickness ratio

$$= \frac{0.15}{0.3} = 0.5$$

For negative rake angle

$$\tan\beta = \frac{r\cos\alpha}{1 + r\sin\alpha}$$

where α = Rake angle

$$\tan\beta = \frac{0.5\cos 8}{1 + 0.5\sin 8}$$

$$= 26.5°$$

Shear strain $= \tan(\beta - \alpha) + \cot\beta$

$$= \tan[26.5 - (-8)] + \cot 26.5$$

$$= \tan 34.5° + \cot 26.5 = 2.68$$

Shear stress : $f_s = \dfrac{F_H\cos\beta\sin\beta - F_V\sin^2\beta}{b_1 . t_1}$

Now $F_H = 130$ kg

$F_V = 35$ kg

$\beta = 26.5°$

$$f_s = \frac{130\cos 26.5\sin 26.5 - 35\sin^2 26.5}{2\times 0.15}$$

$$= 145 \text{ kg/mm}^2$$

Shear energy per unit volume

= Shear stress × Shear strain

$= 145 \times 2.68$

$= 388.6$ kg/mm^2 **Ans.**

Example 2.14. *During orthogonal turning operation the following data was obtained.*

Cutting force (F_z) = *120 kg.*

Feed force (F_x) = *30 kg.*

Rake angle = *10°*

Feed = *0.2 mm/revolution.*

Width of cut = *2.3 mm.*

Chip thickness = *0.4 mm.*

Cutting speed = *120 m/min.*

Determine the following.

(a) Chip thickness ratio.

(b) Shear angle

(c) Shear stress.

Solution. (*a*) r = Chip thickness ratio $= \dfrac{t_1}{t_2}$

t_1 = Chip thickness before cutting

= 0.2 mm.

t_2 = Chip thickness = 0.4 mm

$$r = \frac{0.2}{0.4} = 0.5$$

(*b*) β = Shear angle

α = Back rake angle = 10°.

$$\tan\beta = \frac{r\cos\alpha}{1 - r\cos\alpha} = \frac{0.5\cos 10}{1 - 0.5\sin 10}$$

$$= \frac{0.5\times 0.9848}{1 - 0.5\times 0.1736} = 0.54$$

$\beta = 28.4°$

(*c*) F_H = Cutting force = F_z

= 120 kg

F_V = Feed force

$= F_x = 30$ kg

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

$= 120\cos 28.4 - 30\sin 28.4$

$= 120\times 0.8796 - 30\times 0.4756 = 91.2$ kg

$$A = \text{Shear area} = \frac{t_1\times b_1}{\sin\beta}$$

where b_1 = Width of chip

= 2.3 mm

$t_1 = 0.2$ mm.

$$A = \frac{0.2\times 2.3}{\sin 28.4} = \frac{0.2\times 2.3}{0.4756}$$

$$= 0.97 \text{ mm}^2$$

f_S = Shear stress

$$= \frac{F_S}{A} = \frac{91.2}{0.97} = 94 \text{ kg/mm.}$$

Example 2.15. *During machining of C 20 steel with a triple carbide cutting tool 0—8—6—7—10—70—1 mm ORS shape the following data was obtained.*

Feed = *0.18 mm/revolution.*

Depth of cut = *2 mm*

Cutting speed = *120 m/min.*

Chip thickness = *0.4 mm.*

Determine (a) Chip reduction coefficient

(b) Shear Angle.

Solution. In orthogonal turning

K = Chip reduction co-efficient

$$= \frac{t_2}{f . \sin\phi}$$

where t_2 = Chip thickness = 0.4 mm

f = Feed – 0.18 mm

ϕ = Principal cutting edge angle

= 70°.

$$K = \frac{0.4}{0.18 \times \sin 70} = \frac{0.4}{0.18 \times 0.9397}$$

$$= 2.36$$

(*b*) β = Shear angle

α = Rake angle = 8°.

$$\tan \beta = \frac{\cos \alpha}{K - \sin \alpha}$$

$$\tan \beta = \frac{\cos 8}{2.36 - \sin 8}$$

$$= \frac{0.99}{2.36 - 14} = 0.446$$

$$\beta = 24° - 2'.$$

Example 2.16. *During machining C 20 steel with a carbide cutting tool having a tool geometry given by 0—5—6—6—8—75—1 mm ORS, the following forces have been recorded by a two dimensional dynamometer.*

$$F_z = 130 \text{ kg}$$

$$F_x = 80 \text{ kg}.$$

Determine the following :

(*a*) *Radial component of force, F_y*

(*b*) *Frictional force P and normal force N*

(*c*) *Kinetic coefficient of friction, μ.*

Solution. (*a*) In this case ϕ is less than 90°.

It is a case of orthogonal system of first kind.

F_z = Feed force = 80 kg.

ϕ = Principal cutting angle = 75°

$$F_x = F_{xy} \sin \phi$$

$$80 = F_{xy} \sin \phi$$

$$F_{xy} = \frac{80}{\sin 75} = \frac{80}{0.9652} = 82.83 \text{ kg}.$$

$$F_y = F_{xy} \cos \phi = 82.83 \times \cos 75$$

$$= 82.83 \times 0.2588 = 21.43 \text{ kg}.$$

(*b*) α = orthogonal rake angle = 5°

P = Frictional force

$$= F_{xy} \cos \alpha + F_z \sin \alpha.$$

$$= 82.83 \cos 5 + 130 \sin 5$$

$$= 82.83 \times 0.9962 + 130 \times 0.0871$$

$$= 82.5 = 11.3 = 93.8 \text{ kg}.$$

N = Normal force

$F_z = F_H$ = cutting force

$$N = F_z \cos \alpha - F_{zy} \sin \alpha$$

$$= 130 \cos 5 - 82.83 \sin 5$$

$$= 130 \times 0.9962 - 82.83 \times 0.0871$$

$$= 129.5 - 7.2 = 136.7 \text{ kg}.$$

(*c*) μ = Kinetic coefficient of friction

$$= \frac{F_{zy} \cos \alpha + F_z \sin \alpha}{F_z \cos \alpha - F_{xy} \sin \alpha}$$

$$= \frac{82.83 \cos 5 - 130 \sin 5}{130 \cos 5 - 82.83 \sin 5}$$

$$= \frac{82.83 \times 0.9962 - 130 \times 0.0871}{130 \times 0.9962 - 82.83 \times 0.0871}$$

$$= \frac{82.5 - 11.3}{129.5 - 7.2} = \frac{71.2}{122.3} = 0.58.$$

Example 2.17. *During machining C 25 steel with 0—10—6—7—8—90—1 mm ORS shaped triple carbide cutting tool, the following observations have been made.*

Feed = *0.18 mm/rev.*

Depth of cut = *2 mm.*

Cutting speed = *150 m/min.*

F_z = *160 kg.*

F_x = *80 kg.*

Chick thickness = *0.4 mm.*

Determine :

(*i*) *Chip reduction coefficient.*

(*ii*) *Shear force and normal force at shear plane.*

(*iii*) *Kinetic coefficient friction.*

(*iv*) *Specific energy of friction.*

Solution. (*a*) ϕ = principal cutting edge angle = 90°

$$\lambda = 0.$$

It is a case of orthogonal system of second kind

α = Orthogonal rake angle = 10°

K = Chip reduction coefficient

$$= \frac{t_2}{f \,.\, \sin \phi}$$

where t_2 = Chip thickness

= 0.4 mm.

$$f = \text{Feed} = 0.18 \text{ mm/rev.}$$

$$\sin\phi = \sin 90 = 1$$

$$K = \frac{0.4}{0.18} = 2.22$$

(*b*) $F_S = \text{Shear force} = F_H \cos\beta = F_r \sin\beta$

where $F_H = \text{Cutting force} = F_z$

$= 160$ kg.

$F_V = \text{Feed force}$

$= F_{xy} = F_x = 80$ kg

β = shear angle

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

r = Chip thickness ratio

$= t_1/t_2$.

where t_1 = Chip thickness before cutting

= Feed = 0.18 mm

t_2 = Chip thickness after cutting

= 0.4 mm.

$$r = \frac{0.18}{0.4} = 0.45$$

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

$$= \frac{0.45\cos 10}{1 - 0.45\sin 10}$$

$$= \frac{0.45 \times 0.9848}{1 - 0.45 \times 1736} = 0.4782$$

$$\beta = 25.5°$$

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

$$= 160\cos 25.5 - 80\sin 25.5$$

$= 110$ kg.

F_x = Force normal to shear plane $= F_V\cos\beta + F_H\sin\beta$

$= 80\cos 25.5 + 160\sin 25.5 = 140.8$ kg.

(*c*) μ = Kinetic coefficient of friction

$$= \frac{F_H\sin\alpha + F_v\cos\alpha}{F_H\cos\alpha - F_v\sin\alpha} = \frac{160\sin 10 + 80\cos 10}{160\cos 10 - 80\sin 10}$$

$$= \frac{160 \times 0.1736 + 80 \times 0.9848}{160 \times 0.9848 - 80 \times 0.1736} = \frac{106.55}{143.66} = 0.74.$$

(*d*) Specific friction energy $(E_f) = \dfrac{P}{kb_1t_1}$

where $b_1 = \text{Width of chip} = \dfrac{d}{\sin\phi} = \dfrac{2}{1} = 2$ mm.

d being depth of cut. P = Frictional force

$$= F_{xy}\cos\alpha + F_z\sin\alpha = 80\cos 10 + 160\sin 10$$

$$= 80 \times 0.9848 + 160 \times 0.1736 = 106.55 \text{ kg.}$$

$$E_f = \frac{106.55}{2.22 \times 2 - 0.18} = 133.3 \text{ kg/mm}^2.$$

Example 2.18. *A medium steel workpiece is turned on a lathe from 34 mm diameter to 31 mm diameter when depth of cut is 1.5 mm and cutting speed is 50 metre per minute. The lathe has a 5 kW motor whose efficiency is 0.85. If a power of 0.07 kW per cubic centimeter per minute is required for stock removal, find the feed.*

Solution. V = Volume of metal removed $= f.t.V$

where f = feed mm/rev.

t = Depth of cut,

$= \dfrac{1.5}{10}$ cm.

V_1 = cutting speed

= 50 metre per minute = 50 × 100 cm per minute

$$V = \frac{f}{10} \times \frac{1.5}{10} \times 50 \times 100$$

$N = 75 f$. cu. cm/min ...(1)

Now P = Power of motor = 5 kW

η = Efficiency of motor = 0.85

S = Power required for removing once cubic centimeter of material per minute

= 0.07 kW

V = volume of metal removed

$$= \frac{P \times \eta}{S} = \frac{5 \times 0.85}{0.07}$$

$V = 60.7$ cu. cm/min ...(2)

From (1) and (2)

$75 f = 60.7$

$f = 0.81$ mm/rev. **Ans.**

Example 2.19. *Design a lather turning tool tipped with cemented carbide for making a shaft of steel of ultimate strength about 70 kgf/mm². The diameter of shaft is 75 mm, allowance per side (metal to be removed) is 3.6 mm, feed is 0.2 mm/rev. and tool over hang is 60 mm.*

Solution. D = shaft diameter = 75 mm

t = Allowance per side = 3.5 mm

f = Feed = 0.2 mm per revolution

L = Over hang = 60 mm

F_H = Cutting force = $k.f.t.\ k_w.\ k_r.$ kv

where k = Specific cutting resistance

= 200 – 300 kg/mm^2 for steel

f = Feed

= 0.2 mm/revolution

t = Allowance per side

= 3.6 mm

k_w = Correction factor for wear

= 0.96 (say)

k_r = Correction factor for rake angle

= 0.9 (say)

k_v = Correction factor for cutting speed

= 0.92 (say)

$$F_H = 300 \times 0.2 \times 3.6 \times 0.96 \times 0.9 \times 0.92$$

$$= 171.7 \text{ kg :}$$

For rectangular cross section of tool

B = Width of tool shank

$$= \sqrt[3]{\frac{6\,F_H \, . \, L}{2.56 \times \sigma}} \quad \text{where } H = 1.6\,B$$

where F_H = Cutting force

= 171.7 kg.

L = Over hang = 60 mm

σ = Bending stress for tool material

= 20 – 30 kg/mm^2 for carbon steel tools

= 40 – 60 kg/mm^2 for H.S.S. tools

$$B = \sqrt[3]{\frac{6 \times 171.7 \times 60}{2.56 \times 20}}$$

$$= 10.7 \text{ mm}$$

H = Height of shank

$$= 1.6 \times B = 1.6 \times 10.7 = 17.1 \text{ mm}$$

Check for tool strength

F_{HP} = Maximum load permitted by tool strength

$$= \frac{BH^2\sigma}{6L}$$

$$= \frac{10.7 \times 17.1^2 \times 20}{6 \times 60}$$

$$= 174 \text{ kg.}$$

F_{HR} = Maximum load permitted by tool rigidity

$$= \frac{3.C.E.I.}{L^3}$$

where C = Deflection

= 0.05 mm for finishing tool

= 0.1 mm for roughing tool.

E = Modulus of Elasticity

= 2 × 10^4 kg/mm^2 for carbon steel tools.

= 4 × 10^4 – 5 × 10^4 kg/mm^2 for H.S.S. tools

I = Moment of inertia

$$= \frac{BH^3}{12}$$

$$= \frac{10.7 \times 17.1^3}{12}$$

$$= 4458.5 \text{ mm}^4$$

$$F_{HR} = \frac{3 \times 0.1 \times 4 \times 10^4 \times 4458.5}{60^3}$$

$$= 249 \text{ kg.}$$

Since F_{HP} and F_{HR} are more than F_H so the tool is safe.

Example 2.20. *A steel tube 42 mm outside diameter is turned on a lathe. The following data was obtained.*

Rake angle = *32°*

Cutting speed = *18 m/min.*

Feed = *0.12 mm/rev.*

Length of continuous chip in one revolution = 52 mm.

Cutting force = *180 kg*

Feed force = *60 kg.*

Determine

(a) Chip thickness ratio

(b) Chip thickness

(c) Shear plane angle

(d) Velocity of chip along tool face

(e) Coefficient of friction.

Solution. D = Diameter of tube

L_1 = Length of continuous chip in one revolution

= 52 mm.

L_2 = Length of undeformed chip = $\pi \times D = \pi \times 42$

r = Chip thickness ratio

$$= \frac{L_1}{L_2} = \frac{52}{42\,\pi} = 0.394$$

t = Chip thickness

f = Feed = 0.12 mm/rev.

$$r = \frac{0.12}{t}$$

$$t = \frac{0.12}{0.394} = 0.3$$

β = Shear plane angle

α = Rake angle = 32°

$$\tan \beta = \frac{r \,.\, \cos \alpha}{1 - r \sin \alpha}$$

$$\tan \beta = \frac{394 \times 0.848}{1 - 0.394 \times 0.529}$$

$$\beta = 22.6^\circ$$

V = Cutting speed = 18 m/min

V_C = Chip velocity = $r \times V = 0.394 \times 18$

= 7.1 m/min.

F_H = Cutting force = 180 kg

F_V = Feed force = 60 kg.

μ = Coefficient of friction

$$= \frac{F_V + F_H \tan \alpha}{F_H - F_V \times \tan \alpha} = \frac{60 + 180 \tan 32}{180 - 60 \tan 32}$$

= 0.62.

PROBLEMS

2.1. Describe how to calculate the result force acting on a single point tool in turning.

2.2. Explain the relationship between various forces of orthogonal cutting.

2.3. Sketch Merchant's circle diagram and explain the different quantities involved.

2.4. (*a*) What are the three velocities of interest in the cutting process.

(*b*) Explain the relationship between cutting velocity and chipflow velocity and between shear velocity and cutting velocity.

2.5. Write short note on the following :

(*a*) Shear stress in shear plane. (*b*) Shear strain.

(*c*) Power required in metal cutting.

(*d*) Specific horse power. (*e*) Machine tool efficiency.

(*f*) Metal removal rate. (*g*) Lee and Shaffer's theory.

2.6. Prove that according to Ernst. Merchant theory the relation between rake angle (α), shear angle (β) and friction angle (γ) is given by

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

2.7. In orthogonal cutting of a mild steel component if the rake angle of tool is 10° and the shear angle is 30°. Calculate the chip thickness ratio.

2.8. (*a*) In orthogonal cutting of stainless steel depth of cut is 3.125 mm and rake angle of tool is 10° which results in a chip thickness of 4 mm determine the following :

(*i*) Cutting Ratio.

(*ii*) Shear Angle.

(*b*) If Shear Strength = 8000 kg/cm^2

Width of cut = 12 mm

Cutting speed = 10 m/min.

Coefficient of friction 0.11.

Determine the following :

(*i*) Shearing force. (*ii*) Friction angle.

(*iii*) Cutting force. (*iv*) Horse power.

2.9. Determine the cutting speed and machining time per cut when the work having 35 mm diameter is rotated at 200 R.P.M. The feed given is 0.2 mm/revolution and length of cut is 60 mm. [Ans. 22 m/minute, 1.5 minute]

2.10. Determine the cutting speed (V) and feed (f) to be used for turning a mild steel component with a H.S.S. cutting tool under the following conditions :

Cutting force (F_H) = 280 kg.

Tool life (T) = 70 minutes

Depth of cut (t) = 2.1 mm.

Use the following relationships

$$F_H = 200\, f^{3/4} t$$

$$V_T^{0.125} \times f^{0.37} \times t^{0.78} = 37$$

Also determine the R.P.M. of the component if the diameter of the component is 30 mm.

2.11. What is the difference between orthogonal system of first kind and second kind.

2.12. Prove that kinetic coefficient of friction (μ) is given by

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

where F_H is cutting force and F_V is feed force.

2.13. Prove that dynamic shear strain (e) is given by

$$e = \frac{k^2 - 2k \sin \alpha + 1}{k \,.\, \cos \alpha}$$

where k is chip reduction coefficient and α is orthogonal rake angle.

2.14. (*a*) Show the Merchant's circle diagram of forces and its utility.

(*b*) During machining of C-20 steel with a carbide tool having a shape of 0—(- 5)—6—9—8—75—1 mm (ISO) the following force have been measured by a two dimensional electro-mechanical dynamometer :

$$P_z = 140 \text{ kg}, \qquad P_x = 15 \text{ kg}.$$

Calculate : (*i*) The radial force, P_y

(*ii*) The friction force, F (*iii*) The normal force, N

(*iv*) The kinetic co-efficient, μ. (*A.M.I.E.* 1977)

2.15. A soft steel component is to be turned on a lathe from 40 mm diameter to 37 mm diameter when depth of cut is 1.5 mm and cutting speed is 40 m/min. If lathe has a motor of 4 kW whose efficiency is 0.8 find the feed assuming that a power of 0.05 kW is required for removing one cu. cm. of material per minute.

2.16. When turning a 400 mm diameter round bar on a lathe, the force exerted on the tool was found to be 50 N. If the machine is running at a speed of 300 RPM find the work alone per minute. [Ans. 18840 N-m]

2.17. Write short notes on the following

(*a*) Velocities in metal cutting

(*b*) Power consumed in metal cutting.

2.18. (*a*) What is dynamometry in metal cutting.

(*b*) What is a dynamometer ? Discuss various types of dynamometers used for force measurement during metal cutting.

3

Machinability

3.1. Machinability

Chips may be cut from some materials with relative case and from others with the greater difficulty. This difference may be attributed to the machinability of the respective materials. Machinability is defined as the case with which the metal is cut satisfactorily for the purpose intended. In general good machinability is associated with the removal of material with moderate forces, the formation of rather small chips, not excessive tool abrasion and good surface finish. It is commonly observed that high hardness gives poor machinability because of high temperature power consumption high tool wear.

Machinability depends upon the following factors :

(*i*) Chemical composition if workpiece material.

(*ii*) Micro-structure of workpiece material.

(*iii*) Physical properties such as tensile strength, ductility and hardness of workpiece material.

(*iv*) Rigidity of tool and work holding devices.

(*v*) Cutting conditions such as cutting speed, feed, etc.

The machinability of plain carbon steels falls steadily as its carbon content rises. Steels up to 300 H.B. hardness do not present great machining difficulty unless large amounts of alloying materials are present.

Fine grained materials take a good surface finish but have an increased resistance to machining. In general good machinability is associated with the removal of material with moderate forces, the formation of rather small chips, not excessive tool abrasion and good surface finish.

It is easier to machine fine grained steel than coarse grained steel and that the addition of small amount of certain elements for example up to 0.1% S or up to 0.2% Pb) can improve the machinability of steel without appreciable changing mechanical properties. Heat resisting steels and super alloys have very poor machinability. Free cutting steels, non ferrous and light alloys can be easily machined at high cutting speeds. A dull cutting tool operating at too small a feed may fail to cut a chip and will work harden the surfaces of the material some of the plastics are much softer than most metals but are more difficult to machine because the abrasive nature of the material results in excessive tool wear. In evaluating the machinability the following criteria may be considered.

(*i*) Rate of metal removal per tool grind.
(*ii*) Tool life between grinds.
(*iii*) Magnitude of cutting forces.
(*iv*) Quality of surface finish.
(*v*) Shape and size of chips.
(*vi*) Temperature during cutting.
(*vii*) Power consumed during machining.

In case of a metal having high machinability.

(*a*) Good surface finish can be produced.
(*b*) Higher cutting speed can be used.
(*c*) Metal removal rate is high.
(*d*) Cutting tool wear is less.
(*e*) There is low power consumption.

3.2. Machinability Index

It is used to compare the machinability of different metals. The rated machinability of two or more metals may vary for different processes of cutting such as heavy turning, light turning, forming, milling etc.

I = Machinability index.
V_i = Cutting speed of metal investigated for 20 minutes tool life.
V_S = Cutting speed of a standard steel for 20 minutes tool life.

$$I(\%) = \frac{V_i}{V_S}$$

For cutting steel having carbon 0.13 (maximum) manganese 0.06 to 1.1 and sulphur 0.08 to 0.03 per cent is taken as standard steel. Its machining index is relatively fixed at 100 per cent, machinability index for some of the materials is shown in Table 3.1.

Table 3.1

Material	*Machinability Index (%)*
Low carbon steel	55—60
Stainless steel	25
Red Brass (Cu = 77 to 80%)	180
Aluminium alloy	390—1500
Magnesium alloy	500—2000

3.2.1. Effect of micro Structure on Machining

A high degree of homogeneity decreases the ease machinability giving tearing, poor finish and build up. Hence the difficulty of machining pure metals such as iron (ferrite) and copper and full solid solutions. Hetrogenous alloy whose components are segregated into bands or excessively large grains is also bad and so arises the bad machinability of wrought steel in which ferrite banding has occured. Hard and soft components uniformly dispersed tend to give good cutting properties. A uniformly heterogeneous structure gives best machining.

3.3. Basic Objectives of Economical Machining

The basic objectives of an efficient and economical machining are as follows :

(*i*) Quick metal removal. (*ii*) Low tool cost.
(*iii*) Good surface finish.
(*iv*) Minimum idle time of machine tools.
(*v*) Less power consumption.

In any machining operation the most important characteristics requiring due considerations are as follows :

(*i*) The life of a tool-workpiece combination.
(*ii*) The surface finish produced.
(*iii*) The type of chip produced.
(*iv*) The power consumed in the formation of chips.

The relative importance of each characteristic depends upon the application.

3.4. Tool Failure

Cutting tools usually reach the end of their useful life either by breaking or by wearing. Breaking is usually caused by overloading or neglect. Tool wear refers to abrasion on the flank below the cutting edge and abrasion of tool face just back of cutting edge.

During cutting the tool should perform satisfactorily. Unsatisfactory performance of the cutting tool indicates tool failure. Tool failure may occur because of failure of the geometry of cutting tool or it results from tool wear. The following drawbacks are observed when the tool failure takes place.

(*i*) The tool ceases to produce the workpiece according to the required dimensions.

(*ii*) The tool gets over heated.

(*iii*) Excessive surface roughness is observed.

(*iv*) Tool failure leads to increased cutting forces and therefore power requirement will be more.

(*v*) Some times a burnishing band will appear on the workpiece if the tool is failing.

It is a judgement decision as to how long a tool should be permitted to operate after preliminary indications that the tool is beginning to fail. The tool engineer must weigh the factors of the economics of stopping production and regrinding the tool versus allowing it continue to operate.

Permature failure of cutting tools by mechanical breakage and plastic deformation can be successfully overcome by providing adequate strength toughness and hot hardness in tool materials and by controlling tool geometry. Hardness is essential so that the cutting edge can penetrate into workpiece material. Poor toughness causes breaking of the cutting edge. Heat resistance enables the cutting edge to maintain its hardness when it gets heated due to friction in chip removal.

The failure of tool may be classified in three general ways as follows :

(*i*) Temperature failure (*ii*) Rupture of tool point.
(*iii*) Gradual wear at the tool point.

3.4.1. Temperature failure

Heat produced during metal cutting is mainly responsible for tool failure. When the temperature during cutting becomes very high the tool becomes too soft to function properly and failure ensues. This type of failure occurs quite rapidly, is the frequently accompanied by sparkling and is easily recognised.

The various tool materials can withstand. Various heating temperature (critical temperatures) before they lose the required hardness.

Carbon tool steel	200 to 250°C
High speed steel	560 to 600°C
Cemented carbides	800 to 1000°C

Rupture of Tool point. Because of high hardness required the tip of a cutting tool is mechanically weak and brittle. This type of tool failure is commonly observed in carbide and diamond tipped tools. This failure takes place when the cutting forces exceed the critical value for a given tool when small portions of the cutting edge begin to chip off or the entire tip may break away in one piece. For a given tool material the tendency towards a rupture failure can be diminished either by reducing the causal forces, redirecting them or redesigning the tool to withstand them. Fig. 3.1 show how a redesion of tool from (*a*) to (*b*) redirects the resultant force *P* so that the tendency for rupture is removed. The forces can also be reduced by increasing the rigidity of tool and workholder.

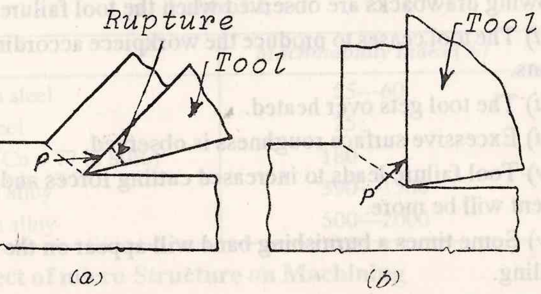


Fig. 3.1

Gradual wear at the tool point. When a tool has been in used for some time, wear becomes evident. In metal cutting main causes of wear are as follows :

(*i*) Adhesion wear
(*ii*) Abrasion wear
(*iii*) Diffusion wear.

Adhesion wear. In metal cutting junctions between the chip and tool materials are formed as part of friction mechanism. When these junctions are fractured small fragments of tool material can be torn out and carried away on the underside of the chip or on the new workpiece surface.

Abrasion wear. This type of wear takes place when hard particles on the under side of the chip pass over the tool face and remove total material by mechanical action.

Diffusion wear. This type of wear takes place due to diffusion process where atoms in a metallic crystal lattice move from a region of high atomic concentration to one of low concentration. During cutting when temperature is quite high at interface of tool and workpiece the atoms move from tool material to work piece material and thus weaken the surface structure of the tool.

3.4.1. Types of wear

Tool wear may be attributed to two basic causes :

(*i*) The plowing action of carbides and other hard constituents in the matrix of metal cut.

(*ii*) Wear which results from instantaneous welds which are formed when the finished surface (or chip) slides across a tool face.

The most prevalent type of wear are as follows :

(*i*) Crater wear
(*ii*) Flank wear.

Crater wear. The major tendency for wear is due to the abrasion between the chip and the face of the tool, a short distance from the cutting edge. This results in a crater being formed in the tool face. The crater is formed on the surface of the tool by the action of chip particles flowing over it because of very high temperature. When cratering becomes excessive the cutting edge may break from the tool. Cratering is commonly observed while machining ductile materials, which produce continuous chips. The maximum depth of the crater is usually a measure of the amount of the crater wear and can be determined by a surface measuring instrument.

Flank wear. The second area in which wear takes place is on the flank below the cutting edge resulting from the abrasive contact with the machined surface. Brittle materials tend to cause excessive flank wear because tool cutting edge tends to scrape over the machined surface and due to low abrasive action of loose fractured chips on the tool face while the flank is in constant contact with the work.

The worn region at the flank is called wear land. The increased wear land means that frictional heat will cause excessive temperature of the tool at the cutting point and therefore the tool will rapidly loose its hardness and tool failure will take place. Flank wear result in a rough machined surface. Fig. 3.2 shows regions of tool wear in metal cutting.

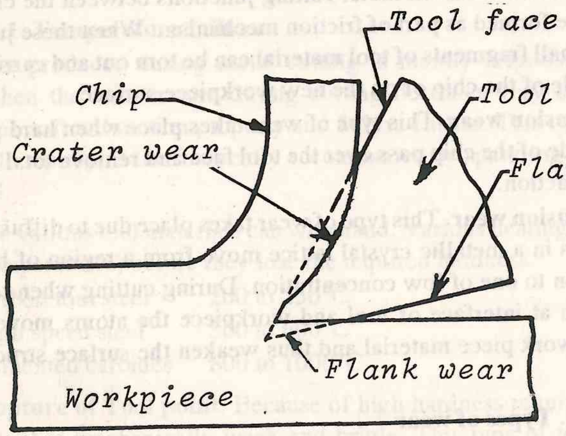


Fig. 3.2

In machining tough (ductile) metals tool wear will proceed in a more complex manner. Flank wear predominates at low cutting speeds when there is no built up edge because of sliding speed being higher on the flank than that of the chip on the tool face.

Whereas in case of heavy chip when pressure on the face is higher a wear crater is formed. Both flank and crater wear take place when feed is more than 0.15 mm/rev. at low and moderate speeds. The dependence of wear on the time of tool operation is expressed by the wear and time curve (Fig. 3.3) that can be divided into three sections.

Section *A* is wear in period (initial wear) during which heavy abrasion of the most salient parts of the surface, occurs. Smoother friction surfaces will produce lower rate of wear. Section *B* is the period of normal wear. Section *C* is the period of rapid (destructive) wear.

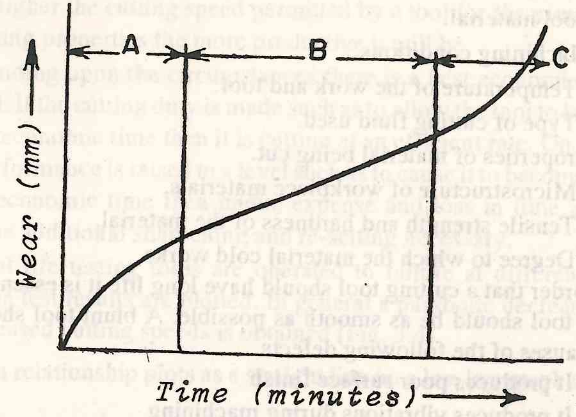


Fig. 3.3

Period of rapid wear is not observed with carbide tipped tool because of the high hardness of cemented carbides and very slight reduction in hardness at high temperatures.

The use of cutting fluids, reduces tool wear (especially face wear) because it cases chip formation, reduces friction force on sliding surface and lowers the temperature to which the tool is heated.

3.5. Tool Life

The life is defined as the time elapsed between two successive grindings of the tool. During this period the tool cuts efficiently and effectively.

The cutting tool life is one of the most important economic considerations in metal cutting. The cutting tool should have longer life. Conditions giving a very short tool life will be uneconomical because tool grinding and tool replacement costs will be high. Any tool or work material improvements that increase tool life will be beneficial.

There are number of ways of expressing tool life such as :

(*i*) Volume of metal removed.
(*ii*) Number of work pieces machined.
(*iii*) Time unit.

It is most commonly expressed in minutes. The life of cutting tool is affected by the various factors mentioned below :

1. Machining variables.
   (*i*) Cutting speed.
   (*ii*) Feed.
   (*iii*) Depth of cut.

2. Type of cutting such as continuous and intermittent cutting.
3. Tool geometry
4. Tool material.
5. Machining conditions.
(*i*) Temperature of the work and tool.
(*ii*) Type of cutting fluid used.
6. Properties of material being cut.
(*i*) Microstructure of workpiece materials.
(*ii*) Tensile strength and hardness of the material.
(*iii*) Degree to which the material cold works.

In order that a cutting tool should have long life it is essential that the face of the tool should be as smooth as possible. A blunt tool should not be used as it causes of the following defects.

(*i*) It produces poor surface finish
(*ii*) It produces vibrations during machining
(*iii*) It increases the cutting forces and therefore power consumption is increased.
(*iv*) Tool gets over heated.

Tool life is said to be over when any one or more of following appear.

(*i*) Spoiled cutting edge.
(*ii*) Presence of chatter marks on the workpiece.
(*iii*) Sudden increase in power.
(*iv*) Over heating due to friction.
(*v*) Poor surface finish.
(*vi*) Dimensional unstability.

Expected tool life is as follows :

(*i*) Cast tool steel = 124 minutes.
(*ii*) High speed steel tool = 60 to 120 minutes.
(*iii*) Cemented carbides tool = 420 to 480 minutes.

3.6. Relationship between the Cutting Speed and Tool Life

There is a definite relationship between the cutting speed and tool life. The higher the cutting speed the shorter is the tool life. The relation between cutting speed and tool life is given by Taylor formula as follows :

$$VT^n = C$$

where V = Cutting speed in metre/min.
T = Tool life in minutes.
n = an index closely related to the cutting tool material.
= 0.1 to 0.5 for high speed steel tools.
= 0.2 to 0.4 for tungsten carbide tool.
= 0.4 to 0.6 for ceramic tools.

C = Constant. It is numerically equal to cutting speed that gives a tool life of one minute.

The higher the cutting speed permitted by a tool for the same life, the better its cutting properties the more productive it will be.

Depending upon the circumstances there is a best economic tool life for every tool. If the cutting duty is made such as to allow the tool to last longer than the best economic time then it is cutting at an efficient rate. On the other hand if its performance is raised to a level such as to cause it to become blunted in less than economic time then undue expense and loss in time are being incurred in the additional sharpening and re-setting necessary.

In tool life testing tools are operated to failure at different cutting speeds and the test results are plotted. In general a parabolic decrease in tool life with increased cutting speeds is obtained (Fig. 3.4).

Such a relationship plots as a straight line on a log-log graph as shown in Fig. 3.5.

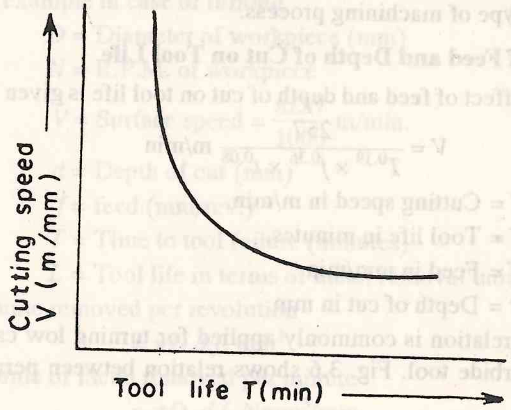


Fig. 3.4

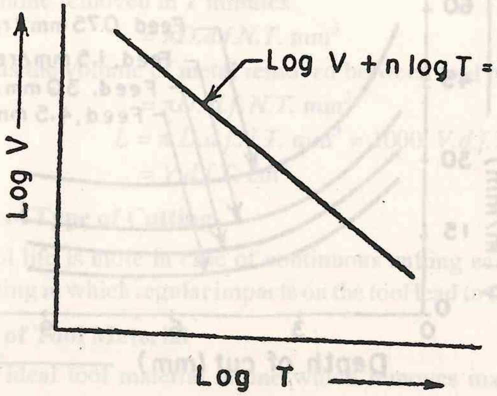


Fig. 3.5

Cutting tool life and efficiency can be improved by giving a surface finish of high quality to the cutting edge of the tool.

This is due to the reason that friction between tool and chip is minimised. Roughness of the tool's cutting edge could result in a concentration of stresses which may cause surface cracks and eventual chipping of tool.

The following factors influence the cutting speed permitted by a tool.

(*i*) Tool life.
(*ii*) Physico-mechanical properties of metal being machined.
(*iii*) Material of the cutting element of the tool.
(*iv*) Rate of feed and depth of cut.
(*v*) Tool geometry.
(*vi*) Size of the tool shank.
(*vii*) Cutting fluid used.
(*viii*) Maximum permissible amount of wear.
(*ix*) Type of machining process.

3.7. Effect of Feed and Depth of Cut on Tool Life

The effect of feed and depth of cut on tool life is given by the formula.

$$V = \frac{257}{T^{0.19} \times f^{0.36} \times t^{0.08}} \text{ m/min}$$

where V = Cutting speed in m/min.
T = Tool life in minutes.
f = Feed in mm/min.
t = Depth of cut in mm.

This relation is commonly applied for turning low carbon steel by a cemented carbide tool. Fig. 3.6 shows relation between permissible cutting speed (V) and depth of cut at different feed's for H.S.S. tool with tool life 20 minutes and rake angle 20°.

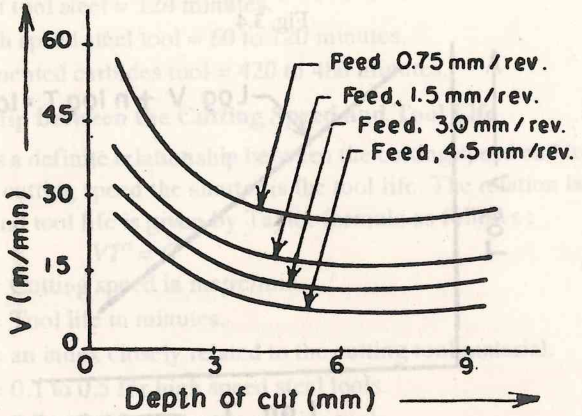


Fig. 3.6

Expected tool life for tools made up of different materials is as follows :

(*i*) Cemented carbides = 240 to 480 minutes.
(*ii*) High speed steel = 60 to 120 minutes.
(*iii*) Cost tool steel = 20 minutes.

Tool life excludes the following points :

(*a*) Removing. (*b*) Regrinding. (*c*) Resetting.

The time for the above three operations should be minimum to increase the productive time.

3.7. (*a*) Tool Life in Terms of Metal Removed

During tool wear studies it is convenient to express tool life in terms of metal removed.

For example in case of turning

Let, D = Diameter of workpiece (mm)
N = R.P.M. of workpiece
V = Surface speed $= \frac{\pi DN}{1000}$ m/min.
d = Depth of cut (mm)
f = feed (mm/rev.)
T = Time to tool failure (minutes)
L = Tool life in terms of metal removal unit

Volume removed per revolution

$= \pi D.d.f. \text{ mm}^3$

Volume of metal removed per minute

$= \pi D.\ d.f.\ N \text{mm}^3/\text{min.}$

Volume removed in T minutes

$= \pi D.d.f.N.T. \text{ mm}^3$

Thus the volume of metal removed between tool regrinds

$= \pi D.\ d.f.\ N.T. \text{ mm}^3$

or $L = \pi\, D.d.f.N.T. \text{ mm}^3 = 1000.\ V.d.f.T. \text{ mm}^3$

$= V.d.f.T. \text{ cm}^3.$

3.8. Effect of Type of Cutting

Tool life is more in case of continuous cutting as compared to intermittent cutting in which regular impacts on the tool lead to failure much earlier.

3.9. Effect of Tool Material

An ideal tool material is one which removes maximum volume of material at all cutting speeds.

For a given cutting speed work material removed by different tool materials in increasing order, is as follows :

(*a*) Cemented oxide. (*b*) Cemented carbide. (*c*) H.S.S.

3.10. Effect of Tool Geometry on Tool Life

- The larger the cutting angle the greater the deformation, heat generation and forces acting on the tool, the more intensive tool wear and shorter the tool life. When cutting angle is reduced (positive rake angle is increased), the cutting forces, deformation and heat generation are reduced and tool life is increased. The more the relief angle of the tool, the less the friction of the tool on the work, the less the tool wear and longer tool life larger values of end cutting edge angle give more life to tool. Similarly a higher values of side cutting edge angle gives longer life to tool. Increase in nose radius improves tool life as the smaller nose radius results in excess stress concentration and greater heat generation. The relationship between cutting speed, tool life (*T*) and nose radius (*r*) is given by

$$VT^{0.0927} = 331r^{0.244}$$

where *V* is the cutting speed in feet per minute, *T* is the tool life in minutes and *r* is the nose radius in inch.

Fig. 3.7 shows the tool life relationship with positive rake angle.

The optimum value of rake angle (α) is more for smaller values of tensile stress (*ft*), of work material. The tensile stress $ft_3 > ft_2 > ft_1$. The optimum rake angle $\alpha_3 > \alpha_2 > \alpha_1$. The typical relationship between tool life and relief angle is shown in Fig. 3.8. The greater the relief angle of the tool the less the friction of tool on the work, less tool wear and tool will have longer life. The optimum relief angle for work material at different feed (*f*) is different. Feed $f_3 > f_2 > f_1$ and relief and $\alpha_3 > \alpha_2 > \alpha_1$.

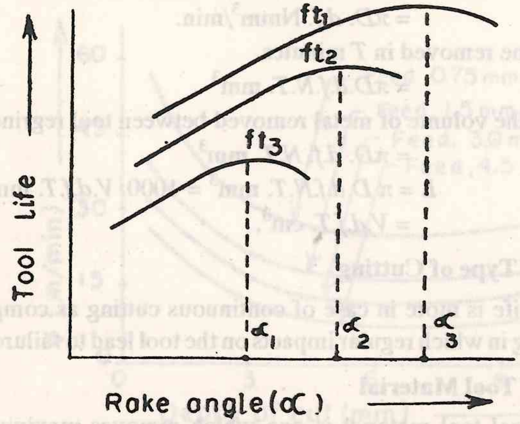


Fig. 3.7

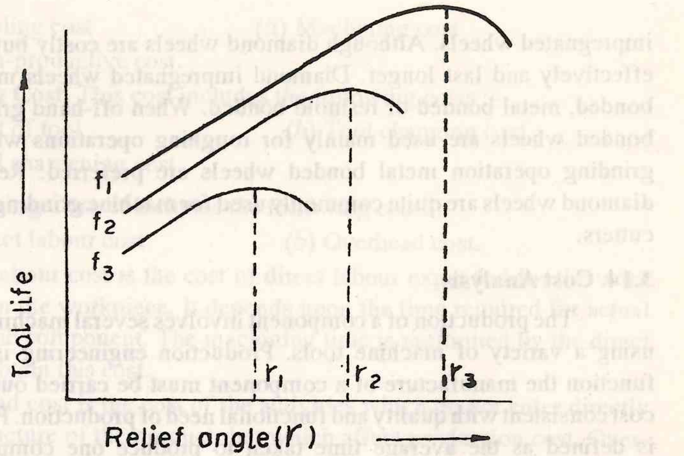


Fig. 3.8

3.11. Effect of Work-piece Material

The microstructure of the work-piece material affects tool life. Hard constituents in the structure result in poor tool life. On the basis of tool life the micro constituents have been placed in the order. Pearlite, Sorbite, Troostite, Bainite and Martansite.

3.12. Effect of Cutting Fluid

Heat produced during metal cutting is carried away from the tool and work by means of cutting fluids. This reduces the coefficient of friction and the cutting temperature. This will help the tool to maintain its hardness and therefore the tool life will be increased.

Cutting fluid which directly controls the amount of heat at the chip tool interface plays an important role in increasing tool life. Schallbroch, Schaumann, and Wallich gave the following formula between tool life and temperature of cutting tool

$$T\theta^n = C$$

where T = Tool life (minutes)

θ = Temperature at chip tool interface (°C)

n = An exponent. Its value depends of material and shape of cutting tool

C = Constant.

3.13. Tool Grinding

Lathe and shaping machine tools are ground on the off-hand grinding machine.

When grinding carbide tipped tools it is important to ensure than the tool's steel shank does not come into contact with the grinding wheel cemented carbides may be ground with either silicon carbide grinding wheel or diamond impregnated wheels. Although diamond wheels are costly but they cut more effectively and last longer. Diamond impregnated wheels may be vitrified bonded, metal bonded or resinoid bonded. When off-hand grinding vitrified bonded wheels are used mainly for roughing operations whereas for fine grinding operation metal bonded wheels are preferred. Resinoid bonded diamond wheels are quite commonly used for machine grinding of multi-point cutters.

3.14. Cost Analysis

The production of a component involves several machining operations using a variety of machine tools. Production engineering is an economic function the manufacture of a component must be carried out, at the lowest cost consistent with quality and functional need of production. Production time is defined as the average time taken to produce one component and the production cost is defined as the total average cost of performing the machining operation on a component.

The production cost of a component includes :

(*i*) Cost of material of the work-piece.
(*ii*) Wages to labour.
(*iii*) Overhead charges.

3.14.1. Treatment of Tool

Following types of treatments are carried out in order to increase the strength and hardness of cutting tools :

(*i*) Carburising (*ii*) Nitriding
(*iii*) Finishing (*iv*) Plating.

Carburising and nitriding are heat treatments processes by which tool surface lapers are saturated with carbon and nitrogen respectively. Processes like lapping and superfinishing may be carried out to improve strength. Hardness can be increased to considerable extent by chromium plating using electrolysis process.

Frictional wear of tools can be reduced by the application of very hard low friction layers to tools. These layers characterised by :

(*i*) high hardness ;
(*ii*) low coefficient of friction ;
(*iii*) high bond strength ;
(*iv*) antiweld behaviour ; and
(*v*) resistance to acids and bases.

can be applied to hot and cold working tools and cutting tools.

3.15. Cost per Component

The cost of manufacturing a component is composed of the following elements :

(*i*) Tooling cost (*ii*) Machining cost
(*iii*) Non-productive cost.

Tooling Cost. This cost includes the following costs :

(*a*) Cost of tool (*b*) Tool changing cost
(*c*) Tool sharpening cost.

Machining Cost. It includes the following costs :

(*a*) Direct labour cost (*b*) Overhead cost.

Direct labour cost is the cost of direct labour expended for the work done directly on the workpiece. It depends upon the time required for actual machining of the component. The machining time is multiplied by the direct labour rate to obtain this cost.

Overhead cost is the cost of the activities which do not enter directly into the manufacture of the product, but which affect production cost. Overhead cost is composed of the following costs :

(*a*) Indirect labour cost (*b*) Indirect material cost
(*c*) Fixed cost.

Indirect labour cost includes wages of managers, foremen, supervisors, office staff, and maintenance staff. Indirect material cost includes cost of lubricants, cotton wastes, lighting etc. Fixed cost includes the following :

(*a*) Interest on investment (*b*) Depreciation
(*c*) Taxes (*d*) Insurance.

Non-productive Cost. This cost is related to the activities which are necessary for preparing the machine tool. It is calculated taking into account the time required for the following activities.

(*i*) **Set up time.** It includes the time required to collect all the tools and materials, time required to set these into the machine tool, and make the necessary trial runs and adjustment.

(*ii*) Loading and unloading time.

(*iii*) Time required for inspection and gauging.

(*iv*) Time required for fatigue and personal needs.

(*v*) **Down time.** It includes the time required for unpredictable circumstance such as breakdown in machine tool, delay in supply of materials, tool etc.

Many techniques are available to reduce manufacturing costs and increase manufacturing productivity. These measures include using the following :

(*i*) Improved materials, tools and processes.
(*ii*) Automation wherever it improves efficiency.
(*iii*) More effective organisation and factory layout, assembly techniques and material handling.

3.16. Objectives of Machining

Metal cutting is primarily an economic activity. The aim is to remove a particular volume of metal in minimum time or at minimum cost. The basic objectives of efficient and economical machining are as follows :

(*i*) High metal removal rate (*ii*) Good surface finish
(*iii*) Low tool cost (*iv*) Minimum idle time of machine tools
(*v*) Less power consumption.

3.17. Choice of Cutting Speed

The metal removal rate (w) is given by

$$w = f.t.V.\ \text{cm}^3/\text{min}.$$

where f = Feed in cm/rev. ; t = Depth of cut in cm.
V = Cutting speed in cm/min.

Any increase in cutting speed for a particular combination of feed and depth of cut will give a directly proportional increase in metal removal rate. This will reduce the machining cost.

But an increase in cutting speed will decrease the tool life and tool and grinding cost will increase. The total cost of machining will be sum of separate costs. Fig. 3.2 shows the variation of costs and cutting speed. The cutting speed corresponding to minimum cost is called economical cutting speed and tool life at this speed is called economical tool life.

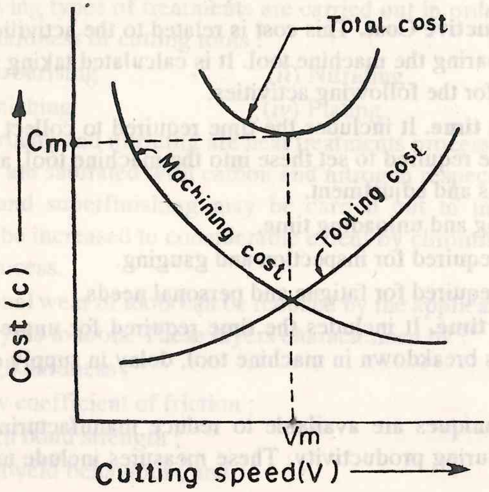


Fig. 3.9

The economical cutting speed is found as follows :

Let H = Machining cost/minute
= Labour cost/minute + Overheads/min.
E = Tooling cost

= Cost of changing tool + Cost of regrinding + tool depreciation

S_1 = Cost of machining metal/unit volume of metal cut
S_2 = Cost of servicing tools/unit of volume of metal cut
S = total cost/unit volume of metal cut
$= S_1 + S_2$
f = Feed
T = Total life
V = Cutting speed
t = Depth of cut.

Time to machine a unit volume of metal in minutes

$$= \frac{1}{t.f.V}$$

At t and f are constant

Let $\frac{1}{t.f} = K.$

$\therefore$ Time to machine a unit volume of metal in minutes.

$$= K/V$$

where K is constant.

$$\therefore \quad S_1 = H\frac{K}{V}.$$

Now number of tool change in $\frac{K}{V}$ minutes

$$= K/TV$$

$$\therefore \quad S_2 = \frac{EK}{TV}$$

As the relation between cutting speed (V) and tool life (T) is given by

$$VT^n = C$$

$$T = \left(\frac{C}{V}\right)^{1/n}$$

$$S_2 = \frac{EK}{\left(\frac{C}{V}\right)^{1/n} . V}$$

$$= \frac{EK}{C^{1/n}} . V\frac{1-n}{n}$$

$$S = S_1 + S_2$$

$$= \frac{HK}{V} + \frac{EKV\frac{1-n}{n}}{C^{1/n}}$$

Differentiating w.r.t. V, we get

$$\frac{dS}{dV} = \frac{-HK}{V^2} + \frac{1-n}{n}\,\frac{EK}{C^{1/n}}\,V\,\frac{1-2n}{n}$$

= 0 for the cost to be minimum.

$$\frac{H}{V^2} = \frac{1-n}{n}\cdot\frac{E}{C^{1/n}}\cdot V\,\frac{1-2n}{n}$$

$$H = \frac{1-n}{n}\,.\,E\,.\left(\frac{V}{C}\right)^{1/n} \qquad \ldots(1)$$

Let $Q = \frac{E}{H}$.

$$\therefore \qquad \frac{1}{Q} = \frac{1-n}{n}\left(\frac{V}{C}\right)^{1/n}$$

$$V = C.\left[\frac{n}{Q\,(1-n)}\right]^n$$

This will give the required economical speed at which the cost will be minimum.

From equation (1)

$$\frac{1}{Q} = \frac{1-n}{n} \times \frac{1}{T}$$

as $\left(\frac{V}{C}\right)^{1/n} = \frac{1}{T}$

$$\frac{T}{Q} = \frac{1-n}{n} \quad \text{or} \quad \frac{HT}{E} = \frac{1-n}{n}$$

This will give economic tool life.

3.18. Trends in Conventional Machining (Metal Cutting)

Conventional manufacturing processes have been able to meet major requirements in the field of manufacturing because of the following reasons :

(*i*) due to improvement in cutting tool materials and tool geometry.

(*ii*) due to advent of very powerful strong, rigid and highly automatic machine tools.

(*iii*) due to the introduction of very fast and accurate worktool handling systems.

(*iv*) integrated computerisation and flexible manufacturing system have added new dimension in machining.

Some or all of the following objectives should be fulfilled during machining by conventional machining methods in addition to basic dimensional requirements with maximum attainable machinability.

(*i*) Minimisation of machining time per component.

(*ii*) Minimisation of production rate.

(*iii*) Minimisation of machining cost per component.

Machining cost can be reduced with following ways :

(A) Reduction of actual cutting time

This is achieved by

(*a*) by using highly powerful, rigid and dynamically stable machine tools.

(*b*) by using machine-fixture-tool work system having high process capability.

(*c*) by using proper tool material and tool geometry.

(*d*) by using sufficiently strong and rigid work and tool holding devices.

(*e*) by using proper cutting fluids.

(*f*) by eliminating vibrations produced during machining.

(*g*) by compounding the processing operations and/or their sub-groups incorporating multi tool and multi spindle working systems.

(B) Reduction of idle time

This can be achieved by

(*a*) reducing the number of idle operations.

(*b*) Mechanisation for flow less and quick handling operations like mounting, setting indexing, unloading and transfer of blanks and cutting tools.

(*c*) using proper chip control and disposal methods.

(*d*) on-line inspection.

(C) Reduction of tool-change time

This is achieved by

(*a*) using cutting tools of longer life.

(*b*) using quick systems for the removal of worm out tools and for setting of new tools.

(D) Reduction of cutting tool cost

This is achieved by

(*a*) using durable cutting tools

(*b*) using in expensive but quality cutting tools.

(E) Maximisation of profit rate

This is achieved by

(*a*) Minimising machining cost.

(*b*) Minimising rejections through on-line inspection and gauging.

(*c*) Proper replacement of in effective cutting tools.

(*d*) Minimisation of heavy breakdowns.

(*e*) Incorporating proper maintenance schedule for machine tools etc.

Thus higher productivity and overall economy during machining methods can be achieved by using the following :

(*i*) High powerful and rigid machine tools.

(*ii*) Cutting tools of proper materials and strength.

(*iii*) On-line inspection.

(*iv*) Automation of motions, inspections, handling of tools, work pieces etc.

Example 3.1. *Determine the optimum cutting speed for an operation carried on a lathe machine using the following operations.*

Tool change time = *4 minutes*

Tool regrind time = *3 minutes*

Machine running cost = *20 paise per minute*

Depreciation tool regrind = *Re 1.*

The tool life equation is given by

$$VT^n = C$$

Assume $C = 60,\ n = 1/5.$

Solution. H = Machining cost = 20 paise/minute

E = Tooling cost

= Tool change cost + Cost of regrinding

+ Tool depreciation

Tool change cost = 4 × 20 = 80 paise

Tool regrinding cost = 3 × 30 = 60 paise

Tool depreciation = Re. 1

E = Tooling cost = 80 + 60 + 100

= 240 paise

$$Q = \frac{E}{H} = \frac{240}{20} = 12$$

Now V = Optimum cutting speed

$$C = \left[\frac{n}{Q(1-n)}\right]^n = 60\left(\frac{0.2}{12(1-0.2)}\right]^{0.2}$$

= 26.6 m/min. **Ans.**

Example 3.2. *Find the optimum cutting speed and tool life for minimum cost for machining medium carbon steel under the following conditions : Cost of operating the machine*

= 20 paise per minute.

Total cost of tool change = Rs. 8

The [illegible] speed is 40 [illegible] per min [illegible] tool life is 50 minutes or the depth of cut and feed employed. Assume

n = 0.2 in the relation

$$VT^n = C.$$

Solution. H = Machining cost/minute = 20 paise

E = Tooling cost = Rs. 8

We know $\dfrac{HT}{E} = \dfrac{1-n}{n}$

where T = economic tool life

$n = 0.2$

$$\frac{20 \times T}{1 \times 100} = \frac{1-0.2}{0.2}$$

T = 160 minutes.

Now the cutting speed is 40 metre/min when tool life is 50 minutes.

$$40 \times 50^{0.2} = C = VT^n$$

where V = economic cutting speed and T is economic tool life

$$40 \times 50^{0.2} = V.\ 160^{0.2}$$

V = 30 metre/min. **Ans.**

Example 3.3. *Determine the tool cost of a batch of 4000 components made on a capstan lathe. Work rate per piece is 5 paise and the direct material cost is 10 paise per piece. Indirect costs are 500% of direct labour cost.*

Solution. N = Number of components = 400

C_1 = Direct cost

= N[Material cost + Labour cost]

$$= \frac{400\ [10+5]}{100} = \text{Rs. } 60$$

C_2 = Indirect cost

$$= \frac{500}{100} \times \frac{5 \times 400}{100} = \text{Rs. } 100$$

C = Tool cost + C_1 + C_2

= 60 + 100 = Rs. 160. **Ans.**

Example 3.4. *A tool will cut for 4 hours before it needs sharpening. Determine the time charged to one cycle if it takes 12 minutes to change the tool and tool can be sharpened 10 times before it is discarded.*

Solution. t = Time charged to one cycle

$$= \frac{T_1 \times T_2}{T}$$

where T_1 = Cutting time

= 4 × 60 = 240 minutes.

T_2 = Tool charge time = 12 minutes.

T = Tool life = 10 × 4 = [illegible]

= 40 × 60 = 2400 minutes

$$t = \frac{T_1 \times T_2}{T} = \frac{240 \times 12}{2400} = 1.2 \text{ minutes. Ans.}$$

Example 3.5. *It is desired to machine 20 costings in two set ups. What is the cost of production if the following data are used.*

Machining time = 15 minutes per casting
Set up time = 20 minutes per set up
Tool sharpening time = 0.5 minute per casting
Tool change time = 0.8 minute per casting
Overhead cost = 15 paise per casting
Fatigue = 15%
Personal need = 5%
Check and gauging time
= 12 seconds and 5 checks per casting
Direct labour cost = 5 paise per minute.

Solution. H = Direct labour cost = 5 paise per minute

N = Number of castings = 20.

Tooling cost (C_1) = Total changing cost
+ Total sharpening cost
= (Tool change time + Tool sharpening time) × N.H.

$$= (0.8 + 0.5) \times \frac{20 \times 5}{100} = \text{Rs. } 1.3.$$

Machining cost (C_2) = Machining time × N × H + Over head cost × N

$$= 15 \times 20 \times \frac{5}{100} + \frac{15 \times 20}{100} = \text{Rs. } 18.$$

Set up time = 20 min. per set up × Number of set ups
= 20 × 2 = 40 minutes.

Fatigue time $= \frac{15}{100} \times$ machining time

$$= \frac{15}{100} \times 15 = 2.25 \text{ minutes.}$$

Time of personal needs

$$= \frac{5}{100} \times \text{machining time}$$

$$= \frac{5}{100} \times 15 = 0.75 \text{ minute.}$$

Checking and gauging time

$$= \frac{12 \times 5}{60} = 1 \text{ minute.}$$

Non productive cost (C_3)

= Set up time cost + Fatigue cost + Cost of personal needs + Cost of checking and gauging.

$$C_3 = 40 \times \frac{5}{100} + 2.25 \times 20 \times \frac{5}{100} + 0.75 \times 20 \times \frac{5}{100} + 1 \times 20 \times \frac{5}{100}$$

$$= 2 + 2.25 + 0.75 + 1 = \text{Rs. } 6$$

Total cost, $C = C_1 + C_2 + C_3 = 1.3 + 18 + 6$
= Rs. 25.3. **Ans.**

Example 3.6. *Determine the cost of manufacturing a component using the following data :*

Initial cost of the machine = Rs. 10,000
Depreciation rate of machine = Rs. 2000 per year
Labour rate = Rs. 3 per hour
Operator and machine overloads = 100%
Number of working days per year = 250
Working hours per day = 8
Machine time = 3 minutes
Non-productive time = 2 minutes
Tool changing and resetting time = 0.6 min per component
Cost of regrinding the tool per component = 7 paise
Total depreciation per component = 6 paise.

Solution. Machine depreciation per minute.

$$= \frac{2000 \times 100}{250 \times 8 \times 60} = 1.66 \text{ paise/min.}$$

Labour rate $= \frac{3 \times 100}{60} = 5$ paise/min.

Machine and operator over heads = 100%

∴ Machine and operator rate

= 1.66 + 1.66 + 5 + 5 = 13.32 paise/min.

Machining cost = 13.32 × 3 = 39.96 paise

Non productive cost = 13.32 × 2 = 26.64 paise.

Total cost = Tool changing and resetting cost
+ Cost of grinding + Tool depreciation
= 0.6 × 13.3 + 7 + 6 = 21 paise.

Total cost = Machining cost + Non-productive cost
+ Tooling cost
= 39.26 + 26.64 + 21 = 87.60 paise. **Ans.**

Example 3.7. *Three different methods of production utilising three different grades of labour have been suggested for the manufacture of a component. The manufacturing information is as follows :*

Method	*Machining time per component (minutes)*	*Hourly Rate*	*Tool cost*	*Number of set up per year*	*Set up time (Hours)*	*Hourly Rate for set up*
A	*20*	*Rs. 4*	*Nil*	*10*	*2*	*Rs. 8*
B	*12*	*Rs. 6*	*Rs. 240*	*8*	*2.5*	*Rs. 6*
C	*9*	*Rs. 7*	*Rs. 960*	*4*	*3*	*Rs. 7*

Assuming all time saved can be gainfully used, prepare a graph and show at what quantities methods A and B cease to be the most economic.

Solution. Let C_1 = Total cost per year for method A

C_2 = Total cost per year for method B

C_3 = Total cost per year for method C

n = Number of components produced per year.

Method A

$$C_1 = \text{Tooling cost + Cost of set up + Machining cost}$$
$$= 0 + 10 \times 2 \times 8 + \frac{20}{60} \times 4 \times n$$
$$= \text{Rs. } 160 + \text{Rs. } 1.33\, n$$

Method B

$$C_2 = \text{Tooling cost + Cost of set ups + Machining cost}$$
$$= 240 + 8 \times 2.5 \times 6 + \frac{12}{60} \times 6 \times e$$
$$= \text{Rs. } 360 + 1.2\, n$$

Method C

$$C_3 = \text{Tooling cost + Cost of set ups + Machining cost}$$
$$= 960 + 4 \times 3 \times 7 + \frac{9}{60} \times 7 \times n$$
$$= \text{Rs. } 1044 + 1.05\, n$$

The break even point between methods A and B occurs when

$$C_1 = C_2$$
$$160 + 1.33n = 360 + 1.2n$$
$$n = 1538$$

Now break even point between methods B and C occurs when $C_2 = C_3$

$$360 = 1.2n = 1044 + 1.05n$$
$$n = 4560.$$

Method A cease to be economic when more than 1438 components are required per year and method B cease to be economic when more than 4560 components are required. Fig. 2.10 shows cost quantity graph indicating break-even points.

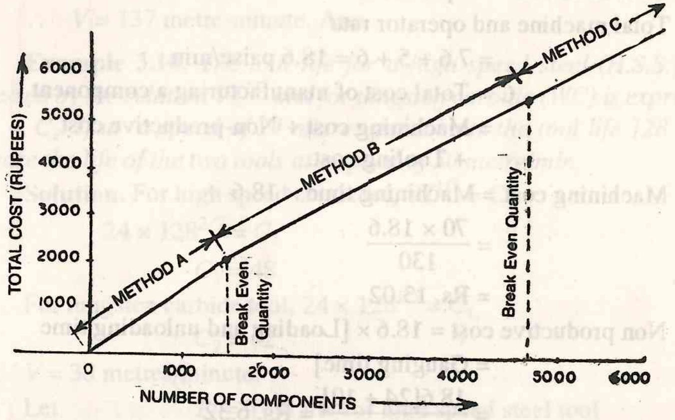


Fig. 3.10. Number of component.

Example 3.8. *A component is being manufactured by a manufacturing organisation. The manufacturing information is as follows :*

Cost of machine = *Rs. 24,000*

Depreciation rate of machine = *Rs. 2400 per year*

Cost of tools consumption = *Rs. 8000 per year*

Fixture cost = *Rs. 3000*

Depreciation reach of fixture = *600 per year.*

Production rate per day = *4 components.*

Number of working days per year = *300*

Working hours per day = *8*

Labour cost = *5 paise/min.*

Over head cost = *6 paise/min.*

Machining time per component = *70 min*

Tool changing and sharpening time = *10 min*

Handling time = *6 min*

Loading and unloading time = *24 min.*

Gauging time = *10 min.*

Determine the cost of manufacturing.

Solution. Fixed cost per year

= Depreciation rate of machine

+ Cost of tool consumption

+ Depreciation rate of fixture.

= 2,400 + 8,000 + 600 = Rs. 11,000.

Fixed cost per minute

$$= \frac{11000 \times 100}{300 \times 8 \times 60} = 7.6 \text{ paise}$$

Labour cost = 5 paise/min.

Over head cost = 6 paise/min.

Total machine and operator rate

$$= 7.6 + 5 + 6 = 18.6 \text{ paise/min.}$$

$$C = \text{Total cost of manufacturing a component}$$

$$= \text{Machining cost} + \text{Non-productive cost} + \text{Tooling cost.}$$

$$\text{Machining cost} = \text{Machining time} \times 18.6$$

$$= \frac{70 \times 18.6}{130}$$

$$= \text{Rs. } 13.02$$

$$\text{Non productive cost} = 18.6 \times [\text{Loading and unloading time} = \text{Gauging time}]$$

$$= \frac{18.6[24 + 10]}{100} = \text{Rs. } 6.32$$

$$\text{Tooling cost} = [\text{Tool sharpening and changing time} + \text{Handling time}] \times 18.6$$

$$= \frac{[10 + 6] + 18.6}{100} = \text{Rs. } 2.97$$

Tool cost of manufacturing a component

$$= 13.02 + 6.32 + 2.97$$

$$= \text{Rs. } 22.31. \text{ Ans.}$$

Example 3.9. *For a cutting tool the tool life is expressed by the equation*

$$VT^n = C$$

In a certain tool test a single point cutting tool had a life of 10 minutes when operating at 240 metres/minute. At what speed should the tool have to be operated in order to have a tool life of 3 hours. Assume n = 0.2.

Solution. Tool life is expressed by the equation

$$VT^n = C$$

where V = cutting speed (m/min)

T = Tool life (minutes)

$n = 0.2$

C = constant.

Substituting these value in the given equation, we have

$$240(10)^{0.2} = C$$

$$C = 384$$

when T = 180 minutes

$n = 0.2$

$C = 384$

then

$$VT^n = C$$

$$V(180)^{0.2} = 384.$$

$$\therefore \quad V = 137 \text{ metre-minute. Ans.}$$

Example 3.10. *The tool life for a high speed steel (H.S.S.) tool is expressed by the relation* $VT^{1/7}$ *and for tungsten carbide (WC) is expressed as* $VT^{1/5} = C_2$. *If at a speed of 24 metres per minute the tool life 128 minutes compare the life of the two tools at a speed of 30 metre/min.*

Solution. For high speed steel tool, $VT^{1/7} = C_1$

$$24 \times 128^{2/7} = C_1$$

$$C_1 = 48$$

For tungsten carbide tool, $24 \times 128^{1/5} = C_1$

$$C_2 = 62$$

when V = 30 metres/minute.

Let T_1 = Tool life for high speed steel tool

T_2 = Tool life for tungsten carbide tool.

For high speed steel tool.

$$\therefore \quad 30 \times T_1^{1/7} = 48$$

$$T_1 = 29 \text{ minutes.}$$

For tungsten carbide tool.

$$30 \times T_2^{1/5} = 62$$

$$T_2 = 38 \text{ minutes}$$

$$\therefore \quad \frac{T_1}{T_2} = \frac{29}{38} = 0.7. \text{ Ans.}$$

Example 3.11. *A tool life of 80 minute is obtained at a speed of 30 mpm and 8 minute at 60 m.p.m. Determine the following :*

(a) Tool life equation.

(b) Cutting speed for 4 minute tool life.

Solution. V_1 = 30 m.p.m.

T_1 = 80 minutes

V_2 = 60 m.p.m.

T_2 = 8 minutes.

Now the tool life equation is

$$VT^n = C$$

$$V_1 T_1^n = V_2 T_2^n$$

$$30(80)^n = 60(8)^n$$

$$\frac{30}{60} = \left(\frac{8}{10}\right)^n$$

$$\frac{1}{2} = \left(\frac{1}{10}\right)^n$$

$$n = 0.3$$

$\therefore$ The tool life equation is

$$VT^{0.3} = \text{constant.}$$

Let V_3 = cutting speed

T_3 = Tool life = 4 minutes

$$\therefore \quad V_1T_1^n = V_3T_3^n$$

$$30(80)^n = V_3(4)^n$$

$$30(80)^{0.3} = V_3(4)^{0.8}$$

V_3 = 82 metres/minute. **Ans.**

Example 3.12. *Determine the percentage change in cutting speed required to give 60% reduction in tool life (i.e. to reduce tool life to 2/5 of its former value). The speed/life relationship of cutting tool is given by $VT^n = C$. Take $n = 0.2$.*

Solution. V_1 = cutting speed

T_1 = Tool life

V_2 = cutting speed

T_2 = Tool life

$n = 0.2$

$$V_1T_1^n = V_2T_2^n$$

$$\frac{V_1}{T_2} = \left(\frac{T_h}{T_2}\right)^{0.2}$$

$$= \left(\frac{1}{2/5}\right)^{0.2} = 1.2$$

Increase in cutting speed = **20%. Ans.**

Example 3.13. *The speed life relationship for a tool is given by $VT^{1/3} = 200$ for a given set of conditions and the time taken to change the tool is 6 minutes. Show that operating at a cutting speed of 75 metre per minute gives higher output than operating at either 110 metre/min or 50 metre per minute if other conditions remain unchanged.*

Solution. $VT^{1/3} = 200$

where V = cutting speed

T = Tool life.

$\therefore$ when cutting speed $V = 50$, $T = 60$ minutes

$V = 75$, $T = 18$ minutes

$V = 110$, $T = 6$ minutes

The average cutting speed at different values of V can be calculated as follows.

Time taken to change the tool is = 6 minutes.

when $V = 50$, Average cutting speed $= \dfrac{50 \times 64}{64 \times 6} = 45.7$ m/min

$V = 75$, Average cutting speed $= \dfrac{75 \times 18}{18 + 6} = 56.2$ m/min

$V = 110$, Average cutting speed $= \dfrac{110 \times 6}{6 \times 6} = 55$ m/min

Therefore on a time basis 75 metre/minute is the best of the three cutting speeds. **Ans.**

Example 3.14. *The cutting speed and tool life relationship for a tool is given by $VT^n = C$, where V is the cutting speed in metre per minute and T is tool life in minutes. During Machining 18 mm bar on a lathe at a cutting speed of 110 metre per minute the life of tool is found to be 60 minutes. If $n = 0.2$ calculate the speed at which the spindle should be run to give a tool life of 5 hours. If a length of 50 mm per component is machined what is the cutting time per piece and how many pieces can be produced between tool changes. The feed used is 0.15 mm/rev.*

Solution. V_1 = cutting speed

= 110 mpm

T_1 = 60 minutes

T_2 = 300 minutes

$n = 0.2$

$$V_1T_1^n = V_2T_2^n$$

$$V_2 = V_1\left(\frac{T_1}{T_2}\right)^{0.2}$$

$$= 110\left(\frac{60}{300}\right)^{0.2}$$

= 80 metre/min.

Let N = spindle speed

D = diameter of bar = 1.8 cm.

$$\pi DN = 80$$

$$\pi \times \frac{1.8}{100} \times N = 80$$

N = 1415 R.P.M.

f = feed = 0.15 mm/rev

L = length of piece = 50 mm.

Cutting time per piece

$$= \frac{L}{f \times N}$$

$$= \frac{50}{0.15 \times 1415} \text{ minutes}$$

$$= \frac{50 \times 60}{0.15 \times 1415} = 14.2 \text{ seconds.}$$

Number of components produced in 5 hours

$$= \frac{5 \times 60 \times 60}{14.2} = 1267. \textbf{ Ans.}$$

Example 3.15. *During a tool life cutting test of H.S.S tool material used to cut a special die steel the following values were obtained.*

Cutting speed V (m/min)	*52*	*50*	*49*	*46*	*42*
Tool life (T) (minutes)	*3*	*4*	*4.9*	*10.5*	*30*

Use the above values to calculate the constants of the tool life equation $VT^n = C$.

Solution. $VT^n = C$

$$\log V + n \log T = \log C$$

In order to obtain satisfactory results a straight line graph should be plotted. This can be obtained by plotting the equation

$$\log V + n \log T = \log C$$

$$\log V = -n \log T + \log C.$$

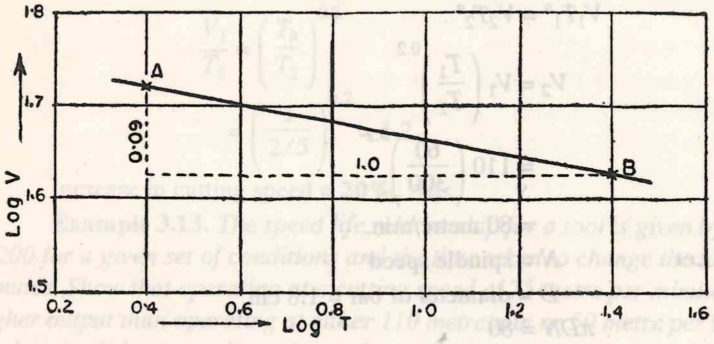


Fig. 3.11

log V	1.7160	1.6990	1.6902	1.6638	1.6232
log T	0.4771	0.6081	0.6902	1.0212	1.4771

The resulting graph between log V and log T is shown in Fig. 3.11.

To obtain the value of n consider any two points A and B on the graph

slope $= n = +\,0.09$

$$\therefore \qquad n = 0.09$$

Now $\log V + n \log T = \log C$

$$1.72 + 0.09\,(0.4) = \log C$$

(For point A)

$$\log C = 1.756$$

$$C = 57$$

Therefore the tool life equation is

$$VT^{0.09} = 57. \textbf{ Ans.}$$

Example 3.16. *A tool cutting at 32 m/min has a life of 54 minutes when used for a rough cut. Determine tool life when used for a light finishing cut.*

Given $n = 0.124$ *for rough cut*

$= 0.1$ *for finish cut.*

Solution. Tool life equation is given by :

$$VT^n = C$$

For rough cut $V = 32$ m/min

$$T = 54 \text{ minutes}$$

$$n = 0.124$$

$$\therefore \qquad 32 \times 54^{0.124} = C$$

$$C = 52.5$$

For finish cut $V = 32$ m/min

$$n = 0.1$$

$$32 \times T^{0.1} = 52.5$$

$$T = 141 \text{ minutes. } \textbf{Ans.}$$

Example 3.17. *State the conditions for a cutting tool to give maximum production with minimum maintenance and trouble.*

Solution. A cutting tool will give maximum production with least troubles and maintenance if it satisfies the following conditions.

(*i*) If the tool is made of proper material.

(*ii*) If the cutting tool geometry is properly designed.

(*iii*) If the tool is properly heat treated.

(*iv*) If proper cooling is used during the application of cutting tool.

Example 3.18. *A carbide tool while machining a mild steel workpiece was found to have a life of 1 hour and 40 minutes when cutting at 50 metre per minute. Find the tool life if the tool is to operate at speed 30% higher than previous one. Also calculate the cutting speed if tool is required to have a life of 2 hours and 45 minutes. Assume Taylor's exponent n = 0.28.*

Solution. (*a*) V = Cutting speed = 50 metre/min.

T = Life of cutting tool

= 100 minutes.

$$VT^n = C$$

$$50 \times 100^{0.28} = C \qquad \ldots(1)$$

When speed is increased by 30%

$$V_1 = \text{Cutting speed}$$

$$= 50 + 50 \times \frac{30}{100}$$

$$= 65 \text{ metre per minute}$$

$$T_1 = \text{Tool life}$$

$$V_1 T_1^n = C$$

$$65 \times T_1^{0.28} = C \qquad \text{...(2)}$$

From (1) and (2), we get

$$50 \times 100^{0.28} = 65 \times T_1^{0.28}$$

$$T_1 = 39 \text{ minutes. Ans.}$$

(*b*)

$$T_2 = \text{Tool life}$$

$$= 165 \text{ minutes}$$

$$V_2 = \text{Cutting speed}$$

$$V_2 T_2^n = C$$

$$V_2 \times 165^{0.28} = C \qquad \text{...(3)}$$

From (1) and (3)

$$50 \times 100^{0.28} = V_2 \times 165^{0.28}$$

$$V_2 = 43.4 \text{ metre per minute. Ans.}$$

Example 3.19. *(a) Define machining time in a lathe operation.*

(b) A mild steel pin is of 38 mm diameter and 400 mm length is to be turned on a lathe. Determine the turning time to reduce the pin to 36.5 mm is one pass when cutting speed is 30 metres per minute and a feed of 0.7 mm per revolution is used.

Solution. (*a*) Machining time in a lathe operation is defined as follows :

$$T = \text{machining time for one pass or cut}$$

$$= \frac{L}{f \cdot N}$$

where L = Length of cut, mm

f = Feed, mm/revolution

N = R.P.M. of workpiece.

(*b*)

$$V = \text{Cutting speed}$$

$$D = \text{Diameter of workpiece}$$

$$= 38 \text{ mm}$$

$$V = \frac{\pi DN}{1000}$$

$$30 = \frac{\pi \cdot 38 \cdot N}{1000}$$

$$N = 251 \text{ R.P.M.}$$

$$T = \text{Machining time}$$

$$= \frac{L}{f \cdot N}$$

$$= \frac{400}{0.7 \times 251} = 2.27 \text{ minutes.}$$

Example 3.20. *Calculate the time required to drill a 20 mm diameter hole in a workpiece having thickness of 60 mm. The cutting speed is 14 metres per minute and feed is 0.3 mm per revolution. Neglect the length of approach.*

Solution. V = Cutting speed.

$$= \frac{\pi DN}{1000}$$

$$14 = \frac{\pi \times 20 \times N}{1000}$$

$$N = 223 \text{ R.P.M.}$$

$$T = \text{Drilling time}$$

$$= \frac{L}{f \cdot N}$$

where L = Thickness of workpiece

$$= \frac{60}{0.3 \times 223} = 0.89 \text{ minutes.}$$

PROBLEMS

3.1. (*a*) What is machineability ? State the factors which come into play while evaluating machineability of any metal.

(*b*) Define machineability index.

3.2. (*a*) State the reasons responsible for tool failure.

(*b*) Explain

(*i*) Crater wear.

(*ii*) Flank wear.

3.3. (*a*) Define tool life. State the factors which affect tool life.

(*b*) Explain the relationship between tool life and cutting speed ?

(*c*) Explain the effect of tool geometry and cutting variables on tool life.

3.4. If $VT^n = C$ is the tool-life equation, calculate the cutting speed that will give a tool life of 1 hour if $n = 0.2$ and $C = 90$.

3.5. Write short notes on the following :

(*i*) Causes of wear.

(*ii*) Tool grinding.

(*iii*) Treatments of tool.

3.6. When turning under certain conditions the relationship between cutting speed and tool life could be expressed as $VT^n = C$. In the tool test, a single point tool had a life of 10 minutes when operating at 200 metres/minute. At what speed would the tool have to be operated to have a tool life of 240 minutes. Assume $n = 0.2$. **[Ans.** 106 m/min]

3.7. A tool cutting at 24 m/min gave a life of 50 minutes between regrinds when operating on rough cuts with medium carbon steel. What will be its probable life when engaged on light finishing cuts. Assume $n = 0.125$ for rough cutting and $n = 0.1$ for finishing cuts in the tool life and cutting speed relationship $VT^n = C$.

3.8. Define the following :

(*a*) Direct labour cost.

(*b*) Overhead cost.

(*c*) Fixed cost.

3.9. List the cost items which are classified in the non-machining (non productive) type. Explain each and give example.

3.10. State the basic objectives of efficient and economic machining.

3.11. Derive an expression for the optimum cutting speed at which the cost will be minimum.

3.12. (*a*) Discuss economic tool life.

(*b*) The time required to handle and machine a workpiece is 60 minutes. If the allowance for fatique is 20% and for personal needs is 5%. Calculate the total time required for each workpiece.

3.13. A company is to manufacture 200 parts per set up and that the job calls for 6 set ups. Calculate the cost of production using the following data :

Machining time = 24 minutes per component.
Non-machining time = 16 minutes per component
Tool sharpening = 2 minutes per component.
Set up time = 80 minutes per set up.
Gauging and inspection = 16 seconds and 8 checks per component
Tool change = 13 minutes
Fatique = 20%
Personal needs = 4%
Tool life = 12 hours
Direct labour cost = Rs. 3 per hour.

3.14. A batch of 1200 components are to be rough turned to 70 mm diameter for 250 mm of their length using a feed of 0.23 mm per revolution. The tool life equation is given by

$$VT^{0.26} = 26$$

where V is the cutting speed in metres per second and T is tool life in seconds. If the cost per cutting edge including cost of tool depreciation and cost of resting the cutting edge is rupees six and total machine rate including operator cost is Rs. 62, calculate the following.

(*a*) Tool life to give minimum production costs.

(*b*) Cutting speed that will result in this optimum tool life.

(*c*) Total production time assuming time taken to reset the cutting edge of tool is 40 seconds, time taken to load and unload a components is 50 seconds and initial set up time for the batch is 45 minutes.

(*d*) Total production cost.

3.15. The Taylorian tool life equation for machining C-40 steel with 18-4-1 H.S.S. at a feed of 0.2 mm/min and a depth of cut of 2 mm is given by $VT^n = C$ where n and C are constants depending on cutting conditions and tool work combinations

The following V and T observations have been noted

Cutting speed (V) m/min	25	36
Tool-life (T) minute	88	20

Calculate the index n and constant C. Hence recommend the cutting speed for a desired tool life of 65 minutes.

3.16. Write short note on the following :

(*i*) Machining time in a lathe operation.

(*ii*) Machining time in drilling.

3.17. Discuss the trends in conventional machining (metal cutting).

4

Cutting Fluids

4.1. Cutting Fluids

During metal cutting heat is generated as a result of the work done. Heat is carried away from the tool and work by means of cutting fluids which at the same time reduce the friction between the tool and chip and between tool and work and also facilitates the chip formation. Cutting, fluids usually in the form of a liquid are applied to the chip formation zone to improve the cutting conditions compared to dry cutting conditions. If sufficient quantity of cutting fluid is properly applied heat can be removed almost as fast as it is generated and the temperature of tool, workpiece and chip can be kept within limit. Cutting fluid is one of the 'important aids to improve production efficiency'.

Most practical cutting fluids have a mineral oil or vegetable oil base the mineral oil being the more widely used.

4.2. Sources of Heat in Metal Cutting

The main factors likely to cause excessive heat during a metal cutting operation are as follows :

(*i*) Cutting speed too high.
(*ii*) Poor surface finish on the cutting face of the tool.
(*iii*) Worn or incorrectly ground cutting tool.
(*iv*) Formation of a built up edge on cutting face of the tool.
(*v*) Friction between tool and work-piece.

4.3. Thermal Aspects of Metal Machining

During metal cutting considerable amount of heat is produced due to the friction between tool and work and plastic shearing of metal in the form of chips. This heat reduces the hardness of the cutting tool, makes it less wear resistant and changes its dimensions. Heat also leads to changes in the dimensions of machined surfaces. These temperature deformations of the tool and work reduce the machining accuracy.

The colour of the chip is frequently noted as a measure of the temperature obtaining at the tool point. A blue temper color on the surface of a chip formed in dry cutting is taken to mean that the tool point is hotter than when an uncolored silvery chip is obtained when cutting with a fluid.

There are three zones at which heat is generated.

(*i*) Shear zone (Primary deformation zone)
(*ii*) Friction zone (Secondary zone)
(*iii*) Work tool contact zone.

The heat produced at zone Z_1 (Shear zone) is maximum because of the plastic deformation of metal and practically all of this heat is carried away by the chips. Only a small portion of this heat (5 – 10%) is conducted to the workpiece. The heat is produced at zone Z_2 (Friction zone) due to the friction between moving chip and tool face. In zone Z_3 (work tool contact zone) the heat is generated due to burnishing friction and the heat in this zone goes on increasing with time as the wear land on the tool develops and goes on increasing. From these zones the maximum heat flows to work piece or chip as indicated by arrows (Fig. 4.1). However some heat flows in other directions also. A typical distribution of heat in chips tool and work piece versus cutting speed is shown in Fig. 4.2.

It is observed that distribution of heat in chips, tool and work piece is nearly in the ratio 80 : 10 : 10. When carbide cutting tools are used at speeds about 30 mpm. In Fig. 4.2, V is the cutting speed in metre per minute and φ is total heat.

Rate of energy consumption during metal cutting is found as follows

$$E = F_H \times V$$

where E = Rate of energy consumption.
F_H = Cutting force
V = Cutting speed.

Conversion of this energy into heat occurs into various regions of plastic deformation such as shear zone (Primary deformation zone), secondary zone and tool and new workpiece surface zone. However the tool and new workpiece surface zone will be a very small heat source

$$E = E_S + Ef$$

where E_S = Rate of heat generation in primary deformation zone (Shear zone heat rate)
Ef = Rate of heat generation in the secondary deformation zone (Frictional heat rate)

$$Ef = P \times V_C$$

where P = frictional force on the tool face
V_C = velocity of chip flow.

4.3.1. Temperature in the primary deformation zone

Some of heat produced in the primary deformation zone is conducted into the workpiece and remainder is transported with the chip

$$\theta_S = \frac{(1-k)\,.\,E_S}{\rho \times S \times V \times t \times b}$$

where θ_S = Average temperature rise in the material passing through the primary deformation zone

K = Fraction of heat conducted into the workpiece

E_S = Rate of heat generation in the primary deformation zone.

ρ = Density

S = Specific heat capacity.

V = Velocity of the material relative to the heat source

t Undeformed chip thickness

b = Width of chip.

4.3.2. Heat distribution in metal cutting

The maximum temperature occurs along the tool face some distance from the cutting edge.

$$E = E_c + E_w + E_t$$

where E = Total heat generation

E_c = Rate of heat transportation by the chip

E_w = Rate of heat conduction into the workpiece

E_t = Rate of heat conduction into the tool

Since chip material near the tool face is flowing rapidly, it has a much greater capacity for the removal of heat than the tool. For this reason rate of heat conduction into the tool (E_t) usually forms a very small proportion of total rate of heat generation and may be neglected.

4.3.3. Temperatures in the secondary deformation zone.

In secondary deformation zone the maximum temperature in the chip occurs where the material leaves the secondary deformation zone.

$$\theta_m = \theta_1 + \theta_2 + \theta_3$$

where θ_1 = Initial workpiece temperature

θ_2 = Temperature rise of material passing through the primary deformation zone

θ_3 = Temperatures rise of the material passing through the secondary zone.

4.4. Functions of Cutting Fluid

Most machining operations can be carried out advantageously by using a cutting fluid. During metal cutting heat and wear are inevitably produced due to fricition and shearing action that takes place as the chip is being formed. Both heat and wear are undesirable in order to obtain a reasonable tool life and good surface finish. One way of improving metal cutting operation is by using a cutting fluid. The cutting fluids can benefit metal cutting in several ways but by far the most important is heat removal. The various functions of a cutting fluid are as follows :

(*i*) It cools the cutting tool and workpiece. The heat produced is carried away by the fluid by supplying adequate quantity of cutting fluid. This makes possible more accurate production and measurement.

(*ii*) It lubricates the cutting tool and thus reduces the coefficient of friction between the chip and tool. This increases tool life.

(*iii*) The use of a cutting fluid result in better surface finish.

(*iv*) As friction gets reduced, the tool forces are also reduced and therefore the power consumption during cutting is also reduced.

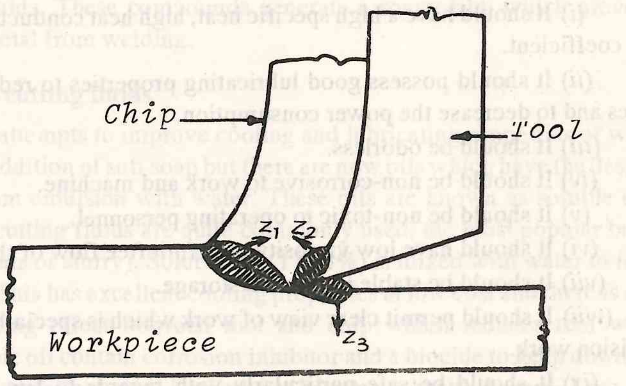


Fig. 4.1

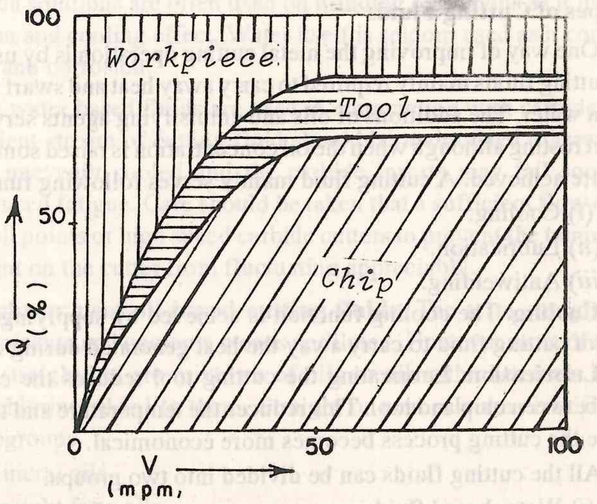


Fig. 4.2

(*v*) It causes the chips be break up into small pieces.

(*vi*) It washes away the chips from the tool.

(*vii*) It prevents corrosion of work and machine.

(*viii*) Removal of heat from the cutting zone also reduces thermal distortion of the work and permits improved dimensional control.

In performing the above functions the cutting fluid enables the maximum possible cutting speed to be used thus reducing time and cost of production.

4.5. Properties of Cutting Fluid

A cutting fluid should possess the following properties.

(*i*) It should have a high specific heat, high heat conductivity and high film coefficient.

(*ii*) It should possess good lubricating properties to reduce frictional forces and to decrease the power consumption.

(*iii*) It should be odorless.

(*iv*) It should be non-corrosive to work and machine.

(*v*) It should be non-toxic to operating personnel.

(*vi*) It should have low viscosity to permit free flow of the liquid.

(*vii*) It should be stable in use and storage.

(*viii*) It should permit clear view of work which is specially desirable in precision work.

(*ix*) It should be safe particularly with regards to fire and accident hazards.

4.6. Types of Cutting Fluids

One way of improving the metal cutting operation is by using a cutting fluid. Cutting fluids mainly required to carry away heat and swarf are generally based on water. The additions of oils and emulsifying agents serves primarily to inhibit rusting although when the oil concentration is raised some lubrication effects are achieved. A cutting fluid mainly serves following functions.

(*i*) Cooling.

(*ii*) Lubrication.

(*iii*) Antiwelding.

Cooling. The cooling function is achieved by supplying an adequate volume of cutting fluid to carry away the heat generated during cutting.

Lubrication. Lubricating the cutting tool reduces the coefficient of friction between chip and tool. This reduces the temperature and tool wear and therefore the cutting process becomes more economical.

All the cutting fluids can be divided into two groups.

(*i*) Water based fluids.

(*ii*) Straight or neat oil based fluids. Many additives are used in conjunction with each of these fluids to accomplish a variety of specific objectives. The most common gaseous cutting fluids are the oxygen and the water vapours in the ordinary atmosphere. In some machining operations are also plays an important role. The best cutting fluid is one that possesses good oiliness in addition to its cooling properties.

Antiwelding. The cutting fluid prevents intimate contact between the surface of chip and tool face. In spite of the lubricating and cooling action of cutting fluids there always exists some metal to metal contact between the tool and the chip and temperature high enough to weld the contacting asperities of the metal. It is prevented by adding compounds of sulphur, chlorine etc. to the cutting fluids. These compounds generate a soapy film which prevents particles of metal from welding.

Water based cutting fluids

Early attempts to improve cooling and lubricating properties of water included the addition of soft soap but there are now oils which have the desired effect and from emulsion with water. These oils are known as soluble oils. Water based cutting fluids are quite commonly used, the most popular being soluble oil (suds or slurry), Soluble oil (1 to 5%) is mixed with water to form an emulsion. This has excellent cooling properties at low cost and there is also some lubricating effect between tool and chip which reduces tool wear. Modern soluble oil contain corrosion inhibitor and a biocide to keep down the growth of bacteria that would otherwise become a health hazard. Less frequently used forms of water based cutting fluids are based on chemical solutions. Soda solutions are often used on grinding operations as it has good flushing action and cooling effect. Water itself is seldom used as it coolant as it causes rust and corrosion.

When water based fluids are used in conjunction with carbide tipped tools a sufficient stream of cutting fluid should be maintained otherwise the tool may be unevenly cooled and the carbide inserts may fail soon by a thermally induced fatigue. Care should be taken that a sufficient flow of fluid is applied at all points of high speed carbide cutters to prevent the temperature at a given point on the cutter from fluctuating appreciably.

Straight or neat oil based cutting fluids. The term straight when applied to lubricants and coolants means undiluted. However most of the oils are not used straight but are mixtures of oils or oil with chemicals such as sulphur and chlorine added to them. Straight or neat oils are classified into following subgroups.

(*i*) Mineral oils.

(*ii*) Straight fatty oils.

(*iii*) Compounded or blended oils.

(*iv*) Sulphurised oils.

(*v*) Chlorinated oils.

1. **Mineral oils.** Mineral oils are primarily composed of hydro carbons of different structures and molecular weights. These oils are normally used for light machining operations such as turret and capstan lathes and single spindle automatics where free cutting brasses and steels are being machined.

2. **Straight fatty oils.** The most important variety of straight fatty oils is lard oil. These oils are not stable and rapidly lose their lubricating properties. Neither are they satisfactory coolants as they have a high viscosity. Lard oil is mainly used during thread cutting with taps and dies. These oils are more expensive and less plentiful than mineral oils.

3. **Compounded or blended oils.** These are mixtures of mineral and fatty oils. The film strength of fatty oils is retained ever when diluted with 75% mineral oil. As a result they are much cheaper and more fluid than neat fatty oils. They are suitable for heavier duty operations such as threading on capstan and turret lathes, thread milling and medium capacity automatic lathes.

4. **Sulphurised oils.** When sulphur (about 5%) is mixed in lard oil it is called sulphurised cutting oil. It is used for heavy duty lathe work, gear cutting and thread grinding.

Extreme pressure (E.P.) cutting oils are mineral oils containing extreme pressure additives like sulphur. Depending on the form in which sulphur is added there are mainly three types of sulphurised E.P. oils :

(*i*) Those containing combined sulphur

(*ii*) Those containing free sulphur

(*iii*) Those containing both combined and free sulphur.

The first type of E.P. oils are called ''In active oils'' because they do not stain yellow metals whereas second and third type of E.P. oils mentioned above are called Active oils'' since they stain yellow metals.

5. **Chlorinated oils.** When chlorine (about 3%) is added in mineral oils it is called chlorinated cutting oil. When both chlorine and sulphur (upto 5%) are present in mineral oil they give the oil and extreme pressure property and are suitable for severe cutting operations on strong and tough materials such as stainless steels and nickel alloys. In broaching operation also these oils are quite commonly used.

4.7. Lubricants

Solid lubricants are employed in a finely divided state and are kept in suspension in the liquid vehicle by means of a depressing agent. Under certain conditions during metal cutting the lubricant reduces the friction on the tool face and thus reduction in power consumption, increase in tool life and improvement in surface finish of the machined surface by reducing the occurrence of a build up edge is achieved. A lubricant used in metal cutting should process the following properties.

(*i*) It should contain suitable reactive ingredients that on reaction with the work material forms a compound of lower shear strength that acts as a boundary lubricant.

(*ii*) It should be sufficiently unstable to be broken down under the temperature and pressure existing at the chip tool interface.

(*iii*) It should have a small molecular size in order to allow rapid diffusion and penetration to the chip tool interface. It should maintain a conventional hydrodynamic film between the chip and the tool face.

Carbon tetrachloride (CCl_4) chloroform ($CH Cl_3$), trichloroethane ($CH_3 CCl_3$) and certain other chlorinated hydrocarbons are quite commonly used lubricants when cutting metals at low speeds.

4.8. Selection of a Cutting Fluid

The cutting fluid should be carefully chosen. It is observed that each metal being machined and even each type of machining has its optimum cutting fluid. The selection of a particular type of cutting fluid depends on factors listed below :

(*i*) Cutting speed.

(*ii*) Feed rate.

(*iii*) Depth of cut.

(*iv*) Cutting tool material.

(*v*) Workpiece material.

(*vi*) Velocity of cutting fluid.

(*vii*) Expected cutting tool life.

(*viii*) Cost of cutting fluid.

(*ix*) The life of cutting fluid and loss of cutting fluid during operation.

Low speed and shallow cuts require little cooling or lubrication. A lubricant of considerable oiliness is required while machining tough metals at low speeds and heavy cuts. Shallow cuts at high speeds require good coolants therefore emulsions of soluble and sulphur base cutting oils are frequently employed A lubricant that excels as a coolent as well as a lubricant is used for heavy cuts at high speeds. Brittle materials like cast iron are often cut without the use of a lubricant although emulsions of soluble oil in water are sometimes used.

Cutting lubricants may be applied by hand from a can, by a gravity feed drops system or by some medium of forced circulation such as centrifugal pump. While using pump care should be taken to filter effectively the lubricant that is returned order to prevent the chips from damaging the pump.

Table 4.1 shows the cutting fluids used during machining for some of workpiece materials.

Table 4.1

Material	*Turning*	*Tapping*	*Drilling*
Cast Iron	Machined dry	Machined Dry or 25% lard oil + 75% mineral oil	Machined dry
Tool and low carbon steels	25% to 70% lard oil mineral oil	20 to 40% lard oil + mineral oil	Soluble oil with 95% water
Alloy steel	25% Sulphur base oil + 75% mineral oil	30% lard oil + 70% mineral oil	Soluble oil with 80% water
Copper	Soluble oil with 90 to 95% water		
Aluminium	Mineral oil with 10% soluble oil	Lord oil	Soluble oil with 75 to 90% water

4.9. Cutting Fluid Penetration

The various properties of a cutting fluid which are considered to be essential for the penetration into the capillaries between the chip and tool are as follows :

(*i*) Wetting and spreading

(*ii*) Surface tension.

(*iii*) Small fat molecules.

The molecules of the fluid should be more attracted to the surface than to each other so that cutting fluid spreads over the surface and wets the surface.

For efficient cooling it is necessary that the fluid penetrates as much as possible to the chip tool interface. Fig. 4.3 shows nature of chip tool interface where the hills and valleys that form a labyrinth of fine capillaries are shown to a greatly increased scale. Surface tension forces in the fluid and the action of pressure difference of one atmosphere due to the tendency to form a vacuous cavity as the tool penetrates the workpiece, will cause the fluid to flow between the capillaries and reach the tool point against the abverse motion of the chip. It would appear unlikely that the fluid can be in the form of a liquid as it penetrates the very fine labyrinth of capillaries. The material is probably carried to a point close to the tool point in the liquid state by capillary forces and is then converted to a vapour upon absorption of some of the heat generated by the cutting process. The vapour could then penetrate the capillaries, physically absorbing on the freshly cut nascent metal as it goes.

The field can enter at two pieces one at P and the other at Q as shown in Fig. 4.3. The motion of the chip across the tool face will tend to prevent fluid from reaching the tool tip from P and similarly the motion of the workpiece across the clearance surface of the tool will tend to prevent fluid

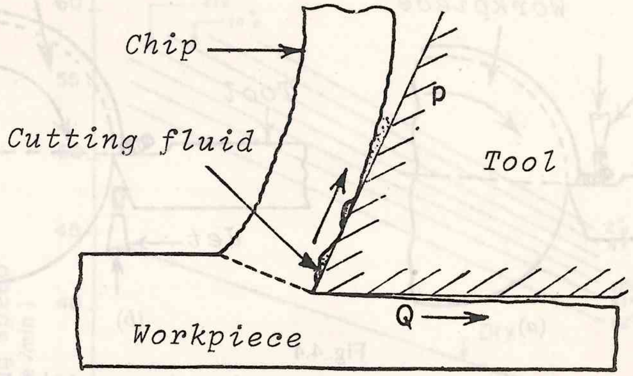


Fig. 4.3

from entering at Q. While the relative velocity of the surfaces at B will be more than that at P the distance of intimate contact to be traversed at Q will usually be much less than that at P. The net result is that there will usually be a greater tendency for penetration along the charance surface than along the tool face.

The penetration of the cutting fluid to the tool chip interface becomes difficult at high cutting speeds because of high relative velocity of chip over the cutting face of the tool. This tends to retard the motion of the fluid. In order that a cutting fluid works effectively at higher cutting speed at high velocity stream of fluid is used. Nozzles of 3.3 mm to 0.375 mm diameter are used to obtain high velocity stream of cutting fluid. A fluid of smaller particle size and lower surface tension can enter the voids between tool and chip more readily than a fluid of larger particle size and higher surface tension.

The fluid that finds its way into asperties between chip and tool in the vicinity of tool point is subjected to the following unique combination of conditions.

(*i*) High local temperature

(*ii*) High local pressure approaching the hardness of the metal cut.

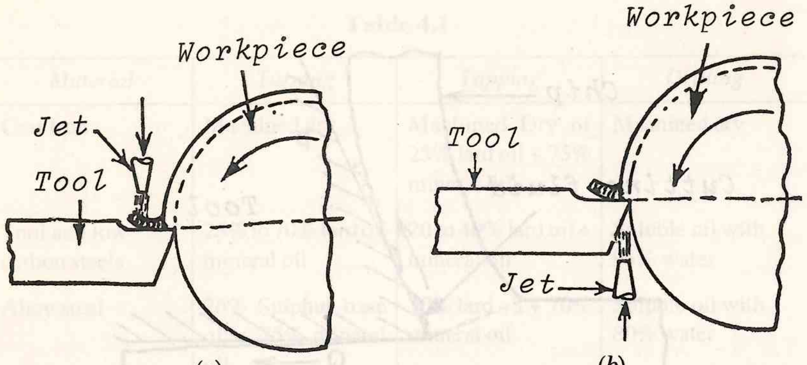
(*iii*) Smooth surface produced

(*iv*) Highly stressed metal.

During cutting under above conditions the chip may be made to react with the fluid to form a low shear strength solid lubricant. The thin layer of solid so formed prevents the formation of a weld between the chip and tool this helps in reducing the coefficient of friction between the chip and tool.

4.10. Application of Cutting Fluid

Most of the larger machine tools have an adequate coolant system usually enclosed with in the body of the machine itself. The cutting fluid should be well filtered and stored in a cool area from where it is pumped through a



(*a*) (*b*)

Fig. 4.4

piping system to the area of tool work contact. A continuous supply should be maintained at chip tool interface where heat and wear are produced. A intermittent supply of cutting fluid is not desirable because when the supply stops the temperature of the tool quickly rises and when the supply is maintained again it cools the tool which may lead to cracks at the cutting edge. It is preferable to direct a jet of cutting fluid to the cutting area. The stream of cutting fluid should be directed on the point of chip removal (Fig. 4.4) and delivered in a sufficient quantity (8 to 12 and at high speeds up to 20 liters/min). A high lubricating and cooling effect is obtained if the cutting liquid is mixe with compressed air at a pressure of about 1.5 to 2 kg/cm^2 and supplied through a nozzle, directed at the tool flank. The liquid delivered thus in the atomised state not only reduces friction and facilitates chip formation but removes heat more intensively.

4.11. Effect of Cutting Fluid on Cutting Speed and Tool Life

Cutting fluids also affect the cutting speed permitted by the cutting tool. The cutting speed can be increased by about 40% in comparison to machining dry if the emulsion cutting fluid is cooled to + 2°C before used. Lower the temperature of the cutting fluid and the farther the curve is from the line representing dry machining the higher the cutting speed permitted by the tool for the same tool life. Fig. 4.5 shows relationship between the cutting speed and tool life at various temperature of the cutting fluid when structural steel having carbon 0.6% is being machined with a high speed steel tool.

The increase in tool life is about 50% in case of carbon tool steel when using cutting the fluid as compared to dry machining. Whereas the increase in tool life is 25% in case of high speed steel tools and 5 to 10% in case of carbide tools. (Fig. 4.6).

Tests made by Earnst and Merchant on a variety of cutting fluids shows that use of cutting fluids generally increases the chip thickness ratio (cutting ratio) but that the effect within the normal cutting speed range falls as the cutting speed is increased. A relationship between cutting ratio and cutting speed and various cutting fluids is shown in Fig. 4.7. It is observed from these results that the depth of penetration of cutting fluid into the area of contact where friction occurs falls with the increase in cutting speed.

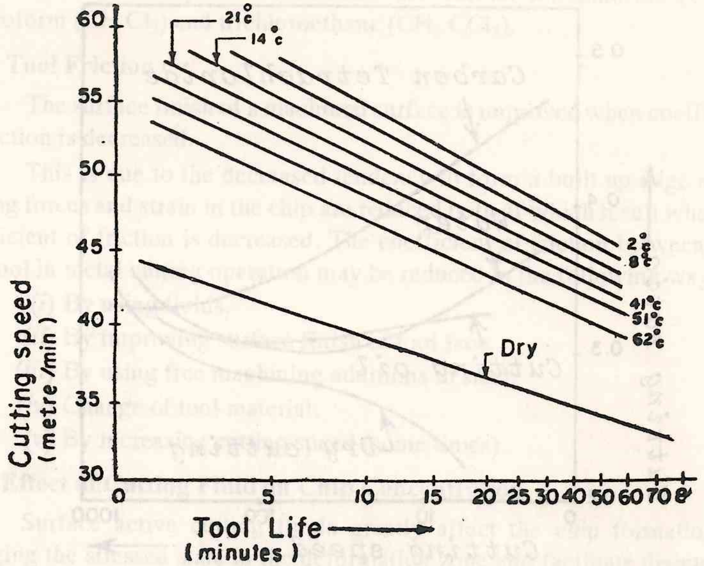


Fig. 4.5

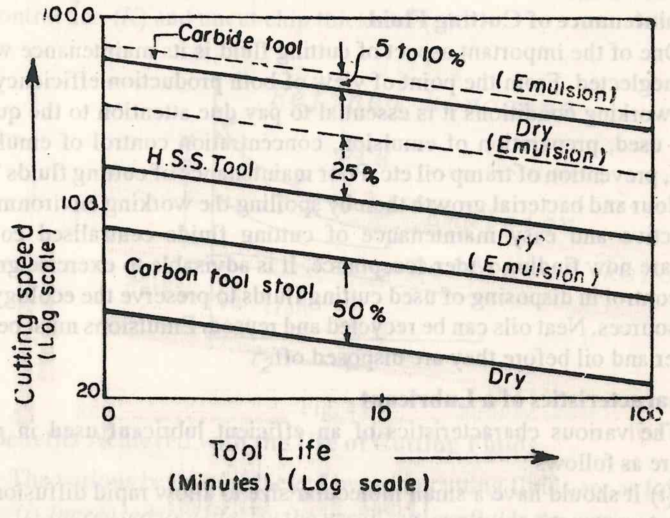


Fig. 4.6

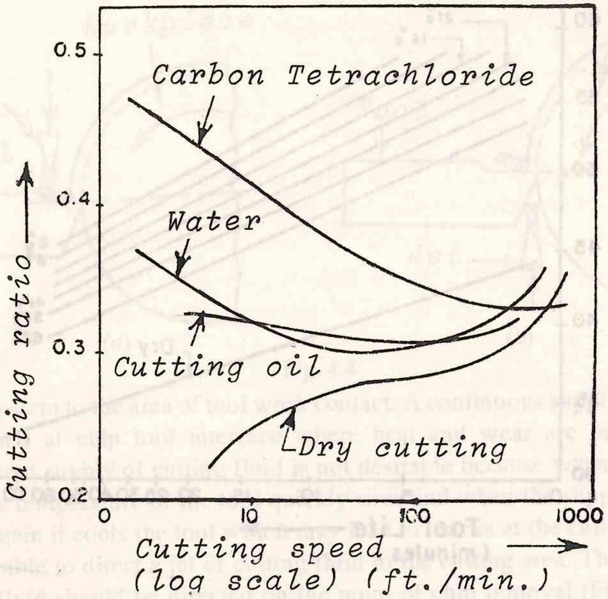


Fig. 4.7

4.12. Maintenance of Cutting Fluid

One of the important aspect of cutting fluid is its maintenance which is often neglected. From the point of view of both production efficiency and hygenic working conditions it is essential to pay due attention to the quality of water used, preparation of emulsion, concentration control of emulsion, filtration, prevention of tramp oil etc. Poor maintenance of cutting fluids leads to bad odour and bacterial growth thereby spoiling the working environments. For effective and easy maintenance of cutting fluids centralised coolant systems are now finding wider acceptance. It is advisable to exercise greater care on control in disposing of used cutting fluids to preserve the ecology and water resources. Neat oils can be recycled and reused. Emulsions must be slipt into water and oil before they are disposed off.

4.13. Characteristics of a Lubricant

The various characteristics of an efficient lubricant used in metal cutting are as follows :

(*i*) It should have a small molecular size to allow rapid diffusion and penetration to the chip tool interface.

(*ii*) It should be sufficiently unstable to be broken down under the temperature and pressure existing at the chip tool interface.

(*iii*) The lubricant should have a suitable reactive ingredient which on reaction with the work material forms a compound of lower shear strength that as a boundary lubricant.

The commonly used lubricants are carbon tetrachloride ($C\ Cl_4$) chloroform ($CH\ Cl_3$) and trichloroethane ($CH_3\ CCl_3$).

4.14. Tool Friction

The surface finish of a machined surface is improved when coefficient of friction is decreased.

This is due to the decreased tendency to form a built up edge as the cutting forces and strain in the chip are reduced both of which result when the coefficient of friction is decreased. The coefficient of friction between chip and tool in metal cutting operation may be reduced in the following ways :

(*i*) By using fluids.

(*ii*) By improving surface finish of tool face.

(*iii*) By using free machining additions to steel.

(*iv*) Change of tool material.

(*v*) By increasing cutting speed (some times).

4.15. Effect of Cutting Fluid on Chip Concentration

Surface active cutting fluids greatly affect the chip formation by changing the stressed state in the deformation zone and facilitate disintegration. Fig. 4.8 shows the effect of various surface active cutting fluids in reduction of chip contraction. The various curves are between coefficient of chip contraction (K) and uncut chip thickness (t_2).

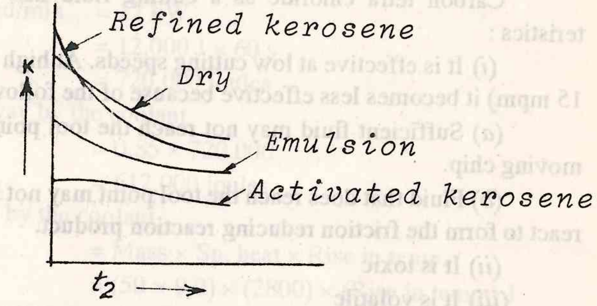


Fig. 4.8

4.16. Benefits Achieved with the Use of Cutting Fluids

The various benefits achieved by using cutting fluids are as follows :

(*i*) *Increased tool life.* By the use of cutting fluids the cutting temperature is reduced and therefore, tool life gets increased.

(*ii*) *Better surface finish.* By using cutting fluids better surface finish can be obtained.

(*iii*) *Lower tool forces.* By using cutting fluids, the coefficient of friction between chip and tool face is reduced and this reduces the tool forces.

(*iv*) Finished surfaces are protected from corrosion.

(*v*) Better dimensional stability of work piece is obtained.

4.17. How coefficient of friction is reduced

The fluid that finds its way between the asperities between chip and tool in the vicinity of the tool point is subjected to the following unique combination of conditions.

(1) High local temperatures approaching

(*a*) hardness of the metal cut.

(*b*) the melting point of the chip metal on the high points of the surface asperities.

(2) Highly stresses metal

(3) Smooth surface produced.

Because of these conditions the chip may react with the cutting fluid to form a low shear strength solid lubricant. The thin layer of solid thus formed prevents the formation of a weld between the chip and tool and hence reduces the coefficient of friction between the chip and the tool.

For example when carbon tetra chloride is used as cutting fluid at low cutting speeds, to cut steels, then iron chloride which is an ionic crystal of low shear strength is formed and is not readily displaced from the surface on which it is produced. This prevents the steel chip from welding to the tool face and thus coefficient of friction is reduced.

Carbon tetra chloride as a cutting fluid has the following characteristics :

(*i*) It is effective at low cutting speeds. At high cutting speeds (above 15 mpm) it becomes less effective because of the following reasons.

(*a*) Sufficient fluid may not reach the tool point against the outward moving chip.

(*b*) Fluid that does reach the tool point may not have sufficient time to react to form the friction reducing reaction product.

(*ii*) It is toxic

(*iii*) It is volatile

(*iv*) Its cost is more.

Example 4.1. *Under certain machining conditions the power required is 0.05 H.P./cm^3/min when the cutting speed is 24 metre/minute depth of cut is 6 mm and feed is 0.25 mm/rev. The work is cooled by a flow of 2 kg/min of coolant having a specific heat of 0.82. If 80% of heat produced is taken away by the coolant, calculate the rise in the temperature of coolant.*

Solution. w = Metal removed per minute

= Feed × Depth of Cut × Cutting speed

$= 0.025 \times 0.6 \times 24 \times 100 = 36 \text{ cm}^3/\text{min}.$

Horse power consumed in cutting

$= 0.05 \times 36 = 1.8$

Heat produced per minute

$$= 1.8 \times 4500 \times \frac{2.34}{10^3} = 19 \text{ kcal.}$$

Heat taken away by the coolant

$= 19 \times 0.8 = 15.2$ kcal.

Let, W = Weight of coolant supplied per minute

W × Specific heat × Rise in temperature

$= 15.2$

∴ Rise in temperature

$$= \frac{15.2}{2 \times 0.82}$$

= 9.3°C. **Ans.**

Example 4.2. *A machining operation is cooled by soluble oil having a specific heat capacity of 2800 J/kg °C flowing at the rate of 50 litres/min. If 12 kW is being absorbed at the cutting point and 85% of the heat generated is taken away by the cooling oil, determine its rise in temperature. (1 litre = 0.9 kg).*

Solution. Assuming all the power to be dissipated as heat at the cutting point we have

Heat generated/min = 12 kW

$= 12{,}000 \text{ J} \times 60 \text{ s}$

= 720,000 joules

Heat taken away by the coolant

$= 0.85 \times 720{,}000$

= 612,000 joules

Heat taken up by the coolant

= Mass × Sp. heat × Rise in temp.

= (50 × 9.0) × (2800) × (Rise in temp.) J

612,000 = 50 × 0.9 × 2800 × Rise in temp.

Rise in temperature

= 4.9°C. **Ans.**

Example 4.3. *Compare the cooling, lubricating and anti-welding properties of the following cutting fluids :*

(*i*) *Water*

(*ii*) *Mineral oil*

(*iii*) *Fatty oil*

(*iv*) *E.P. cutting oil.*

Solution. The properties are compared are follows :

Cutting fluid	*Cooling properties*	*Lubricating properties*	*Anti-welding properties*
Water	Excellent	Poor	Poor
Mineral oil	Fairly good	Good	Fair
Fatty oil	Fair	Excellent	Fair
E.P. cutting oil	Fair	Good	Excellent

Example 4.4. *Describe the cutting fluids used for the following metal cutting operations stating the main requirements placed on the cutting fluids.*

1. For Cast Iron. (i) Finish and form machining of cast iron (reaming, tapping etc.)

2. For Steels. (i) Rough machining
(a) at low cutting speed
(b) at high cutting speed.
(ii) Rough and finish machining of high strength and heat resisting steels and alloys
(iii) Finish and form machining
(a) at low and medium cutting speeds
(b) at high cutting speeds.

3. Rough and finish machining of high strength and heat resisting steels and alloys.

Solution. The selection of cutting fluids for various machining operations for different types of metals and alloys depends on many factors. Some of these factors are as follows :

(*i*) Rate of heat released
(*ii*) Contact pressure and temperature
(*iii*) Types of machining operations.
(*iv*) Wear of tools.

Table 4.2 indicates the cutting fluids used for various machining operations.

Table 4.2

Machining operation	*Typical conditions in contact area*	*Main requirements of cutting fluid*	*Suggested cutting fluid*
(*i*) Rough machining at			
(*a*) Low cutting speed	Low heat release rate	Lubrication	Mineral oils sulphurised oils
(*b*) high cutting speed	High heat release rate	Cooling action	Water base emulsions
(*ii*) Finish and form machining of steels at			
(*a*) low and medium cutting speeds	Low heat release rate	Lubrication	Straight oils sulphurised oils
(*b*) high speeds	High heat release rate	To reduce cutting temperature	Emulsions with 5 to 10% emulsifying oil
(*c*) of cast iron	Abrasive wear of tool	Lubrication and flushing action	Kerosene
(*iii*) Rough and finish machining of			
(*a*) high strength and heat resisting steels (*b*) alloy steels	High temperature and high pressure	High resistance to normal pressure	Emulsions containing surfactant additives.

Example 4.5. *Name the commonly used cutting fluids for machining of*

(i) Brass (ii) Bronze

While carrying out (a) Turning (b) milling (c) Drilling (d) Tapping.

Solution. The commonly used cutting fluids are as follows :

Material	*Turning*	*Milling*	*Drilling*	*Tapping*
Brass	Mineral oil + 10% fatty oil	Soluble oil (96% water)	Soluble oil (75% to 90% water Remaining mineral oil)	10 to 20% lard oil with mineral oil
Bronze	Soluble oil	Soluble oil	Soluble oil	20% lard oil and 10% mineral oil

PROBLEMS

4.1. (*a*) What are the sources of heat generation in metal cutting ?
(*b*) Show with the aid of a simple sketch the areas of heat generation that occur when using a single point cutting tool on a tathe.

4.2. (*a*) State the functions of a cutting fluid.
(*b*) What are the essential properties of a cutting fluid ?

4.3. Explain the following types of cutting fluids :
(*a*) Water based cutting fluids.
(*a*) Straight or neat oil based cutting fluids.

4.4. Write short notes on the following :

(*a*) Selection of a cutting fluid.

(*b*) Application of cutting fluid.

(*c*) Maintenance of cutting fluids.

4.5. Describe the effect of cutting fluid on cutting speed and tool life.

4.6. Explain the cutting fluid penetration during metal cutting.

4.7. How does a lubricant and cutting fluid differ from each other.

4.8. Describe tool friction.

4.9. (*a*) State the characteristics of a lubricant used in metal cutting.

(*b*) Name the commonly used lubricants.

4.10. Explain the effect of cutting fluids on chip contraction.

4.11. Write short notes on the following :

(*i*) Benefits achieved with the use of cutting fluids.

(*ii*) E.P. cutting oils.

5

Surface Finishing Processes

5.1. Surface Finish

A fine surface can be taken to mean which has a greater degree of smoothness than is customarily produced by normal cutting methods. More accurately a tool does it work the less rough is the surface produced. The selection of the method by which a surface is to be produced will depend on a large number of variables ranging from the physical limitations imposed by the material and the duties to be imposed on the surface to the commercial considerations of output. It has been observed that limits of surface finish are primarily governed by the machine and the setting of the tool.

Surface finishing processes for machined surface may be classified into two groups, namely those employing hardened steel tools such as burnishing, scraping and filing and those employing abrasives such as grinding, honing laping, superfinishing and polishing.

5.1.1. Grinding

It is a metal cutting process, that employs an abrasive tool called grinding wheel. The cutting elements of grinding wheel are grains of abrasive material having high hardness and a high heat resistance. They have sharp edges and are held together by bonding materials. Grinding provides high accuracy and a good surface finish. Therefore it is used as a finishing operation. This process removes comparatively little material usually from 0.25 mm to 0.5 mm. Tolerances as small as 0.0025 mm can be obtained by commercial grinding.

During grinding temperature rises with the increased wear of grains which may lead to distortion of workpiece structural changes and crack formation in the ground surface. Hence an abundant flow of coolant is commonly used in grinding. The coolant also slows down softening of wheel bond which is due to heating.

The various cutting fluids used in grinding steel are as follows :

(*i*) A one per cent solution of soda ash with 0.15 per cent sodium nitrite.

(*ii*) A two per cent aqueous solution of powdered soap.

(*iii*) A 3.5% aqueous solution of a neutral paste type emulsion with an oleinic acid base.

Cast iron and copper are often ground dry. Aluminium is ground by using kerosene with or without the addition of mineral oil as coolant.

The grinding process has certain specific features as follows :

(*i*) As the abrasive grains are some distance apart a grinding wheel has an interrupted cutting edge and not a continuous one as on a milling cutter.

(*ii*) A grinding wheel can be self sharpening during the course of the grinding process.

(*iii*) The process of chip removal by a grain takes place in a very short period.

(*iv*) Due to the pyramidal and rounded shape of the cutting element of the abrasive grains the thickness and width of the uncut chip are inter-related in grinding.

A grinding wheel can be compared to a milling cutter both having the following similarities.

(*i*) Both have a number of cutting edges, each cutting edge having adequate rake and clearance angles.

(*ii*) Each cutting edge is in action only for a short time.

(*iii*) The chip formation process in grinding is similar to cutting by the tooth of a milling cutter. The chip has the same structure and appearance as obtained in milling. Adequate chip space is available for a free cutting action. In the case of a grinding wheel the chip space is available between bonded abrasive particles.

The process of grinding is dependent upon the following inherent properties of the grinding wheel :

(*i*) Type of abrasive

(*ii*) Size and distribution of grits.

(*iii*) Amount and type of bond material

(*iv*) Volume of pores relative to that of grits and bonds.

5.2. Abrasive Materials

Materials used as the cutting grains are of two types.

(*a*) Natural abrasives.

(*b*) Artificial or manufactured abrasives.

Natural Abrasives. They include sand stone, diamond, corundum and emery. The principal component of corrundum and emery is natural aluminium oxide (alumina). Corrundum is composed of about 85% aluminium oxide and 15% iron oxide. Emery contains 60% aluminium oxide and 40% iron oxide. The relative abrasive action of each substance depends upon the properties of aluminium oxide.

Diamond abrasive wheels are used extensively for sharpening carbide and ceramic cutting tools. Diamonds are also used for truing and dressing other types of abrasive wheels. Because of their high cost, diamonds are used only when other cheaper abrasives will not produce the desired result.

Artificial Abrasives. They include silicon carbide (SiC) and aluminium oxide (Al_2O_3). Silicon carbide is made by charging an electrical furnace with silica sand, coke, salt and sawdust. A temperature of over 2300°C is maintained for several hours obtained by passing heavy current through the charge and a solid mass of silicon carbide results. After the furnace has cooled the mass of crystals is removed, crushed and graded to various desired sizes. Silicon carbide is very hard (though less than boron carbide and diamond). It has high heat resistance and excellent cutting properties. Two types of silicon carbide is available, namely black and green. The black silicon carbide is of lower quality and contains about 95% SiC. Green silicon carbide is some what harder and has a high grinding capacity and contains at least 97% SiC.

Green silicon carbide is mainly used for sharpening carbide tipped cutting tools.

Aluminium oxide abrasive is the crystalline form of aluminium oxide (Al_2O_3). It is produced in an arc furnace from bauxite, iron filings and small amount of coke. The mass of aluminium that is formed is crushed and the particles are graded to size. It is softer than silicon carbide but it is considerably tougher and is a more general purpose abrasive. Common trade names for aluminium oxide abrasives are Alundum and Aloxite.

The physical properties of the material to be cut dictate the kind of abrasive to be selected. As a general guide silicon carbide is used for grinding brittle materials and materials of low tensile strength such as cemented carbides, cast iron, ceramics and low tensile strength metals including brass, soft bronze, and copper. Aluminium oxide having less brittle grains is used for tougher and higher strength material such as steel, wrought iron, hardened steel, alloy steel and hard brass and bronze.

In general the physical properties of aluminium oxide compared with silicon carbide are as follows :

(*i*) Silicon carbide is harder than aluminium oxide.

(*ii*) Aluminium oxide can withstand greater stresses than silicon carbide.

(*iii*) Aluminium oxide is more tough than silicon carbide.

(*iv*) Aluminium oxide wheels are generally used for grinding high tensile strength and tough materials whereas silicon carbide wheels are used to grind low tensile strength and non-metallic materials.

5.2.1. Abrasive Grain Size

Abrasive materials are crushed in ball mills and screened for classification into different sizes. The size of abrasive grain required in a grinding wheel depends on the following factors :

(*i*) Amount of material to be removed.
(*ii*) Finish desired.
(*iii*) Hardness of material being ground.

The grit or grain size of an abrasive is denoted by a number representing the number of meshes per inch of the screen through which the grains of crushed abrasives are passed for grinding. The standard grains sizes for grinding wheels are represented in Table 5.1.

Table 5.1

Grit Designation	*Grain Size or Grit Number*						
Coarse	10	12	14	16	20	24	
Medium	30	36	46	54	60		
Fine	80	100	120	150	180		
Very fine	220	240	280	320	400	500	600

The coarser grit will remove the stock at a faster rate and finer finish will require a finer grit.

Sizes from 240 to 600 are designated as flour sizes. These are primarily used for lapping and honing stones.

5.2.2. Bonds

Bonding materials are used as binders to hold the abrasive particles in place. The firmness with which the grains are held in the wheel and the strength of wheel itself in which large centrifugal forces are developed in rotation depend on the bonding material. The bonding material determines whether the wheel is rigid or flexible. It also determines the force that is required to dislodge an abrasive particle from the wheel which plays a major role in the cutting action.

Six types of bonding materials are commonly used.

(*i*) **Vitrified Bonds.** Vitrified bond is made of clay and water. The abrasive grains and clay are thoroughly mixed together with sufficient water to make the mixture uniform. The material is formed into a wheel usually by pressing and then these wheels are dried. They then are fired in a kiln which results in the bonding material becoming hard and strong. Vitrified bonds are used most extensively. Vitrified abrasive wheels have a high production capacity, and are moisture proof.

About 75% of grinding wheels have vitrified bonds.

(*ii*) **Resinoid Bond.** Resinoid bonding is produced by mixing abrasive grains with synthetic resins. Resinoid bonded wheels are strong, elastic and permit high peripheral speeds but are destroyed by alkaline cooling fluids. This can be avoided by impregnating the wheel with paraffin. These wheels normally operate at surface speeds in the region of 3000 m/min. They are particularly suitable for use in grinding steel, cast iron and malleable iron castings.

(*iii*) **Shellac Bond.** Shellac bonded wheels are made by mixing the abrasive grains with shellac in a mixer. After the mixture has been rolled or pressed into desired wheel shapes they are then hardened by baking for several hours at about 160°C. Thin wheels that are strong but possess some elasticity have shellac bond. They can produce high polish and are used in grinding such parts as camshafts and mill rolls.

(*iv*) **Rubber Bond.** A rubber bond is essentially a mixture of rubber softened by gasoline and sulphur (30%). A rubber bonded wheel has high strength and elasticity and is moisture proof. They are commonly used for snagging work in foundries and for thin cut-off wheels.

(*v*) **Silicate Bond.** This bond is produced by mixing abrasive grains with silicate of soda (water glass). The mixture is given the desired wheel shape and baked at about 260°C for a day or more. This silicate bonded wheels are soft, comparatively weak and have low production capacity. Such wheels has limited applications.

(*vi*) **Oxy Chloride Bond.** This bond is produced by mixing abrasive grains with oxide and chloride of magnesium.

Different types of bonds used in grinding are represented by different symbol as shown in table 5.2.

Table 5.2

Type of bond	*Symbol*
Vitrified bond	*V*
Resinoid bond	*B*
Shellac bond	*E*
Rubber bond	*R*
Silicate bond	*S*
Oxy chloride bond	*O*

5.2.3. Grade

Grade or hardness indicates the strength, with which the bonding material holds the abrasive grains in the grinding wheel. The easier a grain is torn out of the bond, the softer the wheel and *vice versa*. The degrees of hardness are specified by the use of letters of the alphabet. Different grades of grinding wheels are shown in table 5.3.

Table 5.3

Soft	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*		
Medium	*I*	*J*	*K*	*L*	*M*	*N*	*O*	*P*		
Hard	*Q*	*R*	*S*	*T*	*U*	*V*	*W*	*X*	*Y*	*Z*

The grinding wheel of required grade should be selected for each grinding job. The selection of a particular grade of wheel is largely governed by the nature of work, its composition, size and hardness. Hard wheels are used for softer materials and *vice versa*.

5.2.4. Structure

It indicates the spacing between the abrasive grains or in other words density of the wheel. Structure of grinding wheel is designated by a number. The higher the number the wider the spacing. It is observed that the tendency for burns to appear on the ground surface is reduced when a wheel of more open structure is used. Table 5.4 indicates the two types of structure with their numbers.

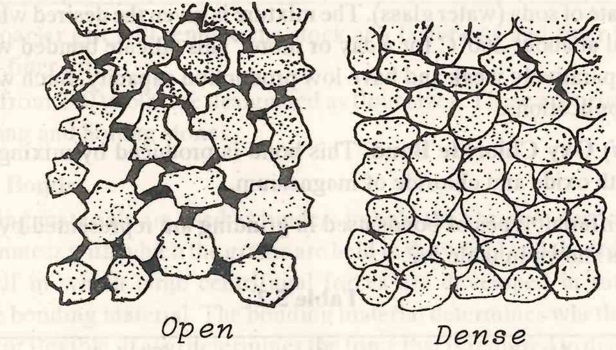


Fig. 5.1

Fig. 5.1 shows open and dense structure.

Table 5.4

Structure	*Symbol*							
Dense	1	2	3	4	5	6	7	8
Open	9	10	11	12	13	14	15	or more

5.2.5. Marking System of Grinding Wheels

The Indian Standards Institution (IS : 551—1954) has specified a standard system of marking the grinding wheels. According to this system the following elements are represented in a definite order :

1. Abrasive
2. Grain size of Grit
3. Grade
4. Structure
5. Bond.

In addition to this manufacturer may add some symbol to indicate the abrasive used.

Apart from the above information diameter of grinding wheel its thickness and bore diameter should also be mentioned.

A grinding wheel with the markings 300 × 30 × 35 W A 36 M 5 S 17 will have the following specifications :

Wheel diameter = 300 mm
Wheel thickness = 30 mm
Bore diameter = 35 mm

W—Manufacture's symbol for abrasive used (Use optional)
A—Abrasive (Al_2O_3)
36—Grain size
M—Grade
5—Structure
S—Bond (silicate bond).
17—Manufacturer's symbol for the type of grinding wheel (Use optional)

5.3. Grinding Wheel Cutting Action

During cutting action of a grinding wheel the spacing of the abrasive particles and the effect of the bonding material which holds them in the wheel are very important. Each exposed grain constitutes a small cutting edge thus providing a multiplicity of cutting edges, some having positive rake angles and others having negative rake angles. Each cutting edge acts exactly the same

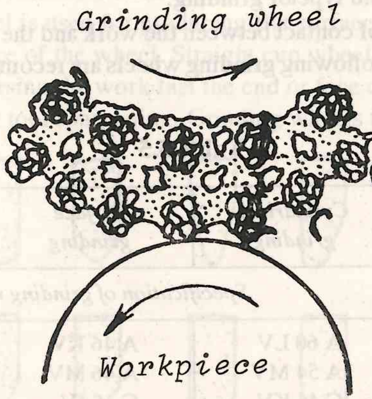


Fig. 5.2

as any other cutting edge under similar conditions with chips being formed (Fig. 5.2). As the cutting edges are small therefore the chips produced are also small. Feed and depth of cut should also be small. In order to achieve close tolerances and excellent surface finish large number of cutting edges small depth of cut and small feed should be used.

5.4. Grinding Wheel Selection

In order to achieve optimum results the proper grinding wheel should be selected for a given job. The shape of grinding wheel should be such that is permits proper contact between wheel and the surface to be ground. The size of the grinding wheel depends so spindle speed available on the grinding machine and the cutting speed for the wheel. The grinding wheel should be of proper abrasive, grain size structure grade and bond. Various factors on which the selection of grinding wheel depends are as follows :

(*i*) Properties of material to be ground such as material, hardness, strength and toughness. Hard dense materials require a relatively soft grade of wheel, hard brittle materials require fine grain or closely spaced abrasives very hard material such as tungsten carbide require widely spaced abrasive wheel to permit rapid release of worm abrasive particles since the material ground is as hard as abrasive. Aluminium oxide wheels are commonly used for materials of high tensile strength, where the materials is neither very brittle nor easily penetrated such as carbon, alloy and high speed steels and wrought iron and tough bronzes. Silicon carbide wheels are used for materials of low tensile strength such as brasses, aluminium, glass and marble.

(*ii*) Amount of material to be removed.

(*iii*) Type of surface finish desired.

(*iv*) Dimensional accuracy required.

(*v*) Rigidity of the grinding machine.

(*vi*) Method and type of grinding.

(*vii*) The area of contact between the work and the wheel. According to IS : 1249—1958 the following grinding wheels are recommended for different materials :

Table 5.5

Material to be grounded	*Cylindrical grinding*	*Surface grinding*	*Internal grinding*
	Specification of grinding wheels.		
Hardened Steel	A 60 LV	A 46 KV	A 24 JV
Soft Steel	A 54 MV	A 46 MV	A 46 JV
Cast Iron	C 46 KV	C 46 JV	C 36 JV

5.5. Shapes of Grinding Wheels

Grinding wheels are manufactured in various standard shapes. Different shapes of grinding wheels are as shown in Fig. 5.3. Straight, recessed on one side and recessed both sides wheels are used primarily for grinding external or internal cylindrical surface and for plain surface grinding. The cylinder shaped wheel is used for producing flat surfaces the grinding being done with the end face of the wheel. Straight cup wheel is used for grinding flat surfaces by traversing the work fast the end or face of the wheel. Flaring cup wheel is used for tool sparpening. Grinding wheels tapered on two sides

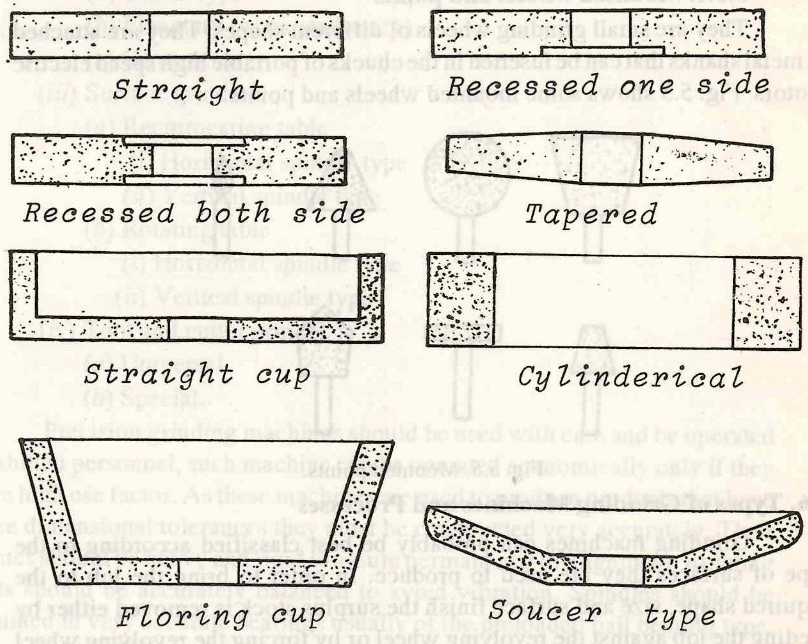


Fig. 5.3. Standard grinding wheel shapes.

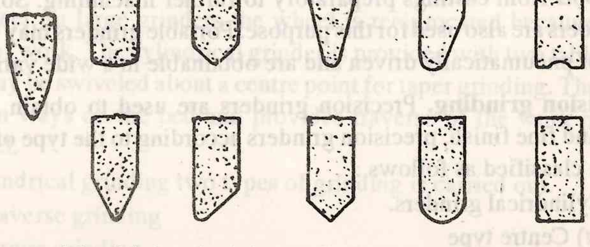


Fig. 5.4. Standard shapes of grinding wheel faces.

are used for grinding the gear teeth and threads. Dish type are used for grinding tools saws. Straight grinding wheels can be obtained with a variety of standard faces some of these are shown in Fig. 5.4.

5.5.1. Mounted wheels and points

They are small grinding wheels of different shapes. They are attached to metal shanks that can be inserted in the chucks of portable high speed electric motors. Fig. 5.5 shows some mounted wheels and points.

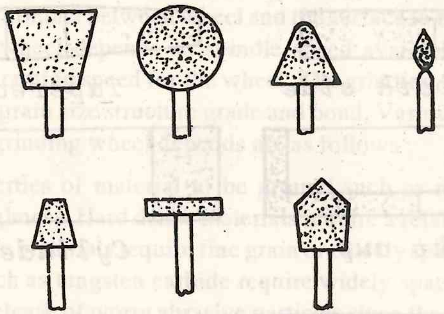


Fig. 5.5. Mounted points.

5.6. Types of Grinding Machines and Processes

Grinding machines can probably be best classified according to the type of surfaces they are used to produce. In order to bring the job to the required shape, size and surface finish the surplus stock is removed either by feeding the job against the revolving wheel or by forcing the revolving wheel against the job. According to the quality of surface finish produced grinding machines are classified into two groups.

(*i*) Rough grinders.
(*ii*) Precision grinders.

Rough Grinders. These grinders are used to produce rough surfaces and the accuracy in dimensions is not high. The various grinders used for rough grinding are swing frame grinders, bench grinder and portable grinder. Pedestal types or swing frame grinders, are usually used for snagging. Snagging is a type of rough grinding that is done in a foundry to remove fins, gates, risers and rough spots from castings preparatory to further machining. Sometimes portable grinders are also used for this purpose. Portable grinders may be either electrically or pneumatically driven and are obtainable in a wide variety.

Precision grinding. Precision grinders are used to obtain accurate dimensions and fine finish, precision grinders according to the type of surface produced are classified as follows :

(*i*) Cylindrical grinders.
  (*a*) Centre type

  (*b*) Centreless
  (*c*) Chuck type.
(*ii*) Internal grinders.
  (*a*) Chuck type
  (*b*) Planetary (work stationary)
  (*c*) Centreless.
(*iii*) Surface grinders.
  (*a*) Reciprocating table
    (*i*) Horizontal spindle type
    (*ii*) Vertical spindle type
  (*b*) Rotating table
    (*i*) Horizontal spindle type
    (*ii*) Vertical spindle type.
(*iv*) Tool and cutter grinder
  (*a*) Universal
  (*b*) Special.

Precision grinding machines should be used with care and be operated by shilled personnel, such machine can be operated economically only if they have high use factor. As these machines are used to produce products that have close dimensional tolerances they must be constructed very accurately. Their frames should be heavy and rigid to assure permanency of alignment. Rotating parts should be accurately balanced to avoid vibration. Spindles should be mounted in very accurate bearings usually of the preloaded ball bearing type. Controls should be provided in order that all movements that determine dimensions of the workpiece can be made with accuracy. The abrasive dust produced during grinding should not enter between the moving parts.

5.6.1. Cylindrical grinders

Centre type cylindrical grinders are quite commonly used to produce external cylindrical surfaces. (Fig. 5.6). It is equipped with head-stock and tail-stock. The workpiece is mounted and rotated between centres. The grinding wheel rotates. Grinding wheel and the workpiece move in the opposite direction at their point of contact. The depth of cut is determined by the in feed of the wheel or workpiece. Provision is made to transverse the workpiece with respect to wheel. In large grinders the wheel is reciprocated because of the massiveness of work. The cylindrical grinder is provided with two tables. The upper table may be swiveled about a centre point for taper grinding. The lower table slides on ways on the bed and provides traverse of the work past the grinding wheel.

In cylindrical grinding two types of grinding is carried out.

(*i*) Traverse grinding
(*ii*) Plunge grinding.

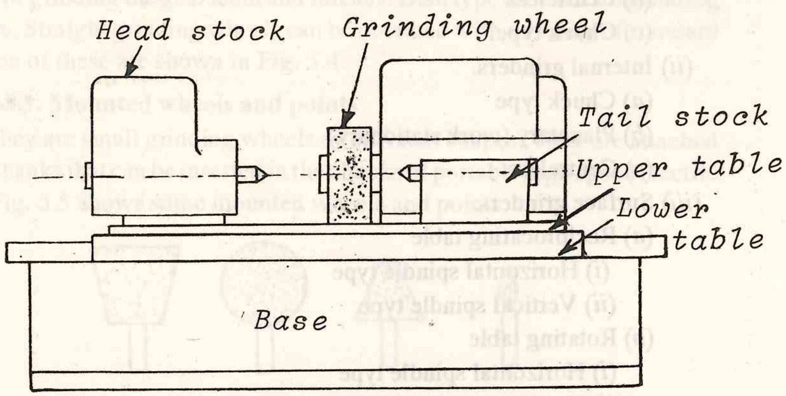


Fig. 5.6. Center-type cylindrical grinder.

In traverse grinding the work is reciprocated as the wheel feeds to produce cylinders longer than the width of wheel face. In plunge grinding the wheel is fed to the workpiece rotating in a fixed position and grinding is carried out on workpiece in a length equal to or shorter than the width of grinding wheel. This method is used in grinding for relatively short work and especially in form grinding. The output is very high in plunge grinding. Fig. 5.7 shows traverse grinding and plunge grinding is shown in Fig. 5.8.

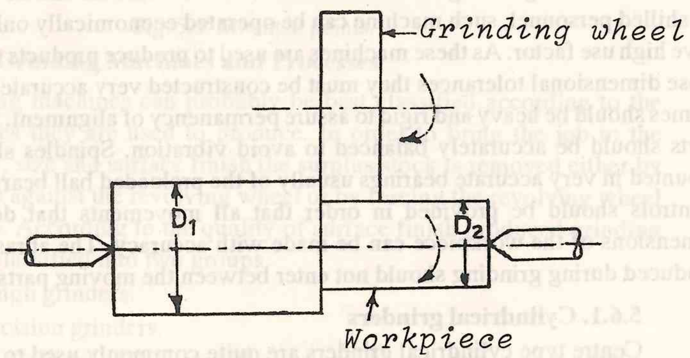


Fig. 5.7. Traverse grinding.

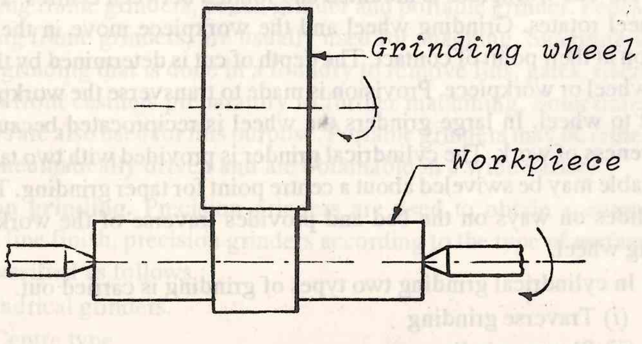


Fig. 5.8. Plunge grinding.

5.7. Depth of Cut

It is the thickness of metal removed by the grinding wheel in one traverse stroke (lengthwise)

$$t = \text{Depth of cut}$$
$$= \frac{D_1 - D_2}{2}$$

where D_1 = Diameter of workpiece before grinding

D_2 = Diameter of workpiece after grinding.

In finish grinding depth of cut is taken as 0.005 to 0.015 mm per stroke. Other conditions being equal the best surface finish is obtained in grinding with higher speeds of wheel rotation, lower rates of traverse, and smaller depths of cut.

5.8. Feed

In cylindrical grinding feed is the longitudinal movement of the workpiece per revolution.

$$f = \text{feed in mm per workpiece revolution.}$$
$$= K_1 B$$

where B = Face width of wheel in mm

K_1 = Constant

= 0.4 to 0.6 for finish grinding

= 0.6 to 0.9 for rough grinding

Work or table traverse in metre/minute

$$= \frac{f \times N}{1000}$$

where N = Workpiece speed in R.P.M.

5.9. Cutting Speed

It is relative speed of wheel (V_1) and the workpiece. It is expressed in m/sec.

$$V = \text{Cutting speed} = V_1 = \frac{\pi D N_1}{1000 \times 60}$$

where D = Diameter of grinding wheel in mm.

N_1 = Speed of wheel in R.P.M.

5.10. Machining Time

Machining time in traverse cylindrical grinding is given by the formula

$$T = \text{Machining time}$$

$$= \frac{L.h}{N.ft}.K$$

where L = Length ground in mm

h = Allowance on each side in mm.

f = Longitudinal feed in mm/rev.

N = R.P.M. of workpiece

t = Depth of cut (Rate of infeed per stroke) in mm.

K = Accuracy factor

= 1.1 for rough grinding

= 1.4 for finish grinding.

Fig. 5.9 shows an internal cylindrical grinder. It uses a chuck to hold the work with the grinding wheel revolving the table moves from right to left causing the wheel to enter the work and grind its internal surface.

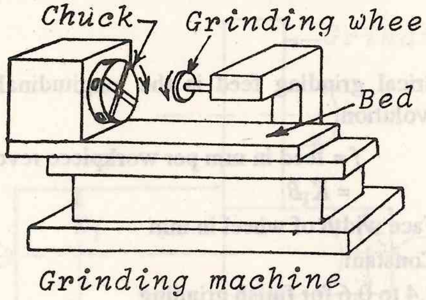


Fig. 5.9

5.11. Surface Grinders

Surface grinding is used mainly to machine flat surfaces. It can be performed either with the periphery of a straight wheel or the face of a cup, cylinder or segmental wheel. A surface grinder uses a magnetic chuck mounted on table to hold the workpieces. There are two basic types of surface grinding machines differing in movement of their tables and the orientation of the grinding wheel spindles.

1. Reciprocating surface grinders
   - (*i*) Horizontal wheel spindle and reciprocating table.
   - (*ii*) Vertical wheel spindle and reciprocating table.
2. Rotary surface grinders.
   - (*i*) Horizontal spindle and rotary table.
   - (*ii*) Vertical spindle and rotary table.

Reciprocating table surface grinder. The most common type of surface grinding machine is the one having a reciprocating table and horizontal spindle (Fig. 5.10). The table is mounted on horizontal way and can be reciprocated longitudinally either by hand wheel or by hydraulic powers. Cross feed is given by moving the wheel head in and out. Infeed is controlled by a hand wheel that lowers the grinding wheel towards the work. In such grinders usually the grinding wheel is mounted directly on the motor spindle. The size of the grinder is designated by the dimensions of the working area of table.

Reciprocating table surface grinder with vertical spindle (Fig. 5.11) is primarily used for production type work. In this grinder the wheel diameter should exceed the width of surface to be machined.

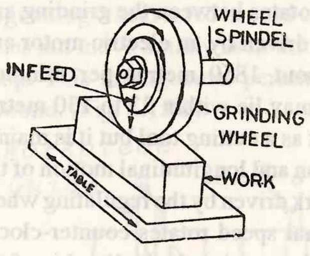


Fig. 5.10

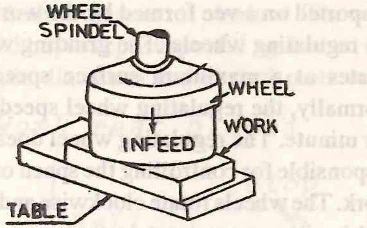


Fig. 5.11

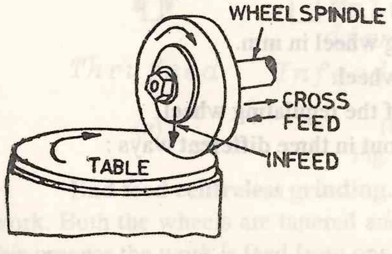


Fig. 5.12

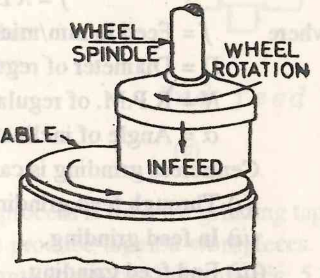


Fig. 5.13

Rotary table surface grinder. If horizontal spindle rotary table surface grinder (Fig. 5.12) the workpieces are arranged in a circle concentric with the round chuck. The table is made to rotate under revolving wheel both rotating in opposite direction. In vertical spindle rotary table surface grinder (Fig. 5.13) a cup wheel is used. Vertical feed to the wheel is given by moving wheel head.

5.12. Tool and Cutter Grinder

This grinder is used to sharpen cutting tool like milling cutters, drills, hobs, reamers taps and braches. The depth of cut in this grinder is quite small as the grinding is carried out dry to give the operator a good view. Generally cup and dish shaped grinding wheels are used in this machine. The wheels used are soft and cool cutting. For a carbide tipped tools diamond impregnated wheels are used.

5.13. Centreless Grinding

Centreless grinding makes it possible to grind both external and internal cylindrical surfaces without the necessity of the workpiece being mounted between centres in a chuck. The principle of centreless external grinding is shown in Fig. 5.14. In centreless grinding two wheels are used. The larger wheel called grinding wheel operates as regular grinding speeds and does the actual grinding. The small wheel called regulating wheel is mounted at an angle to the plane of grinding wheel. The work with its both ends freely supported on a vee formed by the work rest, rotates between the grinding and the regulating wheels. The grinding wheel is driven by an electric motor and rotates at a maximum surface speed of about 1850 metres per minutes. Normally, the regulating wheel speed range may lie within 33 to 130 metres per minute. The regulating wheel does not act as a cutting tool but it is mainly responsible for controlling the speed of rotation and longitudinal motion of the work. The wheels rotate clockwise and the work driven by the regulating wheel and having approximately the same peripheral speed rotates counter-clockwise. Axial traverse of the work is controlled by varying the inclination of the regulating wheel. The axial feed is approximately calculated by the formula :

$$f = \pi DN \sin \alpha.$$

where f = Feed in mm/minute.
D = Diameter of regulating wheel in mm.
N = R.P.M. of regulating wheel.
α = Angle of inclination of the regulating wheel.

Centreless grinding is carried out in three different ways :

(*i*) Through feed grinding.
(*ii*) In feed grinding.
(*iii*) End feed grinding.

Through feed grinding. Through feed grinding is normally used for grinding plain cylindrical workpieces. In this process the work is automatically fed through continuously between the grinding wheel and the regulating wheel which have already been set with a particular gap. The grinding starts as soon as the work enters the grinding wheels and grinding of work is complete as soon as it comes out of the wheels. Since the work has to remain outside the wheels before and after grinding operation suitable supports or guides are provided. (Fig. 5.15 *a*).

Infeed Centreless grinding. In this process the work rest and the regulating wheel are retracted so that the work can be put in position and removed when grinding is completed. When the work is in position the regulating wheel is fed inward until the desired diameter is obtained. The work does not move axially as in through feed but is kept supported against an end stop. This arrangement permits multiple diameters and curved parts to be ground. (Fig. 5.15 *b*).

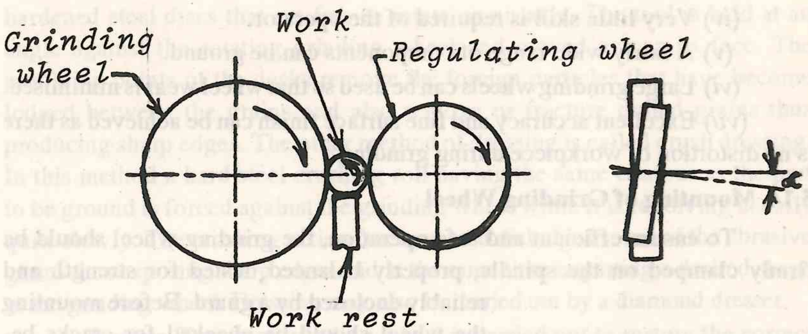
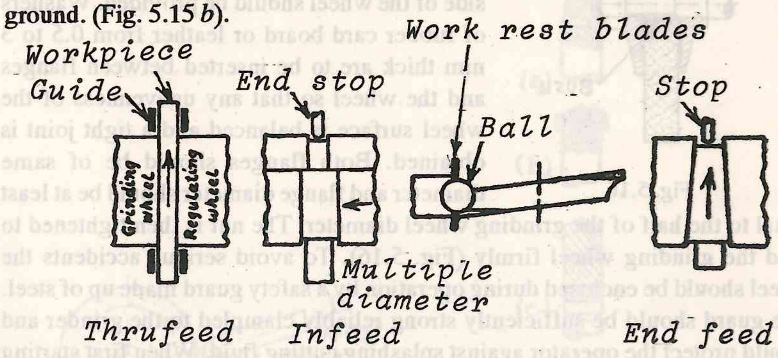


Fig. 5.14



(*a*) (*b*) (c)

Fig. 5.15

End feed centreless grinding. This process is used for grinding taper work. Both the wheels are tapered and thus produce tapered workpieces. In this process the work is feed from one side until it reaches the stop. Fig. 5.15 (*c*) shows the work being ground by the end feed method.

Advantages. Various advantages of centreless grinding are as follows :

(*i*) Work chucking and its centring is not required. This saves setting time. Further errors associated with centering are absent and thus grinding allowance can be reduced.

(*ii*) The work-piece is supported rigidly during the operation and therefore no deflection takes place during grinding. This allows heavier cuts to be taken resulting in economical grinding.

(*iii*) It is very rapid process. Frequently it can be made automatic.

(*iv*) Very little skill is required of the operator.

(*v*) A fairly wide range of components can be ground.

(*vi*) Large grinding wheels can be used so that wheel wear is minimised.

(*vii*) Excellent accuracy and fine surface finish can be achieved as there is no distortion of workpiece during grinding.

5.14. Mounting of Grinding Wheel

To ensure efficient and safe operation, the grinding wheel should be firmly clamped on the spindle, properly balanced, tested for strength and reliably enclosed by a guard. Before mounting the wheel should be checked for cracks because they may not be seen. For this sound the wheel cracks. If the wheel is not cracked it will give off a dull ringing sound. The wheel should be fit freely on the sleeve. One flange on each side of the wheel should be provided. Washers of rubber card board or leather from 0.5 to 3 mm thick are to be inserted between flanges and the wheel so that any unevenness of the wheel surface is balanced and a tight joint is obtained. Both flanges should be of same diameter and flange diameter should be at least equal to the half of the grinding wheel diameter. The nut is then tightened to hold the grinding wheel firmly (Fig. 5.16). To avoid serious accidents the wheel should be enclosed during operation by a safety guard made up of steel. The guard should be sufficiently strong reliably clampled to the grinder and should protect the operator against splashing cutting fluid. When first starting the wheel, the operator should stand aside and allow the wheel to come to the speed before attempting any grinding.

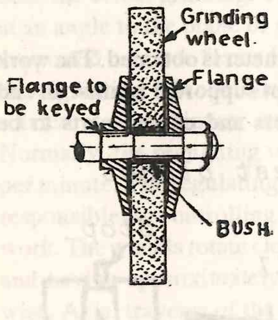


Fig. 5.16

5.15. Dressing and Truing

Grinding wheels must be occasionally dressed or trued to remove dull grains of abrasive and metal particles to resorb the original shape and accuracy of the wheel face.

During grinding operation the grains of the wheel are subjected to wear and the wheel loses its cutting capacity. Along with grain wear another factor that reduces the cut properties of a grinding wheel is the loading of the voids between the grains with the waste material of the grinding process such as sintered metal dust, abrasive grit and particles of bonding material. A worn and loaded wheel ceases to cut properly. This requires sharpening of grinding wheel in order to restore sharp cutting edges and to unload the grinding wheel.

Dressing removes the worn grains and the waste products of grinding. Dressing is carried out by a steel dressing tool consisting of irregularly shaped hardened steel discs that are free to rotate on an axle. The tool is held at an angle against the rotating grinding wheel and moved across its face. The revolving points of the desks remove the foreign particles that have become lodged between the grains and also remove or fracture dulled grains thus producing sharp edges. The other method of dressing is called crush dressing. In this method a hard steel crushing roll having the same contour as the part to be ground is forced against the grinding wheel while it is revolving usually quite slowly. The crushing action fractures and dislodges some of the abrasive grains thus exposing sharp edges and at the same time imparting a desired shape to the grinding wheel. Dressing may also be carried out by a diamond dresser.

Truing. Truing of grinding wheel is carried out to restore the correct geometric shape of the wheel which has been lost due to non-uniform wear. Truing makes the face of the wheel concentric and the sides plane and parallel. Truing is carried out by means of a diamond dresser. The dresser being held at an angle of 10° to 15° to the wheel face (Fig. 5.17). Diamond wheels are not dressed, they are trued when their shape is no longer sufficiently accurate. Metal bonded diamond wheels are trued with a green silicon carbide dressing stick having a vitrified bond. Fig. 5.18 shows mounted diamonds for truing grinding wheels. During grinding of hard materials the abrasive grains dull more quickly than in grinding soft materials. Therefore wheel for grinding hard materials should lose its grains rapidly. Thus softer grade wheels are used for grinding hard materials and harder grade wheels for soft materials.

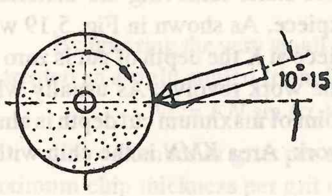


Fig. 5.17

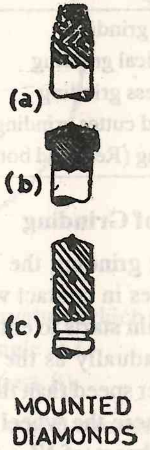


Fig. 5.18

5.16. Grinding Wheel Balancing

All the wheels should be tested for balance periodically. Because of high rotative speeds involved, a slight unbalance will produce vibrations that