Introduction to Manufacturing, AGE-1320

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Manufacturing Engineering Technology in SI Units, 6th Edition

Chapter 24: Machining Processes: Milling (Milling, Broaching, Sawing, Filing and Gear Manufacturing)

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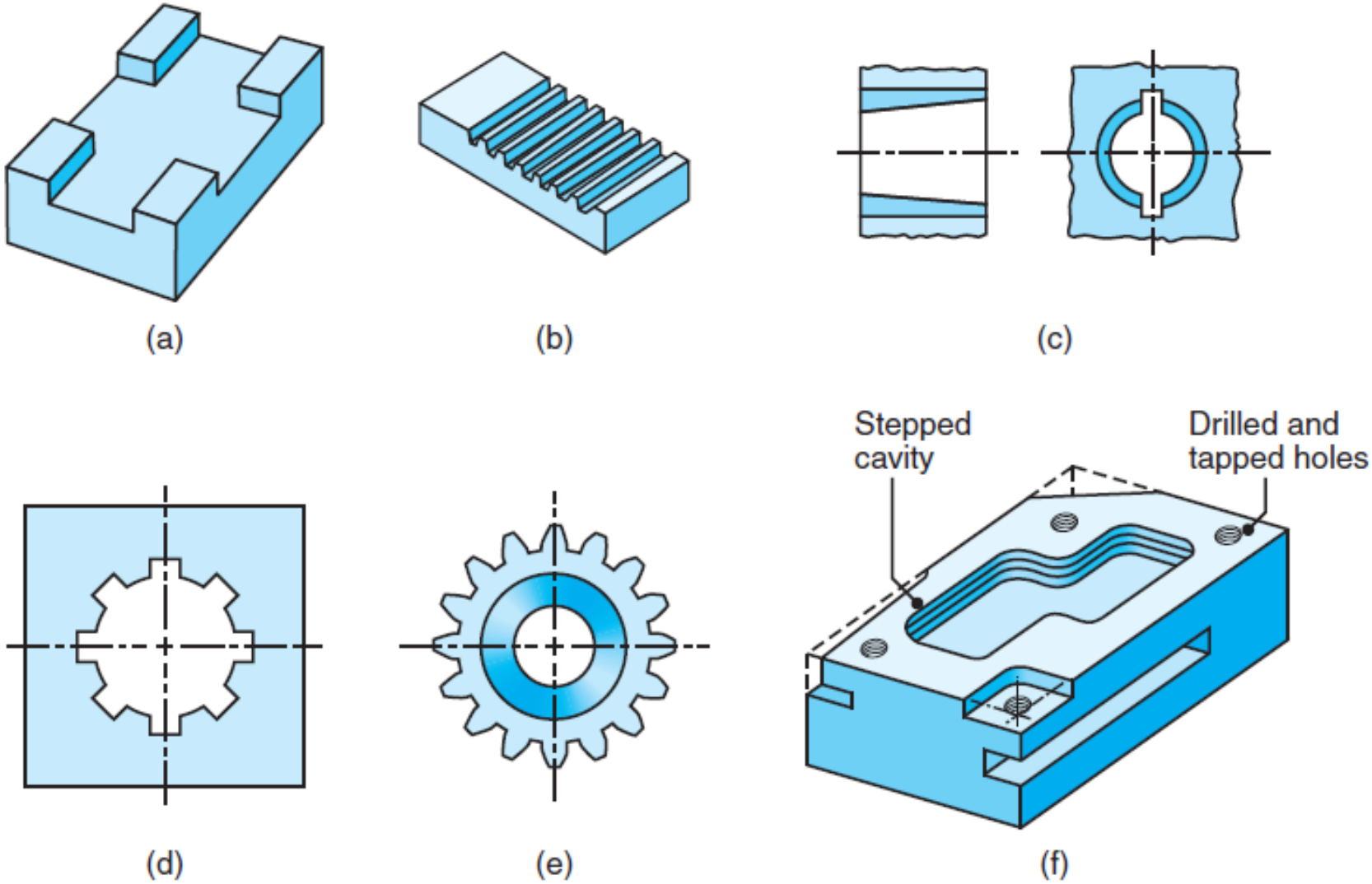
Chapter Outline

1. **Introduction**
2. **Peripheral milling**
3. **Face milling**
4. **End milling**
5. **Other milling operations**
6. **Milling machines**

1. Introduction

Introduction

- Last chapter: processes that produce round shapes
- Milling:
  - One of most common, versatile, economical machining processes
  - Rotating cutter removes material, traveling along various axes w.r.t. workpiece:
  - Milling cutter – multitooth tool: produces num. of chips / 1 rev
  - Takes place in a variety of configurations
  - Produces parts w/ complex external and internal features
- Similar processes (not discussed here):
  - Planing, shaping, broaching, sawing, filing, gear manufacturing
  - Either tool or workpiece travel along straight path
  - Produce flat or various shaped surfaces



Typical parts and shapes that can be produced with machining processes described in this chapter. Can you guess how a) – f) are produced?

Introduction

Some basic types of milling cutters and milling operations:

a) Peripheral (aka plain milling)

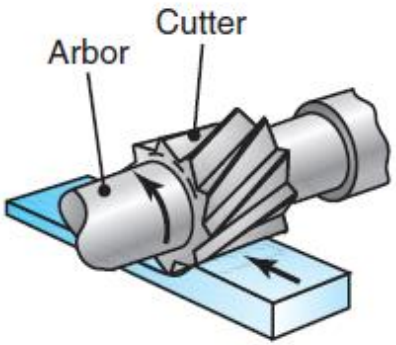
b) Face milling

c) End milling

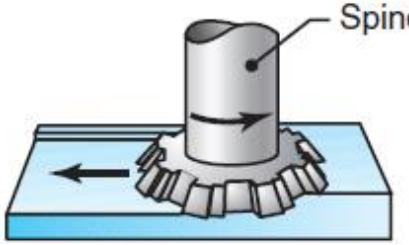
d) Ball-end mill (with indexable coated-carbide inserts)

e) End mill using 5-axis NC machine

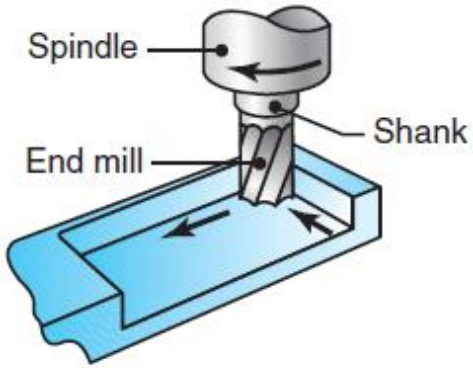
4-Flute Ball Nose End Mill



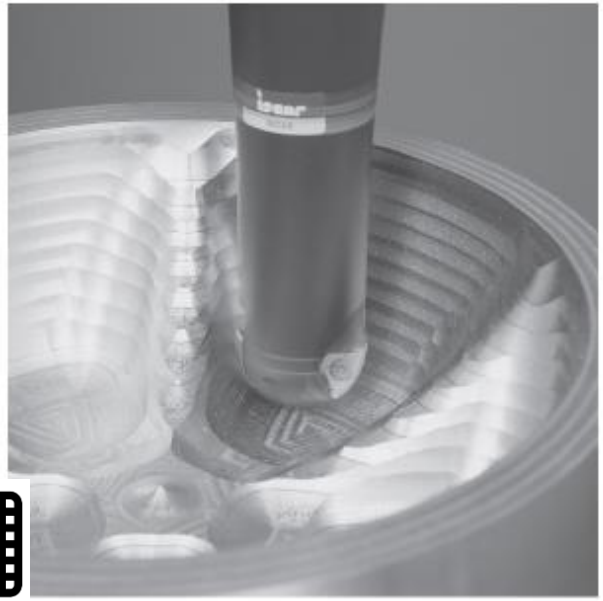
(a) Peripheral milling



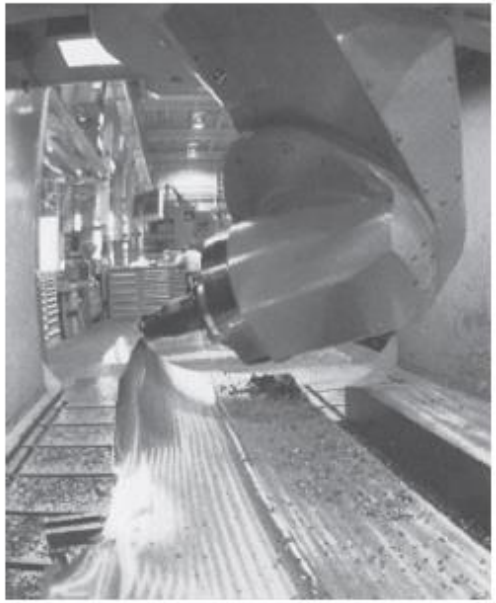
(b) Face milling



(c) End milling



(d)

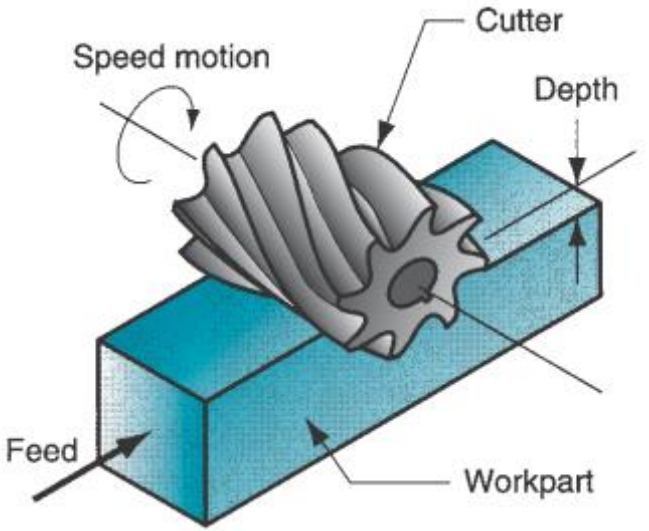


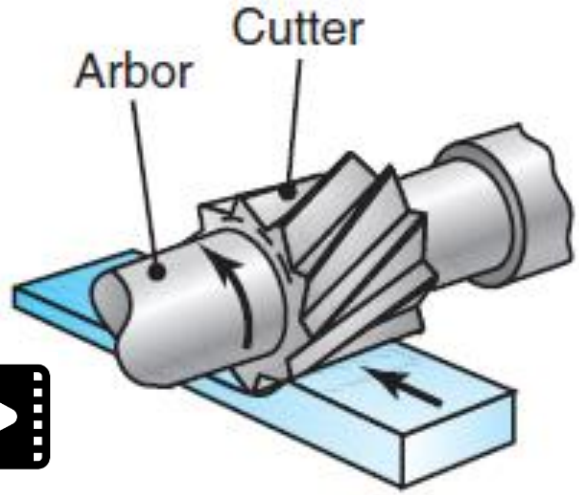
(e)

2. Peripheral Milling

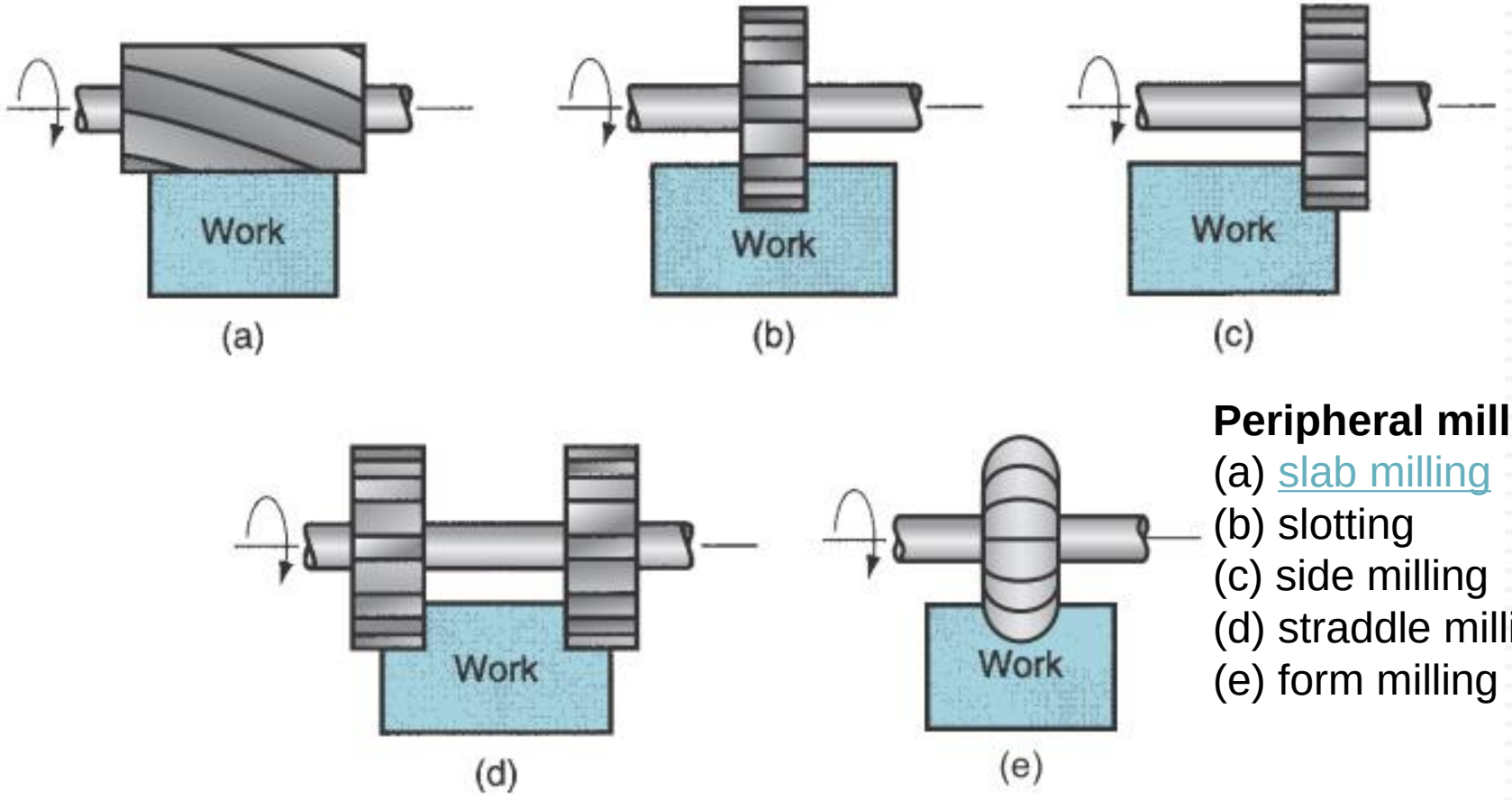
Milling and Milling Machines: Peripheral Milling

- Axis of cutter rotation: parallel to workpiece surface
- Cutter body:
  - Generally made of high-speed steel
  - Has # of teeth along its circumference
  - Each tooth acts like a single-cutting tool
- When cutter: longer than width of cut
  - ⇒ process is called *slab milling*
- Other types of peripheral milling are shown on the next slide





Milling and Milling Machines: Peripheral Milling

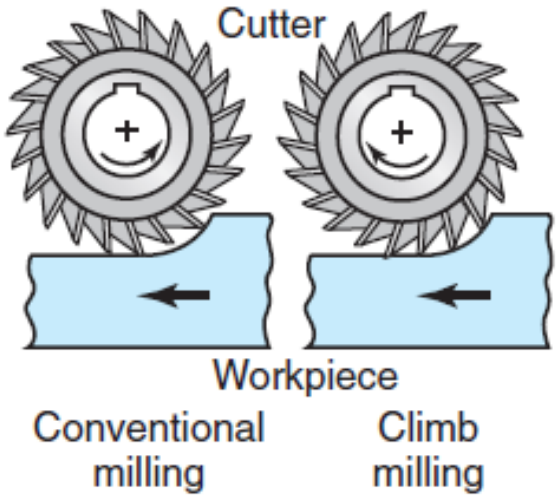


Peripheral milling:
(a) slab milling
(b) slotting
(c) side milling
(d) straddle milling
(e) form milling

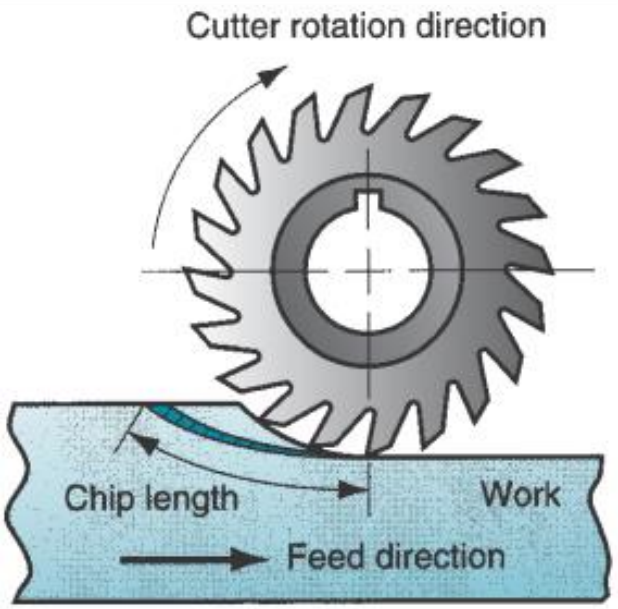
Milling and Milling Machines: Peripheral Milling

Conventional Milling and Climb Milling

- Cutter rotation:
  - Conventional (aka up) milling,
  - Climb (aka down) milling
  - This is significant in operation

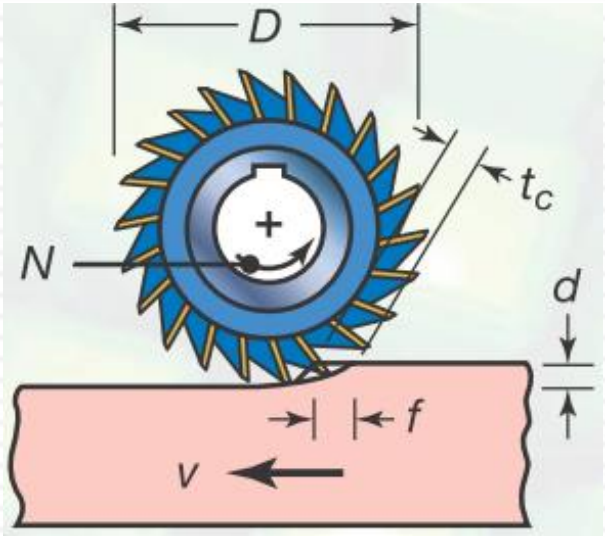


Milling and Milling Machines: Peripheral Milling



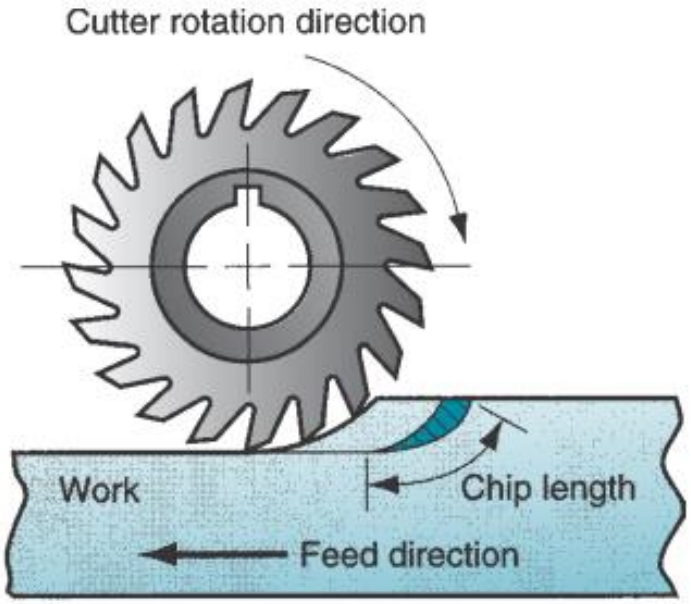
Cont. Conventional / Climb Milling

- Conventional (more common) milling:
  - max. t_c is at end of cut
  - i.e. as tooth leaves workpiece (→)
- Advantage:
  - Tooth engagement: not function of workpiece surface characteristics
- Disadvantages:
  - If cutter teeth not sharp ⇒ tooth rubs on surface before cutting
  - Also: tool may chatter; workpiece may be pulled upward



Milling and Milling Machines: Peripheral Milling

Cont. Conventional / Climb Milling



- Climb milling*:*
  - Cutting starts at surface of workpiece where chip is thickest →
- Advantage:
  - Downward component of F_c holds workpiece in place (esp. thin parts)
- Disadvantages:
  - Requires rigid work-holding setup
  - Not suitable for workpieces with scale (e.g. hot-worked metals)
  - Note, scale ⇒ more wear ⇒ lower T (tool life)

Milling and Milling Machines: Peripheral Milling

Slab milling operation showing:

$\boldsymbol{d}$: depth of cut

$\boldsymbol{f}$: feed per tooth

$\boldsymbol{w}$: width of cut (not shown)

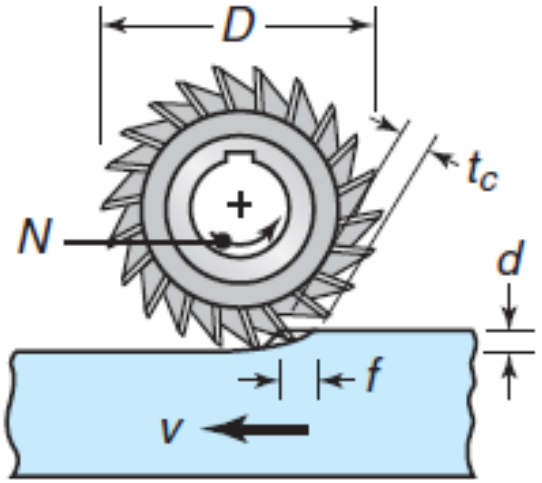
$\boldsymbol{t_c}$: chip depth of cut

$\boldsymbol{v}$: workpiece speed (feed rate)

$\boldsymbol{D}$: cutter diameter

$\boldsymbol{N}$: cutter rotational speed

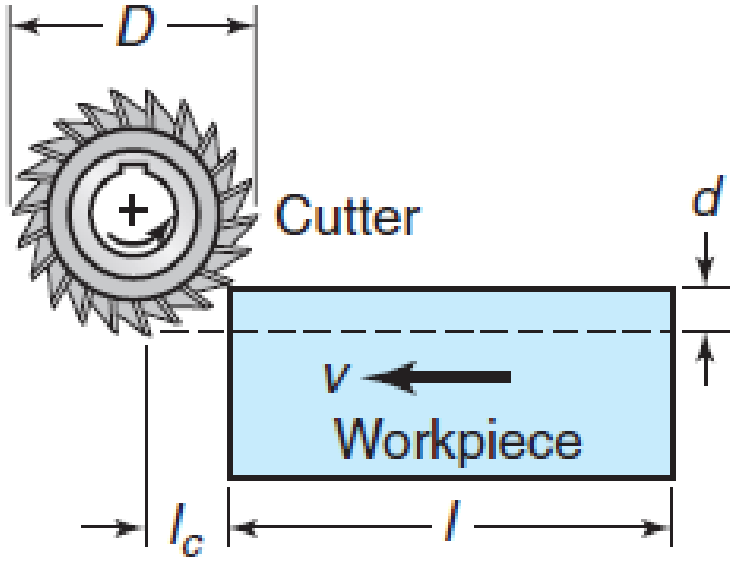
$\boldsymbol{n}$: number of teeth on cutter periphery



Schematic illustration of:

$\boldsymbol{l_c}$: cutter travel distance (horizontal) to reach full depth of cut

$\boldsymbol{l}$: length of workpiece

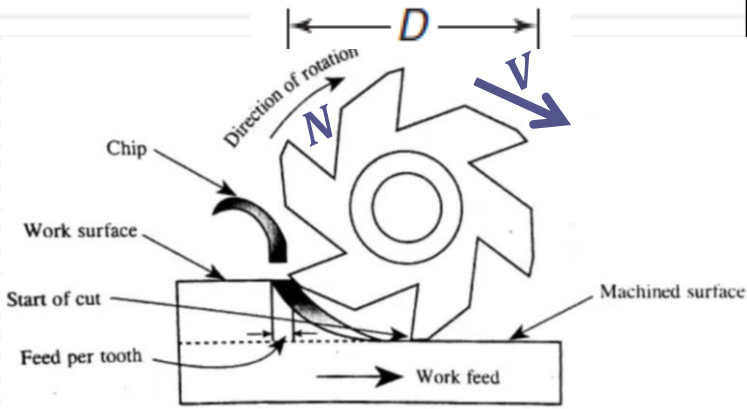


Milling and Milling Machines: Peripheral Milling

Milling Parameters

- Cutting speed in peripheral milling is surface speed of cutter:

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



- t_c in slab milling:
  - Varies along its length (due to relative longitudinal motion between cutter and workpiece)
  - As $t_c \uparrow \Rightarrow F_c \uparrow$
  - For straight-tooth cutter, approx. t_c:

$$\boldsymbol{t_c = 2f\sqrt{\frac{d}{D}}}$$

Milling and Milling Machines: Peripheral Milling

Milling Parameters (cont.)

- f: distance workpiece travels per tooth of cutter:

$$\boldsymbol{f = \frac{v}{Nn}}$$

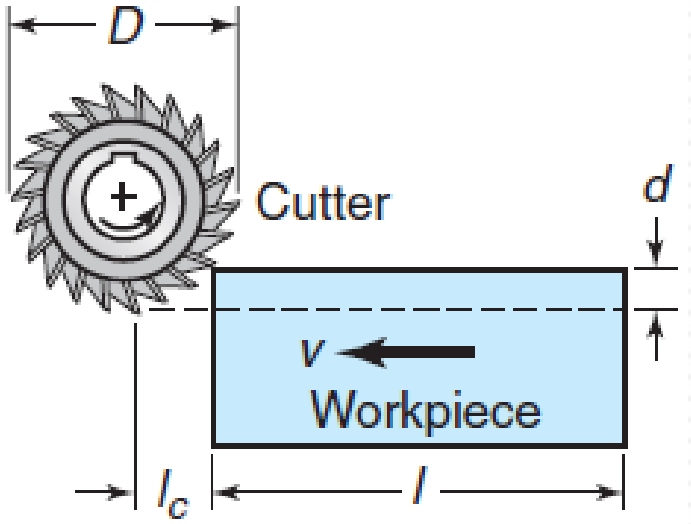
  - Note, dimensional accuracy can be checked:
    $[mm/tooth] = [mm/min]/[rev/min][num.of\ teeth/rev]$

- Cutting time is given by:

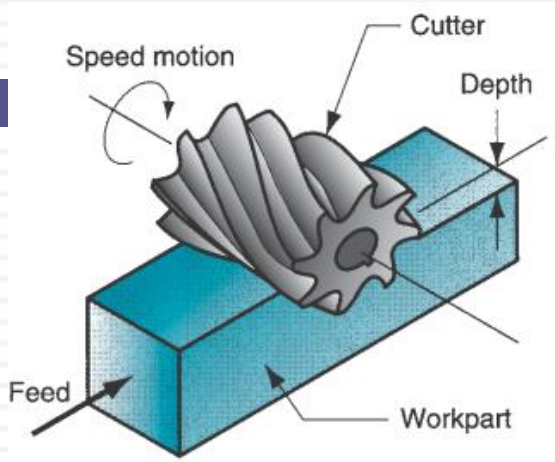
$$\boldsymbol{t = \frac{l + l_c}{v}}$$

  - Note, l_c: horizontal extent of cutter's first contact with workpiece
  - l_c can be approximated using:

$$\boldsymbol{l_c = \sqrt{d(D - d)}}$$



Milling and Milling Machines: Peripheral Milling



Milling Parameters (cont.)

- Assuming $l_c \ll l \Rightarrow$ MRR is given by:

$$\boldsymbol{MRR = \frac{lwd}{t} = wdv}$$

  - Note, in slab milling: w is same as w of workpiece
  - Also, as with turning, non-cutting time should be minimized

- Power requirement on spindle:
  - Calculated similar to technique used in drilling
  - Note, forces on cutter (tangential, radial, axial):
    - Difficult to calculate (since many variables are involved)
    - Many variables related to cutting-tool geometry

Milling and Milling Machines: Peripheral Milling

Summary of Peripheral Milling Parameters and Formulas

N = Rotational speed of the cutter, rpm
F = Feed, mm/rev
D = Cutter diameter, mm
n = Number of teeth on cutter
v = Linear speed of the workpiece or feed rate, mm/min
V = Surface speed of cutter m/min
= πDN
f = Feed per tooth, mm/tooth
= v/Nn
l = Length of cut, mm
t = Cutting time, s or min
= $(l + l_c)/v$, where l_c = extent of the cutter's first contact with the workpiece
MRR = mm^3/min
= wdv, where w is the width of cut
Torque = N · m
= $F_c D/2$
Power = kW
= (Torque)(ω), where $\omega = 2\pi N$ radians/min

$$t_c = 2f\sqrt{\frac{d}{D}}$$

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

(advanced)

Milling and Milling Machines: Peripheral Milling

EXAMPLE 24.1

Material-removal Rate and Cutting Time in Slab Milling

A slab-milling operation is being carried out on a 300-mm-long, 100-mm-wide annealed mild-steel block at a feed f 0.25 mm/tooth and a depth of cut d 3.0 mm. The cutter is D=50 mm in diameter, has 20 straight teeth, rotates at 100 rpm and, by definition, is wider than the block to be machined. Calculate the material-removal rate and calculate the cutting time.

Milling and Milling Machines: Peripheral Milling

Solution

Material-removal Rate, Power, Torque, and Cutting Time in Slab Milling

The linear speed of the workpiece is

$$v = fNn = (0.25)(100)(20) = 500 \text{ mm/min}$$

The material-removal rate is

$$MMR = (100)(3)(500) = 150{,}000 \text{ mm}^3/\text{min}$$

The cutting time is

$$t = \frac{300 + \sqrt{Dd}}{500} = \frac{300 + \sqrt{(50)(3)}}{500} = 0.62 \text{ min} = 37.2 \text{ s}$$

3. Face Milling

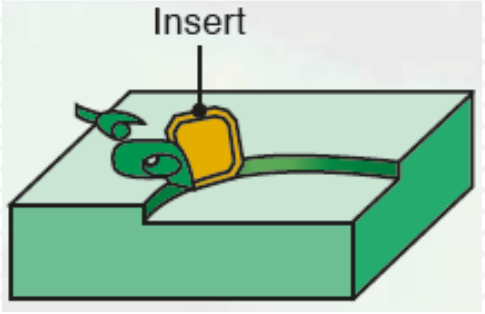
Milling and Milling Machines: Face Milling

Indexable Face Mill (FAST)

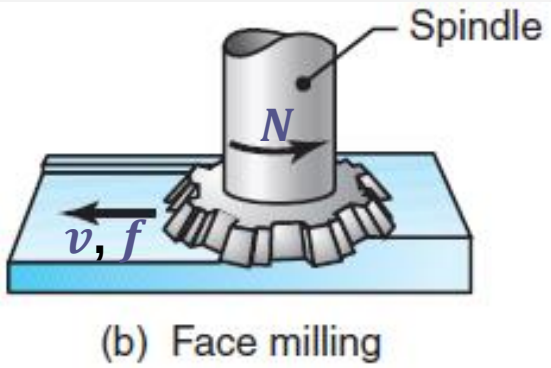


- Face milling cutter:
  - Mounted on a spindle
  - Axis of rotation: ⊥ to workpiece surface
  - Removes material in manner shown (→)
  - Cutting teeth:
    - Example: carbide inserts
    - Mounted on the cutter body

Precision Face Milling

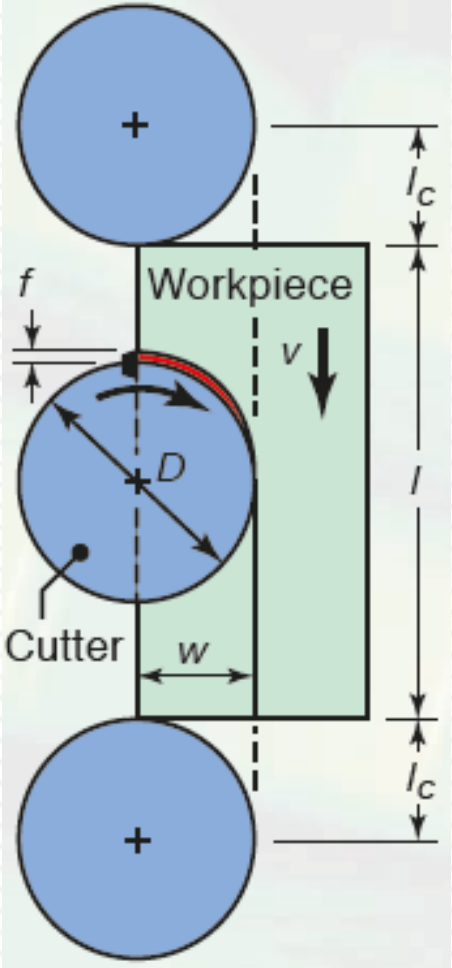


  - Cutter: rotates at rotational speed, N
  - Workpiece: moves along straight path at linear speed, v
  - Rotates as: climb or conventional milling (next slide)

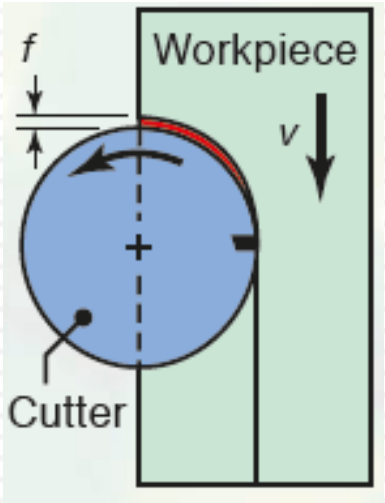


(b) Face milling

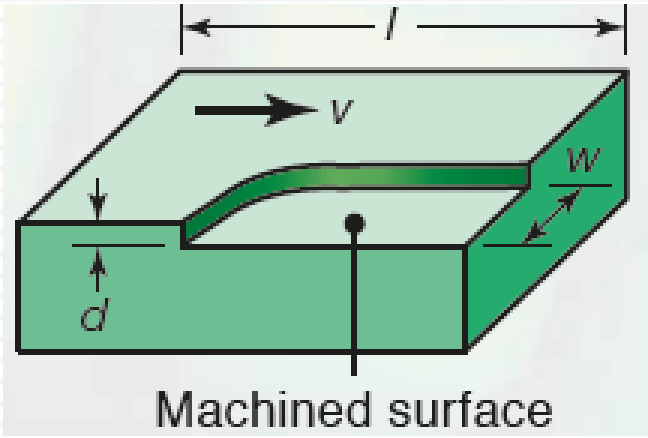
Milling and Milling Machines: Face Milling



Climb milling



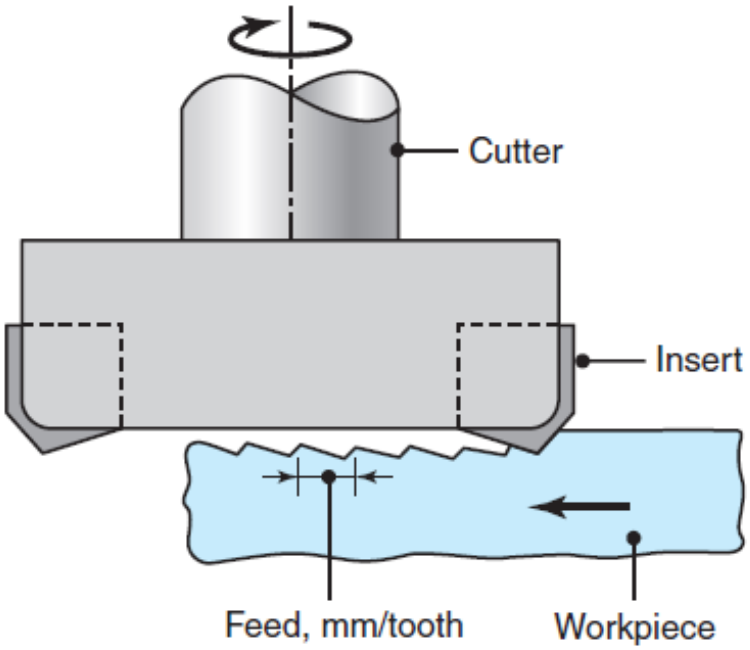
Conventional milling



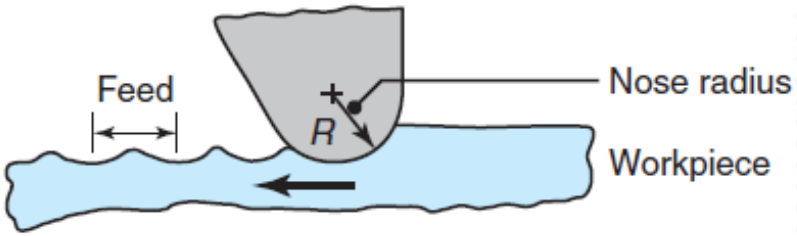
Dimensions in face milling

Milling and Milling Machines: Face Milling

- Relative motion between cutter teeth and workpiece ⇒ **feed marks** on machined surface (↓)
  - Note, these marks are similar to those left by turning
  - Roughness of workpiece depends on: corner geometry and f

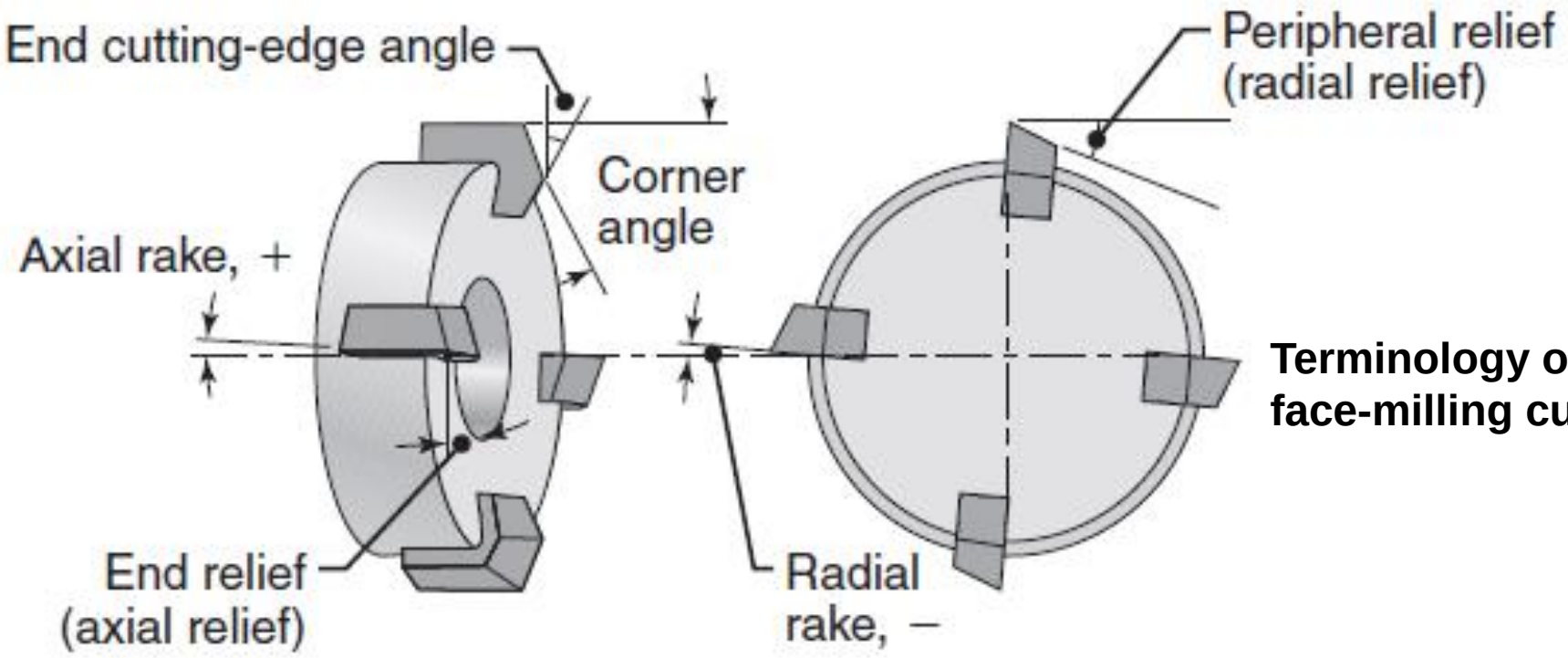


Feed marks due to various insert shapes



Milling and Milling Machines: Face Milling

- Face-milling cutter: terminology and various angles:
  - 2 cutting angles
  - 2 rake angles
  - 2 relief angles

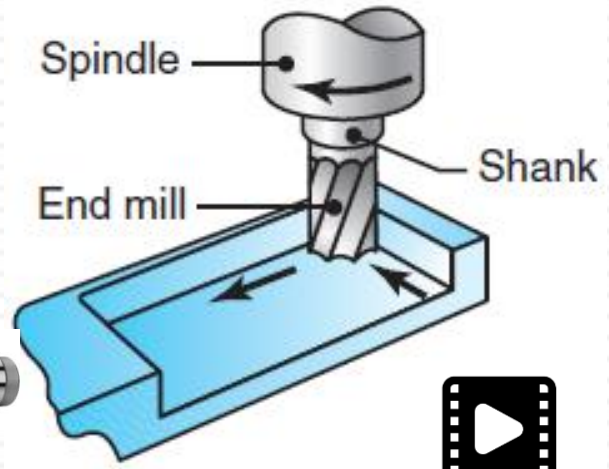


Terminology of a face-milling cutter

4. End Milling

Milling and Milling Machines: End Milling

- End milling:
  - Important and common machining process
  - Versatile: produces various profiles, curved surfaces



- Cutter (aka **end mill**):
  - Has straight shank, or
  - Tapered shank (for larger sizes)
  - Mounted into spindle of milling machine
  - Made of HSS or carbide inserts (like face milling)
  - Usually rotates on axis ⊥ to workpiece surface
  - Can be tilted to conform to curved surfaces

Taper Shank

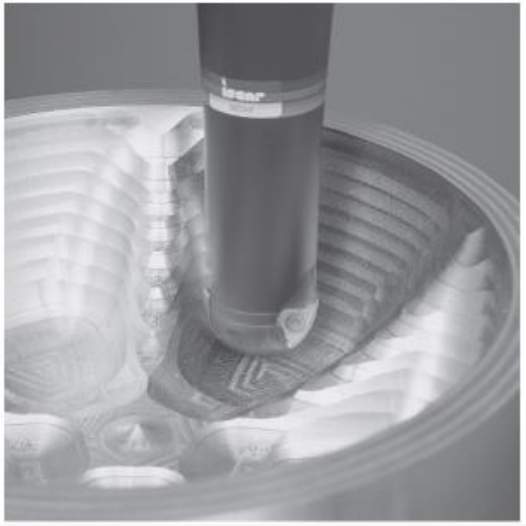


End Milling (CNC)

Milling and Milling Machines: End Milling



- Cont. end mills:
  - Available with hemispherical ends (aka ball nose mills →)
  - Can produce variety of surfaces, at any depth
  - Used in machining dies and molds
  - Examples: curved, stepped, pocketed surfaces (→)
  - Can remove material on both end and cylindrical cutting edges



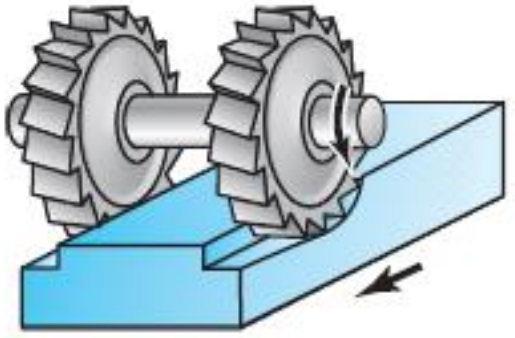


Ball Nose End Mill

5. Other Milling Operations

Milling and Milling Machines: Other Milling Operations and Milling Cutters

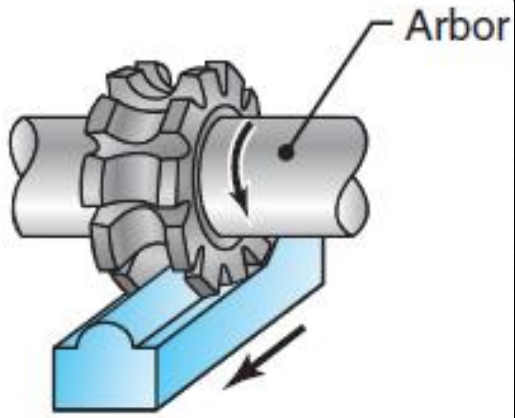
- **Straddle milling**:
  - Two or more cutters: mounted on an arbor
  - Used to machine 2 // surfaces on workpiece



(a) Straddle milling

Profile Milling

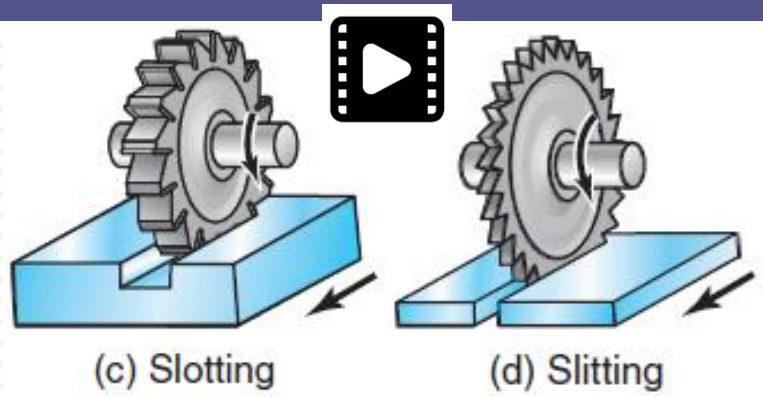
- **Form milling**:
  - Produces curved profiles
  - Uses cutters with specially shaped teeth
  - Also used for cutting gear teeth



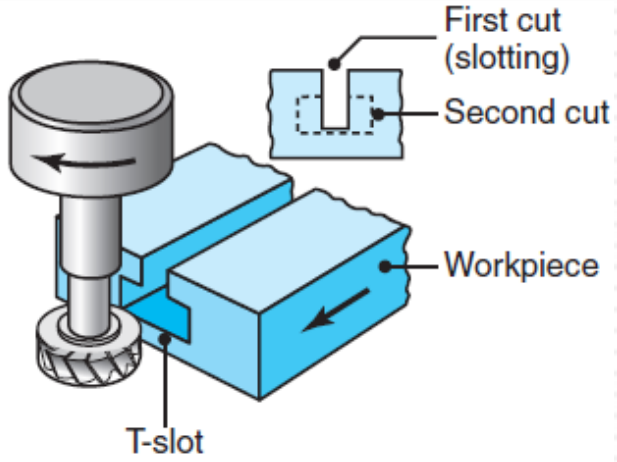
(b) Form milling

Milling and Milling Machines: Other Milling Operations and Milling Cutters

- **Slotting** & **Slitting** operations:
  - Performed with circular cutters
  - Slitting saws: thin (usu. < 5 mm)



- **T-slot cutters:**
  - Used to mill T-slots
  - Application: machine-tool worktables for clamping workpieces
  - Step 1: slot is milled with end mill
  - Step 2: cutter machines profile of T-slot in one pass



Milling and Milling Machines: Milling Process Capabilities

- Table 24.2 shows (for milling), conventional ranges of:
  - Speeds (vary widely: $30 - 3000\ m/\text{min}$)
  - Feed per tooth (typically: $0.1 - 0.5\ mm$)
  - Depths of cut (usually: $1 - 8\ mm$)
- Note, large range of values shown is due to variance in:
  - Workpiece material
  - Workpiece condition
  - Cutting-tool material
  - Process parameters
- Note, cutting fluid recommendations:
  - Same as those used with turning/hole making operations

General Recommendations for Milling Operations

Material	Cutting tool	General-purpose starting conditions: Feed mm/tooth	General-purpose starting conditions: Speed m/min	Range of conditions: Feed mm/tooth	Range of conditions: Speed m/min
Low-carbon and free-machining steels	Uncoated carbide, coated carbide, cermets	0.13–0.20	120–180	0.085–0.38	90–425
Alloy steels					
Soft	Uncoated, coated, cermets	0.10–0.18	90–170	0.08–0.30	60–370
Hard	Cermets, PcBN	0.10–0.15	180–210	0.08–0.25	75–460
Cast iron, gray	Uncoated, coated, cermets, SiN	0.10–10.20	120–760	0.08–0.38	90–1370
Soft					
Hard	Cermets, SiN, PcBN	0.10–0.20	120–210	0.08–0.38	90–460
Stainless steel, Austenitic	Uncoated, coated, cermets	0.13–0.18	120–370	0.08–0.38	90–500
High-temperature alloys	Uncoated, coated, cermets, SiN, PcBN	0.10–0.18	30–370	0.08–0.38	30–550
Nickel based					
Titanium alloys	Uncoated, coated, cermets	0.13–0.15	50–60	0.08–0.38	40–140
Aluminum alloys					
Free machining	Uncoated, coated, PCD	0.13–0.23	610–900	0.08–0.46	300–3000
High silicon	PCD	0.13	610	0.08–0.38	370–910
Copper alloys	Uncoated, coated, PCD	0.13–0.23	300–760	0.08–0.46	90–1070
Plastics	Uncoated, coated, PCD	0.13–0.23	270–460	0.08–0.46	90–1370

Source: Based on data from Kennametal Inc.

Note: Depths of cut, *d*, usually are in the range of 1 to 8 mm. PcBN: polycrystalline cubic-boron nitride. PCD: polycrystalline diamond. See also Table 23.4 for range of cutting speeds within tool material groups.

6. Milling Machines

Milling and Milling Machines: Milling Machines

- Milling machines:
  - Among most versatile/useful machine tools
  - First milling machines: 1820
  - Machines today have many features
  - Standard milling machines now being replaced with computer controls (CNC) and machining centers
  - Manually controlled machines: inexpensive, still used today for small production
  - Typical machines are described in upcoming slides

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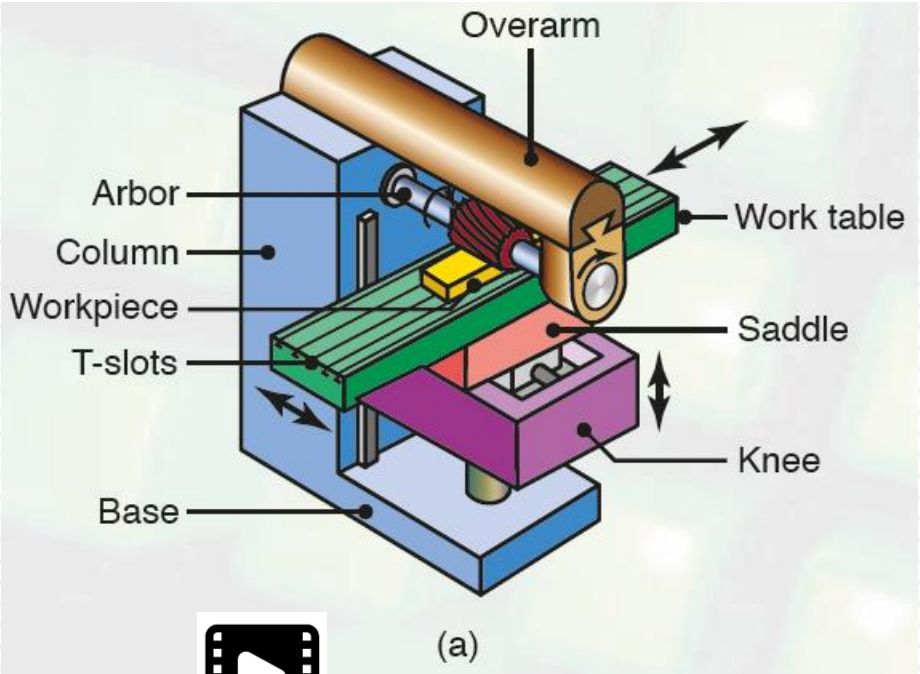
Milling and Milling Machines: Milling Machines

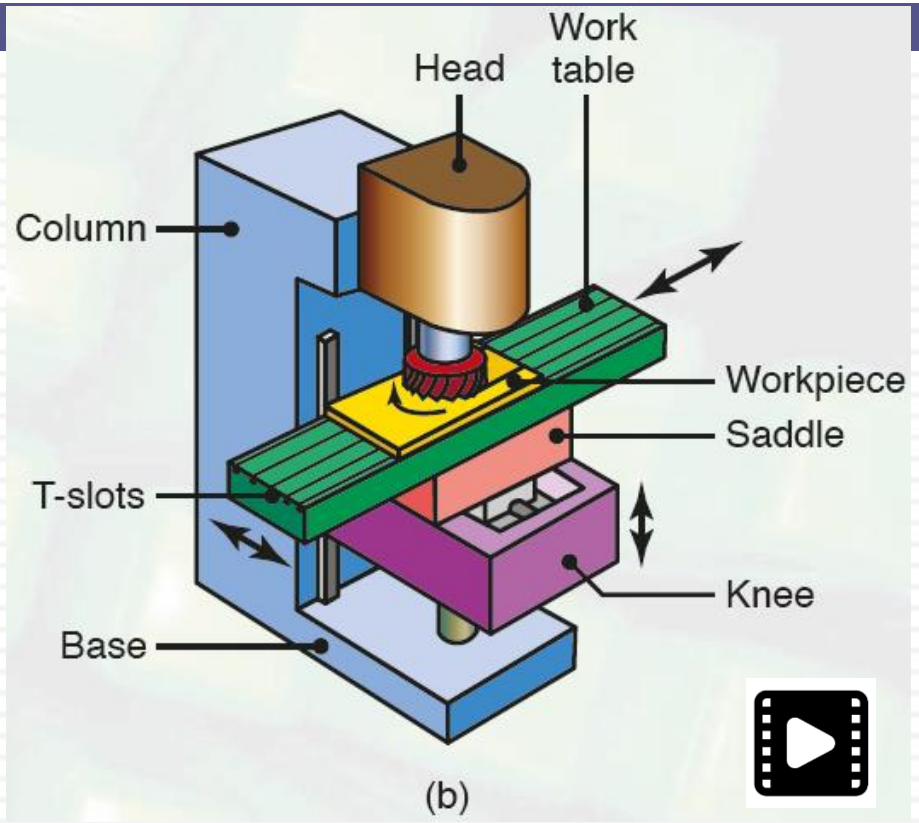
Column-and-knee-type Machines

- Used for general-purpose milling operations
- Most common milling machines
- Spindle on which cutter is mounted may be either (next):
  - Horizontal (for peripheral milling)
  - Vertical (for face and end milling, boring, drilling)
- Usually have 3 axes of movement
  - aka plain milling machines
  - Motion takes place manually or powered

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Milling and Milling Machines: Milling Machines

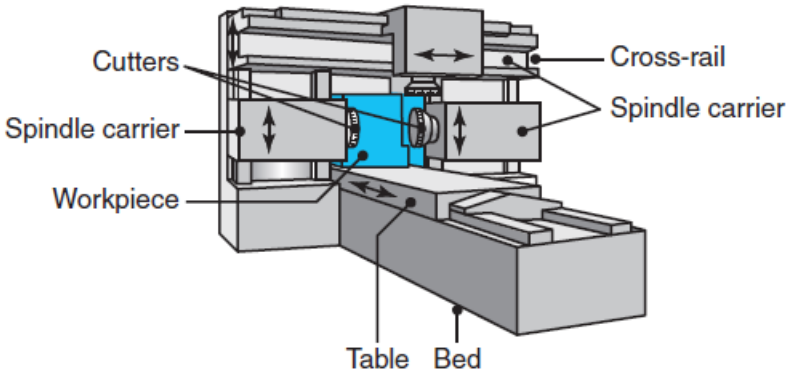




Horizontal or Vertical?

Fig. 24.15 (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.

Milling and Milling Machines: Milling Machines



Bed-type Milling Machines

- Worktable replaces knee
- Can move only longitudinally

Other Types of Milling Machines

- Planer-type milling machines:
  - Have several heads and cutters to mill different surfaces
- Computer numerical-control (CNC) machines (→):
  - Used for high production quantities
  - Capable of: milling, drilling, boring, tapping

Planer machine

