Cutting forces, Power Consumption , and Removal Rate of machine tool

The main (cutting) force F_v (Newton) in the direction of the cutting speed V can be calculated from

$$F_v = k_s A_c \left(N\right)$$

Where k_s is the specific cutting energy in N/mm^2. Hence, the cutting power N_c in kW becomes

$$N_c = \frac{F_v V}{60 \times 10^3} \left(kW\right)$$

Extra power N_{fg}, is required to overcome friction in the guideways. Therefore, the total power N_t becomes

$$N_t = N_c + N_{fg}$$

For the shaper machine, N_{fg} becomes

$$N_{fg} = \frac{\left(W - F_p\right)\mu_s V}{60{,}000}$$

For planning,

$$N_{fg} = \frac{\left(W + G_w + F_p\right)\mu_s V}{60{,}000}$$

Where

F_v is the main cutting force (in the direction of the cutting force V) in N

V is the cutting speed in m/min

W is the weight of the shaper ram/planer table in N

G_w is the weight of the shaper ram/planner table in N

F_p is the vertical component of the cutting force in N

μ_s is the coefficient of friction in the guideways (0.1- 0.3)

The motor power required can be calculated on the basis of the cutting power N_c as

$$N_m = \frac{F_v V}{60 \times 10^3 \ \eta_m} \left(kW\right)$$

Where η_m is the efficiency of the machine used in the cutting process.

The maximum cutting force F_{vx} is achieved when the total motor power N_m is utilized in the machining process. Therefore,

$$F_{vx} = \frac{60 \times 10^3 \eta_m N_m}{V} (N)$$

Feed rates and rotational speeds should consequently be selected such that F_v is less than F_{vx}.

For a given feed rate S, the maximum possible depth of cut, t_x, becomes

$$t_x = \frac{60 \times 10^3 \eta_m N_m}{VS} (mm)$$

The rate of material removal (VRR) inn mm^3/min is given by

$$VRR = 10^3 VSt\ (mm^3/min)$$

where V is the cutting speed in m/min, which for the shaper machine with a rocker arm mechanism, is measured at the middle of the stroke, it is given by

$$V = 10^{-3} NH_s \left(1 + \frac{1}{r_s}\right) (m/\min)$$

Where

H_s is the length of machining stroke in mm, which is normally taken as 1.2 times the length of the machined workpiece

r_s is the ratio between the return speed v_r and the cutting speed V.

Shaping Time

The time for shaping a length l times a width B is determined by

$$t_m = \frac{B}{SN} (\min)$$

where

B is the total machining width in mm

S is the feed rate in mm/stroke

N is the speed of reciprocation in stroke/min

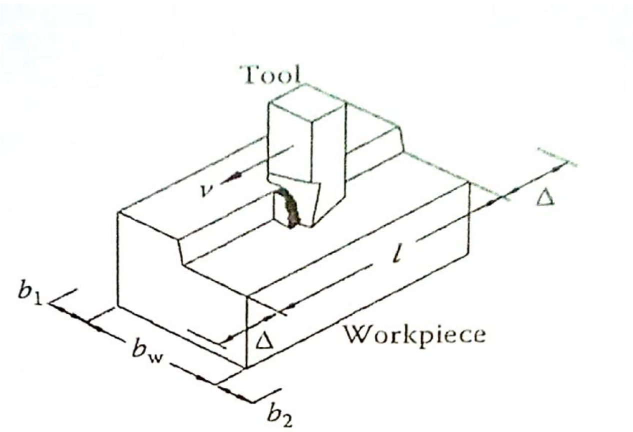
As shown in Figure below, the total width B can be expressed by

$$B = b_w + b_1 + b_2\ (mm)$$

Where b_1 and b_2 are the width allowances, which are taken as 5mm

$$N = \frac{10^3 V}{H_s\left(1+\left(1/r_s\right)\right)} \left(stroke/\min\right)$$

$$H_s = 1 + 2\Delta$$



Elements of shaping

$$\Delta = 0.1 \times 1$$

Where l is work piece length in mm. therefore, the machining time t_m becomes

$$t_m = \frac{(b_w + b_1 + b_2) H_s \left(1 + (1 + (^1/_{r_s})\right)}{10^3 SV} \quad \text{(min)}$$

Selection of Cutting Variables

1. Determine the depth of cut
2. Select the feed rate
3. Select the cutting speed permitted by the cutting tool
4. Calculate the number of strokes/min, correct for the available values and then calculate the actual cutting speed
5. Check for the available power $N_m > N_c$; otherwise, reduce the cutting speed and then the feed rate.
6. Check that the vertical component of forces is less than or equal to the minimum force developed by the ram.

Example

A shaper is operated at 2 cutting strokes/s and is used to machine a workpiece of 150mm in length at a feed of 0.4 mm/stroke and depth of cut of 6mm. Calculate

1. The cutting speed
2. The total machining time to produce 100 components each of 100 mm in width if $r_s = 2$
3. The material removal rate

Solution

a. Given than N = 2 stroke/s, l = 150mm, S = 0.4mm/stroke, b= 100mm, and t= 6mm, the length of stroke H_s is given by

$$H_s = l + 2\Delta$$

$$H_s = l + 0.2\, x\, l = 150 + 30 = 180 mm$$

The cutting speed, V, is therefore

$$V = 10^{-3} NH\left(1 + \frac{1}{r_s}\right)$$

$$N = 2 \times 60 = 120 \, stroke/\min$$

$$V = 10^{-3} \times 120 \times 180 \left(1 + \frac{1}{2}\right)$$

$$V = 32.4 m/\min$$

$$t_m = \frac{B}{SN} = \frac{b+5+5}{SN} = \frac{100+5+5}{0.4 \times 120} = 2.29 \min$$

b. For machining 100 piece, the total machining time is given by

$$\text{Total } t_m = 2.29 \times 100 = 229 \min$$

c. The volumetric removal rate (VRR) is

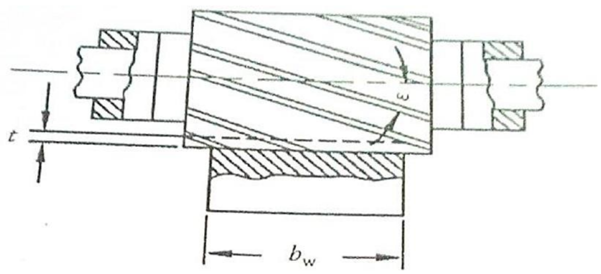
$$\text{VRR} = 10^3 \text{VSt}$$

$$\text{VRR} = 32.4 \times 10^3 \times 0.4 \times 6$$

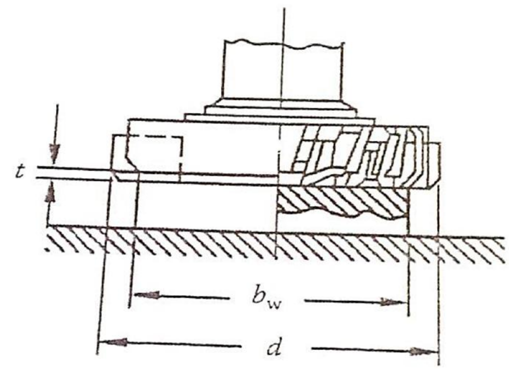
$$\text{VRR} = 77{,}760 \text{ mm}^3/\text{min}$$

Milling

Milling is a machining process where the cutting tool carries out a rotary motion and the workpiece a rectilinear motion. The process is used to machine external surfaces, slots, and contoured surfaces using multitoothed milling cutters or end mills. Milling cutters are also available for cutting surfaces of revolution, cutting off metals, machining threads, and cutting gears as shown below



Plain-milling cutter



Face-milling cutter

During milling, the process of cutting by each tooth is periodically interrupted and the traverse cross section of the undeformed chip is not constant. The principal types of milling processes are horizontal (peripheral or plain) milling and vertical milling:

Horizontal (plain) milling: In this type of milling

- The cutting teeth are arranged on the surface of the cylindrical tool.
- There is a contact between the cylindrical surface of the cutter and the machined surface
- The machined surface is parallel to the cutter's axis of rotation.

Vertical (face) milling: this type has the following features:

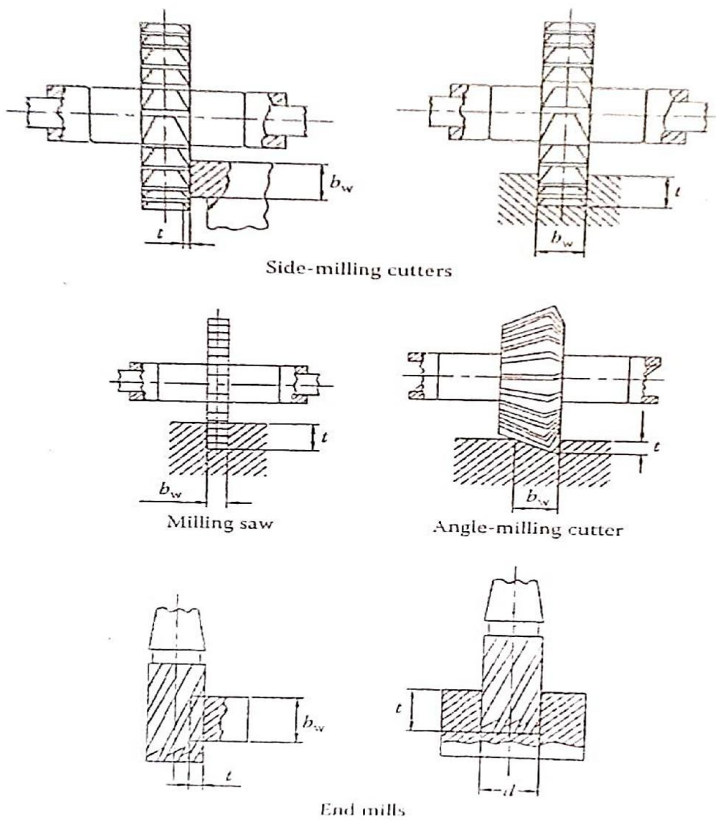
- The cutting edges are situated both on the face of the end mill and on its cylindrical surface.
- There is a contact between the face of the milling cutter and the machined surface
- The milled surface is generated at right angle to the cutter axis of rotation.

Milling cutters with cutting edges that are situated on the face and on a large part of the cylindrical surface are called shell end mills.

Horizontal (Plain) Milling

Depending on the direction of cutter rotation with respect to the movement of the workpiece, plain milling is divided into up and down milling operations .

Up (conventional) milling: In this case, the direction of workpiece feed, f, is opposing the direction of the milling cutter rotation, N (Figure 18a).



Different types of milling cutters

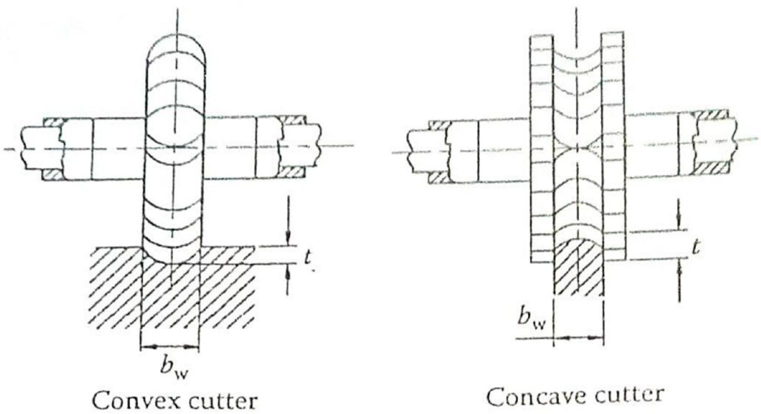
The chip varies from a minimum value at the tooth entry to a maximum thickness at the tooth exit. The forces acting on the workpiece are directed upward. Up milling possesses the following advantages :

- Does not require a backlash eliminator in the milling machine.
- Safer in operation due to the separating forces between the cutter and workpiece
- Fragments or built-up edge (BUE) are absent from the milled surfaces.
- The life of the cutter is not affected by the sandy or scaly surfaces.
- Loads are not acting suddenly on the teeth.
- Looseness in moving parts is not detrimental to the cutting motion.

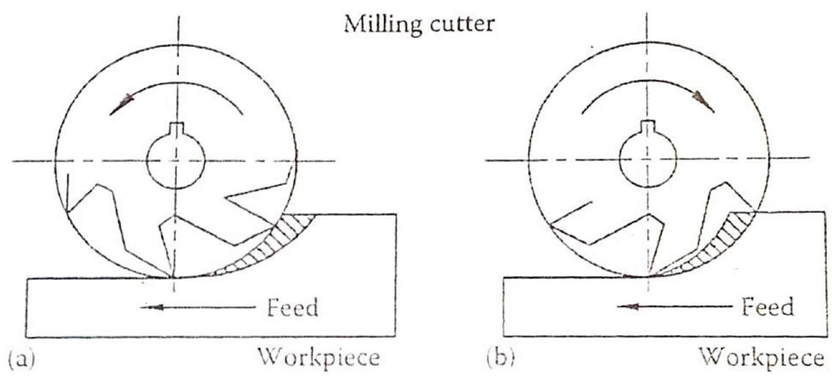
Down milling: In this case, the cutter rotation is in the direction of workpiece feed as shown in Figure 18 b. The chip thickness varies from a maximum value at the tooth entry to a minimum value at the tooth exit. The forces in down milling are directed downward. The advantages of down milling are:

- It is possible to use simplified fixtures to mill parts that cannot be easily held on the machine.
- Milled surfaces are not affected by the revolution marks and are easily polished
- The method requires lower machining power

- The tendency of vibrations and chattering is low
- Cutting edge blunting is less possible



Form milling cutters



Up and down milling arrangements (a) Up milling and (b) down milling

Generally, down milling is preferred because it provides favourable cutting conditions that lead to better surface quality. However, it requires more rigid equipment without looseness in the feeding mechanism because the cutter tends to climb on the workpiece.

Cutting speed of Tool and Workpiece Feed

The cutting speed V is the peripheral speed of the cutter rotary motion:

$$V = \frac{\pi d N}{1000} \quad (\text{m/min})$$

where

d is the outer diameter of the milling cutter in mm

N is the rotational speed in rev/min

The feed motion of the workpiece may be linear, curvilinear, or helical (gears and threads). For a linear workpiece motion, a feed rate f in mm/min, and a milling cutter having Z_C teeth, the feed per revolution, S, equals

$$S = \frac{f}{N} \quad \text{(mm/rev)}$$

The feed per tooth S_z in mm/tooth becomes

$$S_z = \frac{f}{NZ_c} \, \text{(mm/tooth)}$$

Values of feed per tooth, S_z , are usually smaller than those normally used in turning and planing operations.

Forces and Power in Milling

The maximum tangential force on a single tooth, F_e, is

$$F_e = k_s b_w h_e \left(N / tooth\right)$$

$$F_e = k_s b_w \frac{2f}{NZ_c}\sqrt{\frac{t}{d}}\left(N / tooth\right)$$

The mean tangential cutting force, F_m, becomes

$$F_m = k_s b_w h_m \left(N / tooth\right)$$

where h_m is mean chip thickness

$$F_m = k_s b_w \frac{f}{NZ_c}\sqrt{\frac{t}{d}}\left(N / tooth\right)$$

The number of teeth cutting at the same time, Z_e, is given by

$$Z_e = \frac{\bar{\phi}_c}{2\pi} Z_c$$

Because

$$\bar{\phi}_c = \sin \phi_c$$

$$Z_e = \frac{Z_c}{\pi}\sqrt{\frac{t}{d}}$$

Where

ϕ_c is the contact angle

Z_c is the number of cutter teeth

The total mean cutting (tangential) force, F_{mt}, caused by the effective number of teeth Z_c, becomes

$$F_{mt} = \frac{k_s t f b_w}{\pi d N}(N)$$

Variation of cutting forces with time: During plan up milling, the thickness of the chip to be cut by each tooth increases from zero to a certain maximum value and decreases to zero again. This means that the cutting forces will are in the same trend. Better uniformity of tooth loading and quick work is obtained by increasing the number of teeth cutting at one time or by using helical teeth. The mean cutting power N_c in kW is calculated as follows:

$$N_c = \frac{F_{mt} V}{60 \times 10^3}(kW)$$

Example

In horizontal milling, if d =144 mm, Z_c=10 teeth, t = 4mm, V = 50 m/min, S_z = 0.12 mm/tooth, b_w = 40mm, and k_s = 2500 N/mm^2, calculate

1. The maximum tangential force on a single tooth
2. The mean cutting power

Solution

a. The maximum hip thickness, h_e, is

$$h_e = 2 S_z \sqrt{\frac{t}{d}}$$

$$h_e = 2 \times 0.12 \sqrt{\frac{4}{144}} = 0.04 mm$$

The maximum tangential force on a single tooth F_e, is therefore

$$F_e = k_s b_w h_e$$
$$F_e = 2500 \times 40 \times 0.04 = 4000 N$$

b. The mean cutting power N_c is

$$N = \frac{1000V}{\pi d} = \frac{1000 \times 50}{\pi \times 144} = 110.58\, rpm$$

$$f = S_z Z_c N = 0.12 \times 10 \times 110.58 = 132.7\, mm/\min$$

Therefore

$$F_{mt} = \frac{k_s t f b_w}{\pi d N} = \frac{2500 \times 4 \times 132.7 \times 40}{\pi \times 144 \times 110.58} = 1061.6N$$

$$N_c = \frac{F_{mt V}}{60 \times 10^3} = \frac{1061.1 \times 50}{60,000} = 0.88kW$$