Milling process

Milling is a machining operation in which a work part is fed past a rotating cylindrical tool with multiple cutting edges, (In rare cases, a tool with one cutting edge, called a ***fly-cutter***, is used). The axis of rotation of the cutting tool is perpendicular to the direction of feed. This orientation between the tool axis and the feed direction is one of the features that distinguishes milling from drilling. In drilling, the cutting tool is fed in a direction parallel to its axis of rotation. The cutting tool in milling is called a ***milling cutter*** and the cutting edges are called teeth. The conventional machine tool that performs this operation is a ***milling machine***. The geometric form created by milling is a plane surface. Other work geometries can be created either by means of the cutter path or the cutter shape. Owing to the variety of shapes possible and its high production rates, milling is one of the most versatile and widely used machining operations.

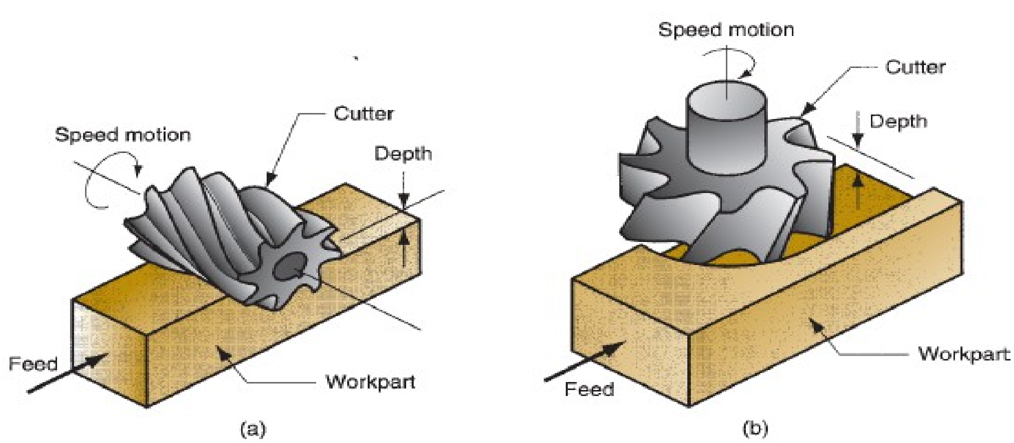

Figure 1: Two basic types of milling operations: a) peripheral or plain milling, b) face milling

Milling is an ***interrupted cutting*** operation; the teeth of the milling cutter enter and exit the work during each revolution. This interrupted cutting action subjects the teeth to a cycle of impact force and thermal shock on every rotation. The tool material and cutter geometry must be designed to withstand these conditions.

TYPES OF MILLING OPERATIONS

There are two basic types of milling operations, shown in Figure 1: (a) peripheral milling and (b) face milling. Most milling operations create geometry by generating the shape.

Peripheral Milling In peripheral milling, also called ***plain milling***, the axis of the tool is parallel to the surface being machined, and the operation is performed by cutting edges on the outside periphery of the cutter. Several types of peripheral milling are shown in Figure 2: (a) ***slab milling***, the basic form of peripheral milling in which.

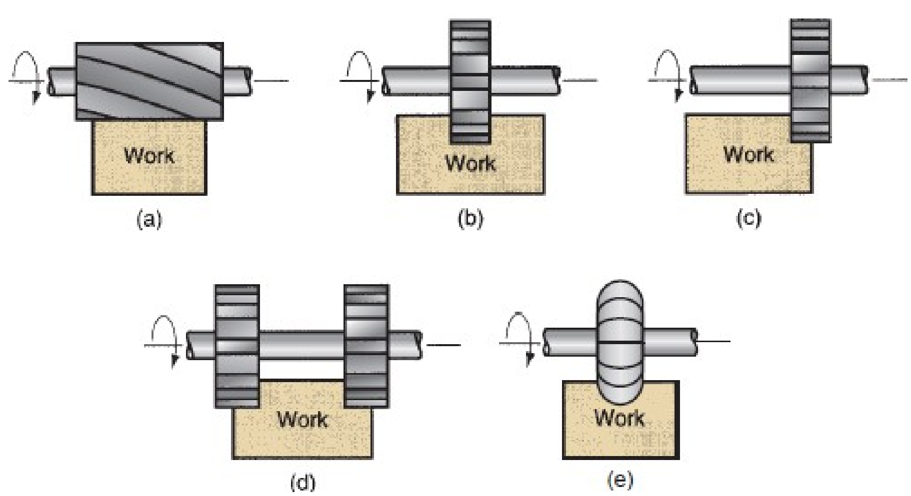

Figure 2: peripheral milling :a) slab milling, b) slotting, c) side milling, d) straddle milling, and e) form milling.

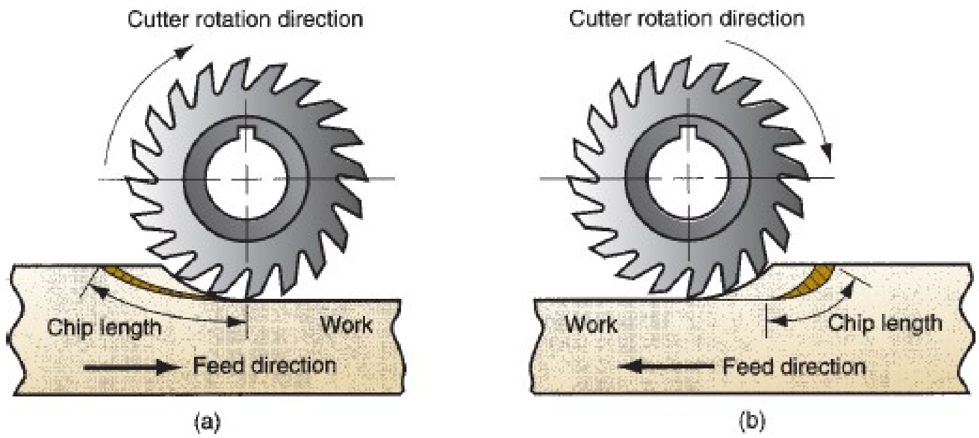

Figure 3: Two forms of peripheral milling operation with 20 tooth cutter: a) up milling, b) down milling

The cutter width extends beyond the workpiece on both sides; (b) ***slotting***, also called ***slot milling***, in which the width of the cutter is less than the workpiece width, creating a slot in the work—when the cutter is very thin, this operation can be used to mill narrow slots or cut a work part in two, called ***saw milling***; (c) ***side milling***, in which the cutter machines the side of the workpiece; (d) ***straddle milling***, the same as side milling, only cutting takes place on both sides of the work; and (e) ***form milling***, in which the milling teeth have a special profi le that determines the shape of the slot that is cut in the work.

In peripheral milling, the direction of cutter rotation distinguishes two forms of milling: up milling and down milling, illustrated in Figure 3. In ***up milling***, also called ***conventional milling***, the direction of motion of the cutter teeth is opposite the feed direction when the teeth cut into the work. It is milling “against the feed.” In ***down milling***, also called ***climb milling***, the direction of cutter motion is the same as the feed direction when the teeth cut the work. It is milling "with the feed."

The relative geometries of these two forms of milling result in differences in their cutting actions. In up milling, the chip formed by each cutter tooth starts out very thin and increases in thickness during the sweep of the cutter. In down milling, each chip starts out thick and reduces in thickness throughout the cut. The length of a chip in down milling is less than in up milling (the difference is exaggerated in the figure).

This means that the cutter is engaged in the work for less time per volume of material cut, and this tends to increase tool life in down milling.

The cutting force direction is tangential to the periphery of the cutter for the teeth that are engaged in the work. In up milling, this has a tendency to lift the work part as the cutter teeth exit the material. In down milling, this cutter force direction is downward, tending to hold the work against the milling machine table.

Face Milling In face milling, the axis of the cutter is perpendicular to the surface being milled, and machining is performed by cutting edges on both the end and outside periphery of the cutter. As in peripheral milling, various forms of face milling exist, several of which are shown in Figure 4: (a) ***conventional face milling***, in which the diameter of the cutter is greater than the work part width, so the cutter overhangs the work on both sides; (b) ***partial face milling***, where the cutter overhangs the work on only one side; (c) ***end milling***, in which the cutter diameter is less than the work width, so a slot is cut into the part; (d) ***profile milling***, a form of end milling in which the outside periphery of a fl at part is cut; (e) ***pocket milling***, another form of end milling used

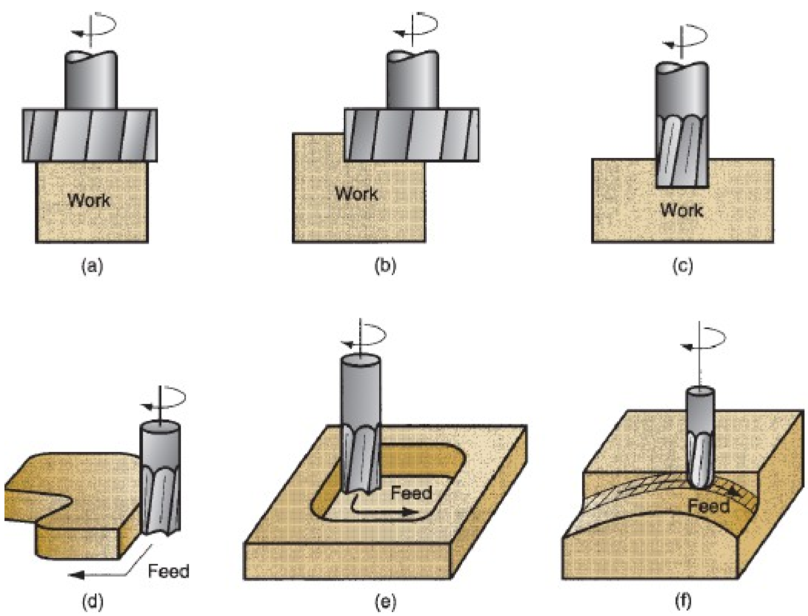

Figure 4: Face milling : a) conventional face milling, b) partial face milling, c) end milling, d) profile milling, e) pocket milling, f) surface contouring.

To mill shallow pockets into fl at parts; and (f) ***surface contouring***, in which a ball-nose cutter (rather than square-end cutter) is fed back and forth across the work along a curvilinear path at close intervals to create a three-dimensional surface form. The same basic cutter control is required to machine the contours of mold and die cavities, in which case the operation is called ***die sinking***.

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 using a formula that should now be familiar:

$$N = \frac{V}{\pi D} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The feed f in milling is usually given as a feed per cutter tooth; called the ***chip load***, it represents the size of the chip formed by each cutting edge. This can be converted to feed rate by taking into account the spindle speed and the number of teeth on the cutter as follows:

$$\boldsymbol{fr = N\, n_t\, f} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where fr= feed rate, mm/min; N = spindle speed, rev/min; n_t= number of teeth on the cutter; and f = chip load in mm/tooth.

Material removal rate in milling is determined using the product of the cross sectional area of the cut and the feed rate. Accordingly, if a slab-milling operation is cutting a workpiece with width $\boldsymbol{w}$ at a depth $\boldsymbol{d}$, the material removal rate is

$$\boldsymbol{MRR = w\, d\, f_r} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

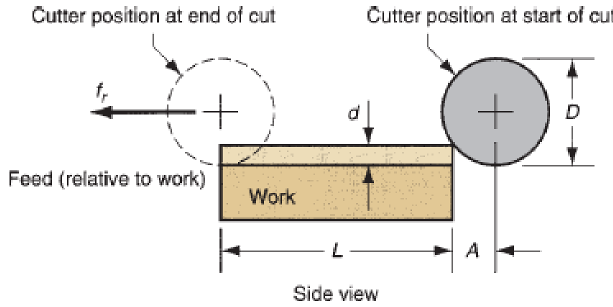

Figure 5: Slab (peripheral) milling showing entry of cutter into the workpiece

This neglects the initial entry of the cutter before full engagement. Equation (3) can be applied to end milling, side milling, face milling, and other milling operations, making the proper adjustments in the computation of cross-sectional area of cut.

The time required to mill a workpiece of length L must account for the approach distance required to fully engage the cutter. First, consider the case of slab milling, Figure 5. To determine the time to perform a slab milling operation, the approach distance A to reach full cutter depth is given by

$$A = \sqrt{d(D-d)} \qquad \text{.. (4)}$$

Where d = depth of cut, mm; and D = diameter of the milling cutter, mm.

The time T_m in which the cutter is engaged milling the workpiece is therefore

$$T_m = \frac{L + A}{f_r} \qquad \text{.. (5)}$$

For face milling, consider the two possible cases pictured in Figure 6. The first case is when the cutter is centered over a rectangular workpiece as in Figure 6(a).

The cutter feeds from right to left across the workpiece. In order for the cutter to reach the full width of the work, it must travel an approach distance given by

$$A = 0.5(D - \sqrt{D^2 - w^2}) \quad \dots\dots (6)$$

Where D = cutter diameter, mm and w = width of the workpiece, mm. If $D = w$, then Equation (6) reduces to $A = 0.5D$. And if $D < w$, then a slot is cut into the work and $A = 0.5D$.

The second case is when the cutter is offset to one side of the work, as in Figure

6 (b). In this case, the approach distance is given by

$$A = \sqrt{w(D - w)} \quad \dots\dots (7)$$

Where w = width of the cut, mm. In either case, the machining time is given by

$$T_m = \frac{L + A}{f_r} \quad \dots\dots (8)$$

It should be emphasized in all of these milling scenarios that *Tm* represents the time the cutter teeth are engaged in the work, making chips. Overtravel distances are usually added at the beginning and end of each cut to allow access to the work for loading and unloading. Thus the actual duration of the cutter feed motion is likely to be greater than T_m.

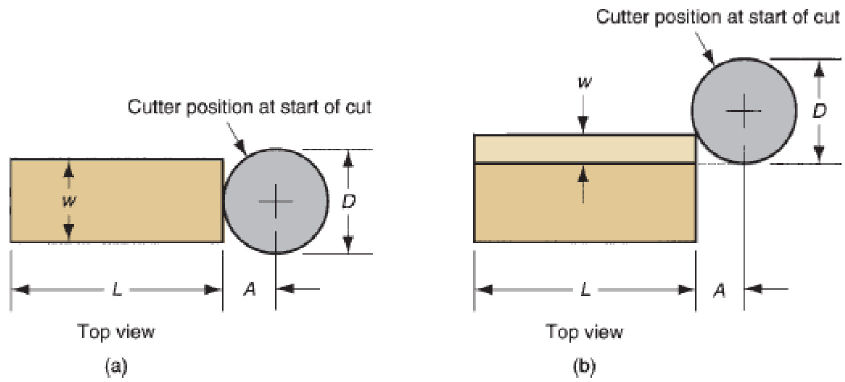

Figure 6: Face milling showing approach and overtravel distance for two cases: (a) when cutter is centered over the workpiece, and (b) when cutter is offset to one side over the work.

Example: A peripheral milling operation is performed on a rectangular workpiece that is 320 mm long by 60 mm wide by 56 mm thick. The 65-mm-diameter milling cutter has 4 teeth, is 80 mm long, and overhangs the work on either side by 10 mm. The operation reduces the thickness of the piece to 50 mm. Cutting speed = 0.50 m/s and chip load = 0.24 mm/tooth. Determine (a) machining time and (b) metal removal rate once the cutter reaches full depth.

Solution: (a)

$N = v/\pi D = 0.50(10^3)/\pi(65) = 2.45$ rev/s

$f_r = N n_t f = 2.45(4)(0.24) = 2.35$ mm/s

Depth of cut $d = 56 - 50 = 6$ mm

$A = (6(65 - 6))^{0.5} = 18.8$ mm

$T_m = (320 + 18.8)/2.35 = 144.2$ s = **2.40 min**

(b)

$MRR = w\, d\, f_r = 60(6)(2.35) =$ **846 mm³/s**

MILLING MACHINES

Milling machines must provide a rotating spindle for the cutter and a table for fastening, positioning, and feeding the work part. Various machine tool designs satisfy these requirements. To begin with, milling machines can be classified as horizontal or vertical. A ***horizontal milling machine*** has a horizontal spindle, and this design is well suited for performing peripheral milling (e.g., slab milling, slotting, side and straddle milling) on work parts that are roughly cube shaped. A ***vertical milling machine*** has a vertical spindle, and this orientation is appropriate for face milling, end milling, surface contouring, and die-sinking on relatively fl at work parts.

Other than spindle orientation, milling machines can be classified into the following types: (1) knee-and-column, (2) bed type, (3) planer type, (4) tracer mills, and (5) CNC milling machines.

The ***knee-and-column milling machine*** is the basic machine tool for milling. It derives its name from the fact that its two main components are a ***column*** that supports the spindle, and a ***knee*** (roughly resembling a human knee) that supports the worktable

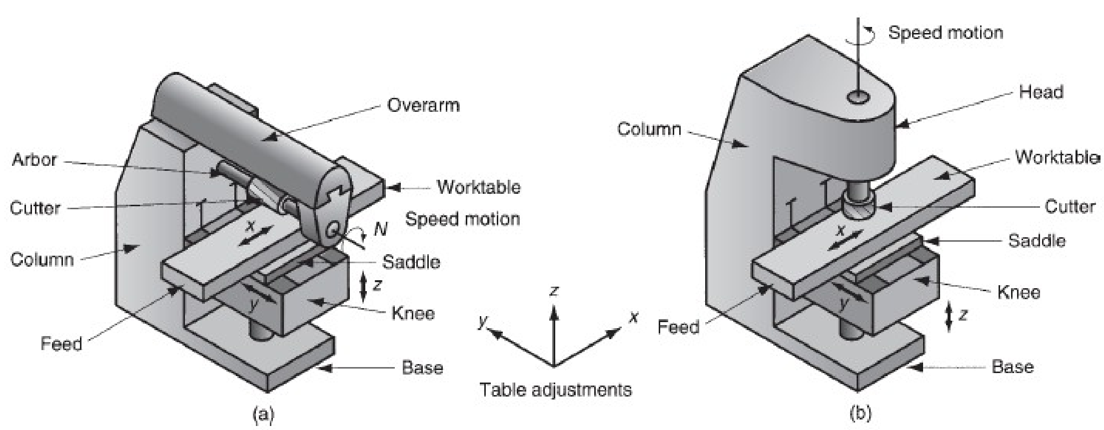

Figure 7: Two basic types of knee and column milling machine: (a) horizontal and (b) vertical.

It is available as either a horizontal or a vertical machine, as illustrated in Figure 7. In the horizontal version, an arbor usually supports the cutter. The ***arbor*** is basically a shaft that holds the milling cutter and is driven by the spindle. An overarm is provided on horizontal machines to support the arbor. On vertical knee-and-column machines, milling cutters can be mounted directly in the spindle without an arbor.

One of the features of the knee-and-column milling machine that makes it so versatile is its capability for worktable feed movement in any of the *x*–*y*–*z* axes.

The worktable can be moved in the *x*-direction, the saddle can be moved in the *y*-direction, and the knee can be moved vertically to achieve the *z*-movement. Two special knee-and-column machines should be identified. One is the ***universal*** milling machine, Figure 7 (a), which has a table that can be swiveled in a horizontal plane (about a vertical axis) to any specified angle. This facilitates the cutting of angular shapes and helixes on work parts. Another special machine is the ***ram mill***,

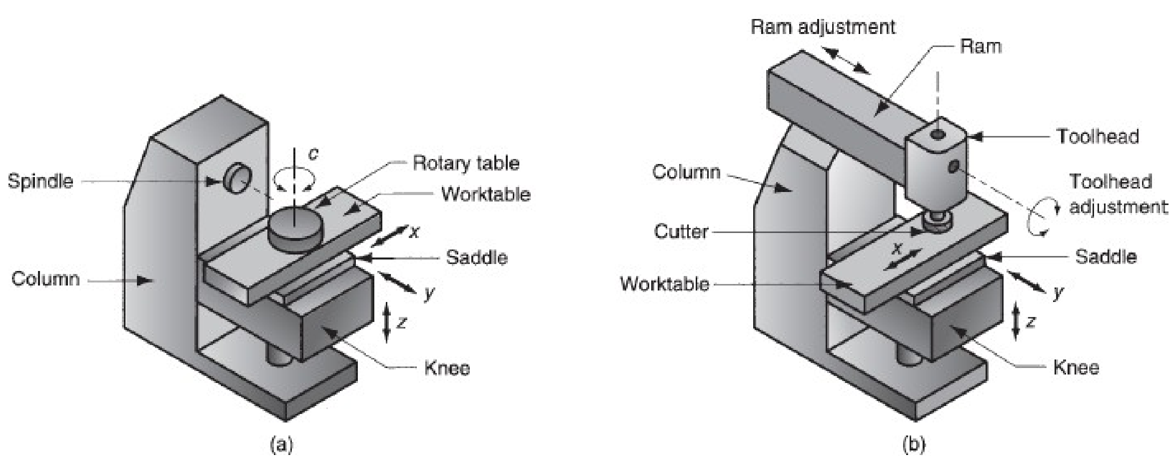

Figure 8: Special types of knee and column milling machine: (a) universal overarm, arbor, and cutter omitted for clarity, and (b) ram type

CNC milling machines are milling machines in which the cutter path is controlled by alphanumerical data rather than a physical template. They are especially suited to profile milling, pocket milling, surface contouring, and die sinking operations, in which two or three axes of the worktable must be simultaneously controlled to achieve the required cutter path. An operator is normally required to change cutters as well as load and unload work parts.