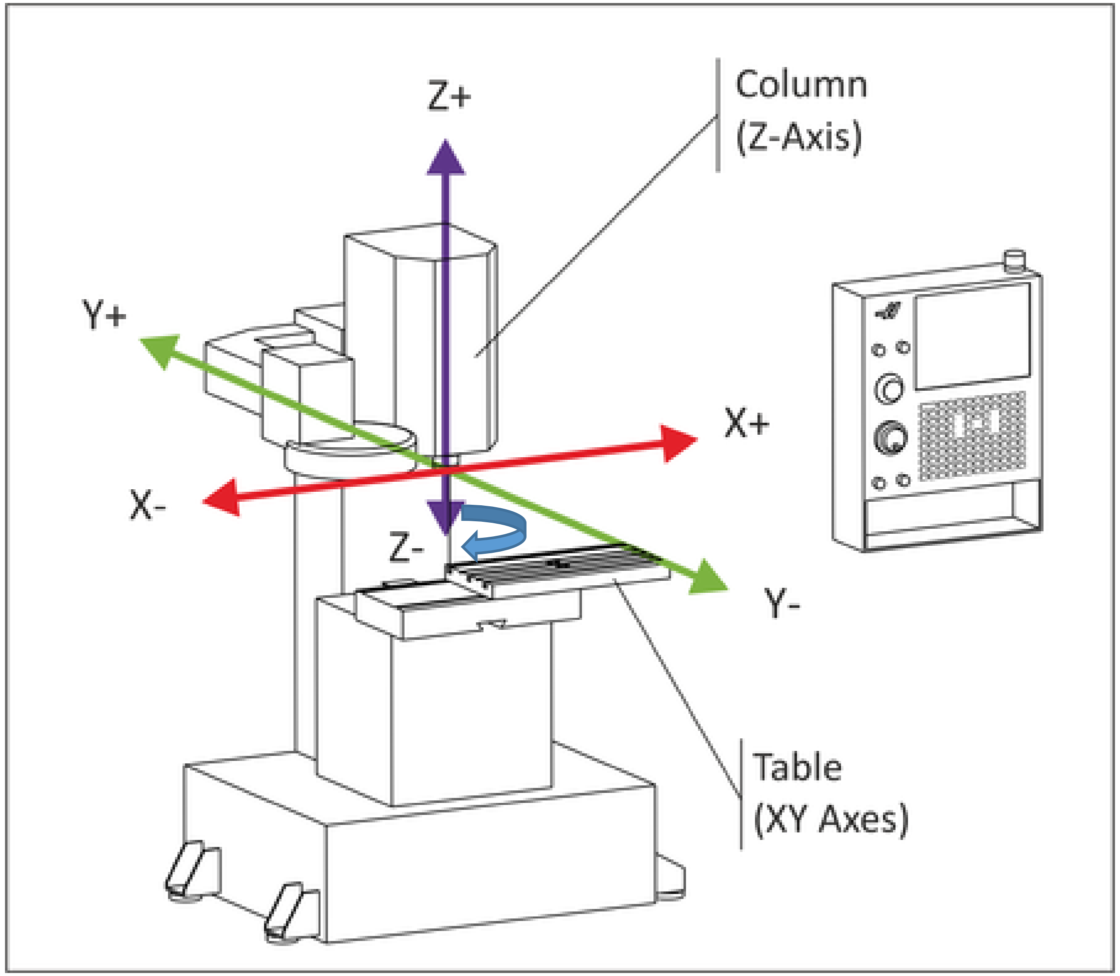
MILLING OPERATION

Milling operation

- Milling is a machining operation in which a workpiece is feed past a rotating cylindrical tool with multiple cutting edges.
- This cutting tool in milling is known as milling cutter and the machine tool that traditionally performs the operation is called milling machine.
- Milling is an interrupted cutting operation, the teeth of milling cutter enter and exit the work during each revolution.

https://www.youtube.com/watch?v=9_iOGGC70mQ
https://www.youtube.com/watch?v=v4pWjZbT0RI
https://www.youtube.com/watch?v=2y_OJv-K0E8

Milling operation



https://www.youtube.com/watch?v=CqePrbeAQoM

Milling operation

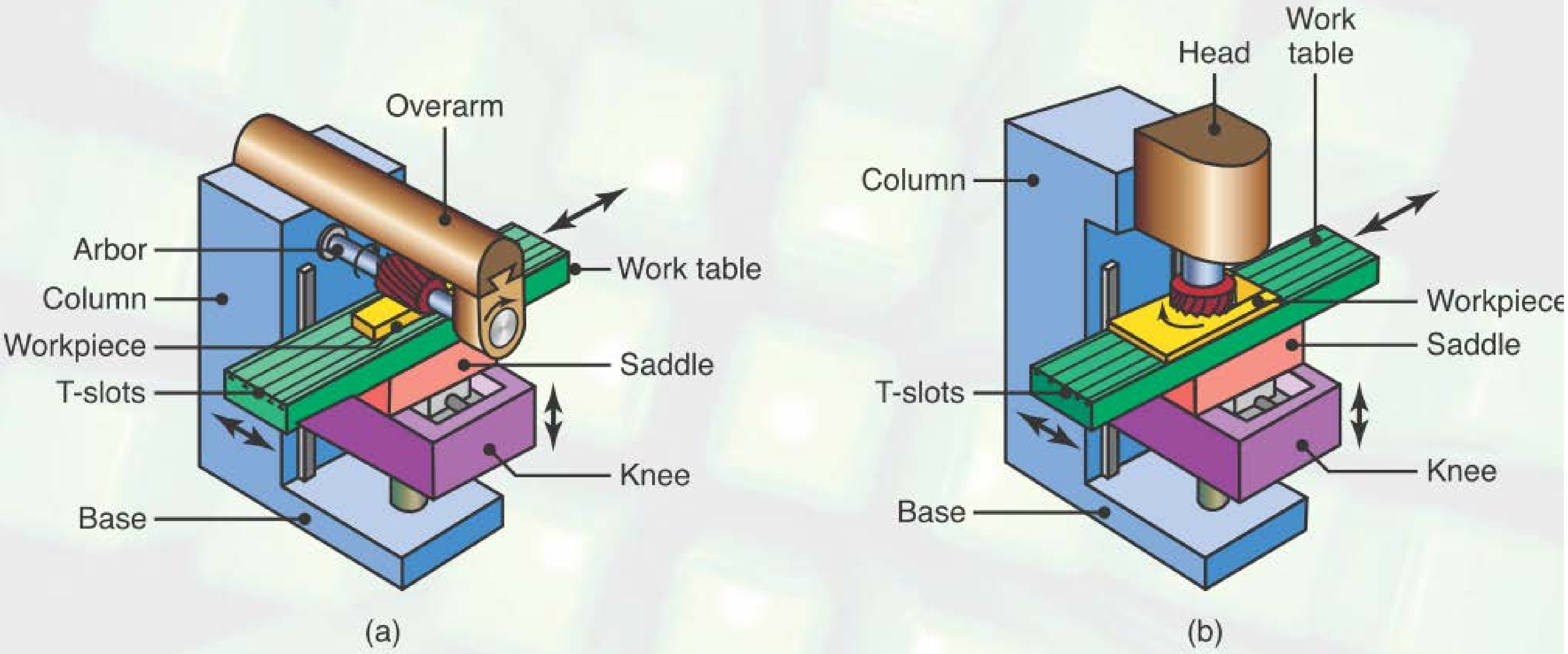


FIGURE 8.59 (a) Schematic illustration of a horizontal-spindle column-and-knee-type milling machine. (b) Schematic illustration of a vertical-spindle column-and-knee-type milling machine. *Source:* After G. Boothroyd.

Manufacturing Processes for Engineering Materials, 5th ed.
Kalpakjian • Schmid

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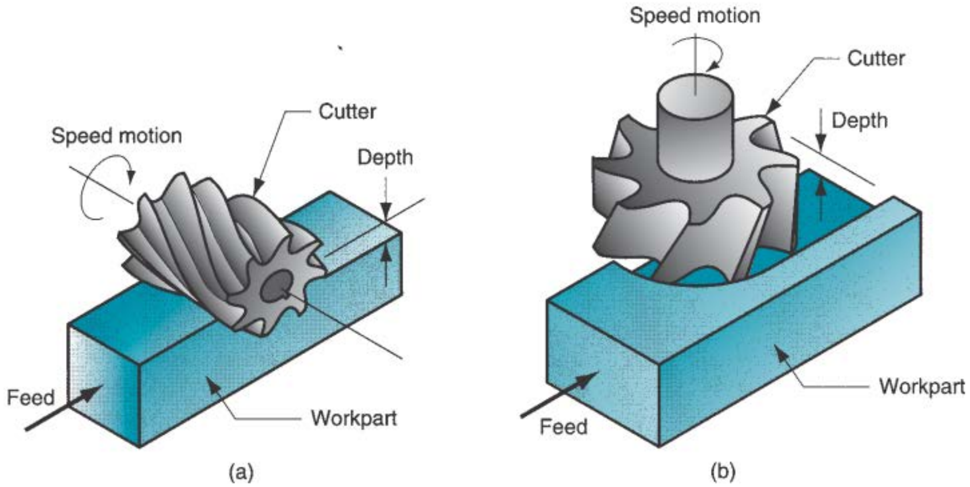
Types of milling operations

There are two basic types of milling operations peripheral or slab milling (horizontal milling) and face milling (vertical milling).

Peripheral or slab milling

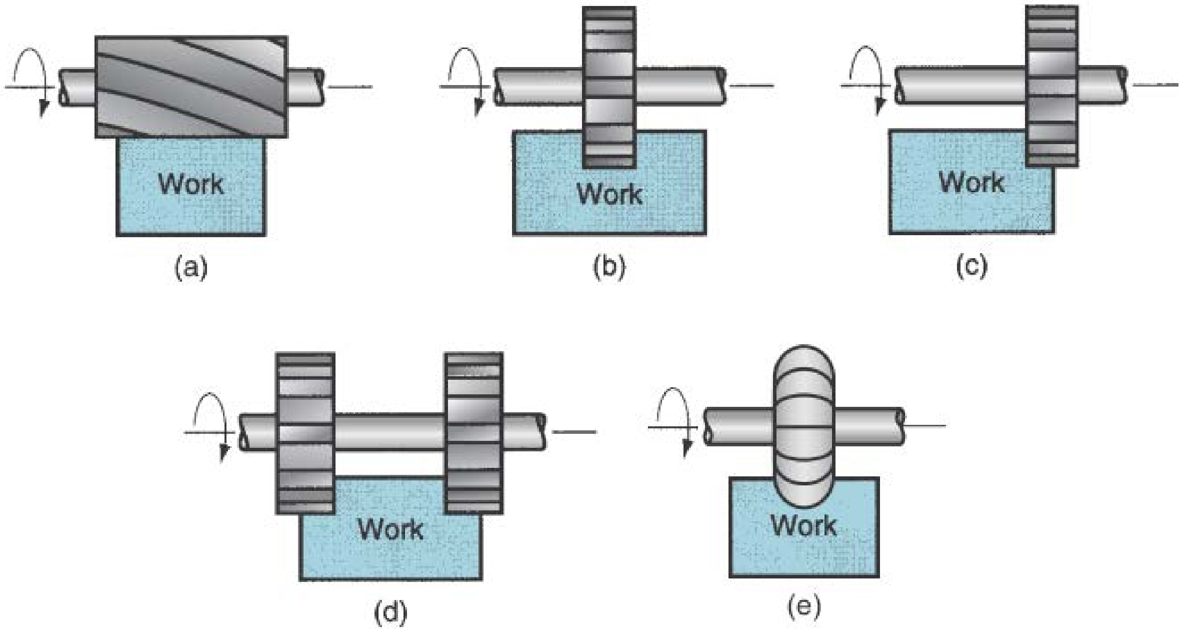
In this milling operation the axis of tool is parallel to the surface being machined. In this operation there are two opposite directions of rotation that the cutter can have with respect to the work.



(a) Peripheral milling operation, (b) face milling

https://www.youtube.com/watch?v=2y_OJv-K0E8

Peripheral or slab milling operations



Peripheral milling: (a) slab milling, (b) slotting, (c) side milling, (d) straddle milling, and (e) form milling.

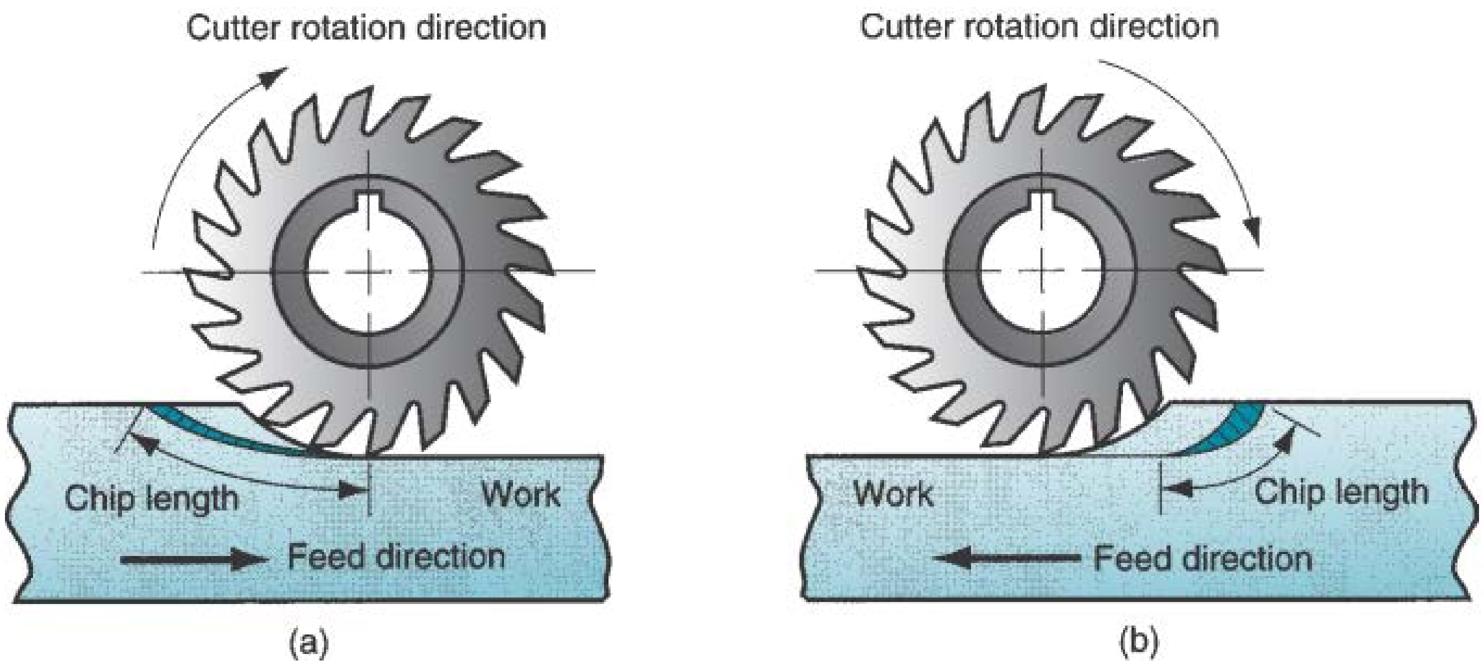
Types of peripheral or slab milling

Up milling: In up milling the direction of motion of the cutter teeth is opposite to the feed direction. In this type of milling operation, the chip formed by each cutter tooth starts out very thin and increases in thickness during the sweep of the cutter. The chip length is longer than in down milling.

Down milling: In down milling, the direction of motion of the cutter teeth is same as the feed direction. In this operation each chip starts out thick and reduces in thickness throughout the cut.

https://www.youtube.com/watch?v=ss475wvN1Qg

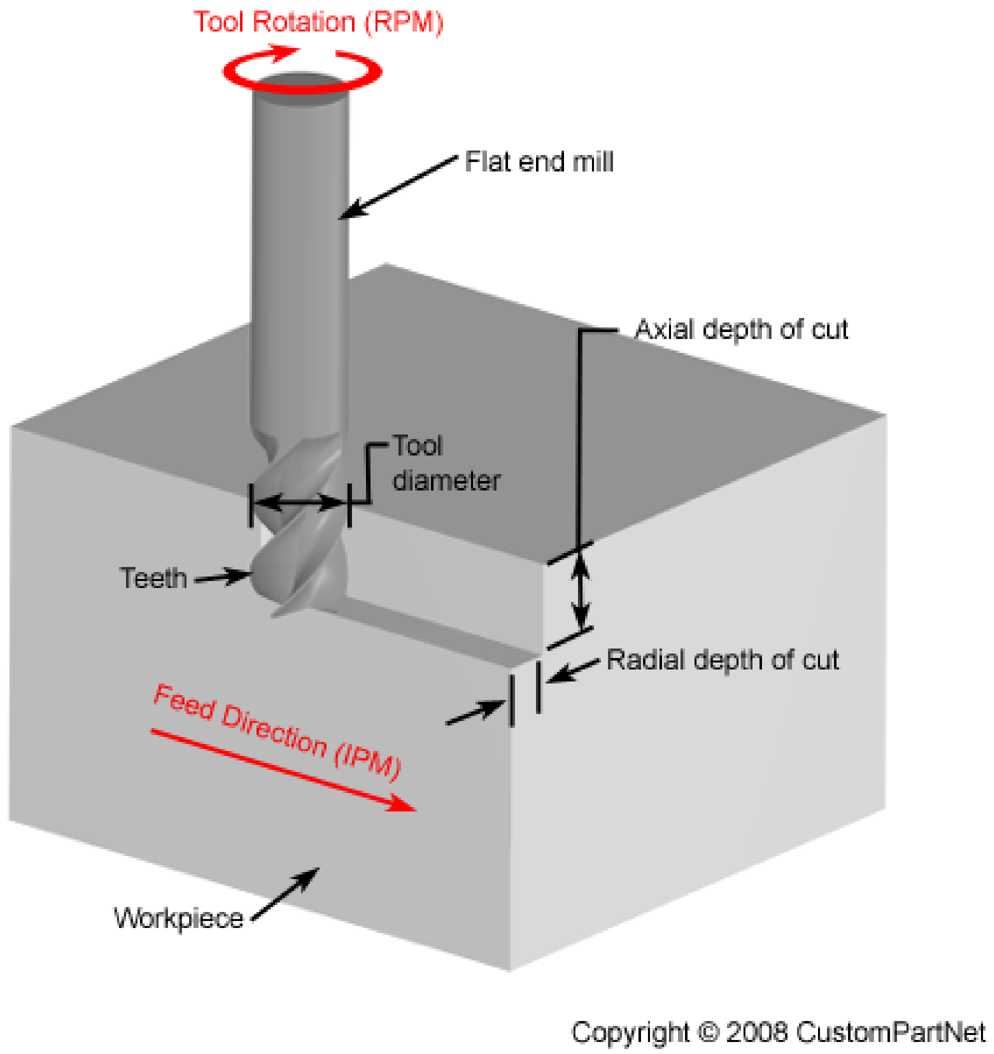
Types of peripheral or slab milling



Two forms of peripheral milling operation with a 20-teeth cutter: (a) up milling, and (b) down milling.

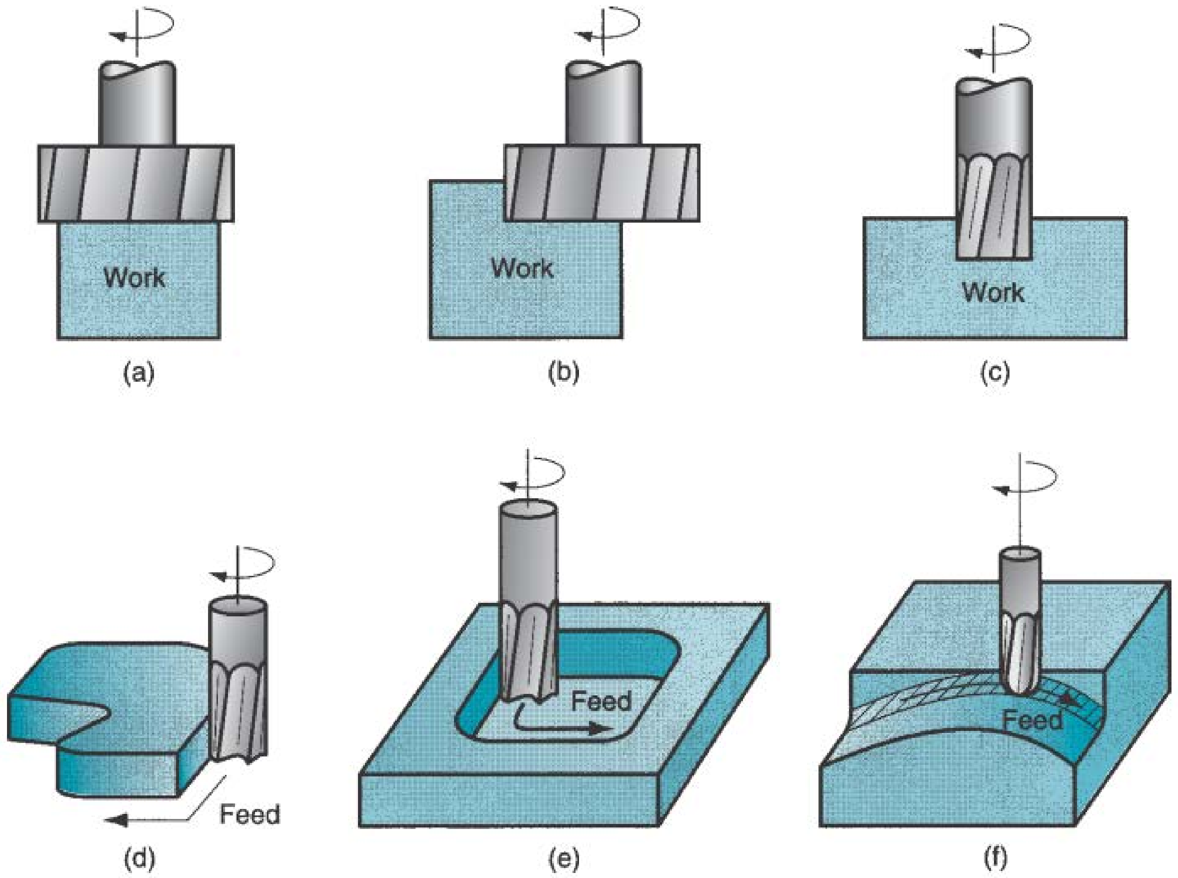
Face milling

In face milling the axis of the cutter is perpendicular to the surface being milled, as shown in the figure 6.5.



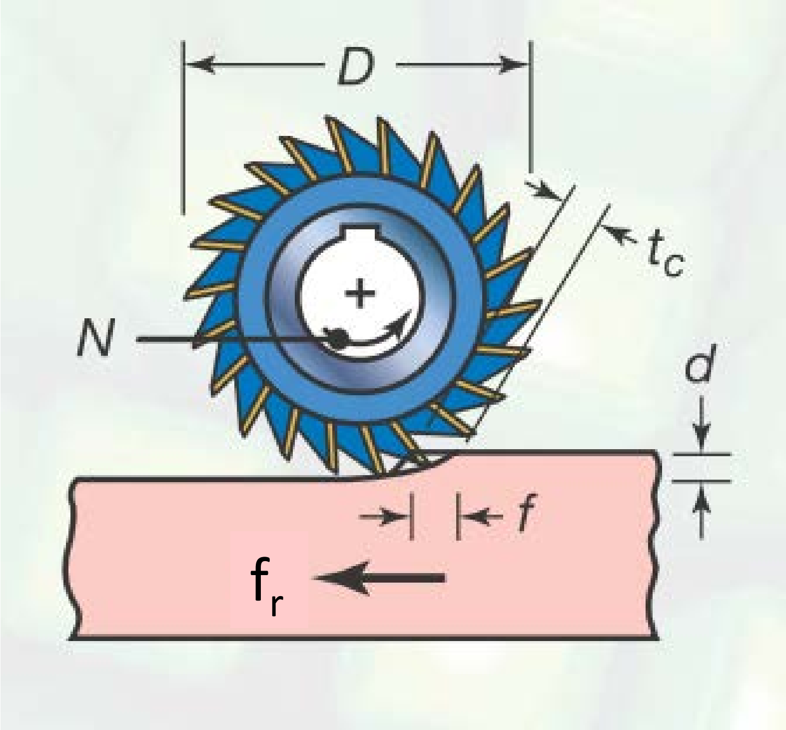
Face milling

Face milling operations

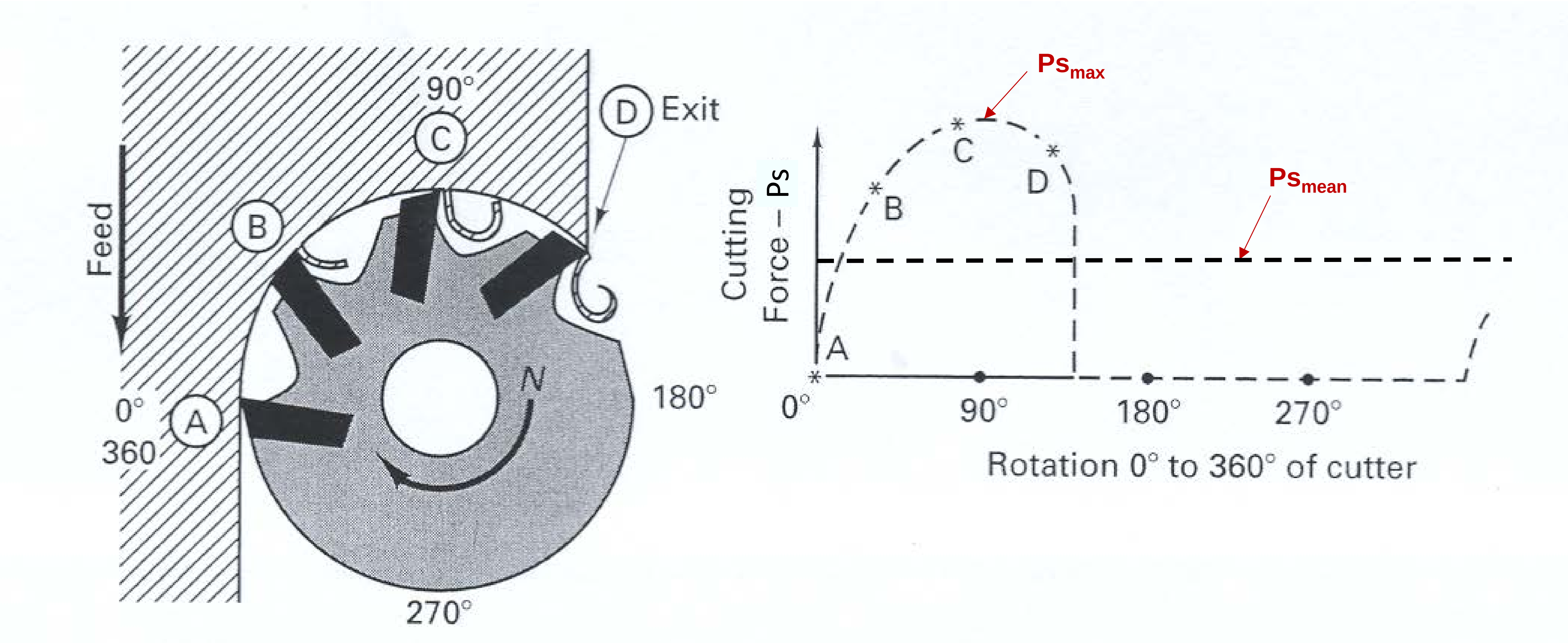


Face milling: (a) conventional facemilling,(b)partialface milling, (c) end milling, (d) profile milling, (e) pocket milling, and (f) surface contouring.

Cutting conditions in milling



Cutting conditions in milling



Conventional face milling with cutting force diagram for Fc, showing the interrupted nature of process.

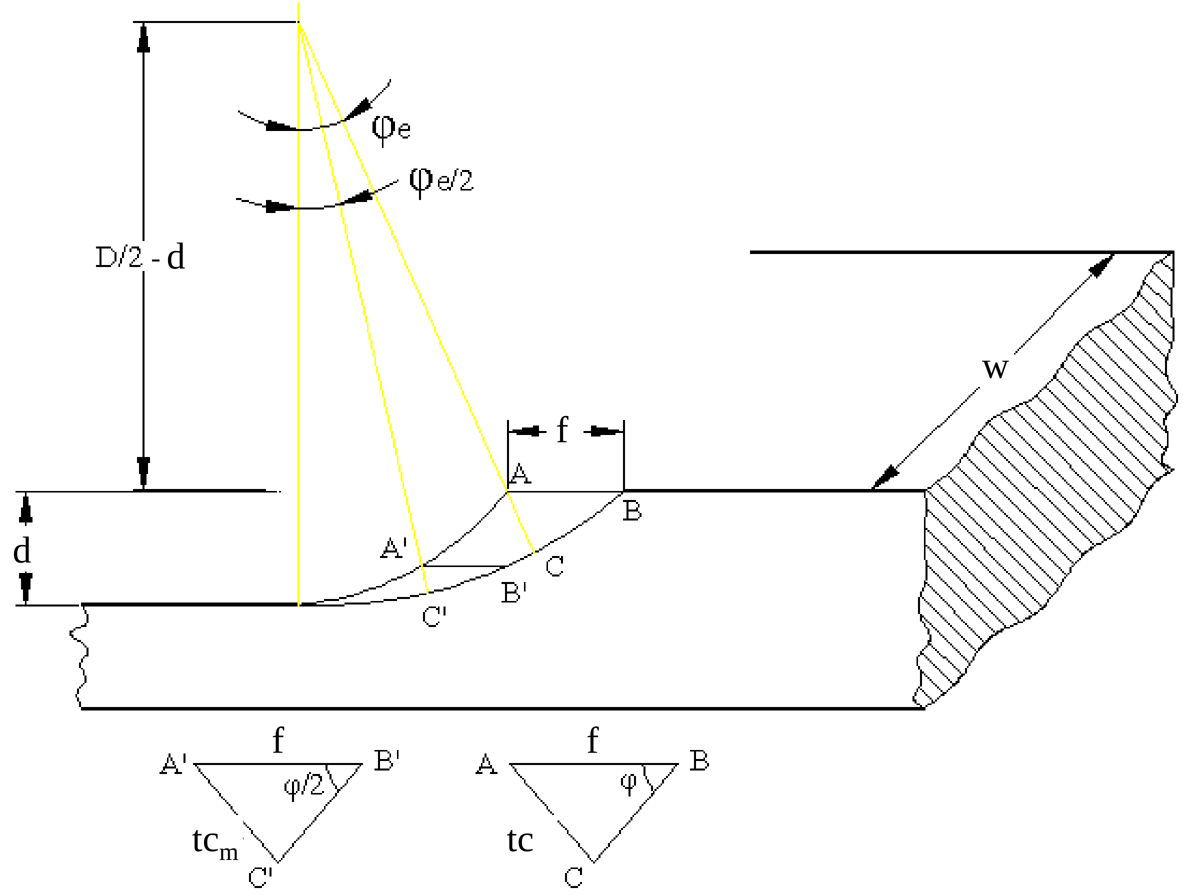
Cutting conditions in milling

The cutting speed is determined at the outside diameter of a milling cutter. This can be converted to spindle rotation speed.

$$N = \frac{V}{\pi D}$$

Cutting conditions in milling

The milling operation is characterized by the changing of chip thickness as the cutting proceeds. Therefore the maximum and mean values of chip thickness are to be calculated.



Symbols key

tc = maximum chip thickness

tc$_m$ = mean chip thickness

f = feed rate in mm/tooth

w = width of the cut

D = diameter of the cutter

d = depth of the cut

φ_e= engagement angle

Chip thickness (tc) detail in milling operation.

Cutting conditions in milling

Since the chip thickness is an important factor for calculating the cutter forces and power, therefore the maximum and mean values of chip thickness will be calculated.

$$tc = f \sin\varphi_e = \frac{f_r}{N * z} * \sin\varphi_e$$

$$tc_m = 1/2tc$$

Where

f = feed of workpiece mm/tooth = f_r/(N*z)

φ_e = angle of rotation of milling cutter during which each tooth remains engaged in workpiece material

f_r = feed of workpiece in mm/min

n = rotational speed of cutter in rpm

z = number of teeth on cutter

since φ_e is small such that sin φ_e = φ_e

$$\sin\varphi_e = \frac{\sqrt{(D/2)^2 - (D/2 - d)^2}}{D/2} = 2\sqrt{d/D}$$

Cutting conditions in milling

Substituting the values of $\sin\varphi_e$

$$tc = \frac{2f_r}{N \times z}\sqrt{d/D}$$

$$tc_m = \frac{f_r}{N \times z}\sqrt{d/D}$$

Cutting forces and power in milling

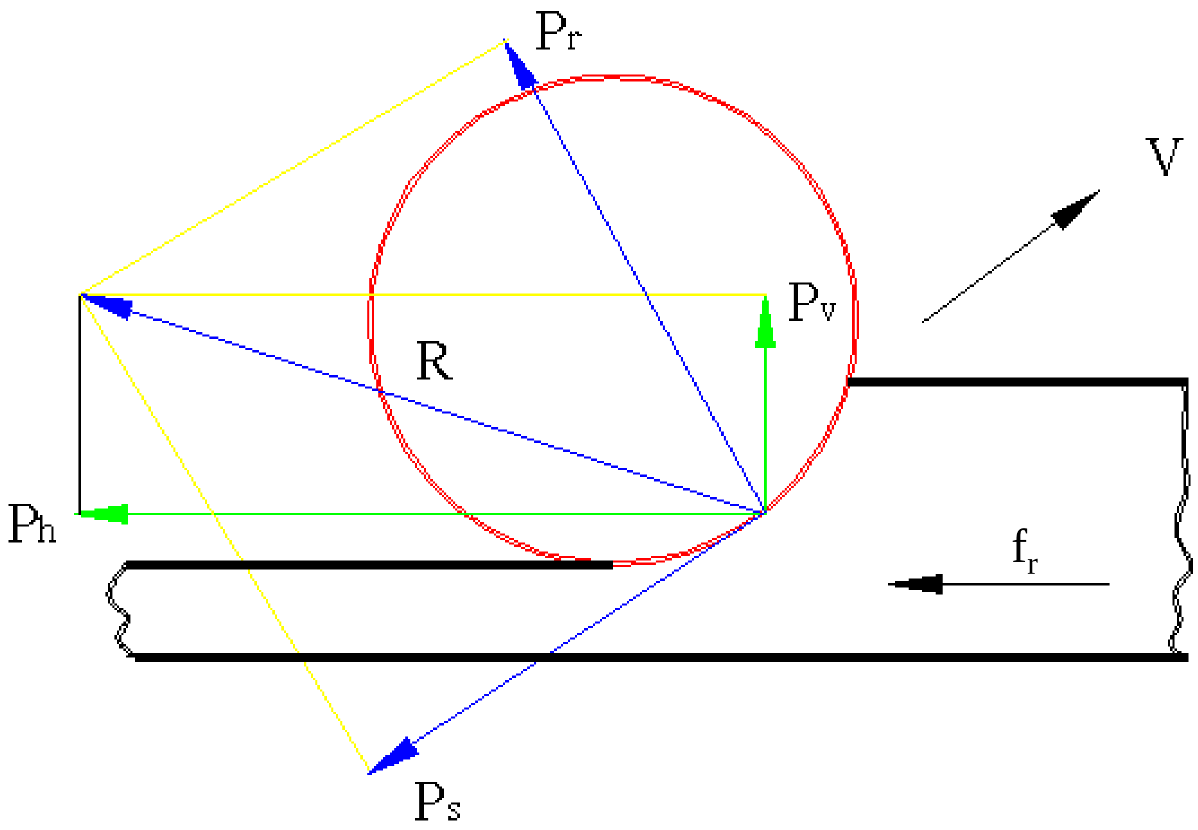
The resultant force R acting on a single tooth in peripheral milling operation can be resolved into tangential and radial components (P_s, P_r) or horizontal and vertical components (P_h, P_v).

Therefore

$$R = \sqrt{P_s^{\,2} + P_r^{\,2}}$$

$$R = \sqrt{P_h^{\,2} + P_V^{\,2}}$$

Cutting forces and power in milling



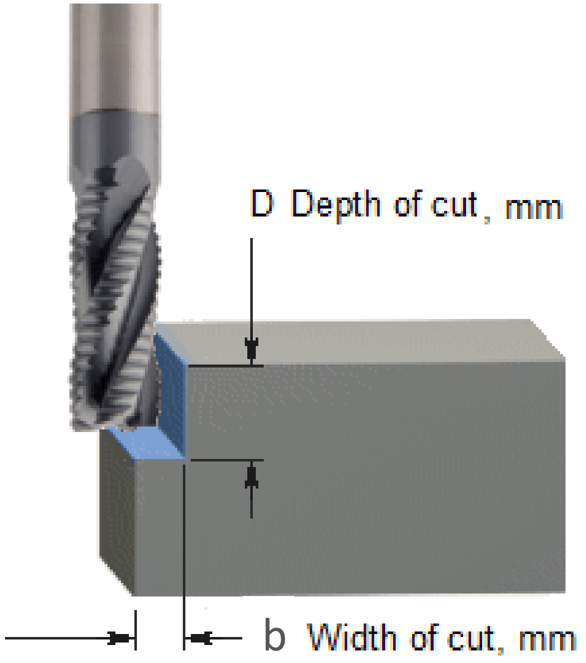
Cutting force components in milling operation

The main cutting force “Ps” in peripheral milling

$$P_s = K_s \times w \times t$$

t = momentary chip thickness changing from zero to “tc” in up milling or from “tc” to zero in down milling *(use tc for maximum cutting force calculation and* tc_m *for mean for calculation)*

w = width of the cut



Cutting forces and power in milling

$$P_{s\max} = K_s \times w \times tc$$

$$P_{s\max} = Ks \times w \frac{2 f_r}{N * z} \times \sqrt{d / D}$$

$$P_{s\,mean} = Ks \times w \frac{f_r}{N * z} \times \sqrt{d / D}$$

The total mean tangential force is:

$$P_{s\,mean(total)} = Z_e \times K_s \times w \frac{f_r}{N * z} \times \sqrt{d / D}$$

Where

Z_e = number of cutting teeth engaged in the same moment

$$Z_e = z \times \frac{\phi_e}{2\pi}$$

Cutting forces and power in milling

After substituting the value of Z_e in total mean cutting force equation

$$P_{s(total)mean} = \frac{f_r \times d \times w}{\pi \times D \times N} \times K_s$$

Cutting forces and power in milling

The mean machining power can be calculated as follows:

$$Power = P_{s(total)mean} \times V$$

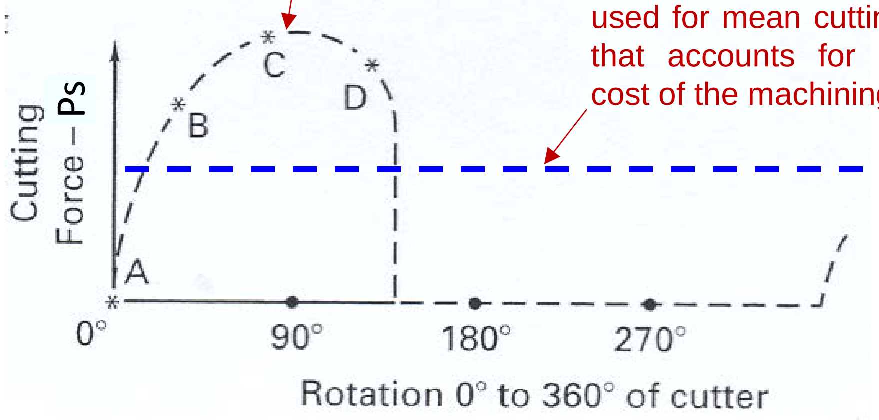
$$Power = \frac{f_r \times d \times w}{\pi \times D \times N} \times K_s \times \pi \times D \times N$$

$$Power = f_r \times d \times w \times K_s$$

$$Power_{motor} = P_{s\max} \times V \times \frac{1}{\eta_{mech}}$$

Ps_{max} this is the maximum force that motor has to overcome during machining and that is why it is used for motor power calculation

Ps_{mean} this is the mean force used for mean cutting power that accounts for the total cost of the machining

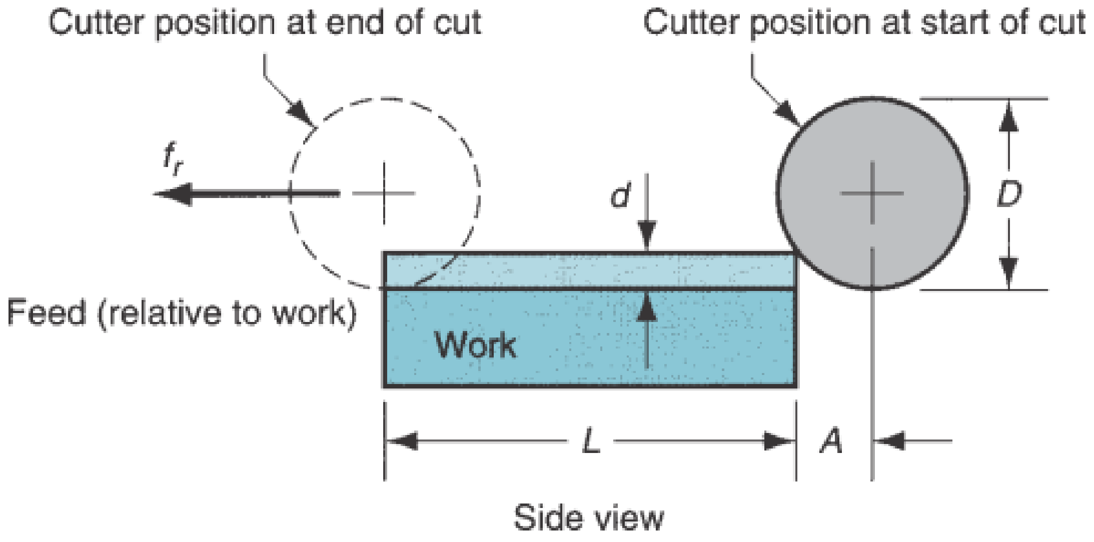


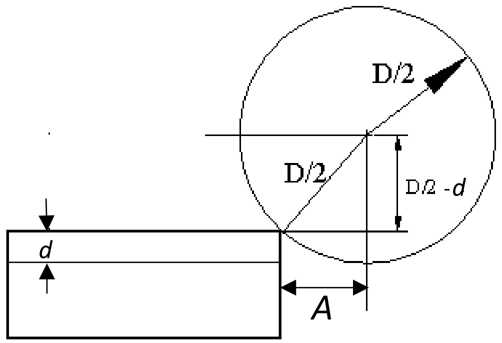
Cutting forces and power in milling

The feed power is given by:

$$Power_{feed} = P_f \times f_r$$

Machining time in peripheral milling





From figure, it can be noted,

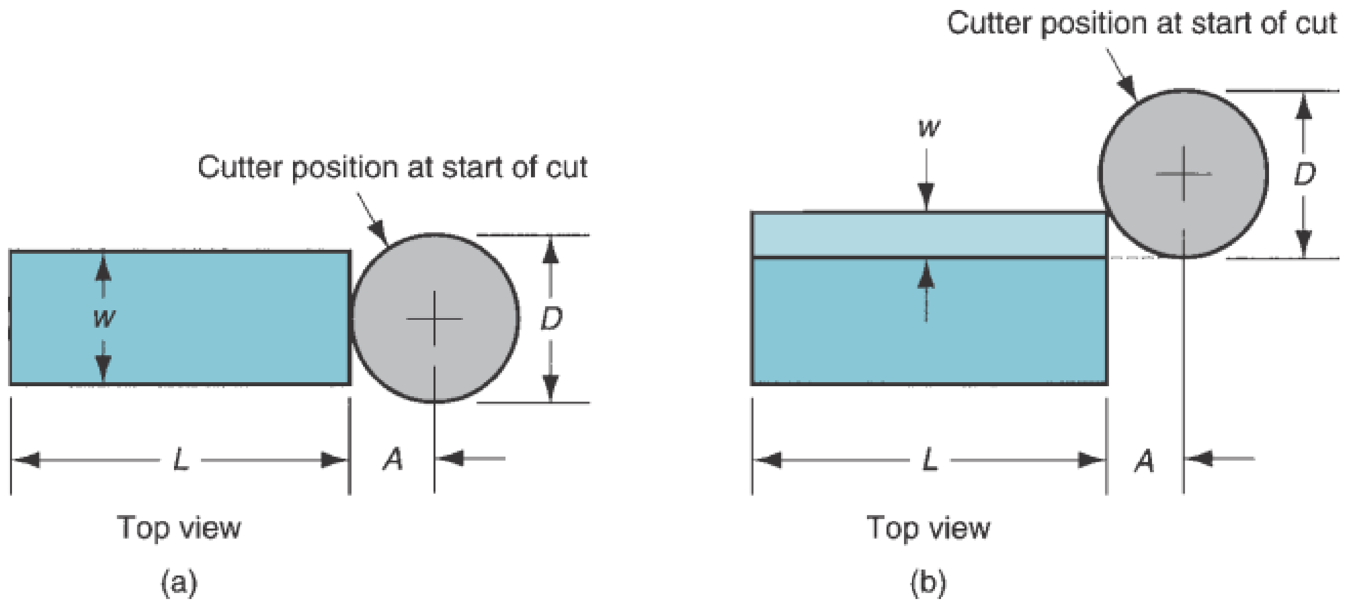
$$A = \sqrt{d(D-d)}$$

A = The approach distance to reach full cutter depth

$$T_m = \frac{L+A}{f_r}$$

$\boldsymbol{T_m}$ = machining time

Machining time in face milling



$$A = 0.5\left(D - \sqrt{D^2 - w^2}\right)$$

$$A = \sqrt{w(D - w)}$$

$$T_m = \frac{L + A}{f_r}$$

Face milling showing approach and over-travel distances for two cases: **(a)** when cutter is centered over the workpiece, and **(b)** when cutter is offset to one side over the work.

From Mikel P Groover, Fundamentals of modern manufacturing, 4th Ed

Material removal rate

Material removal rate can be calculated as following:

$$MRR = \frac{L \times d \times w}{T_m}$$

Where

L = length of the cut

w = width of the cut

d = depth of the cut

T_m = machining time