Lecture 3-3: General-Purpose Machine Tools: Milling Machines and Operations

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MILLING OPERATIONS

- Milling is the removal of metal by feeding the work past a rotating multitoothed cutter. In this operation the material removal rate (MRR) is enhanced as the cutter rotates at a high cutting speed.
- The surface quality is also improved due to the multicutting edges of the milling cutter.
- The action of the milling cutter is totally different from that of a drill or a turning tool. In turning and drilling, the tools are kept continuously in contact with the material to be cut, whereas milling is an intermittent process, as each tooth produces a chip of variable thickness.
- Milling operations may be classified as peripheral (plain) milling or face (end) milling (Figure 3.38).

MILLING OPERATIONS

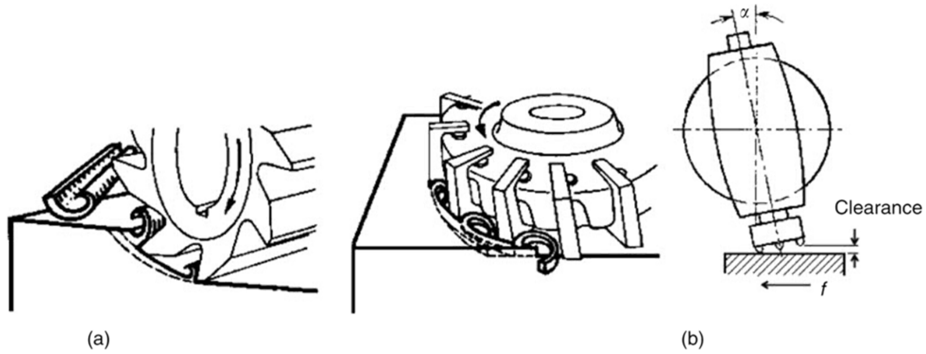


FIGURE 3.38 Plain and face milling cutters: (a) Plain milling and (b) face milling.

MILLING OPERATIONS

- **Up-Milling (Conventional Milling)**
- Up-milling is accomplished by rotating the cutter against the direction of the feed of the WP (Figure 3.39a).
- The tooth picks up from the material gradually; that is, the chip starts with no thickness and increases in size as the teeth progress through the cut.
- This means that the cycle of operation to remove the chip is first a sliding action at the beginning and then a crushing action takes place, which is followed by the actual cutting action.
- In some metals, up-milling leads to strain hardening of the machined surface, and also to chattering and excessive teeth blunting.

MILLING OPERATIONS

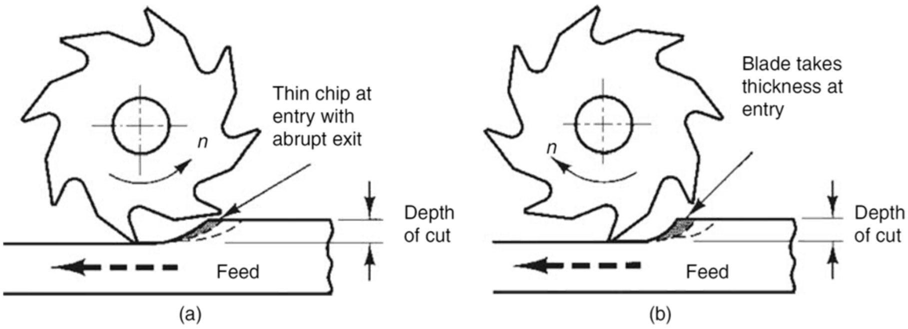


FIGURE 3.39 Up-milling and down-milling: (a) Up-milling (conventional cut) and (b) down-milling (climb cut).

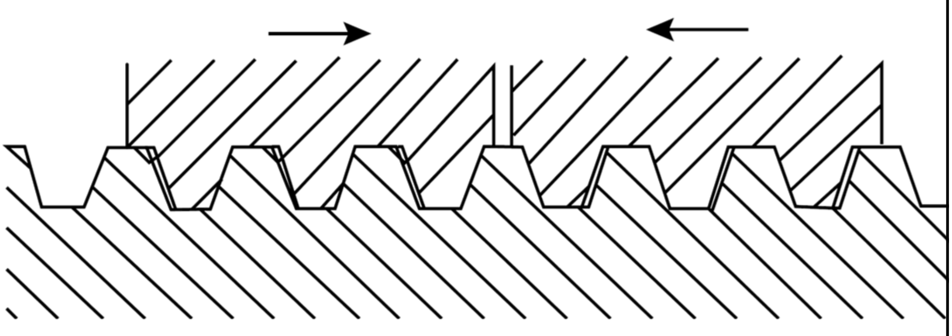
MILLING OPERATIONS

- Advantages of up-milling include the following:
- It does not require a backlash eliminator.
- It is safer in operation (the cutter does not climb on the work).
- Loads on teeth are acting gradually.
- Built-up edge (BUE) fragments are absent from the machined surface.
- The milling cutter is not affected by the sandy or scaly surfaces of the work.

MILLING OPERATIONS

- **Down-Milling (Climb Milling).**
- Down-milling is accomplished by rotating the cutter in the direction of the work feed, as shown in Figure 3.39b.
- In climb milling, as implied by the name, the milling cutter attempts to climb the WP.
- Chips are cut to maximum thickness at initial engagement of cutter teeth with the work, and decrease to zero at the end of its engagement.
- The cutting forces in down milling are directed downward. Down-milling should not be attempted if machines do not have enough rigidity and are not provided with backlash eliminators (Figure 3.40).
- Under such circumstances, the cutter climbs up on the WP and the arbor and spindle may be damaged.

MILLING OPERATIONS



Backlash eliminator in down-milling.

MILLING OPERATIONS

- Advantages of down-milling include the following:
- Fixtures are simpler and less costly, as cutting forces are acting downward.
- Flat WPs or plates that cannot be firmly held can be machined by down-milling.
- Cutter with higher rake angles can be used, which decreases the power requirements.
- Tool blunting is less likely.
- Down-milling is characterized by fewer tendencies of chattering and vibration, which leads to improved surface finish.

MILLING OPERATIONS

- **Face Milling.**
- In face milling, the generated surface is at a right angle to the cutter axis.
- When using cutters of large diameters, it is a good practice to tilt the spindle head slightly at an angle of 1–3° to provide some clearance, which leads to an improved surface finish and eliminate tool blunting (Figure 3.38b).
- Face milling is usually performed on vertical milling machines; for this reason, the process is called vertical milling, which is more productive than plain milling.

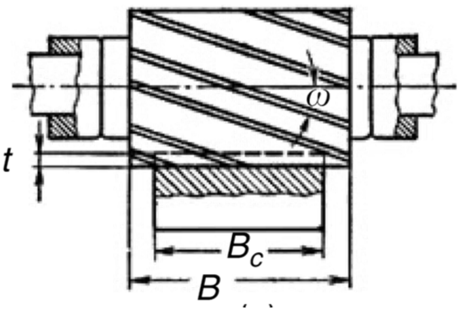
MILLING CUTTERS

- The milling cutters are selected for each specified machining duty.
- The milling cutter may be provided with a hole to be mounted on the arbor of the horizontal milling machines, or provided with a straight or tapered shank for mounting on the vertical or horizontal milling machine.

MILLING CUTTERS

1. Plain milling cutters are either straight or helical ones. Helical milling cutters are preferred for large cutting widths to provide smooth cutting and improved surface quality.

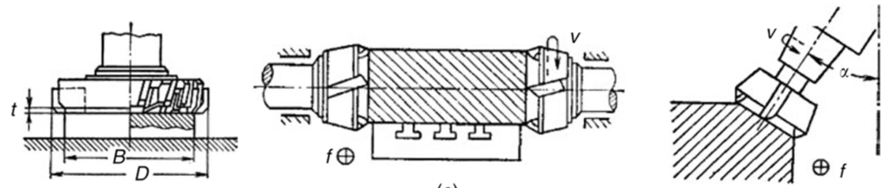
- Plain milling cutters are mainly used on horizontal milling machines.



MILLING CUTTERS

2. Face milling cutters are used for the production of horizontal (Figure 3.41b), vertical (Figure 3.41c), or inclined (Figure 3.41d) flat surfaces.

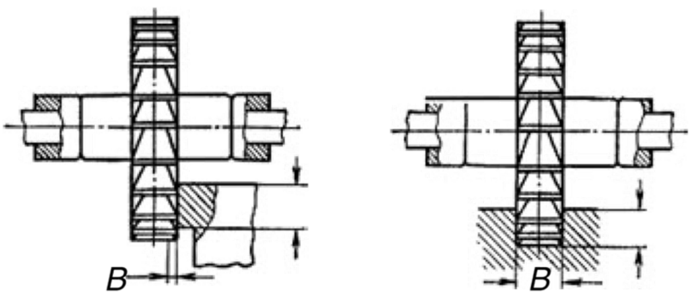
- They are used on vertical milling machines, planer type milling machines, and vertical milling machines with the spindle swiveled to the required angle a, respectively.



(b) (c) (d)

MILLING CUTTERS

3. Side milling cutters are clamped on the arbor of the horizontal milling machine and are used for machining of the vertical surface of a shoulder (Figure 3.41e) or cutting a keyway (Figure 3.41f).



(e) (f)

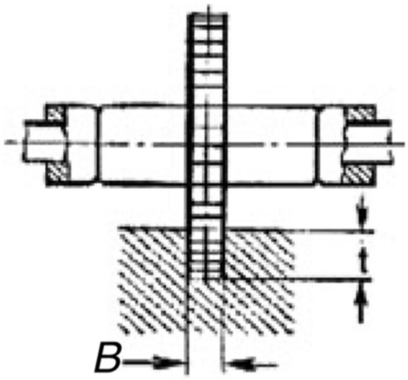
MILLING CUTTERS

4. Interlocking (staggered) side mills (Figure 3.41g) mounted on the arbor of the horizontal milling machines are intended to cut wide keyways and cavities.

(g)

MILLING CUTTERS

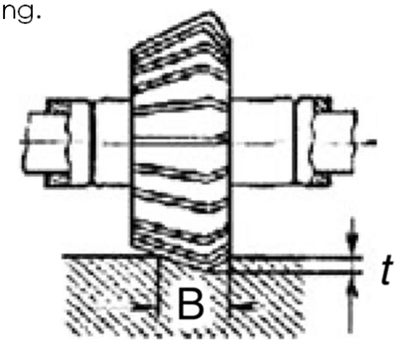
5. Slitting saws (Figure 3.41h) are used on horizontal milling machines.



(h)

MILLING CUTTERS

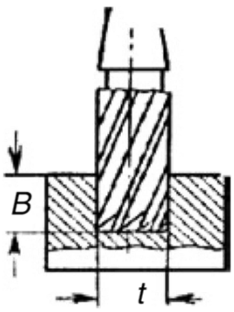
6. Angle milling cutters, used on horizontal milling machines, for the production of longitudinal grooves (Figure 3.41i) or for edge chamfering.



(i)

MILLING CUTTERS

7. End mills are tools of a shank type, which can be mounted on vertical milling machines (or directly in the spindle nose of horizontal milling machines). End mills may be employed in machining keyways (Figure 3.41j) or vertical surfaces (Figure 3.41k).



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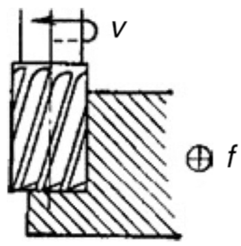
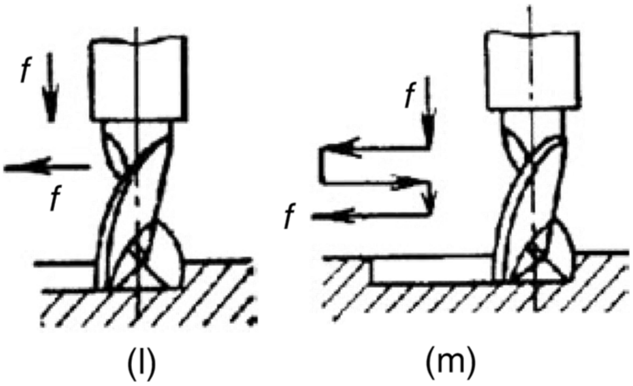


(k)

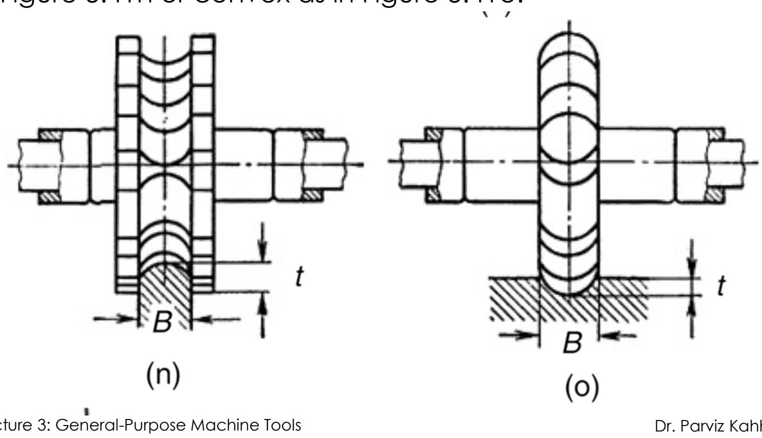
MILLING CUTTERS

8. Key-cutters are also of the shank type that can be used on vertical milling machines. They may be used for single-pass milling or multipass milling operations (Figures 3.41l and 3.41m).



MILLING CUTTERS

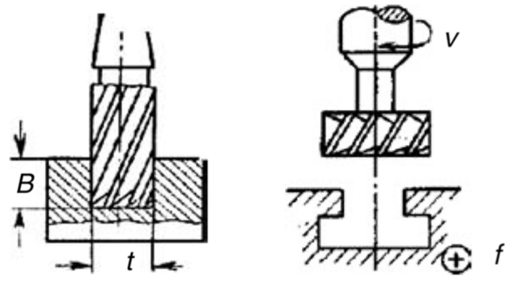
9. Form-milling cutters are mounted on horizontal milling machines. Form cutters may be either concave as shown in Figure 3.41n or convex as in Figure 3.41o.



MILLING CUTTERS

10. T-slot cutters are used for milling T-slots and are available in different sizes. The T-slot is machined on a vertical milling machine in two steps:

- Slotting with end mill (Figure 3.41j)
- Cutting with T-slot cutter (Figure 3.41p)

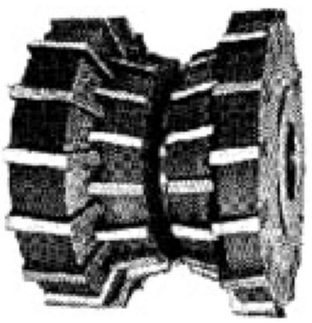


(j)

(p)

MILLING CUTTERS

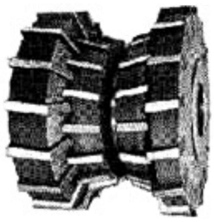
11. Compound milling cutters are mainly used to produce compound surfaces. These cutters realize high productivity and accuracy (Figure 3.41q).



(q)

MILLING CUTTERS

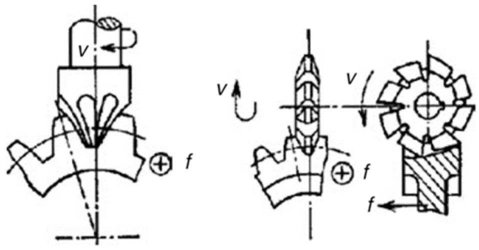
12. Inserted tool milling cutters have a main body that is fabricated from tough and less expensive steel. The teeth are made of alloy tool steel, HSS, carbides, ceramics, or cubic boron nitride (CBN) and mechanically attached to the body using set screws and in some cases are brazed. Cutters of this type are confined usually to large-diameter face milling cutters or horizontal milling cutters (Figure 3.41q).



(q)

MILLING CUTTERS

13. Gear milling cutters are used for the production of spur and helical gears on vertical or horizontal milling machines (Figures 3.41r and 3.41s). Gear cutters are form-relieved cutters, which are used to mill contoured surfaces. They are sharpened at the tooth face. Hobbing machines and gear shapers are used to cut gears for mass production and high accuracy demands.



(r) (s)

GENERAL-PURPOSE MILLING MACHINES

- Milling machines are employed for machining flat surfaces, contoured surfaces, complex and irregular areas, slotting, threading, gear cutting, production of helical flutes, twist drills, and spline shafts to close tolerances.
- Milling machines are classified by application into the following categories:
  - o General-purpose milling machines, which are used for piece and small-lot production.
  - o Special-purpose milling machines, which are designed for performing one or several distinct milling operations on definite WPs. They are used in mass production.

GENERAL-PURPOSE MILLING MACHINES

- The general-purpose milling machines are extremely versatile and are subdivided into these types:

1. Knee-type
2. Vertical bed-type
3. Planer-type
4. Rotary-table

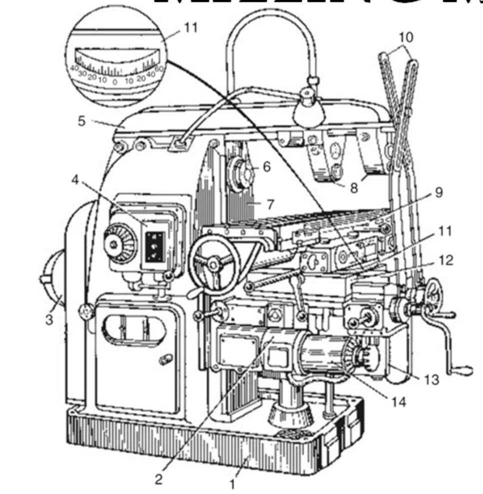
GENERAL-PURPOSE MILLING MACHINES

- **Knee-Type Milling Machines.**
- The special feature of these machines is the availability of three Cartesian directions of table motion.
- This group is further subdivided into plain horizontal, universal horizontal, vertical, and ram-head knee-type milling machines. The name "knee" has been adopted because it features a knee that mounts the worktable and travels vertically along the vertical guideway of the machine column.

GENERAL-PURPOSE MILLING MACHINES

- In plain horizontal milling machines, the spindle is horizontal and the table travels in three mutually perpendicular directions. The universal horizontal milling machines (Figure 3.42) are similar in general arrangement to the plain horizontal machines.
- The principal difference is that the table can be swiveled about its vertical axis through ±45°, which makes it possible to mill helical grooves and helical gears.
- In contrast to horizontal milling machines, vertical-type milling machines have a vertical spindle and no overarm (Figure 3.43).
- The overarm serves to hold the bearing bracket supporting the outer end of the tool arbor in horizontal machines.

GENERAL-PURPOSE MILLING MACHINES



Universal horizontal-spindle milling machine.

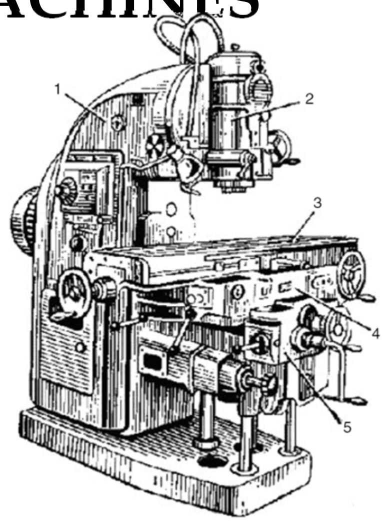


FIGURE 3.43 Vertical milling machine.

GENERAL-PURPOSE MILLING MACHINES

- The ram-head milling machines (Figure 3.44) differ from the universal type in that they have an additional spindle that can be swiveled about both the vertical and horizontal axes.
- In ram-head milling machines, the spindle can be set at any angle in relation to the WP being machined.
- In modern machines, a separate drive for the principal movement (cutter), feed movement (WP), rapid traversal of the worktable in all directions, and a single lever control for changing speeds and feeds are provided. Units and components of milling machines are widely unified.

GENERAL-PURPOSE MILLING MACHINES

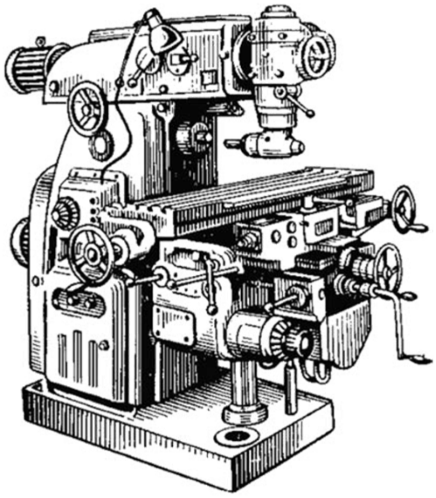


FIGURE 3.44 Ram-head milling machine.

GENERAL-PURPOSE MILLING MACHINES

- Horizontal knee-type milling machine specifications are as follows:
- ✓ Dimensions of table working surface
- ✓ Maximum table travel in the three Cartesian directions
- ✓ Maximum angle of table swivel
- ✓ Arbor diameter
- ✓ Maximum distance between arbor axis and the overarm underside
- ✓ Number of spindle speeds
- ✓ Number of feeds in the three directions
- ✓ Power and speed of main motor
- ✓ Power and speed of feed motor
- ✓ Overall dimensions and net weight

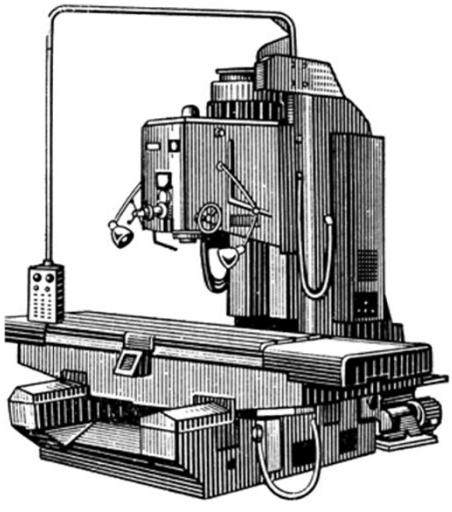
GENERAL-PURPOSE MILLING MACHINES

- Figure 3.42 visualizes the main parts of the horizontal universal milling machine.
- These are Base (1), column (7), knee (13), saddle (12), table swivel plate with graduation (11), worktable (9), overarm (5), holding bearing bracket (8), main motor (3), spindle (6), speed gearbox (4), feed gearbox (2), feed control mechanism (14), braces (10) to link the overarm with the knee for high-rigidity requirements in heavy-duty milling machines.

GENERAL-PURPOSE MILLING MACHINES

- **Vertical Bed-Type Milling Machines.**
- These machines are rigid and powerful; hence, they are used for heavy duty machining of large WPs (Figure 3.45).
- The spindle head containing a speed gearbox travels vertically along the guideways of the machine column and has a separate drive motor.
- In some machines, the spindle head can be swiveled.
- The work is fixed on a compound table that travels horizontally in two mutually perpendicular directions.
- The adjustment in the vertical direction is accomplished by the spindle head.

GENERAL-PURPOSE MILLING MACHINES



Vertical-bed general-purpose milling machine.

GENERAL-PURPOSE MILLING MACHINES

- **Planer-Type Milling Machine.**
- They are intended for machining horizontal, vertical, and inclined planes as well as form surfaces by means of face, plain, and form milling cutters. These machines are of single or double housing, with one or several spindles; each has a separate drive.
- Figure 3.46 shows a single-housing machine with two spindle heads traveling vertically and horizontally.

GENERAL-PURPOSE MILLING MACHINES

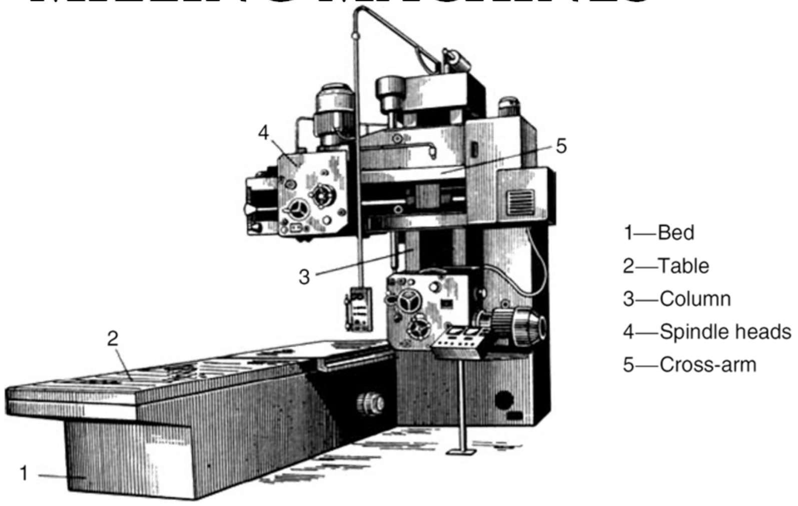
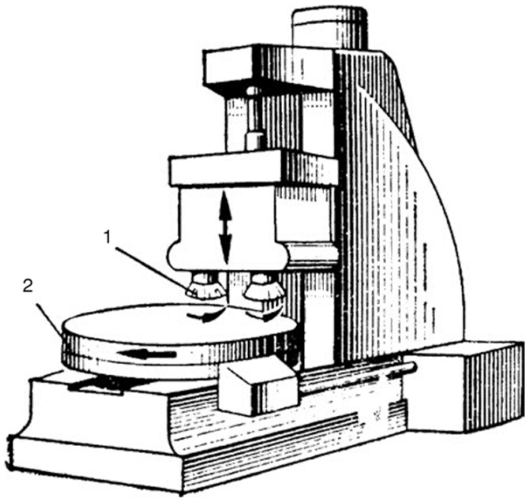


FIGURE 3.46 Planer-type general-purpose milling machine.

GENERAL-PURPOSE MILLING MACHINES

- **Rotary-Table Milling Machines.**
- These are also called continuous milling machines, as the WPs are set up without stopping the operation.
- Rotary-table machines are highly productive; consequently, they are frequently used for both batch and mass production.
- The WPs being machined are clamped in fixtures installed on the
- rotating table (2) (Figure 3.47).
- The machines may be equipped with one or two spindle heads (1).
- When several surfaces are to be machined, the WPs are indexed in the fixtures after each complete revolution of the table.
- The machining cycle provides as many table revolutions as the number of surfaces to be machined.

GENERAL-PURPOSE MILLING MACHINES



Rotary-table milling machine.

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

- **Cutter Mounting.**
- The nose of milling machine spindles has been standardized. It is provided with a locating flange φ H7/h6 and a steep taper socket of 7:24 (1:3.4286) corresponding to an angle of 16° 35.6′ (Figure 3.48) to ensure better location of arbor and end mill shanks.
- Rotation is transmitted to the cutter through the driving key secured to the end face of the spindle.
- Large face milling cutters are
- mounted directly on the spindle flange and are secured to the flange by four screws, whereas rotation is transmitted to the cutter through the driving keys on the spindle (Figure 3.48).

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

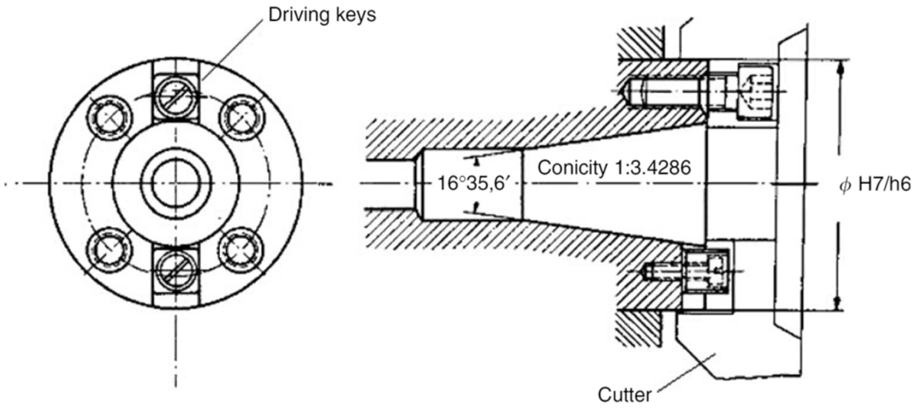


FIGURE 3.48 Typical nose of milling machine spindle.

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

- Plain and side milling cutters are mounted on an arbor whose taper shank is drawn up tight into the taper socket of the spindle (2) with a draw-in bolt 1 (Figure 3.49).
- Milling arbors are long or short (stub arbors).
- The outer end of the long arbor (3) is supported by an overarm support (5) in horizontal milling machines, and the cutter (4) is mounted at the required position on the arbor by a key (or without key in case of slitting saws) and is clamped between collars or spacers (6) with a large nut.

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

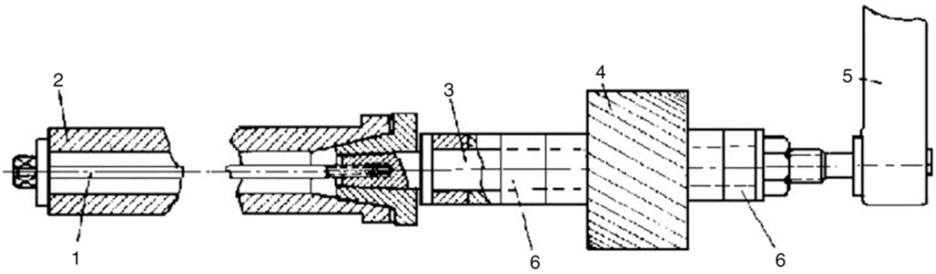


FIGURE 3.49 Milling machine arbor.

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

- The system shown in Figure 3.50 is used in the duplex bed milling machines. On the stub arbors, the shell end mill or the face milling cutters are driven either by a feather key, as shown in Figure 3.50a, or an end key (Figure 3.50b).
- End mills, T-slot cutters, and other milling cutters of tapered shanks are secured with a draw-in bolt directly in the taper socket of the spindle by means of adaptors (Figure 3.51a). Straight shank cutters are held in chucks (Figure 3.51b).

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

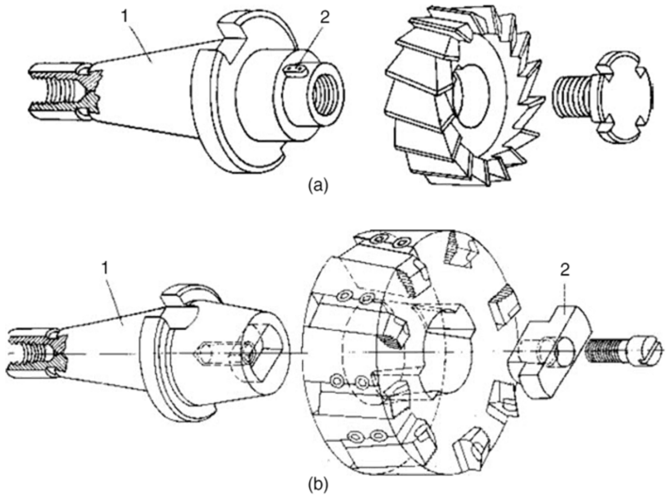


FIGURE 3.50 Mounting of end mills and face milling cutters on duplex-bed milling machine.

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

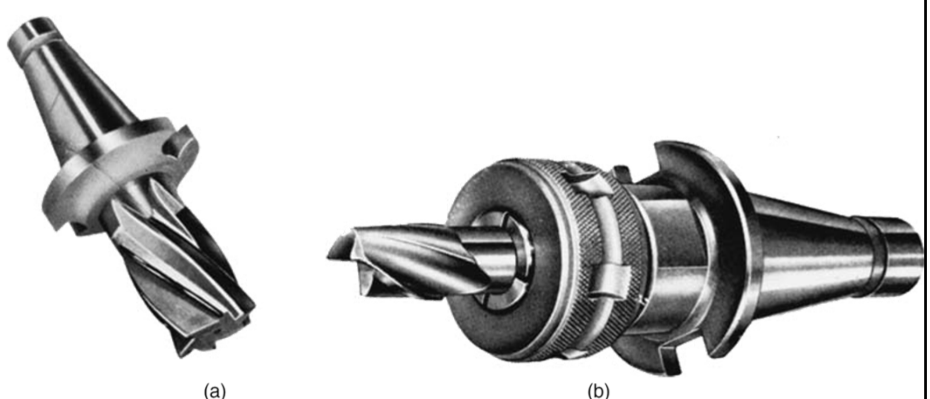


FIGURE 3.51 Mounting of (a) tapered and (b) straight-shank milling cutters.

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

- **Workpiece Fixturing.**
- Large WPs and blanks that are too large for a vise are clamped directly on the worktable using standard fastening elements such as strap clamps, support blocks, and T-bolts (Figure 3.52).
- Small WPs and blanks are clamped most frequently in general-purpose plain, swivel, or universal milling vises fastened to the worktable (Figure 3.53).
- Shaped jaws are sometimes used instead of the flat type to clamp parts of irregular shapes.
- For more accurate and productive work, expensive milling fixtures are frequently used.

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

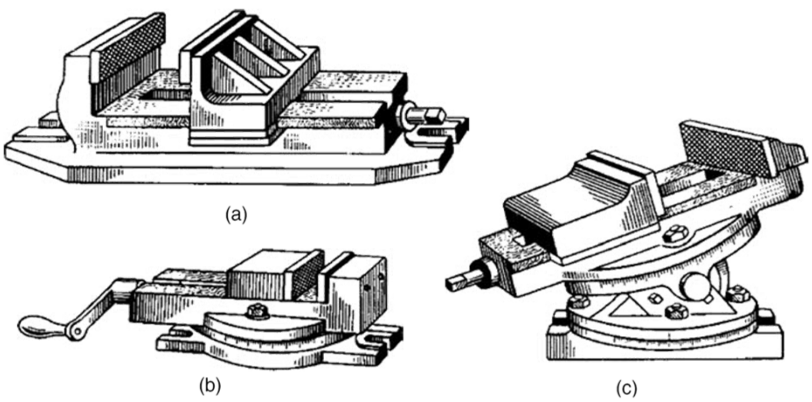
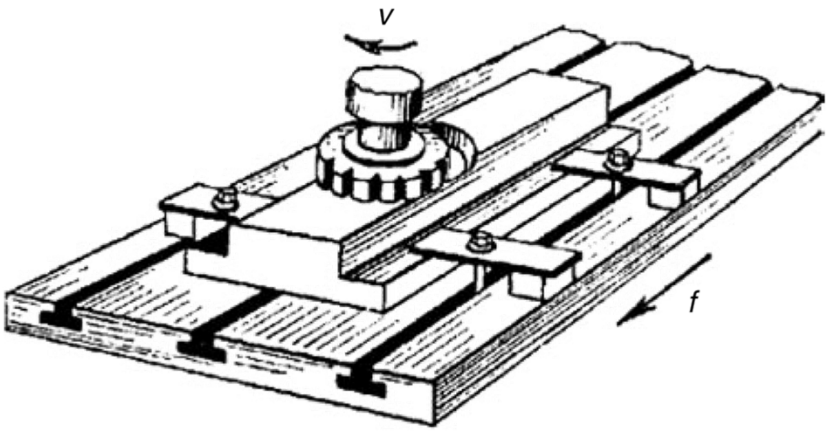


FIGURE 3.53 Vises for clamping of small WPs on milling machines: (a) plain vise, (b) swivel vise, and (c) universal vise.

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES



Clamping of large WPs directly on the worktable.

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

- Figure 3.54 shows a simple milling fixture for a bearing bracket. A full-form and a flatted locator, firmly fitted into the base plate, are used to locate the WP from two previously machined holes.
- The clamping is effected by two solid clamps.
- To achieve correct alignment and, hence, increased accuracy, a tool-setting block is used to locate the cutter with respect to the WP.
- Figure 3.54 illustrates how the height of the cutter is setup using setting blocks and 0.7 mm feeler.
- The main body of the fixture is frequently made of CI because of its ability to absorb vibrations initiated by the milling operation.
- However, welded and other steel constructions are also used for various specialized purposes.

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

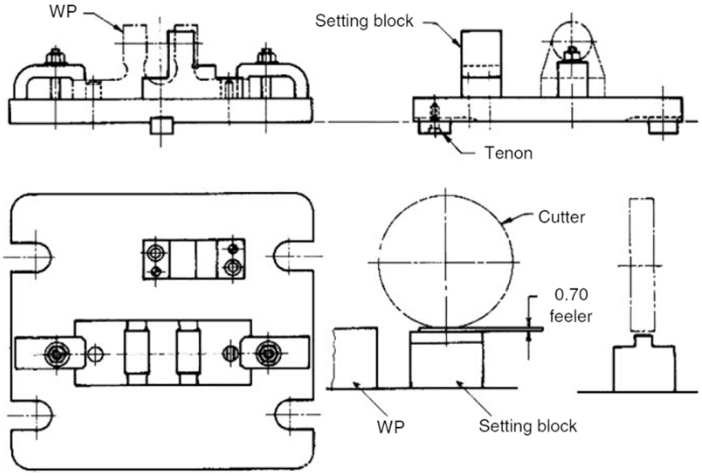


FIGURE 3.54 Simple milling fixture for a bearing bracket. (From Mott, L. C., *Engineering Drawing and Construction*, Oxford University Press, Oxford, 1976. With permission.)

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

- Figure 3.55 illustrates a vise used as a fixture for milling six cylindrical WPs in one clamp.
- The setting block is designed for a feeler gage of 0.025 mm, the thickness of which should be stamped on the setting block in some suitably prominent position.
- In this type of fixture, it is essential that
- when the components are unloaded, all the swarf must be removed; otherwise, the component subsequently loaded into the fixture will not seat correctly.

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

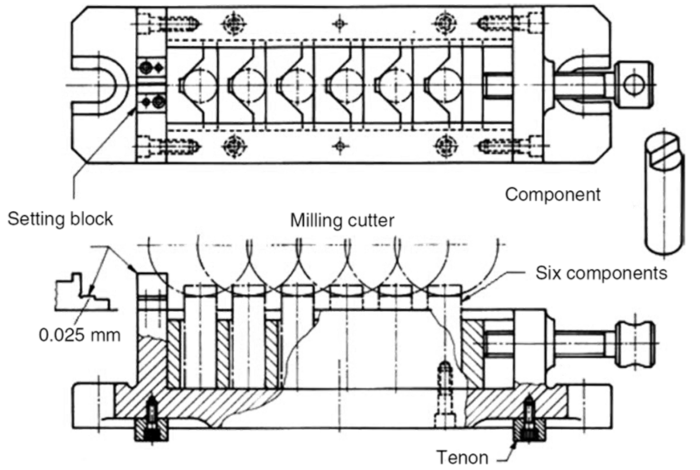


FIGURE 3.55 Special fixture for milling six cylindrical WPs. (From Mott, L. C., *Engineering Drawing and Construction*, Oxford University Press, Oxford, 1976. With permission.)

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

- Figure 3.56 shows a WP and fixture of more specialized nature designed by the U.S. Naval Gun Factory. Two rectangular components are to be milled together.
- They are located and clamped between two mating surfaces.
- The holding plate is positioned by two spring-loaded dowels and a central fixing stud.
- A setting block is doweled and screwed to the fixture.
- It is designed for use with a feeler gage of 0.08 mm thickness.
- The disadvantage of this setup is that the arbor is unsupported at its free end and, therefore, only light cuts are taken.
- Duplex milling machines enable WPs to be machined from both sides at once to ensure high accuracy and enhance productivity.

HOLDING CUTTERS AND WORKPIECES ON MILLING MACHINES

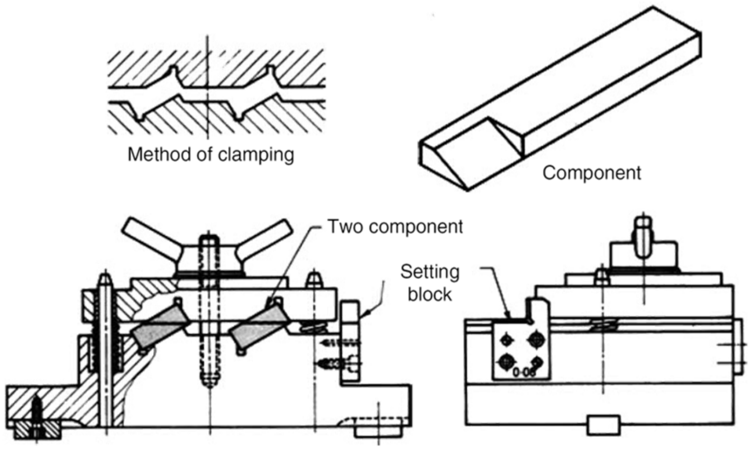


FIGURE 3.56 A special milling fixture for mounting two rectangular components. (From Mott, L. C., *Engineering Drawing and Construction*, Oxford University Press, Oxford, 1976. With permission.)

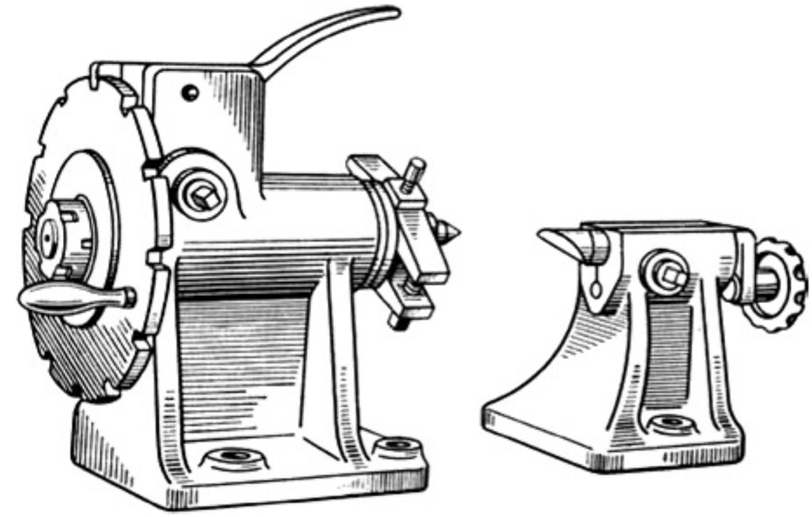
DIVIDING HEADS

- Dividing heads are attachments that extend the capabilities of the milling machines.
- They are mainly employed on knee-type milling machines to enhance their capabilities toward milling straight and helical flutes, slots, grooves, and gashes whose features are equally spaced about the circumference of a blank (and less frequently unequally spaced).
- Such jobs include milling of spur and helical gears, spline shafts, twist drills, reamers, milling cutters, and others. Therefore, dividing heads are capable of indexing the WP through predetermined angles.
- In addition to the indexing operation, the dividing head continuously rotates the WP, which is set at the required helix angle during milling of helical slots and helical gears.

DIVIDING HEADS

- There are several versions of dividing heads:
  - Plain dividing heads (Figure 3.57) are mainly used for indexing milling fixtures.
  - Universal dividing heads.
  - Optical dividing heads are commonly used for precise indexing, and also for checking the accuracy of marking graduation lines on dial scales. Their main drawback is that they cannot be used in milling of helical gears.

DIVIDING HEADS



Plain milling dividing head.

SHAPERS, PLANERS, AND SLOTTERS AND THEIR OPERATIONS

- **Shaping, Planing, And Slotting Processes.**
- These processes are used for machining horizontal, vertical, and inclined flat and contoured surfaces, slots, grooves, and other recesses by means of special single-point tools.
- The difference between these three processes is that in planing, the work is reciprocated and the tool is fed across the work, while in shaping and slotting, the tool is reciprocating and the work is fed across the cutting tool.
- Moreover, the tool travel is horizontal in shaping and planing and vertical in case of slotting (Figure 3.63).

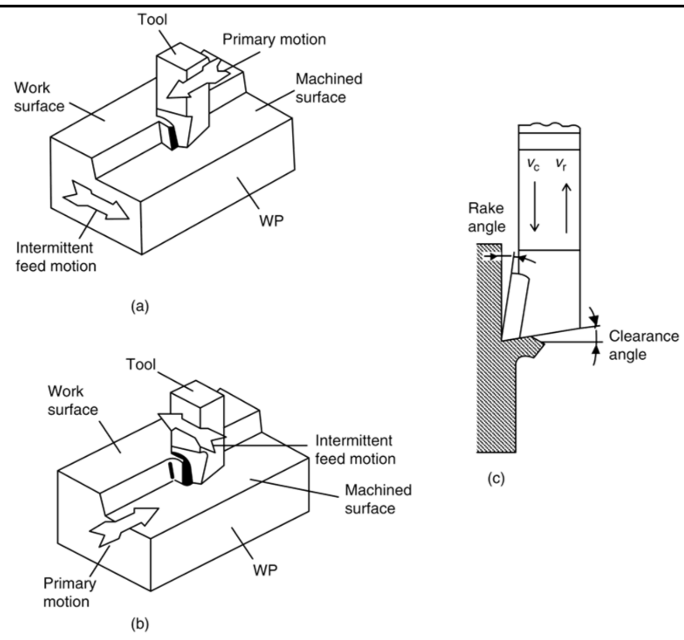


FIGURE 3.63 (a) Shaping, (b) planing, and (c) slotting operations.

SHAPERS, PLANERS, AND SLOTTERS AND THEIR OPERATIONS

- The essence of these processes is the same as of turning, where metals are removed by single point tools similar in shape to lathe tools.
- A similarity also exists in chip formation. However, these operations differ from turning in that the cutting action is intermittent, and chips are removed only during the forward movement of the tool or the work. Moreover, the conditions under which shaping, planing, and slotting tools are less favorable than in turning, even though the tools have the opportunity to cool during the return stroke, when no cutting takes place.

SHAPERS, PLANERS, AND SLOTTERS AND THEIR OPERATIONS

- That is because these tools operate under severe impact conditions.
- For these conditions, the related machine and tools are designed to be more rigid and strongly dimensioned, and the cutting speed in most cases does not exceed 60 m/min.
- Consequently, tools used in these processes should not be shock-sensitive, such as ceramics and CBN.
- It is sufficient to use low-cost and easily sharpened tools such as HSS and carbides.

SHAPERS, PLANERS, AND SLOTTERS AND THEIR OPERATIONS

- The limited cutting speed and the time lost during the reverse stroke are the main reasons behind the low productivity of shaping, planing, and slotting compared to turning.
- However, in planing, not only the productivity but also the accuracy are enhanced due to the possibility of using multiple tooling in one setting.
- Figure 3.64 illustrates the kinematics and machining parameters in shaping, planing, and slotting.

SHAPERS, PLANERS, AND SLOTTERS AND THEIR OPERATIONS

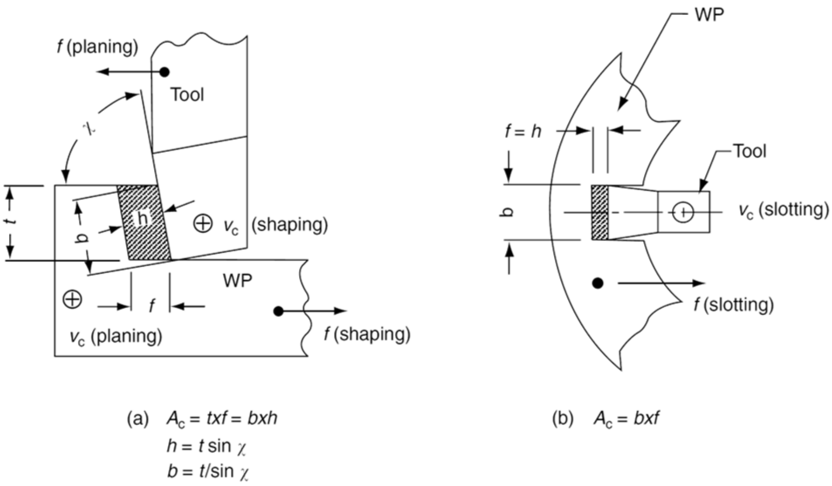


FIGURE 3.64 Kinematics and machining parameters in (a) shaping and planning and (b) slotting.

SHAPERS, PLANERS, AND SLOTTERS AND THEIR OPERATIONS

- The basic machining parameters are the average speed during the cutting stroke v_{cm}, the feed f, the depth of cut t, and the uncut cross-section area A_c.
- The feed is the intermittent relative movement of the tool (in planing) or the WP (in shaping and slotting), in a direction perpendicular to the cutting motion and expressed in millimeters per stroke.
- The feed movement is always actuated at the end of the return stroke when the tool is not engaged with the work.
- The depth of cut is the layer removed from the WP in millimeters in a single pass and is measured perpendicular to the machined surface.

SHAPERS, PLANERS, AND SLOTTERS AND THEIR OPERATIONS

- The uncut chip cross-section in square millimeters is given by the following equation for shaping and planing:

$$A_c = b \cdot h = t \cdot f \text{ mm}^2$$

where

b = chip contact length (mm)
$= t/\sin x$
h = chip thickness (mm)
$= f \sin x$
x = setting angle (frequently $x = 75°$)

and the following equation for slotting

$$A_c = b \cdot f \text{ mm}^2$$

where b is the slot width (mm).

SHAPERS, PLANERS, AND SLOTTERS AND THEIR OPERATIONS

- v_{cm} in meters per minute can be calculated depending on the type of machine mechanism.
- It should not exceed the permissible cutting speed which depends upon:
- Machining conditions (depth of cut, feed, tool geometry, and related conditions)
- Tool material used
- Properties of WP material