IE 309 Manufacturing Processes I
Machining Processes: Turning and Milling

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Machining is the removal of material and modification of the surfaces of a workpiece.

Machining involves secondary and finishing operations.
Machining Processes and Machine Tools

Major types of material removal processes:
• Cutting
• Abrasive processes
• Advanced machining processes

Machining operations is a system consisting of the
• Workpiece
• Cutting tool
• Machine tool
• Production personnel
Machining Processes and Machine Tools

The family tree of material removal processes

Material removal processes

Conventional machining

Turning and related operations

Drilling and related operations

Milling

Other machining operations

Abrasice processes

Grinding operations

Other abrasive processes

Nontraditional machining

Mechanical energy processes

Electrochemical machining

Thermal energy processes

Chemical machining
Cutting processes remove material by producing chips

More common cutting processes:

- Turning
- Cutting off
- Slab milling
- End milling
Introduction

Schematic illustration of the turning operation, showing various features

Two-dimensional cutting process
# Mechanics of Cutting

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influence and interrelationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed, depth of cut, feed, cutting fluids</td>
<td>Forces, power, temperature rise, tool life, type of chip, surface finish and integrity</td>
</tr>
<tr>
<td>Tool angles</td>
<td>As above; influence on chip flow direction; resistance to tool wear and chipping</td>
</tr>
<tr>
<td>Continuous chip</td>
<td>Good surface finish; steady cutting forces; undesirable, especially in automated machinery</td>
</tr>
<tr>
<td>Built-up edge chip</td>
<td>Poor surface finish and integrity; if thin and stable, edge can protect tool surfaces</td>
</tr>
<tr>
<td>Discontinuous chip</td>
<td>Desirable for ease of chip disposal; fluctuating cutting forces; can affect surface finish and cause vibration and chatter</td>
</tr>
<tr>
<td>Temperature rise</td>
<td>Influences tool life, particularly crater wear and dimensional accuracy of workpiece; may cause thermal damage to workpiece surface</td>
</tr>
<tr>
<td>Tool wear</td>
<td>Influences surface finish and integrity, dimensional accuracy, temperature rise, forces and power</td>
</tr>
<tr>
<td>Machinability</td>
<td>Related to tool life, surface finish, forces and power, and type of chip</td>
</tr>
</tbody>
</table>
Mechanics of Cutting

Major independent variables in the cutting process:

- Tool material and coatings
- Tool shape, surface finish and sharpness
- Workpiece material and condition
- Cutting speed, feed, and depth of cut
- Cutting fluids
- Characteristics of the machine tool
- Work holding and fixturing
Mechanics of Cutting

Dependent variables in cutting are influenced by changes in the independent variables:

- Type of chip produced
- Force and energy dissipated during cutting
- Temperature rise in the workpiece, the tool and the chip
- Tool wear and failure
- Surface finish and surface integrity of the workpiece
Important question posed is which of the independent variables should be changed first if:

- The surface finish of the workpiece being cut is unacceptable
- The cutting tool wears rapidly and becomes dull
- The workpiece becomes very hot
- The tool begins to vibrate and chatter
Orthogonal cutting is two dimensional and the forces involved are perpendicular to each other.

The cutting tool has a rake angle and a relief or clearance angle.
Mechanics of Cutting

Cutting Ratio

The ratio of $t_0/t_c$ is known as the cutting ratio (or chip-thickness ratio).

Related to two angles by the following relationships:

$$\tan \phi = \frac{r \cos \alpha}{1 - r \sin \alpha}$$

and

$$r = \frac{t_0}{t_c} = \frac{\sin \phi}{\cos(\phi - \alpha)}$$
Shear Strain

Shear strain, $\gamma$, that the material undergoes can be expressed as:

$$\gamma = \frac{AB}{OC} = \frac{AO}{OC} + \frac{OB}{OC},$$

or

$$\gamma = \cot \phi + \tan(\phi - \alpha).$$

Large shear strains are associated with low shear angles or with low or negative rake angles.
Shear Angle

Has great significance in the mechanics of cutting operations

Influences force and power requirements, chip thickness, and temperature

Earliest analyses was based on the assumption that the shear angle adjusts itself to minimize the cutting force

This analysis yielded the expression: $\phi = 45^\circ + \frac{\alpha}{2} - \frac{\beta}{2}$

$\beta$ is the friction angle related to the coefficient of friction
Mechanics of Cutting

Velocities in the Cutting Zone

Note that (since the chip thickness is greater than the depth of cut) the velocity of the chip, $V_c$, has to be lower than the cutting speed, $V$.

\[
\frac{V}{\cos(\phi - \alpha)} = \frac{V_s}{\cos \alpha} = \frac{V_c}{\sin \phi}
\]
Mechanics of Cutting

Types of Chips Produced in Metal Cutting

Commonly observed metal chips in practice and their photomicrographs are shown.

(a) 
(b) 
(c) 
(d) 
(e)
Types of Chips Produced in Metal Cutting

The four main types are as follows:

- Continuous
- Built-up edge
- Serrated or segmented
- Discontinuous
Mechanics of Cutting

Continuous Chips

- Ductile materials
- High cutting speed
- Small feeds and depths
- Sharp cutting edge
- Low tool-material friction
- Good surface finish
- Chips can clog machine
Mechanics of Cutting

Built-Up Edge
- Ductile material
- Low-to-medium cutting speed
- High friction causes portion of chips to adhere to rake face
- BUE forms, then breaks off, cyclically
- Rough surface finish
- Can protect tool if stable
- Can diminish with
  - increasing cutting speed
  - low cutting depth
  - apply cutting fluid
Mechanics of Cutting

Serrated Chips

- Semicontinuous - saw-tooth appearance
- Cyclical chip forms with alternating high shear strain then low shear strain
- Difficult to machine metals at high cutting speed
- Low thermal conductivity
- Decreasing strength with temperature
Mechanics of Cutting

Discontinuous Chips

- Brittle material
- Low cutting speed
- Large feeds and depths or low rake angle
- High tool-chip friction
- Irregular surface finish due to chip discontinuity
- Forces vary continually leading to vibrations and chatter in the machine tool
Chip Curl

In all cutting operations chips develop a curvature (chip curl) as they leave the workpiece surface.

Among the factors affecting the chip curl are the following:

• The distribution of stresses in the primary and secondary shear zones
• Thermal effects
• Work-hardening characteristics of the workpiece material
• The geometry of the cutting tool
• Cutting fluids.
Mechanics of Cutting

Cutting Nonmetallic Materials

A variety of chips in cutting thermoplastics, depending on the type of polymer and process parameters
- depth of cut
- tool geometry
- cutting speed

Chips produced in turning

(a)  
(b)  
(c)  
(d)
Oblique Cutting

The majority of machining operations involve three dimensional tool shapes; thus, the cutting is oblique.

Basic difference between oblique and orthogonal cutting can be seen.

In orthogonal cutting the chip slides directly up the face of the tool, in oblique cutting the chip is helical and at an **inclination angle** \( (i) \)
Forces Acting on Chip

The forces acting in orthogonal cutting are shown.
Resultant force $R$, can be resolved into two components on the tool face: a friction force, $F$, along the tool–chip interface and a normal force, $N$

$$F = R \sin \beta \quad \text{and} \quad N = R \cos \beta$$

resultant force is balanced by an equal and opposite force along the shear plane and is resolved into a shear force, $F_s$, and a normal force, $F_n$

$$F_s = F_c \cos \phi - F_t \sin \phi \quad \text{and} \quad F_n = F_c \sin \phi + F_t \cos \phi$$
Cutting Forces and Power

Forces Acting on Chip

- Friction force $F$ and Normal force to friction $N$
- Shear force $F_s$ and Normal force to shear $F_n$
- Forces acting on chip must be in balance

Resultant forces $R$ and $R'$

- Colinear
- Equal in amplitude
- Opposite in direction
Cutting Forces and Power

Coefficient of Friction

Coefficient of friction between tool and chip

\[ \mu = \frac{F}{N} = \frac{F_t + F_c \tan \alpha}{F_c - F_t \tan \alpha} \]

Friction angle related to coefficient of friction as

\[ \mu = \tan \beta \]

Shear Stress

Shear stress acting along the shear plane

\[ \tau = \frac{F_s}{A_s} \]

where \( A_s = \text{area of the shear plane} \)

\[ A_s = \frac{t_o w}{\sin \phi} \]
Cutting Forces and Power

Power

Product of force and velocity: \( \text{Power} = F_c V \)

Power dissipated in the shear plane: \( \text{Power for shearing} = F_s V_s \)

Specific energy for shearing: \( u_s = \frac{F_s V_s}{\omega t_o V} \)

Power dissipated in friction is: \( \text{Power for friction} = F V_c \)

Specific energy for friction: \( u_f = \frac{F V_c}{\omega t_o V} = \frac{F r}{\omega t_o} \)

Total specific energy: \( u_t = u_s + u_f \)
Measuring Cutting Forces and Power

Cutting forces can be measured using a:

- Force transducer (typically with quartz piezoelectric sensors)
- Dynamometer
- Load cell (with resistance-wire strain gages placed on octagonal rings)
Measuring Cutting Forces and Power

The specific energy in cutting (such as that shown in Table) also can be used to calculate cutting forces.

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific energy $W \cdot s/mm^3$</th>
<th>Specific energy $hp \cdot min/in^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloys</td>
<td>0.4–1</td>
<td>0.15–0.4</td>
</tr>
<tr>
<td>Cast irons</td>
<td>1.1–5.4</td>
<td>0.4–2</td>
</tr>
<tr>
<td>Copper alloys</td>
<td>1.4–3.2</td>
<td>0.5–1.2</td>
</tr>
<tr>
<td>High-temperature alloys</td>
<td>3.2–8</td>
<td>1.2–3</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>0.3–0.6</td>
<td>0.1–0.2</td>
</tr>
<tr>
<td>Nickel alloys</td>
<td>4.8–6.7</td>
<td>1.8–2.5</td>
</tr>
<tr>
<td>Refractory alloys</td>
<td>3–9</td>
<td>1.1–3.5</td>
</tr>
<tr>
<td>Stainless steels</td>
<td>2–5</td>
<td>0.8–1.9</td>
</tr>
<tr>
<td>Steels</td>
<td>2–9</td>
<td>0.7–3.4</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>2–5</td>
<td>0.7–2</td>
</tr>
</tbody>
</table>
Example: Calculating the percentage of friction energy

In an orthogonal cutting operation, \( t_o = 0.005 \) in., \( V = 400 \) ft/min, \( \alpha = 10^\circ \), and the width of cut = 0.25 in. It is observed that \( t_c = 0.009 \) in., \( F_c = 125 \) lb, and \( F_t = 50 \) lb. Calculate the percentage of the total energy that goes into overcoming friction at the tool–chip interface.

Friction energy

\[
\frac{FV_c}{F_cV} = \frac{Fr}{F_c} = r \quad t_o = \frac{5}{9} = 0.555,
\]

\( F = R \sin \beta, \)

\( F_c = R \cos(\beta - \alpha), \)

\[
R = \sqrt{F_t^2 + F_c^2} = \sqrt{50^2 + 125^2} = 135 \text{ lb.}
\]

\( 125 = 135 \cos(\beta - 10), \)

\( \beta = 32^\circ \quad F = 135 \sin 32^\circ = 71.5 \text{ lb}. \)

Percentage

\[
\frac{(71.5)(0.555)}{125} = 0.32, \quad \text{or} \quad 32\%.
\]
Temperatures in Cutting

Heat sources
- Tool-chip friction
- Shear motion on shear plane
- Flank - workpiece sliding

Cutting temperature at tool chip interface

\[ T = \frac{1.2 Y_f}{\rho c} \frac{\sqrt[3]{V t_0}}{K} \]

- \( T \) = temperature rise at tool-chip interface
- \( Y_f \) = flow stress of workpiece material
- \( V \) = cutting speed
- \( t_0 \) = cutting depth
- \( \rho c \) = volumetric specific heat of work material
- \( K \) = thermal diffusivity of work material
Temperatures in Cutting

Effect of Temperatures

• Lower strength, hardness and wear resistance of cutting tool
• Lower dimensional accuracy in workpiece
• Thermal damage to machined surface
• Temperature gradient in tool causing distortion and poor dimensional control
Tool Life: Wear and Failure

Tool Wear

• Factors causing tool wear
  ➢ Tool and workpiece material
  ➢ Processing parameter
    ▪ Eg. cutting speed, feed, cutting depth, cutting fluid

• Wear mechanisms
  ➢ Flank wear
    ▪ Sliding between tool and workpiece
  ➢ Adhesive or abrasive wear
    ▪ Temperature rise
  ➢ Crater wear
    ▪ Temperature
    ▪ Chemical affinity between workpiece and tool
  ➢ Chipping of cutting edge (catastrophic failure)
    ▪ Mechanical shock
    ▪ Thermal fatigue
Tool Life: Wear and Failure

(a) Diagram showing tool wear and failure:
- Rake face wear
- Crater wear
- Flank wear
- Depth-of-cut line

(b) Image showing rake face, flank wear, and flank face.

(c) Image showing rake face, crater wear, and flank face.

(d) Image showing thermal cracking and rake face.

(e) Image showing BUE and flank face.
Tool Life: Wear and Failure

Tool Wear Vs. Time

Tool wear (flank wear) as a function of cutting time

---

- **Break-in period**
- **Steady-state wear region**
- **Failure region**
- **Final failure**
- **Uniform wear rate**
- **Accelerating wear rate**
- **Rapid initial wear**

**Graph:**
- Y-axis: Tool flank wear (FW)
- X-axis: Time of cutting (min)
Tool Life: Wear and Failure

Taylor tool life equation

- $V$ - cutting speed
- $T$ - time to failure
- $n, C$ – constant

$n$ and $C$ will change for a different tool/workpiece combination and cutting condition

$$VT^n = C$$
Tool Life: Wear and Failure

Tool-life Curves

Plots of experimental data obtained by performing cutting tests on various materials under different cutting conditions:

- cutting speed
- feed
- depth of cut
- tool material and geometry
- cutting fluids
Tool Life: Wear and Failure

Allowable Wear Land

Cutting tools need to be replaced (or resharpened) when:

- the surface finish of the machined workpiece begins to deteriorate
- cutting forces increase significantly
- the temperature rises significantly

The recommended cutting speed for a high-speed steel tool is generally the one that yields a tool life of 60 to 120 min, and for a carbide tool, it is 30 to 60 min.
Surface finish influences the dimensional accuracy of machined parts and their properties and also their performance in service.

Figure shows the surfaces obtained in two different cutting operations.
Machinability

The machinability of a material is usually defined in terms of four factors:

- Surface finish and surface integrity of the machined part
- Tool life
- Force and power required
- The level of difficulty in chip control

Good machinability indicates:

- Good surface finish and surface integrity
- Long tool life
- Low force and power requirements
The selection of cutting-tool materials for a particular application is among the most important factors in machining operations.

The selection of mold and die materials was critical for forming and shaping processes.

The cutting tool is subjected to:
- high temperatures
- high contact stresses
- rubbing along the tool–chip interface and along the machined surface.
Cutting-tool material must possess the following characteristics:

- Hot hardness
- Toughness and impact strength
- Thermal shock resistance
- Wear resistance
- Chemical stability and inertness
Cutting-Tool Materials and Cutting Fluids

**Hardness and strength** are important with respect to the mechanical properties of the workpiece material to be machined.

**Impact strength** is important in making interrupted cuts in machining, such as in milling.

**Melting temperature** of the tool material is important as compared to the temperatures developed in the cutting zone.

**The physical properties of thermal conductivity and coefficient of thermal expansion** are important in determining the resistance of the tool materials to thermal fatigue and shock.
## General Characteristics of Cutting-tool Material

<table>
<thead>
<tr>
<th>General Characteristics of Cutting-tool Materials (These Tool Materials Have a Wide Range of Compositions and Properties; Overlapping Characteristics Exist in Many Categories of Tool Materials)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot hardness</td>
</tr>
<tr>
<td>Toughness</td>
</tr>
<tr>
<td>Impact strength</td>
</tr>
<tr>
<td>Wear resistance</td>
</tr>
<tr>
<td>Chipping resistance</td>
</tr>
<tr>
<td>Cutting speed</td>
</tr>
<tr>
<td>Thermal-shock resistance</td>
</tr>
<tr>
<td>Tool material cost</td>
</tr>
<tr>
<td>Depth of cut</td>
</tr>
<tr>
<td>Processing method</td>
</tr>
<tr>
<td>High-speed steels</td>
</tr>
<tr>
<td>Cast-cobalt alloys</td>
</tr>
<tr>
<td>Uncoated carbides</td>
</tr>
<tr>
<td>Coated carbides</td>
</tr>
<tr>
<td>Ceramics</td>
</tr>
<tr>
<td>Polycrystalline cubic boron nitride</td>
</tr>
<tr>
<td>Diamond</td>
</tr>
<tr>
<td>Wrought, cast, HIP sintering</td>
</tr>
<tr>
<td>Cast and HIP sintering</td>
</tr>
<tr>
<td>Cold pressing and sintering</td>
</tr>
<tr>
<td>CVD or PVD</td>
</tr>
<tr>
<td>Cold pressing and sintering or HIP sintering</td>
</tr>
<tr>
<td>High-pressure, high-temperature sintering</td>
</tr>
<tr>
<td>Very light for single-crystal diamond</td>
</tr>
</tbody>
</table>
Cutting-Tool Materials and Cutting Fluids

Tool materials generally are divided into the following categories:

- High-speed steels
- Cast-cobalt alloys
- Carbides
- Coated tools
- Alumina-based ceramics
- Cubic boron nitride
- Silicon-nitride-based ceramics
- Diamond
- Whisker-reinforced materials and nanomaterials
One of the most basic machining processes is **turning**, meaning that the part is rotated while it is being machined.

The starting material is generally a workpiece that has been made by other processes, such as casting, forging, extrusion, drawing, or powder metallurgy.

Turning processes, which typically are carried out on a lathe or by similar machine tools.
Machines are highly versatile and capable of a number of machining processes:

- Turning
- Facing
- Cutting with form tools
- Boring
- Parting
- Threading
- Knurling
## Machining Processes: Turning and Hole Making

<table>
<thead>
<tr>
<th>Process</th>
<th>Characteristics</th>
<th>Typical dimensional tolerances, ±mm (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning</td>
<td>Turning and facing operations on all types of materials, uses single-point or form tools; engine lathes require skilled labor; low production rate (but medium-to-high rate with turret lathes and automatic machines) requiring less skilled labor.</td>
<td>Fine: 0.025–0.13 (0.001–0.005) Rough: 0.13 (0.005)</td>
</tr>
<tr>
<td>Boring</td>
<td>Internal surfaces or profiles with characteristics similar to turning; stiffness of boring bar important to avoid chatter.</td>
<td>0.025 (0.001)</td>
</tr>
<tr>
<td>Drilling</td>
<td>Round holes of various sizes and depths; high production rate; labor skill required depends on hole location and accuracy specified; requires boring and reaming for improved accuracy.</td>
<td>0.075 (0.003)</td>
</tr>
<tr>
<td>Milling</td>
<td>Wide variety of shapes involving contours, flat surfaces, and slots; versatile; low-to-medium production rate; requires skilled labor.</td>
<td>0.13–0.25 (0.005–0.01)</td>
</tr>
<tr>
<td>Planing</td>
<td>Large flat surfaces and straight contour profiles on long workpieces, low-quantity production, labor skill required depends on part shape.</td>
<td>0.08–0.13 (0.003–0.005)</td>
</tr>
<tr>
<td>Shaping</td>
<td>Flat surfaces and straight contour profiles on relatively small workpieces; low-quantity production; labor skill required depends on part shape.</td>
<td>0.05–0.13 (0.002–0.003)</td>
</tr>
<tr>
<td>Broaching</td>
<td>External and internal surfaces, slots, and contours; good surface finish; costly tooling; high production rate; labor skill required depends on part shape.</td>
<td>0.025–0.15</td>
</tr>
<tr>
<td>Sawing</td>
<td>Straight and contour cuts on flat or structural shapes; not suitable for hard materials unless saw has carbide teeth or is coated with diamond; low production rate; generally low labor skill.</td>
<td>0.8</td>
</tr>
</tbody>
</table>
The majority of turning operations involve the use of simple single-point cutting tools.

Workpiece materials has an optimum set of tool angles, which have been developed largely through experience shown in table.

### General Recommendations for Tool Angles in Turning

<table>
<thead>
<tr>
<th>Material</th>
<th>Back rake</th>
<th>Side rake</th>
<th>End relief</th>
<th>Side relief</th>
<th>Side and end cutting edge</th>
<th>Back rake</th>
<th>Side rake</th>
<th>End relief</th>
<th>Side relief</th>
<th>Side and end cutting edge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum and magnesium alloys</td>
<td>20</td>
<td>15</td>
<td>12</td>
<td>10</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Copper alloys</td>
<td>5</td>
<td>10</td>
<td>8</td>
<td>8</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Steels</td>
<td>10</td>
<td>12</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>-5</td>
<td>-5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Stainless steels</td>
<td>5</td>
<td>8–10</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>-5–0</td>
<td>-5–5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>High-temperature alloys</td>
<td>0</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>45</td>
</tr>
<tr>
<td>Refractory alloys</td>
<td>0</td>
<td>20</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>-5</td>
<td>-5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Cast iron</td>
<td>5</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>15</td>
<td>-5</td>
<td>-5</td>
<td>5</td>
<td>5</td>
<td>5</td>
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<tr>
<td>Thermoplastics</td>
<td>0</td>
<td>0</td>
<td>20–30</td>
<td>15–20</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>20–30</td>
<td>15–20</td>
<td>10</td>
</tr>
<tr>
<td>Thermosets</td>
<td>0</td>
<td>0</td>
<td>20–30</td>
<td>15–20</td>
<td>10</td>
<td>0</td>
<td>15</td>
<td>5</td>
<td>5</td>
<td>15</td>
</tr>
</tbody>
</table>
The Turning Process

Tool Geometry

Various angles in a single-point cutting tool have important functions.

Angles are measured in a coordinate system consisting of the three major axes of the tool shank, as can be seen in figure...
The Turning Process

These angles may be different, with respect to the workpiece, after the tool is installed

Rake angle

Important in controlling both the direction of chip flow and the strength of the tool tip

Positive rake angles improve the cutting operation by reducing forces and temperatures

Positive angles also result in a small included angle of the tool tip, possibly leading to premature tool chipping and failure
The Turning Process

Side rake angle

More important than the back rake angle, although the latter usually controls the direction of chip flow.

These angles typically are in the range from -5° to 5°

Cutting-edge angle

Affects chip formation, tool strength, and cutting forces to various degrees.

Typically, the cutting-edge angle is around 15°.
The Turning Process

Relief angle

Controls interference and rubbing at the tool–workpiece interface

If it is too large, the tool tip may chip off; if it is too small, flank wear may be excessive

Relief angles typically are 5°

Nose radius

Affects surface finish and tool-tip strength

The smaller the nose radius (sharp tool), the rougher the surface finish of the workpiece and the lower the strength of the tool
The Turning Process

Material-removal Rate (MRR)

The material-removal rate (MRR) in turning is the volume of material removed per unit time.

For each revolution of the workpiece layer of material has a cross-sectional area the product of the distance the tool (feed, f), and the depth of cut, d.

The volume of this ring is the product of the cross-sectional area \((f)(d)\) and the average circumference of the ring \(\pi D_{\text{avg}}\), where

\[
D_{\text{avg}} = \frac{D_o + D_f}{2}
\]
The Turning Process

Material-removal Rate (MRR)

The rotational speed of the workpiece is $N$

Since there are $N$ revolutions per minute, the removal rate is

$$\text{MRR} = \pi D_{\text{avg}} df N$$

Also can be written as

$$\text{MRR} = df V$$

$V$ is the cutting speed.

The cutting time, $t$, for a workpiece of length, $l$, can be calculated

$$t = \frac{l}{fN}$$
Forces in Turning

The three principal forces acting on a cutting tool are shown

- $F_c$ is the cutting force
- $F_t$ is the thrust or feed force
- $F_r$ is the radial force

These forces are important in the design of machine tools, as well as in the deflection of tools and workpieces for precision-machining operations.
The **cutting force** acts downward on the tool tip and thus tends to deflect the tool downward and the workpiece upward.

Supplies the energy required for the cutting operation.

The **thrust force** acts in the longitudinal direction, also is called the feed force, because it is in the feed direction of the tool.

Tends to push the tool towards the right and away from the chuck.

The **radial force** in the radial direction and tends to push the tool away from the workpiece.
# The Turning Process

<table>
<thead>
<tr>
<th>Summary of Turning Parameters and Formulas</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N ) = Rotational speed of the workpiece, rpm</td>
</tr>
<tr>
<td>( f ) = Feed, mm/rev or in./rev</td>
</tr>
<tr>
<td>( v ) = Feed rate, or linear speed of the tool along workpiece length, mm/min or in./min</td>
</tr>
<tr>
<td>( = fN )</td>
</tr>
<tr>
<td>( V ) = Surface speed of workpiece, m/min or ft/min</td>
</tr>
<tr>
<td>( = \pi D_o N ) (for maximum speed)</td>
</tr>
<tr>
<td>( = \pi D_{avg} N ) (for average speed)</td>
</tr>
<tr>
<td>( l ) = Length of cut, mm or in.</td>
</tr>
<tr>
<td>( D_o ) = Original diameter of workpiece, mm or in.</td>
</tr>
<tr>
<td>( D_f ) = Final diameter of workpiece, mm or in.</td>
</tr>
<tr>
<td>( D_{avg} ) = Average diameter of workpiece, mm or in.</td>
</tr>
<tr>
<td>( = (D_o + D_f)/2 )</td>
</tr>
<tr>
<td>( d ) = Depth of cut, mm or in.</td>
</tr>
<tr>
<td>( = (D_o + D_f)/2 )</td>
</tr>
<tr>
<td>( t ) = Cutting time, s or min</td>
</tr>
<tr>
<td>( = l/fN )</td>
</tr>
<tr>
<td>( MRR ) = mm³/min or in³/min</td>
</tr>
<tr>
<td>( = \pi D_{avg} dfN )</td>
</tr>
<tr>
<td>Torque = N·m or lb·ft</td>
</tr>
<tr>
<td>( = F_cD_{avg}/2 )</td>
</tr>
<tr>
<td>Power = kW or hp</td>
</tr>
<tr>
<td>( = (Torque)(\omega), \text{ where } \omega = 2\pi N \text{ rad/min} )</td>
</tr>
</tbody>
</table>
The Turning Process

Tool Materials, Feeds, and Cutting Speeds

A broad range of applicable cutting speeds and feeds for these tool materials is given as a general guideline in turning operations.
The Turning Process

Cutting Fluids

Many materials can be machined without a cutting fluid.

But in most cases cutting fluid can improve the operation significantly.

<table>
<thead>
<tr>
<th>Material</th>
<th>Type of fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>D, MO, E, MO + FO, CSN</td>
</tr>
<tr>
<td>Beryllium</td>
<td>MC, E, CSN</td>
</tr>
<tr>
<td>Copper</td>
<td>D, E, CSN, MO + FO</td>
</tr>
<tr>
<td>Magnesium</td>
<td>D, MO, MO + FO</td>
</tr>
<tr>
<td>Nickel</td>
<td>MC, E, CSN</td>
</tr>
<tr>
<td>Refractory metals</td>
<td>MC, E, EP</td>
</tr>
<tr>
<td>Steels</td>
<td></td>
</tr>
<tr>
<td>Carbon and low-alloy</td>
<td>D, MO, E, CSN, EP</td>
</tr>
<tr>
<td>Stainless</td>
<td>D, MO, E, CSN</td>
</tr>
<tr>
<td>Titanium</td>
<td>CSN, EP, MO</td>
</tr>
<tr>
<td>Zinc</td>
<td>C, MC, E, CSN</td>
</tr>
<tr>
<td>Zirconium</td>
<td>D, E, CSN</td>
</tr>
</tbody>
</table>

Note: CSN = chemicals and synthetics; D = dry; E = emulsion; EP = extreme pressure; FO = fatty oil; and MO = mineral oil.
Lathes and Lathe Operations

The most common lathe originally was called an **engine lathe** powered with overhead pulleys and belts from nearby engines.

The maximum spindle speed of lathes typically is around 4000 rpm, but may be only about 200 rpm for large lathes.

For special applications, speeds may range to 10,000 rpm, 40,000 rpm.
Lathes and Lathe Operations

Although simple and versatile, an engine lathe requires a skilled machinist, because all controls are manipulated by hand.

Lathes are inefficient for repetitive operations and for large production runs.
Lathes and Lathe Operations

Lathe Components

Lathes are equipped with a variety of components and accessories, as shown

- Tool post
- Spindle (with chuck)
- Headstock assembly
- Spindle speed selector
- Cross slide
- Clutch
- Feed selector
- Apron
- Split nut
- Chip pan
- Compound rest
- Carriage
- Ways
- Dead center
- Tailstock quill
- Tailstock assembly
- Handwheel
- Longitudinal & transverse feed control
- Bed
- Lead screw
- Feed rod
- Clutch
Lathes and Lathe Operations

Lathe Components

Bed
- Supports all major components of the lathe
- Have a large mass and are built rigidly
- Usually from gray or nodular cast iron

Carriage
- Slides along the ways
- Consists of cross-slide, tool post, and apron

Headstock
- Fixed to the bed
- Equipped with motors, pulleys, and V-belts
Lathes and Lathe Operations

Lathe Components

Tailstock
- Slide along the ways
- Clamped at any position
- Supports the other end of the workpiece

Feed Rod and Lead Screw
- Feed rod is powered by a set of gears
- The rod provides movement to the carriage and the cross-slide by means of gears, a friction clutch, and a keyway along the length of the rod
A lathe generally is specified by the following parameters:

- Its swing, the maximum diameter of the workpiece that can be machined (shown in table)
- The maximum distance between the headstock and tailstock centers
- The length of the bed

<table>
<thead>
<tr>
<th>Machine tool</th>
<th>Maximum dimension (m)</th>
<th>Power (kW)</th>
<th>Maximum speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lathes (swing/length)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bench</td>
<td>0.3/1</td>
<td>&lt;1</td>
<td>3000</td>
</tr>
<tr>
<td>Engine</td>
<td>3/5</td>
<td>70</td>
<td>4000</td>
</tr>
<tr>
<td>Turret</td>
<td>0.5/1.5</td>
<td>60</td>
<td>3000</td>
</tr>
<tr>
<td><strong>Automatic screw machines</strong></td>
<td>0.1/0.3</td>
<td>20</td>
<td>10,000</td>
</tr>
<tr>
<td><strong>Boring machines (work diameter/length)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical spindle</td>
<td>4/3</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>Horizontal spindle</td>
<td>1.5/2</td>
<td>70</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Drilling machines</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bench and column (drill diameter)</td>
<td>0.1</td>
<td>10</td>
<td>12,000</td>
</tr>
<tr>
<td>Radial (column to spindle distance)</td>
<td>3</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Numerical control (table travel)</td>
<td>4</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

*Note: Larger capacities are available for special applications.*
They must hold the workpiece securely
Various types of mandrels to hold workpieces for turning are shown

Usually are mounted between centers on a lathe

In (a) both the cylindrical and the end faces of the workpiece can be machined

In (b) and (c) only the cylindrical surfaces can be machined
Types of Lathes

Bench Lathes
• Placed on a workbench or a table
• They have low power
• Usually operated by hand feed
• Are used to machine small workpieces

Special-purpose Lathes
• used for applications such as: railroad wheels, gun barrels, and rolling-mill rolls
• workpiece sizes as large as 1.7 m in diameter by 8 m in length
Types of Lathes

Tracer Lathes
• Have special attachments that are capable of turning parts with various contours
• Also called a duplicating lathe or contouring lathe

Automatic Lathes
• In a fully automatic lathe, parts are fed and removed automatically,
• In semiautomatic machines, functions are performed by the operator

Automatic Bar Machines
• Designed for high-production-rate machining of screws and similar threaded parts
Turret Lathes

- Capable of performing multiple cutting operations
  - Turning
  - boring
  - drilling
  - thread cutting
  - facing
Types of Lathes

Computer-controlled Lathes

Movement and control of the machine tool and its components are achieved by computer numerical control (CNC)

Designed to operate faster and have higher power available compared with other lathes

Their operations are reliably repetitive, maintain the desired dimensional accuracy, and require less skilled labor
**Turning-process Capabilities**

Relative production rates in turning are shown in table

<table>
<thead>
<tr>
<th>Typical Production Rates for Various Machining Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operation</strong></td>
</tr>
<tr>
<td>Turning</td>
</tr>
<tr>
<td>Engine lathe</td>
</tr>
<tr>
<td>Tracer lathe</td>
</tr>
<tr>
<td>Turret lathe</td>
</tr>
<tr>
<td>Computer-controlled lathe</td>
</tr>
<tr>
<td>Single-spindle chuckers</td>
</tr>
<tr>
<td>Multiple-spindle chuckers</td>
</tr>
<tr>
<td>Boring</td>
</tr>
<tr>
<td>Drilling</td>
</tr>
<tr>
<td>Milling</td>
</tr>
<tr>
<td>Planing</td>
</tr>
<tr>
<td>Gear cutting</td>
</tr>
<tr>
<td>Broaching</td>
</tr>
<tr>
<td>Sawing</td>
</tr>
</tbody>
</table>

*Note: Production rates indicated are relative: Very low is about 1 or more parts per hour, medium is approximately 100 parts per hour, and very high is 1000 or more parts per hour.*
Cutting Screw Threads

Screw-thread Cutting on a Lathe

A typical thread-cutting operation on a lathe is shown (a)

A number of passes in the sequence shown in (b) generally are required to produce threads with good dimensional accuracy and surface finish.
Boring and Boring Machines

Boring enlarges a hole made previously by some other process or produces circular internal profiles in hollow workpieces.

The boring bar must be sufficiently stiff to:
- minimize tool deflection
- maintain dimensional accuracy
- avoid vibration and chatter

For this reason, a material with a high elastic modulus (such as tungsten carbide) is desirable.
Boring and Boring Machines

Boring bars have been designed and built with capabilities for damping vibration.

In horizontal boring machines, the workpiece is mounted on a table that can move horizontally in both the axial and radial directions.

A vertical boring mill (shown in figure) is similar to a lathe, has a vertical axis of workpiece rotation.
Drilling, Drills, and Drilling Machines

The vast majority have several holes in various large or small products

Observe, for example:
- The number of rivets on airplane’s wings and fuselage
- the bolts in engine blocks and heads
- numerous consumer and industrial products

Holes typically are used for design purposes such as
- weight reduction
- ventilation
- access to the inside of parts
Drilling, Drills, and Drilling Machines

Drills

Typically have high length-to-diameter ratios; hence, they are capable of producing relatively deep holes.

Two common types of drills: (a) Chisel-edge drill (b) Crankshaft drill are shown.

[Diagram showing parts of a drill and a crankshaft drill]
Drilling, Drills, and Drilling Machines

Other Types of Drills

Several types of drills are shown

- A **step drill** produces holes with two or more different diameters
- A **core drill** is used to make an existing hole larger
- **Counterboring and countersinking** drills produce depressions on the surface
- A **center drill** is short and is used to produce a hole at the end of a piece of stock
- A **spot drill** is used to spot a hole at the desired location on a surface
Gun Drilling

Developed originally for drilling gun barrels, gun drilling is used for drilling deep holes and requires a special drill.

A gun drill, showing various features (a)

Schematic illustration of the gun-drilling operation (b)
Drilling, Drills, and Drilling Machines

Trepanning

The cutting tool produces a hole by removing a disk-shaped piece (core), usually from flat plates.

A hole is thus produced without reducing all of the material that is removed to chips.
Reaming and Reamers

Operation used to make an existing hole dimensionally more accurate than can be achieved by drilling alone and improve its surface finish.

The most accurate holes in workpieces generally are produced by the following sequence of operations:

- Centering
- Drilling
- Boring
- Reaming

(a) Terminology for a helical reamer. (b) Inserted-blade adjustable reamer.
By tapping internal threads in workpieces can be produced

A tap is a chip-producing threading tool with multiple cutting teeth

Taps generally are available with two, three, or four flutes

(a) Terminology for a tap. (b) Tapping of steel nuts in production.
Machining Processes: Milling, Broaching, Sawing, Filing, and Gear Manufacturing

Introduction

In this chapter, several cutting processes and machine tools that using single-point, multitooth, and cutting tools are described

Machining operations can produce many other parts with more complex shapes
Milling and Milling Machines

Includes a number of highly versatile machining operations taking place in a variety of configurations with the use of a milling cutter.
**Peripheral Milling**

The axis of cutter rotation is parallel to the workpiece surface.

The cutter body has a number of teeth along its circumference; each tooth acts like a single-point cutting tool.

When the cutter is longer than the width of the cut, the process is called slab milling.
Milling and Milling Machines

Conventional Milling and Climb Milling

The cutter rotation can be either clockwise or counter-clockwise; this is significant in the operation

(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, $t_c$; and workpiece speed, $v$. (c) Schematic illustration of cutter travel distance, $l_c$, to reach full depth of cut.
Milling and Milling Machines

Conventional Milling

Also called up milling, the maximum chip thickness is at the end of the cut as the tooth leaves the workpiece surface.

The advantages

- tooth engagement is not a function of workpiece surface characteristics
- contamination or scale (oxide layer) on the surface does not adversely affect tool life

Climb Milling

Also called down milling, cutting starts at the surface of the workpiece where the chip is thickest.

The advantage

- the downward component of the cutting force holds the workpiece in place, particularly for slender parts
• **The cutting speed**, \( V \), in peripheral milling is the surface speed of the cutter

\[
V = \pi DN
\]

where \( D \) is the cutter diameter and \( N \) is the rotational speed of the cutter.

• For a straight-tooth cutter, the approximate undeformed **chip thickness** (chip depth of cut), \( t_c \) can be calculated from the equation

\[
t_c = 2f \sqrt{\frac{d}{D}}
\]

where \( f \) is the feed per tooth of the cutter, \( d \) is the depth of cut
Milling Parameters

• **Feed per tooth** is determined from the equation

\[ f = \frac{v}{Nn} \]

where \( v \) is the linear speed (feed rate) of the workpiece and \( n \) is the number of teeth on the cutter periphery.

• The **cutting time**, \( t \), is given by the equation

\[ t = \frac{l + l_c}{v} \]

where \( l \) is the length of the workpiece and \( l_c \) is the horizontal extent of the cutter’s first contact with the workpiece.

• Based on the assumption that \( l_c << l \) the **material-removal rate (MRR)** is

\[ MRR = \frac{lw_d}{t} = w_dv \]
Milling Parameters

<table>
<thead>
<tr>
<th>Summary of Peripheral Milling Parameters and Formulas</th>
</tr>
</thead>
</table>

- **N** = Rotational speed of the milling cutter, rpm
- **F** = Feed, mm/tooth or in./tooth
- **D** = Cutter diameter, mm or in.
- **n** = Number of teeth on cutter
- **v** = Linear speed of the workpiece or feed rate, mm/min or in./min
- **V** = Surface speed of cutter, m/min or ft/min
  
  = \(DN\)

- **f** = Feed per tooth, mm/tooth or in./tooth
  
  = \(v/Nn\)

- **l** = Length of cut, mm or in.
- **t** = Cutting time, s or min
  
  = \((l + l_c)/v\), where \(l_c\) = extent of the cutter’s first contact with the workpiece

- **MRR** = \(mm^3/min\) or \(in^3/min\)
  
  = \(wdv\), where \(w\) is the width of cut

- **Torque** = \(N \cdot m\) or \(lb \cdot ft\)
  
  = \(F_c \cdot D/2\)

- **Power** = kW or hp
  
  = \((Torque)(\omega)\), where \(\omega = 2\pi N\) radians/min
Face Milling

The cutter is mounted on a spindle having an axis of rotation perpendicular to the workpiece surface.

A face-milling cutter with indexable inserts
Schematic illustration of the effect of insert shape on feed marks on a face-milled surface: (a) small corner radius, (b) corner flat on insert, and (c) wiper, consisting of a small radius followed by a large radius, resulting in smoother feed marks. (d) Feed marks due to various insert shapes.
**Face Milling**

**Lead angle** of the insert in face milling has a direct influence on the undeformed chip thickness, as it does in turning operations.

As the lead angle increases, the undeformed chip thickness decreases and the length of contact increases.

*The effect of the lead angle on the undeformed chip thickness in face milling.*
End Milling

Important and common machining operation because of versatility and capability to produce various profiles and curved surfaces.

End mill has either a straight shank (for small cutter sizes) or a tapered shank (for larger sizes).

End mills may be made of high-speed steels or with carbide inserts, similar to face milling.
High-speed End Milling

• Numerous applications, such as the milling of large aluminum-alloy aerospace components and honeycomb structures
• Spindle speeds in the range from 20,000 to 60,000 rpm
• The machines must have high stiffness and accuracy
• At such high rates of material removal, chip collection and disposal can be a significant problem
Milling Machines

Column-and-knee-type Machines

Used for general-purpose milling operations, and are the most common milling machines.

The basic components of these machines are:

- Worktable
- Saddle
- Knee
- Overarm
- Head
In universal **column-and-knee milling machines**, the table can be swiveled on a horizontal plane.

In this way, complex shapes can be machined to produce parts such as gears, drills, taps, and cutters.

Schematic illustration of (a) a horizontal-spindle column-and-knee-type milling machine and (b) vertical-spindle column-and-knee-type milling machine.
Milling Machines

Bed-type Milling Machines

The worktable is mounted directly on the bed, which replaces the knee and can move only longitudinally.

The spindles may be horizontal or vertical and of duplex or triplex types for the simultaneous machining of two or three workpiece surfaces.
Planing and Shaping

Planning

• Relatively simple machining operation
• Usually is done on large workpieces, as large as 25 mx 15 m
• In a planer, the workpiece is mounted on a table that travels back and forth along a straight path
• A horizontal cross-rail, which can be moved vertically along the ways of the column

Typical parts that can be made on a planer.
Planing and Shaping

Shaping

Basically the same as by planing, except that

- it is the tool, and not the workpiece, that travels
- workpieces are smaller, typically less than 1m x 2m of surface area

In a horizontal shaper, the cutting tool travels back and forth along a straight path

Vertical shapers (slotters) are used to machine notches, keyways, and dies

Because of low production rates, only special purpose shapers are in common use today
**Broaching and Broaching Machines**

**Broaching** is similar to shaping with a long multiple-tooth cutter and is used to machine internal and external surfaces.

![Diagram of broaching machine](image)

(a) Typical parts made by internal broaching. (b) Parts made by surface broaching. (c) Vertical broaching machine. *Source:* (a) and (b) Courtesy of General Broach and Engineering Company, (c) Courtesy of Ty Miles, Inc.
Broaches

The rake (hook) angle depends on the material cut and usually ranges from $0^\circ$ to $20^\circ$.

The clearance angle is typically $1^\circ$ to $4^\circ$; finishing teeth have smaller angles.

FIGURE 24.21 (a) Cutting action of a broach, showing various features. (b) Terminology for a broach.
Broaching and Broaching Machines

Turn Broaching

Typically used for broaching the bearing surfaces of crankshafts and similar parts

The crankshaft is rotated between centers, and the broach

Terminology for a pull-type internal broach used for enlarging long holes.
Broaching Machines

Either pull or push the broaches and are either horizontal or vertical.

**Push broaches** usually are shorter, generally in the range from 150 to 350 mm.

**Pull broaches** tend to straighten the hole, whereas pushing permits the broach to follow any irregularity of the leader hole.

The force required to pull or push the broach depends on the:
- strength of the workpiece material
- total depth and width of cut
- cutting speed
- tooth profile
- use of cutting fluids
Sawing

The cutting tool is a blade (saw) having a series of small teeth.

Each tooth removing a small amount of material with each stroke or movement of the saw.

Typical saw-tooth and saw-blade configurations are shown.
(a) Terminology for saw teeth. (b) Types of tooth sets on saw teeth staggered to provide clearance for the saw blade to prevent binding during sawing.
Sawing

Types of Saws

- **Hacksaws**
  - have straight blades and reciprocating motions
  - used to cut off bars, rods, and structural shapes

- **Power Hacksaws**
  - blades are usually 1.2 to 2.5
  - applying as much as 1.3 kN of force to the workpiece

- **Hand hacksaw**
  - blades are thinner and shorter than power hacksaw
  - For sawing sheet metal and thin tubing
Sawing

Types of Saws

• Circular saws
  ➢ used for high-production-rate sawing, a process called cutting off
  ➢ cold sawing is common in industry, particularly for cutting large cross section

• Band saws
  ➢ have continuous, long, flexible blades
  ➢ have a continuous cutting action
  ➢ also available are computer-controlled band saws
Friction Sawing

A process in which a mild-steel blade or disk rubs against the workpiece at speeds of up to 7,600 m/min

Frictional energy is converted into heat, rapidly softens a narrow zone in the workpiece
Filing involves the small-scale removal of material from a surface, corner, edge, or hole—including the removal of burrs

Although filing usually is done by hand, filing machines with automatic features are available for high production rates.

Types of burs used in burring operations.
Gears may be as small as those used in watches or as large as 9 m (30 ft) in diameter, for rotating mobile crane superstructures.

Poor gear-tooth quality contributes to inefficient energy transmission, increased vibration and noise.

The standard nomenclature for an involute spur gear is shown.
Gear Manufacturing by Machining

- Producing gear teeth on a blank by form cutting (a)

- Schematic illustration of gear generating with a pinion-shaped gear cutter (b)

- Gear generating in a gear shaper using a pinion-shaped cutter (c) and (d)