Chapter 23
Machining Processes Used to Produce Various Shapes

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Figures by
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Introduction
• What is milling?
  • A manufacturing process in which a rotating, multitooth cutter removes material while traveling along various axes with respect to the workpiece.
• Other processes will be discussed, such as
  • Planing, shaping, broaching, sawing, filing, and gear manufacturing.

Milling operations
• Slab milling (Figure a)
  • Arbor, cutter
• Face milling (Figure b)
  • Spindle and cutter
• End milling (Figure c)
  • Spindle, shank, end mill

Conventional and Climb Milling
Figure 23.4 (a) Schematic illustration of conventional milling and climb milling. (b) Slab milling operation, showing depth of cut, d, feed per tooth, f, chip depth of cut, tc, and workpiece speed, v. (c) Schematic illustration of cutter travel distance lc to reach full depth of cut.

Milling Parameters
• The velocity at the point of contact
  \[ V = \frac{N \cdot \pi \cdot D}{60} \]
  • Material Removal Rate
  \[ MRR = \frac{w \cdot d \cdot l}{t} \]
• Definitions of symbols
  • tc: chip thickness
  • f: feed per tooth of cutter
  • D: depth of cut
  • N: angular speed in rpm
  • w: number of teeth on cutter periphery
  • l: linear speed (feed rate)
  • v: speed of cutter
  • t: cutting time
  • L: length of the workpiece
  • Lc: extent of the cutter's first contact with the workpiece (illustration on next page)
  • w: width of cut
### Illustration of Lc

L: extent of the cutter's first contact with the workpiece

### Summary of Milling Parameters and Formulas

**TABLE 23.1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>Rotational speed of the milling cutter, rpm</td>
</tr>
<tr>
<td>$f$</td>
<td>Feed, mm/tooth or in/tooth</td>
</tr>
<tr>
<td>$D$</td>
<td>Cutter diameter, mm or in.</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of teeth on cutter</td>
</tr>
<tr>
<td>$v$</td>
<td>Linear speed of the workpiece or feed rate, mm/min or in./min</td>
</tr>
<tr>
<td>$V$</td>
<td>Surface speed of the cutter, m/min or ft/min</td>
</tr>
<tr>
<td>$D\times N$</td>
<td>Feed per tooth, mm/tooth or in/tooth</td>
</tr>
<tr>
<td>$v/N\times n$</td>
<td>Cutting time, s or min</td>
</tr>
<tr>
<td>$l_c$</td>
<td>Extent of the cutter's first contact with the workpiece</td>
</tr>
<tr>
<td>$l$</td>
<td>Length of cut, mm or in.</td>
</tr>
<tr>
<td>$t$</td>
<td>Cutting time, s or min</td>
</tr>
</tbody>
</table>

**MRR** = \( \frac{w \times d \times v}{60} \)

where:
- $w$ is the width of cut
- $d$ is the depth of cut
- $v$ is the linear speed of the workpiece

**Torque** = \( \frac{F_c \times D}{2} \)

where:
- $F_c$ is the cutting force
- $D$ is the cutter diameter

**Power** = \( \frac{\text{Torque} \times \omega}{\text{rad/min}} \)

where:
- $\omega$ is the angular speed (rad/min)

Note: The units given are those that are commonly used; however, appropriate units must be used in the formulas.

### Example

A slab milling operation is being carried out on a 12-in long, 4-in wide annealed mild steel block at a feed $f=0.01$ in/tooth and a depth of cut $d=1/8$ in. The cutter is of 2-in diameter, and has 20 straight teeth, rotates at $N=1000$ rpm, and is wider than the block to be machined. Calculate the material Removal rate, estimate the power and torque required for this operation, and calculate the cutting time.

- **Given:**
  - $w = 4$ in
  - $L = 12$ in
  - $f = 0.01$ in/tooth
  - $d = 1/8$ in
  - $D = 2$ in
  - $n = 20$ teeth
  - $N = 1000$ rpm
  - Cutter width > block width
  - Specific energy: 1.1 hp*min/in. $^3$

- **Find:**
  - Material Removal Rate
  - Power
  - Torque
  - Cutting time

**MRR** = \( \frac{w \times d \times v}{60} \)

\( v = \frac{\pi \times D \times N}{60 \times n} \)

\( MRR = 10 \text{ in.}^3/\text{min} \)

**Power** = \( \frac{\text{Torque} \times \omega}{\text{rad/min}} \)

\( \omega = \frac{2 \pi \times N}{60} \text{ radians/min} \)

\( \text{Power} = 11 \text{ hp} \)

**Torque** = \( \frac{F_c \times D}{2} \)

**Cutting time** = \( \frac{L + L_c}{v} \times n \times 60 \)

\( t = 37.5 \text{ seconds} \)

### Face Milling

- Cutter is mounted on a spindle having an external axis of rotation perpendicular to the workpiece surface.
- Workpiece moves along a straight path at a linear speed, $v$.
- **Direction of cutter**
  - Conventional milling (Fig. a)
  - Up-milling
  - Climb milling (Fig. b)
  - Down-milling
- Leaves feed marks on the machined surface.
- **Terminology in figure**

**Face Milling**

- Leaves feed marks on the machined surface.
- **Terminology in figure**

**Face Milling**

- Leaves feed marks on the machined surface.
- **Terminology in figure**

**Face Milling with Indexable Inserts**

- Source: Courtesy of Ingersoll Cutting Tool Company.

**Cutter and Insert Position in Face Milling**

- **Figure 23.10** (a) Relative position of the cutter and insert as it first engages the workpiece in face milling.
- (b) Insert positions towards the end of the cut, and (c) examples of exit angles of insert, showing desirable (positive or negative) and undesirable (zero angle) positions. In all figures, the cutter spindle is perpendicular to the page.

- Third example in figure c: the insert exits the workpiece suddenly as opposed to exiting with an angle.
The cutter, called an end mill, rotates about an axis perpendicular to the workpiece surface (typically – can be at an angle).

Ball nose: A type of end mill in which the bottom surface is rounded.
- Used in the production of curved surfaces for dies and molds.

**Other Milling Operations and Cutters**

- Straddle milling: two or more cutters are mounted on an arbor and are used to machine two parallel surfaces on the workpiece.
  - Easier to keep tolerances than if milling one surface at a time.
- Form milling: produces curved profiles. Also used in machining gear teeth.
- Circular cutters can be used for slotting and slitting.
  - Slitting saws are typically < 5mm.
- T-slot cutters: used to mill T-slots which are used in clamping workpieces to the worktable. (figure next page)

**Other Milling Operations and Cutters**

- T-slot cutter
  - Note order of cuts:
    1. 1st cut: slot the T-cutter can move
    2. 2nd: finish the T-slot

- Shell milling
  - Has a hollow inside.
  - Mounted on a shank.
  - Allows the same shank to be used for different size cutters.

**Tool holders**

Milling cutters are classified as:
- Arbor cutters
  - Mounted on an arbor
  - Used in slab, face, straddle, and form milling
- Shank cutters
  - The cutter and the shank are one piece.
  - Examples include end mills
  - Straight shanks
    - Mounted using collets, chucks or special end mill holder
  - Tapered shanks
    - Tapered for better clamping
    - Common on larger end mills
    - Mounted in tapered tool holders

**Arbor**

- Mounted a milling cutter on an arbor for use on a horizontal milling machine.

**Milling Process Capabilities**

- Process capabilities include:
  - Surface finish, dimensional tolerance, production rate, and cost consideration
  - Feed rate (typical): 0.1 mm/tooth – 0.5 mm/tooth
  - Depth of cut (typical): 1-8 mm
  - Cutting speeds (varies much): 30m/min to 3000m/min
**Recommendations**

Figure 23.14  Surface features and corner defects in face milling operations; see also Fig. 23.7. For troubleshooting, see Table 23.5. Always京斤昆量京.

**General Recommendations for Milling Operations**

- Use standard milling cutters.
- Internal cavities and pockets with sharp corners should be avoided since cutters have a finite radius.
- Workpieces should be sufficiently rigid to minimize any deflection resulting from clamping and cutting forces.
- Minimizing vibrations:
  - Cutters should be placed close to the spindle to reduce tool deflection.
  - Tool holders and fixtures should be as rigid as possible.
  - If vibration occurs:
    - Modify tool shape or process conditions.
    - Use a cutter with fewer teeth or with random tooth spacing.

**Table 23.2 Typical Capacities and Maximum Workpiece Dimensions for Some Machine Tools**

<table>
<thead>
<tr>
<th>Machine Tool</th>
<th>Maximum dimension (in)</th>
<th>Power (kW)</th>
<th>Maximum speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee-and-column</td>
<td>1.4 (4.8)</td>
<td>20</td>
<td>4000 rpm</td>
</tr>
<tr>
<td>Gear cutting (gear diameter)</td>
<td>5 (16.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broaching machines (length)</td>
<td>2 (6.5)</td>
<td>0.9 MN</td>
<td></td>
</tr>
<tr>
<td>Planers (table travel)</td>
<td>10 (33)</td>
<td>100</td>
<td>1.7</td>
</tr>
<tr>
<td>Knee-and-column</td>
<td>1.4 (4.6)</td>
<td>20</td>
<td>4000 rpm</td>
</tr>
<tr>
<td>Milling machines (table travel)</td>
<td></td>
<td></td>
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</tbody>
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**Table 23.3 Approximate Cost of Selected Tools for Machining**

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<tr>
<th>Tools</th>
<th>Size (in.)</th>
<th>Cost ($)</th>
</tr>
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<tbody>
<tr>
<td>Drills, HSS, straight shank</td>
<td>1/4</td>
<td>1.00–2.00</td>
</tr>
<tr>
<td>Drills, HSS, straight shank</td>
<td>1/2</td>
<td>3.00–6.00</td>
</tr>
<tr>
<td>Drills, HSS, straight shank</td>
<td>1/8</td>
<td>6.00–12.00</td>
</tr>
<tr>
<td>Solid carbide</td>
<td>1/4</td>
<td>2.60–3.00</td>
</tr>
<tr>
<td>Solid carbide</td>
<td>1/2</td>
<td>30–70</td>
</tr>
<tr>
<td>Carbo-tipped</td>
<td>1/2</td>
<td>30–50</td>
</tr>
<tr>
<td>Carbo-tipped</td>
<td>1/4</td>
<td>45–65</td>
</tr>
<tr>
<td>Carbide-tipped</td>
<td>1/8</td>
<td>100</td>
</tr>
<tr>
<td>Carbide-tipped</td>
<td>1/4</td>
<td>10–20</td>
</tr>
<tr>
<td>Carbide-tipped</td>
<td>1/2</td>
<td>10–20</td>
</tr>
<tr>
<td>Reamers, HSS, hand</td>
<td>1/4</td>
<td>10–15</td>
</tr>
<tr>
<td>Reamers, HSS, hand</td>
<td>1/2</td>
<td>15–30</td>
</tr>
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<td>Drills, HSS, straight shank</td>
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**Outline**

1. Surface Features and Corner Defects
2. Capacities and Maximum Workpiece Dimensions for Machine Tools
4. Design and Operating Guidelines for Milling
5. Recommendations

**Guidelines for Turning**

- Parts should be able to be easily fixed to the workholding devices.
- Dimensional accuracy should be as close to final dimensions as possible.
- Sharp parts, tapers (manual), and chamfers (turning) should be avoided (minimum machine time and material waste).
- Milling should be machined to as close to final dimensions as possible.
- Casing tool should be able to travel across the workpiece without obstruction.
- Commonly available cutting tools, inserts, and tool holders should be used.
- Minimize tool overhang.
- Support workpiece rigidity.
- Tools should have high stiffness and clamping capacity.
- When vibration occurs, modify one of the parameters.
Milling Machines

- Column-and-knee type machines
  - Most common
  - The spindle may be horizontal or vertical
- Machine consists of
  - A work table: on which the workpiece is clamped.
  - A saddle: supports the table and moves in a perpendicular direction.
  - A knee: supports the saddle and allows for vertical movement (depth of cut).
  - An overarm: in horizontal machines. It can accommodate different arbor lengths.
  - A head: contains a spindle and cutter holder.
- Plain milling machines: 3 axes
- Universal column-and-knee milling machines: 4th axes (rotational)

Other types of milling machines

- Bed-type milling
  - A bed is used instead of the knee. No vertical movement is possible.
  - The work table is mounted directly on the bed.
  - Used in high production runs for simple parts.

Planing and shaping

- Cutting operation by which flat surfaces, grooves, and notches are produced along the length of the workpiece.
- Typically performed on large workpieces. The workplane is mounted on a table that travels along a straight path.
- A horizontal cross-rail can be moved vertically.
- Shaping: similar to planing but for smaller parts
  - Used to machine notches, keyways

Broaching and Broaching Machines

- What is a broach?
  - A long multi-tooth cutting tool.
- Used for what?
  - To machine internal or external surfaces, such as holes of different sections, teeth of internal gears, multiple spline holes, and flat surfaces.
- Terminology and geometry:
  - Rake angle typically from 0-20 degrees.
  - Clearance angle typically from 0-20 degrees.
  - Pitch = k*sqrt(L) (to find appropriate pitch)
    - k = 1.76 when L is in mm
    - k = 0.35 when L is in inches
    - L = length of surface to be cut
  - At least two or more teeth should be in contact.
- Different type of broaches exist
  - Surface broaches: slab broaches (for cutting flat surfaces), slot, contour, dovetail.
  - Internal broaches: hole, keyway, internal gear, and rifling.

Turn broaching

- The workpiece is rotated between centers, and the broach passes tangentially across the bearing surfaces and remove material.

Broaching Machines

- Either pull or push the broaches and are made either horizontally or vertically.
- Forces required depend on workpiece material, total depth and width of cut, and cutting speed.

Broaching process parameters

- Cutting speeds range from 1.5m/min for high strength alloys to 15m/min for Aluminum alloys.
- Ceramic inserts may be used for finishing operations.

Design Considerations for Broaching

- Parts should be designed such that they can be clamped securely.
- Blind holes, sharp corners, dovetail, splines, and large flat surfaces should be avoided.
Internal Broach and Turn Broaching

Figure 23.24 Terminology for a pull-type internal broach used for enlarging long holes.

Figure 23.25 Turn broaching of a crankshaft. The crankshaft rotates while the broaches pass tangentially across the crankshaft’s bearing surfaces. Source: Courtesy of Ingersoll Cutting Tool Company.

Sawing

Figure 23.26 Terminology for saw teeth. (a) Types of tooth set. (b) Types of tooth set on saw teeth, staggered to provide clearance for the saw blade to prevent binding during sawing.

Sawing

Figure 23.27 Examples of various sawing operations. Source: DoALL Company.

Filing and Finishing

Figure 23.28 Types of burs. Source: The Copper Group.

Gear Manufacturing by Machining

Figure 23.30 Nomenclature for an involute spur gear.

Gear Manufacturing by Machining

Figure 23.31 Production of an involute spur gear.

Sawing

- A saw consists of a blade with a series of small teeth.
- The width of the cut is called the kerf and is typically thin resulting in little waste material.
- At least two or three teeth should be engaged for the blade to prevent snagging (catching the saw teeth on the workpiece).
- The thinner the stock, the finer the saw teeth should be, and the greater the number per unit length.

Sawing

- Types of saws
  - Hacksaw: Straight blades, reciprocating motion. Cutting only takes place during one of the two reciprocating strokes.
  - Circular saw: Also called cold saw.
  - Band saw: Continuous long, flexible blades and have a continuous cutting action.
  - Diamond edge blades and diamond wire saws: High strength wire is coated with diamond particles. Used for cutting hard metallic, nonmetallic, and composite materials.
- Friction sawing
  - A steel blade, or disk, rubs against the workpiece at speeds up to 7600m/min.
  - The frictional energy is converted into heat, which softens a narrow zone in the workpiece.
  - Used to cut hard ferrous metals and reinforced plastics.
  - Commonly used to remove flash from castings.

Filing and Finishing

- Filing: Small scale removal of material from a surface, corner, or hole, including removal of burrs.
- Shapes: flat, round, half round, and triangular
- Rotary files and burs:
  - Used for removing material in die making, deburring, scale removal from surfaces, and producing chamfers on parts

Gear Manufacturing by Machining

- How are gears manufactured?
  - Casting, forging, extrusion, drawing, thread rolling, powder metallurgy, blanking sheet metal, injection molding (non metallic), casting (non metallic), and machining.
- Gears can be machined by
  - Form cutting (future slides)
  - Gear generating (future slides)
- Gear terminology
Form Cutting

- The gear-tooth shape is produced by cutting the gear blank around its periphery.
- After each tooth is cut, the cutter is withdrawn, and the gear blank is rotated (indexed).
- Form cutting can be done on milling machines, with the cutter mounted on an arbor and the gear blank mounted in a dividing head.
- Limitation:
  - Form cutting can only produce gear teeth that have constant width (spur and helical but not beveled gears).

Gear Generating

- The cutting tools in gear generating may be one of the following:
  - A pinion-shaped cutter
    - The cutter is one of the gears in a conjugate pair. The other gear is the blank.
  - A rack-shaped straight cutter
    - The generating tool is a segment of a rack which reciprocates parallel to the axis of the gear blank.

Hob: A worm or screw made into a gear-generating tool.
- It consists of slots that will be used to cut the teeth.
- The angle between the axis of the hob and the gear are about 90 degrees apart.

Grinding

- Form Grinding
  - The shape of the wheel is identical to the tooth spacing (Figure A)
- Generating
  - The grinding wheel acts as shown in Figure (b)

Honing

- The tool is a plastic gear impregnated with fine abrasive particles.
- Improves surface finish.

Lapping

- To further improve surface finish.
- Uses an abrasive compound.

Gear Manufacturers Association

- AGMA: American Gear Manufacturers Association
  - Sets the standards for gears in the US