Fundamentals of Machining / Orthogonal Machining
Material Removal Process

- Types of machining processes
- Basic Chip Formation
- Mechanics of Machining
Machining: Removal of unwanted material in the form of chips in order to create a geometric shape

Market: $60b, Tolerance: 0.0001” or 2.5um

What makes the process unique and difficult?

The complexity induced by:

- difference between material properties
- process is unconstrained and asymmetrical
- Large stress and strain
- Non-robust process (sensitive to tool geometry, material, temp., cutting fluids, process dynamics, chatter, vibration, etc.)
FIGURE 21-1 The fundamental inputs and outputs to machining processes.
Seven basic chip formation processes

Seven types of processes:

1. **Shaping and planing**
2. **Turning**
3. **Milling**
4. **Drilling**
5. **Sawing**
6. **Broaching**
7. **Grinding (abrasive machining)**

**Figure 21-2** The seven basic machining processes used in chip formation.
Basic machining processes in detail

**Turning**

Speed, stated in surface feet per minute (sfpm), is the peripheral speed at the cutting edge. Feed per revolution in turning is a linear motion of the tool parallel to the rotating axis of the workpiece. The depth of cut reflects the third dimension.

\[ L = \text{length of cut} \]

\[ T_m = \frac{L + A}{f_r N_s} \]

**Boring**

Enlarging hole of diameter \( D_1 \) to diameter \( D_2 \). Boring can be done with multiple cutting tools. Feed in inches per revolution, \( f_r \).

**Facing**

Tool feeds to center of workpiece so \( L = D/2 \). The cutting speed is decreasing as the tool approaches the center of the workpiece.

**Grooving, parting or cutoff**

Tool feed perpendicular to the axis of rotation. The width of the tool produces the depth of cut (DOC).
Definitions: Speed, feed, and depth of cut (DOC)

\[ \text{DOC} = \frac{D_1 - D_2}{2} = d \]

\[ V = \frac{\pi D_1 N_s}{12} \]

NOTE
The rpm of the rotating workpiece is \( N_s \). It establishes the cutting speed \( V \), at the tool, according to \( N_s = 12 V/\pi D \).

The depth of cut, \( d \), is equal to \((D_1 - D_2)/2\).

The length of cut is the distance the tool travels parallel to the axis, \( L \).

**FIGURE 21-3**  Turning a cylindrical workpiece on a lathe requires you select the cutting speed, feed, and depth of cut.
Basic Chip formation process:

Chips in metal cutting: Due to shear of material under compression generated by the cutting motion.

Basic Parameters:

Speed or cutting speed, \((V)\), primary cutting motion, \(\text{f/min, in/min, m/min}\)

Feed \((f_r)\), material removed / revolution, \(\text{in/rev, m/rev, m/min}\)

Chip thickness (depth of cut, DOC), \(d\), Tool plunged distance, \(\text{m, in}\)
Basic Machine Tools Lathe (Turning)

Cutting speed \( \rightarrow \) rpm

Recommended Machining Parameters

<table>
<thead>
<tr>
<th>Work Material</th>
<th>Cutting Speed [sfpm (m/min)]</th>
<th>Feed Rate [in./rev (mm/rev)]</th>
<th>Depth of Cut [in. (mm)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roughing</td>
<td>Finishing</td>
<td>Roughing</td>
</tr>
<tr>
<td>Free-machining carbon steels: AISI 1100, 1200 series, 140–190 BHN</td>
<td>205–1100 (76–335)</td>
<td>1000–2000 (305–610)</td>
<td>0.010–0.085 (0.25–2.16)</td>
</tr>
<tr>
<td>Plain carbon steels: AISI 1000 series, 185–240 BHN</td>
<td>200–800 (61–244)</td>
<td>700–1600 (213–488)</td>
<td>0.010–0.085 (0.25–2.16)</td>
</tr>
<tr>
<td>Alloy steels: AISI 1300, 4000, 5000, 8000, and 9000 series, 190–240 BHN</td>
<td>175–600 (53–183)</td>
<td>550–1200 (168–366)</td>
<td>0.010–0.085 (0.25–2.16)</td>
</tr>
<tr>
<td>Cast irons: gray, nodular, and malleable, 150–210 BHN</td>
<td>200–1200 (61–366)</td>
<td>200–750 (61–229)</td>
<td>0.010–0.055 (0.25–1.40)</td>
</tr>
<tr>
<td>Martensitic stainless steels: wrought 400 and 500 series and PH types, 175–210 BHN</td>
<td>175–450 (53–137)</td>
<td>450–850 (137–259)</td>
<td>0.010–0.040 (0.025–1.02)</td>
</tr>
<tr>
<td>Austenitic stainless steels: wrought 200 and 300 series, 140–190 BHN</td>
<td>125–425 (38–130)</td>
<td>425–650 (130–198)</td>
<td>0.010–0.025 (0.25–1.02)</td>
</tr>
<tr>
<td>Superalloys: iron, nickel, titanium, and cobalt alloys, 240–300 BHN</td>
<td>30–150 (9–46)</td>
<td>150–400 (46–122)</td>
<td>0.010–0.065 (0.25–1.02)</td>
</tr>
<tr>
<td>Tool steels, wrought high-speed, shock resistant, and hot and cold work, 210–240 BHN</td>
<td>100–300 (30–91)</td>
<td>275–750 (84–229)</td>
<td>0.010–0.065 (0.25–1.65)</td>
</tr>
<tr>
<td>Nonferrous free-machining alloys: aluminum, copper, zinc, and brass alloys, 80–120 BHN</td>
<td>400–1200 (122–366)</td>
<td>1000–2000 (305–610)</td>
<td>0.010–0.085 (0.25–2.16)</td>
</tr>
<tr>
<td>Nonmetals: nylons, acrylics, and phenolic resins</td>
<td>350–800 (107–244)</td>
<td>800–1500 (244–457)</td>
<td>0.010–0.040 (0.25–1.02)</td>
</tr>
</tbody>
</table>

Example

Material: Carbon Steel

Assume the Max. Allowed Cutting Speed, \( V : 305 \text{ m/min} \)
Feed rate, \( F_r : 0.13 \text{ mm/rev} \)
Depth of cut, \( d : 4.57 \text{ mm} \)

What is the maximum rotational speed (\( N, \text{ in RPM} \)) allowed for turning 100mm dia rod.?

\[
\nu = \pi D_1 N, \text{ m/ min, } D_1 \text{ in m}
\]

\[
N = \frac{\nu}{\pi D_1}, \text{ rpm}
\]

\[
= \frac{305}{(\pi * 100 \times 10^{-3})}
\]

\[
= 970.8 \text{ rpm}
\]
### Table: Selection of Speed and Feed for Turning

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness</th>
<th>Condition</th>
<th>Depth of Cut* in mm</th>
<th>High Speed Steel Tool</th>
<th>Carbide Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Speed</td>
<td>Feed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>rpm/min</td>
<td>ipr/min</td>
</tr>
<tr>
<td>1. FREE MACHINING CARBON STEELS, WROUGHT (cont.)</td>
<td></td>
<td></td>
<td></td>
<td>160</td>
<td>168</td>
</tr>
<tr>
<td>Medium Carbon Steel</td>
<td></td>
<td></td>
<td></td>
<td>125</td>
<td>0.05</td>
</tr>
<tr>
<td>Leaded (cont.)</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>(materials listed on preceding page)</td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td>0.05</td>
</tr>
<tr>
<td>255 Cold Drawn</td>
<td>0.625</td>
<td></td>
<td></td>
<td>49</td>
<td>0.20</td>
</tr>
<tr>
<td>or Quenched and Tempered</td>
<td>16</td>
<td></td>
<td></td>
<td>38</td>
<td>0.40</td>
</tr>
<tr>
<td>335 Temperled</td>
<td>4</td>
<td></td>
<td></td>
<td>30</td>
<td>0.50</td>
</tr>
<tr>
<td>and Quenched</td>
<td>8</td>
<td></td>
<td></td>
<td>26</td>
<td>0.50</td>
</tr>
<tr>
<td>or Tempered</td>
<td>16</td>
<td></td>
<td></td>
<td>150</td>
<td>0.18</td>
</tr>
<tr>
<td>or Quenched and Tempered</td>
<td>16</td>
<td></td>
<td></td>
<td>100</td>
<td>0.07</td>
</tr>
<tr>
<td>to or Quenched and</td>
<td>16</td>
<td></td>
<td></td>
<td>105</td>
<td>0.15</td>
</tr>
<tr>
<td>375 Temperled</td>
<td>8</td>
<td></td>
<td></td>
<td>85</td>
<td>0.20</td>
</tr>
<tr>
<td>or Quenched</td>
<td>16</td>
<td></td>
<td></td>
<td>65</td>
<td>0.30</td>
</tr>
<tr>
<td>or Tempered</td>
<td>16</td>
<td></td>
<td></td>
<td>43</td>
<td>0.40</td>
</tr>
<tr>
<td>or Quenched and</td>
<td>16</td>
<td></td>
<td></td>
<td>30</td>
<td>0.50</td>
</tr>
<tr>
<td>425 Temperled</td>
<td>4</td>
<td></td>
<td></td>
<td>21</td>
<td>0.18</td>
</tr>
<tr>
<td>or Quenched</td>
<td>8</td>
<td></td>
<td></td>
<td>17</td>
<td>0.40</td>
</tr>
<tr>
<td>or Tempered</td>
<td>16</td>
<td></td>
<td></td>
<td>10</td>
<td>0.50</td>
</tr>
<tr>
<td>or Quenched and</td>
<td>16</td>
<td></td>
<td></td>
<td>10</td>
<td>0.50</td>
</tr>
<tr>
<td>425 Temperled</td>
<td>4</td>
<td></td>
<td></td>
<td>17</td>
<td>0.40</td>
</tr>
<tr>
<td>or Quenched</td>
<td>8</td>
<td></td>
<td></td>
<td>14</td>
<td>0.50</td>
</tr>
<tr>
<td>or Tempered</td>
<td>16</td>
<td></td>
<td></td>
<td>11</td>
<td>0.60</td>
</tr>
</tbody>
</table>

### Note
- *A Caution: Check Horsepower requirements on heavier depths of cut.*
- *See section 15.1 for Tool Geometry.
- *See section 16 for Cutting Fluid Recommendations.*
- *Any premium HSS (T15, M35, M41-M47) or (S9, S10, S11, S12).*
Speed, stated in surface feet per minute, (sfpm) is the peripheral speed at the cutting edge. To convert rpm into sfpm, use the following:

\[ V = \frac{\pi D_1 \text{RPM}}{12}, \text{ m/ min, } D \text{ in inches} \]

\[ DOC = \frac{D_1 - D_2}{2}, \text{ in} \]

\[ v = \pi D_1 \text{ RPM}, \text{ m/ min, } D_1 \text{ in m} \]

Speed, stated in surface feet per minute, (sfpm) is the peripheral speed at the cutting edge. To convert rpm into sfpm, use the following:

\[ V = \frac{\pi \times D_1 \times N_s}{12} \text{ (converting D to ft.). This applies to milling, drilling turning and all rotary operations.} \]

**Feed per revolution** in turning ( and drilling ) is a geared feed driven from the main spindle.

\[ f_r : \text{ m/rev, } f_t : \text{ m/tooth, } f_m : \text{ m/min} \]
Slab Milling

\[ v = \frac{\pi D_1 \text{RPM}}{12}, \text{ in } \text{min}, \text{ } D \text{ in inches} \]

\[ v = \pi D_1 \text{RPM}, \text{ in } \text{m/min}, \text{ } D_1 \text{ in } m \]

DOC, \text{ } d, \text{ Tool plunged distance}

Feed (\( f_t \)), \text{ material removed / tooth or material removed / revolution}

\[ f_m = f_t \cdot n \cdot N, \text{ in } \text{m/min} \]

FIGURE Slab milling is an example of a multiple tooth-cutting process which creates a flat surface.
Planing (Linear)

\[ d = D_{ini} - D_{fin} \]

**Speed**: relative motion between tool and work, stated in surface feet per minute (fpm).

Reciprocating motions may be crank-powered, hydraulically, or direct-reversible, electrically driven.

There will always be accelerations for a portion of the stroke. Cutting speed is assumed to be the average speed.

**Feed** with single-point tool is the amount the tool or work table is indexed.
For Turning

\[ MRR = \pi D \cdot d \cdot f_r \cdot N \quad \text{(m m m rev rev min)} \]

\[ = V f_r d, \quad \text{m}^3 / \text{min} \]

Example

Material: Carbon Steel

Assume the Max. Allowed Cutting Speed, \( V : 305 \text{ m/min} \)

Feed rate, \( F_r : 0.13 \text{ mm/rev} \)

Depth of cut, \( d : 4.57 \text{ mm} \)

What is the max. MRR?

\[ MRR = 305 \times 0.00013 \times 0.00457 \]

\[ = 0.0001812 \text{ m}^3 / \text{min} \]

\[ = 181.2 \text{ cm}^3 / \text{min} \]
Milling (slab milling or end milling)

The tool rotates at rpm Ns. The work-piece translates past the cutter at feed rate $f_m$, the table feed.

The length of cut, $L$, is the length of work-piece plus allowance, $L_a$,

$$L_A = \sqrt{\frac{D^2}{4} - \left(\frac{D}{2} - d\right)^2} = \sqrt{d(D-d)}...\text{inches}$$

Basics of the milling process (slab milling) as usually performed in a horizontal milling machine.

$$v = \pi D_1 N, \text{ } m/\text{min}, \text{ } D_1 \text{in } m$$

$$CT = (L + L_A)/f_m$$

$$MRR = Wd f_m, \text{ } m^3/\text{min} \text{ where}$$

$W = \text{width of the cut, } d = \text{depth of cut.}$

$f_m = f_t n Ns, \text{ } m/\text{min}$
Face Milling

$$f_m = f_t \times n \times \text{RPM}$$

Given a selected cutting speed $V$ and a feed per tooth $f_t$, the rpm of the cutter is $N_s = \frac{12V}{\pi D}$ for a cutting of diameter $D$. The table feed rate is $f_m = f_t n N_s$ for a cutter with $n$ teeth.

The cutting time, $CT = (L + L_A + L_o)/f_m$

where $L_o = L_A = \sqrt{W(D - W)}$ for $W < D/2$

or $L_o = L_A = D/2$ for $W \geq D/2$.

The MRR = $Wdf_m$, where $d$ = depth of cut.

$$v = \pi D_1 N, \text{ } m/\text{min}, \text{ } D_1 \text{ } \text{in} \text{ } m$$

MRR = $Wdf_m$, $m^3/\text{min}$

Basics of the milling process (face and end milling) as performed on a vertical spindle machine, including equations for cutting time and metal-removal rate.
Drilling

In drill, \( D \) = diameter of the drill which rotates 2 cutting edges at rpm \( N_s \). \( V \) = velocity of outer edge of the lip of the drill.

\[ N_s = \frac{12V}{\pi D} \]

\[ CT = L + \frac{A}{f_r N_s} \] where \( f_r \) is the feed rate in in. per rev. The allowance \( A = D/2 \).

The MRR = \((\pi D^2 / 4)f_r N_s\) in.\(^3\)/min which is approximately \(3DVf_r\).

Drilling-multiple edge tool
Basic of the drilling (hole making) process, including equations for cutting time (CT) and metal-removal rate (MRR).

\[ v = \pi DN, \text{ } \text{m/min}, \text{ } Din \text{ m} \]

\[ MRR = (\pi D^2 / 4)f_r N, \text{ } \text{m}^3/\text{min} \]
The tool cuts at velocity $V$ with a return velocity of $V_R$ dictated by the rpm of the crank, $N_s$. The cutting speed $V = (l + A)N_s/12R_s$ where $R_s = \text{stroke ratio} = 200°/360°$ and the length of cut is $l = L + \text{ALLOW}$. The tool feed is $f_c$ inches per stroke

$CT = W/N_s f_c$

$MRR = LdN_s f_c \text{ in}^3/\text{min}$

**FIGURE** Basics of the shaping process, including equations for cutting time (CT) and metal-removal rate (MRR).
How to make a square hole?
Broaching

The $CT$ for broaching is $CT = L/12V$. The MRR (per tooth) is $12tWV$ in$^3$/min where $V$ = cutting velocity in fpm, $W$ is the width of cut, $t$ = rise per tooth.


Cutting Speed, Feed rate, DOC are fixed
FIGURE 21-11 Oblique machining has three measurable components of forces acting on the tool. The forces vary with speed, depth of cut, and feed.

3 Force

$F_C$ = Cutting force (vertical)

$F_R$ = Radial force (thrust)

$F_F$ = Feed force
Energy & Power in Machining

- **Fc**: Primary cutting force (largest and accounts for 99% of the required power)
- **Ff**: Feed force (approximately 50% of Fc but small since feed rates are smaller than cutting speeds)
- **Fr**: Radial or thrust force (approximately 50% of Ff, and contributes very little)
Power requirement

\[ P = F_c V \text{(ft-lb/min)} \]

\[ \text{hp} = \frac{F_c V}{33,000} \]

\[ \text{HP}_s = \frac{\text{hp}}{\text{MRR}} \text{(hp/in}^3/\text{min)} \]

\[ \text{HP}_m = \frac{\text{HP}_s \times \text{MRR} \times CF}{E} \]

CF: Tool wear Correction factor, 1.25
E: Mechanical Efficiency, 0.80
### TABLE 21.3. Values for Unit Power and Specific Energy (cutting stiffness)

<table>
<thead>
<tr>
<th>Material (Hardness)</th>
<th>Unit Power (hp-min./in³) HP&lt;sub&gt;s&lt;/sub&gt;</th>
<th>Specific Energy (in.-lb/in³) K&lt;sub&gt;s&lt;/sub&gt; or U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel (120 Bhn)</td>
<td>1.12</td>
<td>443,000</td>
</tr>
<tr>
<td>Steel (120 Bhn)</td>
<td>0.86</td>
<td>347,000</td>
</tr>
<tr>
<td>Steel (120 Bhn)</td>
<td>0.76</td>
<td>301,000</td>
</tr>
<tr>
<td>Steel (120 Bhn)</td>
<td>0.64</td>
<td>254,000</td>
</tr>
<tr>
<td>Steel (120 Bhn)</td>
<td>0.54</td>
<td>214,000</td>
</tr>
<tr>
<td>Steel (160 Bhn)</td>
<td>1.25</td>
<td>495,000</td>
</tr>
<tr>
<td>Steel (160 Bhn)</td>
<td>0.59</td>
<td>234,000</td>
</tr>
<tr>
<td>Steel (200 Bhn)</td>
<td>1.50</td>
<td>594,000</td>
</tr>
<tr>
<td>Steel (200 Bhn)</td>
<td>0.73</td>
<td>290,000</td>
</tr>
<tr>
<td>Steel (300 Bhn)</td>
<td>1.87</td>
<td>740,000</td>
</tr>
<tr>
<td>Steel (300 Bhn)</td>
<td>0.92</td>
<td>364,000</td>
</tr>
<tr>
<td>SAE-302</td>
<td>0.72</td>
<td>285,000</td>
</tr>
<tr>
<td>SAE-350</td>
<td>1.20</td>
<td>475,000</td>
</tr>
<tr>
<td>SAE-410</td>
<td>0.75</td>
<td>297,000</td>
</tr>
<tr>
<td>Gray Cl (130 Bhn)</td>
<td>0.29–0.33</td>
<td>127,000</td>
</tr>
<tr>
<td>Mechanite</td>
<td>0.55–0.76</td>
<td>262,000</td>
</tr>
<tr>
<td>K-Monel</td>
<td>0.80</td>
<td>317,000</td>
</tr>
<tr>
<td>Inconel 700</td>
<td>1.40</td>
<td>554,000</td>
</tr>
<tr>
<td>High-Temperature Alloy A 286</td>
<td>1.20</td>
<td>475,000</td>
</tr>
<tr>
<td>High-Temperature Alloy S 816</td>
<td>1.25</td>
<td>495,000</td>
</tr>
<tr>
<td>Titanium A-55</td>
<td>0.65–0.76</td>
<td>281,000</td>
</tr>
<tr>
<td>Titanium C-130</td>
<td>0.81–0.93</td>
<td>345,000</td>
</tr>
<tr>
<td>Titanium (250–275 BHN)</td>
<td>1.8–2.0</td>
<td></td>
</tr>
<tr>
<td>Aluminum 2014-T6, 2014-T4</td>
<td>0.24</td>
<td>95,100</td>
</tr>
<tr>
<td>Aluminum 6064-TO</td>
<td>0.34</td>
<td>125,000</td>
</tr>
<tr>
<td>Aluminum 3003-O</td>
<td>0.16</td>
<td>63,400</td>
</tr>
<tr>
<td>Aluminum 108 (55 BHN)</td>
<td>0.15</td>
<td>49,400</td>
</tr>
<tr>
<td>Muntz Metal</td>
<td>0.55</td>
<td>218,000</td>
</tr>
<tr>
<td>Phosphor Bronze</td>
<td>0.33</td>
<td>131,000</td>
</tr>
<tr>
<td>Cartridge Brass</td>
<td>0.48</td>
<td>190,000</td>
</tr>
<tr>
<td>Copper Alloys (10–80 R&lt;sub&gt;p&lt;/sub&gt;)</td>
<td>0.5–0.6</td>
<td></td>
</tr>
<tr>
<td>Copper (50 R&lt;sub&gt;p&lt;/sub&gt;)</td>
<td>0.9–1.0</td>
<td></td>
</tr>
<tr>
<td>Magnesium (40–90 BHN at 500 kg)</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>Tungsten, Tantalum (210–320 BHN)</td>
<td>2.6–2.8</td>
<td></td>
</tr>
<tr>
<td>Nickel Alloys (280–360 BHN)</td>
<td>1.8–2.0</td>
<td></td>
</tr>
<tr>
<td>Nickel/Cobalt Alloys (200–360 BHN)</td>
<td>2.0–2.5</td>
<td></td>
</tr>
</tbody>
</table>
Motor Design

- Decide the cutting parameters \((f_m, N, \text{doc})\)
- Calculate MRR (\(\text{MRR}_{\text{max}}\))
- Choose the HPs of the material selected
- Estimate HPm
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Turning</th>
<th>Milling</th>
<th>Drilling</th>
<th>Broaching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting speed, ( f_{\text{rpm}} )</td>
<td>( V = 0.262 \times D_i \times \text{rpm} )</td>
<td>( V = 0.262 \times D_m \times \text{rpm} )</td>
<td>( V = 0.262 \times D_d \times \text{rpm} )</td>
<td>( V )</td>
</tr>
<tr>
<td>Revolutions per minute, ( N_s )</td>
<td>( \text{rpm} = 3.82 \times \frac{V_c}{D_i} )</td>
<td>( \text{rpm} = 3.82 \times \frac{V_c}{D_m} )</td>
<td>( \text{rpm} = 3.82 \times \frac{V_c}{D_d} )</td>
<td>( - )</td>
</tr>
<tr>
<td>Feed rate, in./min</td>
<td>( f_m = f_r \times \text{rpm} )</td>
<td>( f_m = f_r \times \text{rpm} )</td>
<td>( f_m = f_r \times \text{rpm} )</td>
<td>( - )</td>
</tr>
<tr>
<td>Feed per rev tooth pass, in./rev</td>
<td>( f_r )</td>
<td>( f_r )</td>
<td>( f_r )</td>
<td>( - )</td>
</tr>
<tr>
<td>Cutting time, min, ( T_m )</td>
<td>( T_m = \frac{L}{f_m} )</td>
<td>( T_m = \frac{L}{f_m} )</td>
<td>( T_m = \frac{L}{f_m} )</td>
<td>( T_m = \frac{L}{12V} )</td>
</tr>
<tr>
<td>Rate of metal removal, ( \text{in}^3/\text{min} )</td>
<td>( \text{MRR} = 12 \times d \times f_r \times V_c )</td>
<td>( \text{MRR} = w \times d \times f_m )</td>
<td>( \text{MRR} = \pi D^2d/4 \times f_m )</td>
<td>( \text{MRR} = 12 \times w \times d \times V )</td>
</tr>
<tr>
<td>Horsepower required at spindle</td>
<td>( \text{hp} = \text{MRR} \times \text{HP}_s )</td>
<td>( \text{hp} = \text{MRR} \times \text{HP}_s )</td>
<td>( \text{hp} = \text{MRR} \times \text{HP}_s )</td>
<td>( - )</td>
</tr>
<tr>
<td>Horsepower required at motor</td>
<td>( \text{hp}_m = \text{MRR} \times \frac{\text{HP}_s}{E} )</td>
<td>( \text{hp}_m = \text{MRR} \times \frac{\text{HP}_s}{E} )</td>
<td>( \text{hp}_m = \text{MRR} \times \frac{\text{HP}_s}{E} )</td>
<td>( \text{hp}_m = \text{MRR} \times \frac{\text{HP}_s}{E} )</td>
</tr>
<tr>
<td>Torque at spindle</td>
<td>( t_1 = 63,030 \text{ hp/rpm} )</td>
<td>( t_1 = 63,030 \text{ hp/rpm} )</td>
<td>( t_1 = 63,030 \text{ hp/rpm} )</td>
<td>( - )</td>
</tr>
<tr>
<td>Symbols</td>
<td>( D_i = \text{Diameter of workpiece in turning, inches} )</td>
<td>( D_m = \text{Diameter of milling cutter, inches} )</td>
<td>( D_d = \text{Diameter of drill, inches} )</td>
<td>( - )</td>
</tr>
<tr>
<td></td>
<td>( d = \text{Depth of cut, inches} )</td>
<td>( d = \text{Depth of cut, inches} )</td>
<td>( d = \text{Depth of cut, inches} )</td>
<td>( - )</td>
</tr>
<tr>
<td></td>
<td>( E = \text{Efficiency of spindle drive} )</td>
<td>( E = \text{Efficiency of spindle drive} )</td>
<td>( E = \text{Efficiency of spindle drive} )</td>
<td>( - )</td>
</tr>
<tr>
<td></td>
<td>( f_m = \text{Feed rate, inches per minute} )</td>
<td>( f_m = \text{Feed rate, inches per minute} )</td>
<td>( f_m = \text{Feed rate, inches per minute} )</td>
<td>( - )</td>
</tr>
<tr>
<td></td>
<td>( f_r = \text{Feed, inches per revolution} )</td>
<td>( f_r = \text{Feed, inches per revolution} )</td>
<td>( f_r = \text{Feed, inches per revolution} )</td>
<td>( - )</td>
</tr>
<tr>
<td></td>
<td>( f_t = \text{Feed, inches per tooth} )</td>
<td>( f_t = \text{Feed, inches per tooth} )</td>
<td>( f_t = \text{Feed, inches per tooth} )</td>
<td>( - )</td>
</tr>
<tr>
<td></td>
<td>( \text{hp}_m = \text{Horsepower at motor} )</td>
<td>( \text{hp}_m = \text{Horsepower at motor} )</td>
<td>( \text{hp}_m = \text{Horsepower at motor} )</td>
<td>( - )</td>
</tr>
</tbody>
</table>

Values for specific horsepower (unit power) are given in Table 21-4.
Orthogonal Machining (Two-Force Model)

- Cutting tool geometry is simplified from the 3-D (oblique) geometry to a 2-D (orthogonal) geometry.
**Chip Formation:** Simplified Orthogonal Machining in-plane model of the cutting process

**Assumptions**

- **Work-piece:** flat plate
- **Cutting tool:** geometry given by the back rake angle ($\alpha$) only
- **Shear:** in one single plane which is doing $\phi$ degrees with the direction of speed.

**FIGURE** Schematic of orthogonal machining. The cutting edge of the tool is perpendicular to the direction of motion ($V$). The back rake angle is $\alpha$. The shear angle is $\phi$. 

[Diagram of chip formation with annotations for back rake angle, chip thickness ($t_c$), chip formation, and shear plane.]
Chip is formed by shearing. High shear stress over a narrow region.

Large strain and high strain rate plastic deformation due to radial compression.

Compression zone travels ahead of the tool.

Elastic to plastic deformation when yield stress is exceeded.

FIGURE Videograph of the orthogonal machining process.

FIGURE The machining process produces a radial compression ahead of the shear process. The stress reverses from compression to tension across the neutral axis (NA).
Mechanics of machining:

Velocity diagram

Chip thickness ratio, \[ r_c = \frac{t}{t_c} = \frac{AB \sin \phi}{AB \cos(\phi - \alpha)} = \frac{\sin \phi}{\sin(90 - (\phi - \alpha))} = \frac{V_c}{V} \]

Shear angle, \[ \tan \phi = \frac{r_c \cos \alpha}{1 - r_c \sin \alpha} \]

During the cutting, the chip undergoes a shear strain \[ \varepsilon = \frac{2 \cos \alpha}{1 + \sin \alpha} \]

Where, \( AB \) is the length of the shear plane.
Chip Compression ratio = $1/rc$

Quick stop device: Sudden disengagement of the tool

Types of chips: discontinuous, continuous with built-up edge
Mechanics of machining:

R resultant force:  \( F_c \)  cutting force

\( F_t \)  normal (tangential) force:

\( F_s \)  shear force (N)  \( F_n \) -normal force

Friction angle \( \beta \):

\[ \beta = \tan^{-1} \frac{F}{N} \]
Circular Force Diagram

\[ F = F_c \sin \alpha + F_t \cos \alpha \]
\[ N = F_c \cos \alpha - F_t \sin \alpha \]
\[ F_s = F_c \cos \Phi - F_t \sin \phi \]
\[ F_n = F \sin \Phi - F_t \cos \phi \]

\[ \tau_s = \frac{F_s}{A_s} = \frac{F_c \sin \phi \cos \phi - F_t \sin^2 \phi}{t \times w} \]

\[ A_s = \frac{t \times w}{\sin \phi} \]

\[ R = \sqrt{F_c^2 + F_t^2} = \sqrt{F^2 + N^2} \]
Typical shear stress values

![Graph showing shear stress values vs. Brinell hardness number for various materials.](image)

- **B.C.C. matrix (steels)**
  - 9445
  - 8640
  - 52100
  - 1018
  - 4345
  - Iron

- **F.C.C. matrix metals**
  - L605
  - S816 alloy

- **Annealed**
  - Inconel 600
  - 304
  - Nickel 200

- **Cold finished**
  - Tough pitch copper
  - α Brass
  - 2024-T6 aluminum
  - 6061-T6 aluminum

- **1100 aluminum**
• Necessary power of the machine

\[
\text{Power} = \frac{F_c v}{60}, \quad \text{Watts}
\]

• Calculation of the specific power

\[
\text{Specific Power} = \frac{\text{Power}}{\text{MRR}} = \frac{\text{function}(V,F_c)}{\text{function}(V,f_r,d)}
\]

\[
F_c \approx \frac{\text{Spec. Power} \times \text{MRR} \times 60}{v}
\]

• The primary cutting force

The motor Power = Spec. Power * MRR * CF/\eta

### TABLE 21-3. Values for Specific or Unit HPs for Various Metals during Metal Removal

<table>
<thead>
<tr>
<th>Material</th>
<th>Hardness (BHN or R)</th>
<th>HPs</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steels, including plain carbon, alloy, tool, hot or cold rolled, or cast</td>
<td>85–200</td>
<td>1.1</td>
<td>0.050</td>
</tr>
<tr>
<td></td>
<td>35–40Rc</td>
<td>1.4</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td>40–50Rc</td>
<td>1.5</td>
<td>0.068</td>
</tr>
<tr>
<td></td>
<td>50–55Rc</td>
<td>2.0</td>
<td>0.091</td>
</tr>
<tr>
<td></td>
<td>55–58Rc</td>
<td>3.4</td>
<td>0.155</td>
</tr>
<tr>
<td>Cast iron</td>
<td>100–190</td>
<td>0.7–1.0</td>
<td>0.03–0.045</td>
</tr>
<tr>
<td></td>
<td>190–300</td>
<td>1.4–1.6</td>
<td>0.05–0.07</td>
</tr>
<tr>
<td>Stainless steels</td>
<td>150–450</td>
<td>1.2–1.4</td>
<td>0.05–0.068</td>
</tr>
<tr>
<td>Iron-based alloys</td>
<td>180–320</td>
<td>1.2–1.6</td>
<td>0.055–0.073</td>
</tr>
<tr>
<td>Nickel alloys</td>
<td>80–360</td>
<td>1.8–2.0</td>
<td>0.82–0.091</td>
</tr>
<tr>
<td>Nickel–cobalt-based alloys</td>
<td>200–360</td>
<td>2.0–2.5</td>
<td>0.09–0.11</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2014-T6, 2017-T4</td>
<td>0.25 –</td>
<td>0.014 –</td>
</tr>
<tr>
<td></td>
<td>6064-T6</td>
<td>0.34</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>500 kg</td>
<td>0.16</td>
<td>0.007</td>
</tr>
<tr>
<td>Pure-108</td>
<td>55</td>
<td>0.33</td>
<td>0.015</td>
</tr>
<tr>
<td>Hard (rolled)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>40–90 at 500 kg</td>
<td>0.16</td>
<td>0.007</td>
</tr>
<tr>
<td>Copper</td>
<td>50Rb</td>
<td>0.9–1.0</td>
<td>0.041–0.046</td>
</tr>
<tr>
<td>Copper alloys</td>
<td>10–80Rb</td>
<td>0.5–0.6</td>
<td>0.022–0.030</td>
</tr>
<tr>
<td></td>
<td>80–100Rb</td>
<td>0.8–1.0</td>
<td>0.036–0.046</td>
</tr>
<tr>
<td>Titanium</td>
<td>250–375</td>
<td>1.8–2.0</td>
<td>0.82–0.091</td>
</tr>
<tr>
<td>Tungsten, tantalum</td>
<td>210–320</td>
<td>2.6–2.8</td>
<td>0.12–0.13</td>
</tr>
</tbody>
</table>
Heat and temperature in metal cutting

Sources: Shear process

Tool-chip interface (friction)

Tool and work piece interface (friction).

Sinks:
Heat and Temperature in Metal Cutting

1. Primary shear zone
2. Secondary shear zone
3. Flank

Temperature (°C)

300 400 500 600 650 700

Heat affected zone in workpiece

Chip

Tool

Workpiece
Chatter: Unwanted vibration of the tool. Can be reduced by cutting parameters and Active vibration Control.
Cutting Tools for Machining
Introduction

• Workpiece material → Selection of the proper cutting tool (material & geometry)
  • High carbon steels
  • Low/medium alloy steels
  • High-speed steels
  • Cast cobalt alloys
  • Cemented/cast/coated carbides
  • Coated high speed steels
  • Ceramics
  • Sintered polycrystalline cubic boron nitride (CBN)
  • Sintered polycrystalline diamond
  • Single-crystal natural diamond
Selection of a cutting tool:

**Inputs**
- Work material (composition & metallurgical state)
- Type of cut (roughing vs finishing, continuous cut vs intermittent)
- Part geometry & size
- Lot size (small batch vs mass production)
- Machinability data – tool life/specific HP
- Quality/capability needed
- Past experience of decision maker

**Constraints**
- Manufacturing practice (continuous vs intermittent)
- Condition & capabilities of available machine tools (rigidity)
- Geometry, finish, accuracy & surface integrity requirements
- Workholding devices (rigidity)
- Required processing time (production schedule)

**Tool Selection Decision**

**Outputs**
- Selected tools (specific tool material, grade, shape and tool geometry)
- Cutting parameters – speed (rpm), feed, depth of cut, cutting fluids
- Availability (available materials, their composition, properties and applications, available sizes, shapes and geometry, availability, delivery schedule, cost and performance data)

**Figure**

The selection of the cutting tool material and geometry and the cutting conditions for a given application depends on many variables.
Cutting tools for machining

**Proper Tool:** geometry and material

**Selection:** Work material

- Part characteristics (geometry, accuracy, finish, etc.)
- Machine tools characteristics (work holders)
- Fixture support systems (Operator, sensors, lubrication, etc.)

![Diagram](image)

**FIGURE 22-1**
Improvements in cutting tool materials have reduced machining time.
Tool is subjected to 1000°C, severe friction, high local stresses.

Cutting Tool Requirements:

- High hardness
- Resistance to abrasion, wear, chipping
- High toughness (impact strength)
- High hot hardness
- Strength to resist bulk deformation
- Chemical stability with temperature
- Good thermal properties
- High elastic modulus (stiffness)
- Consistent tool life
- Correct geometry and surface finish
Hardness of materials for cutting tools:

Diamond—natural/synthetic
Sintered cubic boron nitride—CBN
CVD-titanium carbide
Sintered silicon carbide
CVD-titanium nitride carbon nitride
CVD-aluminum oxide
CVD-chromium carbide
Diffused layer—CVD-iron boride
Sintered TiC-WC hard metals
Nitrided case of an alloy steel
Electro deposited hard chrome plated
Nitrided case of an unalloyed steel
Hardened steel
Hardened and tempered steel
Iron

Knoop hardness scale – 1,000 Kp/mm²

FIGURE: Vickers hardness ranges for various cutting tool materials.
The cutting tool should be

1. Hard to resist wear
2. Tough to resist cracking and chipping

Life of the tools: depends on the regime the tool is subjected to
<table>
<thead>
<tr>
<th>Property</th>
<th>Carbon and Low/Medium-Alloy Steels</th>
<th>High-Speed Steels</th>
<th>Sintered (Demented) Carbides</th>
<th>Coated HSS</th>
<th>Coated Carbides</th>
<th>Ceramics</th>
<th>Polycrystalline CBN</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toughness</td>
<td>Decreasing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot hardness</td>
<td></td>
<td>Increasing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact strength</td>
<td></td>
<td>Decreasing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wear resistance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Increasing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chipping resistance</td>
<td></td>
<td>Decreasing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutting speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Increasing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth of cut</td>
<td>Light to medium</td>
<td>Light to heavy</td>
<td>Light to heavy</td>
<td>Light to heavy</td>
<td>Light to heavy</td>
<td>Light to heavy</td>
<td>Light to heavy</td>
<td>Very light for single-crystal diamond</td>
</tr>
<tr>
<td>Finish obtainable</td>
<td>Rough</td>
<td>Rough</td>
<td>Good</td>
<td>Good</td>
<td>Very good</td>
<td>Very good</td>
<td></td>
<td>Excellent</td>
</tr>
<tr>
<td>Method of manufacture</td>
<td>Wrought</td>
<td>Wrought cast, HIP sintering</td>
<td>Cold pressing and sintering, PM</td>
<td>PVD(^b) after forming</td>
<td>CVD(^c)</td>
<td>Cold pressing and sintering or HIP sintering</td>
<td>High-pressure–high-temperature sintering</td>
<td>High-pressure–high-temperature sintering</td>
</tr>
<tr>
<td>Fabrication</td>
<td>Machining and grinding</td>
<td>Machining and grinding</td>
<td>Grinding</td>
<td>Machining and grinding, coating</td>
<td>Grinding before coating</td>
<td>Grinding and polishing</td>
<td>Grinding and polishing</td>
<td></td>
</tr>
<tr>
<td>Thermal shock resistance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool material cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Overlapping characteristics exist in many cases. Exceptions to the rule are very common. In many classes of tool materials a wide range of composition and properties is obtainable.

\(^b\) Physical vapor deposition.

\(^c\) Chemical vapor disposition.
Tool Coating Processes

- TiN & TiC
  - CVD: carbide inserts and steel $\rightarrow$ 950-1050 °C
    - Tooling with loose tolerances
    - Punches, trim dies
    - Solid carbide tooling
  - PVD: TiN coatings on HSS and carbide-tipped cutting tools $\rightarrow$ 200-485 °C
    - HSS, solid carbide and carbide-tipped tools
    - Fine punches, dies (fine tolerances)
    - Composition independent process; virtually all tooling materials
Cutting Tool Materials

- **Tool steels:** Carbon steels (0.90-1.30%) and low/medium alloy steels → lose their hardness above 400 °F through tempering
  - Low/medium alloy steels also lose their hardness above 300-650 °F, limited abrasion resistance → relatively inexpensive cutting tools (drills, taps, reamers, broaches) → low-temperature machining

- **High-speed steels (HSS):** High-alloy steels → up to 1100 °F: good red hardness

- Cutting speeds are higher by three or two-fold than those of tool steels → HSS

- Contain: Fe & C + W, Mo, Co, V, Cr (strength, beyond the tempering temperature [hot hardness], hardness, and wear resistance)
  - Toughness – superior rupture strength
  - Easy to fabricate
  - Suitable for forming complex tool geometry (gear cutters, taps, drills, reamers)
Cutting Tool Materials – 2

• **TiN-coated HSS:**
  - Gear-shaper cutters, drills, reamers, taps, broaches, insert tooling, bandsaw, circular saw, end mills and other milling cutters
    - Improved tool wear
    - Higher hardness, higher abrasion resistance, longer tool life
    - Relative inertness (increased adhesion-related tool life)
    - Low coefficient of friction (→ increased shear angle → reduced cutting forces, spindle power, and heat generation)
Cutting Tool Materials – 3

- **Cast Cobalt alloys: stellite tools**
  - Cobalt-rich, Cr, W and WC and CrC cast alloys
  - Intermediate range between HSS & cemented carbides
  - Higher hot hardness than HSS → higher cutting speeds (25% higher) than those of HSS
  - Cannot be softened or heat treated (hard as cast)
  - Usually cast to shape and finished to size by grinding
  - Come in simple shapes only (single-point tools, saw blades - due to high hardness as cast condition)
  - Currently being phased out mostly because **cost**
Cutting Tool Materials – 4

• Carbide or Sintered Carbides: Inserts
  – Straight tungsten grades (for machining cast irons, austenitic stainless steel, nonferrous and nonmetallic materials)
  – Grades with high amount of Ti, Ta (for machining ferritic workpieces)
  – Carbides are nonferrous alloys → also called sintered or cemented carbides → powder metallurgy techniques (Cobalt being the binder)
  – Come as either straight WC or multicarbides of W-Ti or W-Ti-Ta depending of the workpiece material
  – Much harder, chemically more stable, better hot hardness, higher stiffness, lower friction, higher cutting speeds than HSS
  – More brittle & more expensive (due to use of strategic metals – W, Ta, Co)
Cutting Tool Materials – 5

• Carbide or Sintered Carbides: Inserts – Cont’d

  – They come in insert form: squares, triangles, diamonds & rounds
  – Can be either brazed or mechanically clamped (*more popular*) onto the tool shank
  – Can be purchased in the *as pressed* state or they can be *ground* to finish tolerances
  – A chip groove with a positive rake angle (reduce cutting forces)
  – Carbide inserts are recycled after use to reclaim the Ta, WC, and Co (strategic materials)
Type tool materials: Nutshell

- Plain Carbon Steel (0.9% to 1.3% C), hardened and tempered, 400F

- Low-Medium Alloy Steel, (Mo, Cr:Hardness, W, Mo:Wear resistance,), hardened and tempered, e.g. drills, taps, etc.

**High speed steels (HSS)** – Co, W, Mo, Cr  
(Increased hardness, wear resistance), Rc65-70, Greater toughness, easily complicated geometries can be fabricated

TiN Coated HSS: TiN PVD Coated, Rc 80-85,

**Cast cobalt alloys (stellite tools)** – Co, Cr, W, C Cast ally + V, B, Ni, Ta,  
Simple shapes  
Between HSS and Carbide tool  
25% higher cutting speeds than HSS
Carbides or sintered carbides WC, TiC, TaC, v>300m/min

Used as inserts
Ceramics – $\text{Al}_2\text{O}_3$ – Sintering – brittle

Carbide coated tools WC + TiC + Al$_2$O$_3$ + TiN (Abrasion resistant, hard, chemically inactive)

Titanium carbide remains as the basic material covering the substrate for strength and wear resistance. The second layer is aluminium oxide which has proven chemical stability at high temperatures and resists abrasive wear. The third layer is a thin coating of titanium nitride to give the insert a lower coefficient of friction and to reduce edge build-up.

![Diagram of carbide coated tools](image)

**FIGURE 22-6** Triple-coated carbide tools provide resistance to wear and plastic deformation in machining of steel, abrasive wear in cast iron, and built-up edge formation.
Drill performance based on the number of holes drilled with 1/4 inch diam. drill in T-1 structural steel.

**FIGURE** Tool life data for various coated drills. Notice how TiN-coated HSS drills outperform uncoated drills.
**Cermets:** ceramics in metal binders (TiC, Ni, Co, TiN)

High Hot Hardness, Oxidation resistance, good finish, cold pressed

**Diamonds – for precision machining** (High Hardness, Low Friction, very good finish)

---

**Polycrystalline diamond tools are carbides with diamond inserts. They are restricted to simple geometries.**

**FIGURE:** Cermets compared to other tool materials in terms of possible cutting speed and feed rates. SFM, surface feet per minute; ipr, inches per revolution.
Comparison of Tool Materials
Tool Geometry

FIGURE

Standard terminology to describe the geometry of single-point tools.
<table>
<thead>
<tr>
<th>+ve Rake angle</th>
<th>-ve Rake angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting force</td>
<td></td>
</tr>
<tr>
<td>Smaller deflections</td>
<td>Useful for hard materials</td>
</tr>
<tr>
<td></td>
<td>-ve for carbide and diamond tools</td>
</tr>
</tbody>
</table>

**Hardness:**

Higher the hardness → smaller the rake angle

Crabide tools: -6 to +6deg

HSS: +ve rake angle

**Cutting force:**

Smaller Rake angle → Higher compression force, tool force, friction,

Hot and thick chips, highly deformed chips.

Higher Rake angle → Lower compression force, tool force, friction,

cooler and less deformed chips.
But, **Higher Rake angles** $\rightarrow$ Lesser tool strength, Reduced heat transfer.

As wedge angle determines the Tool Strength

**Tool Selection:** Trade off between force, strength, cooling

**Power consumption** $\rightarrow$ 1% decrease for 1deg rake angle

\[
\text{rake angle} \uparrow \rightarrow \text{power} \downarrow
\]

**Wedge angle** $\rightarrow$ increases the tool strength.

**Relief angle** $\rightarrow$ Improves surface quality

5-10deg, normal

smaller angles for harder materials.

**Nose radius:** Determines the cutting force, chipping, surface finish, wear.

\[
\text{radius} \uparrow \rightarrow \text{wear, life and surface finish} \uparrow\]
Tool failure and tool life

**Failure mechanism:**

- **Slow-death mechanism** – gradual tool wear on flanks and rake
- **Sudden death mechanism** – rapid, unpredictable-plastic deformation, brittle fracture, fatigue fracture

**Figure:** Typical tool wear curves for flank wear at different velocities.

**Figure:** Sketch of a worn tool showing various wear elements resulting during oblique cutting: $W_f$, flank wear land length; $t$, uncut chip thickness.
Taylor Tool Life Model

\[ T = \frac{const.}{f_x \times v_y} \quad \text{or} \quad VT^n = C \]

- \( n \) depends on material
- \( C \) depends on all input parameters including feed

**FIGURE** Construction of the Taylor tool life curve using data from deterministic tool wear plots like those of Figure 22-13

**FIGURE** Log-log tool life plots for three steel work materials cut with HSS tool material.

- HSS 0.14-0.16
- Carbide 0.21-0.25
- TiC insets 0.3
- Polydiamonds 0.33
- Ceramic coated 0.4
Sources of variability for Tool Life:

Changes in

- Material (hardness)
- Geometry of the tool
- Vibrations
- Surface Characteristics

Large $\sigma \rightarrow$ Life is not predictable

Coefficient of variation

$C_T = \frac{\sigma_T}{\mu_T} \approx 0.3$ to $0.4$

Mean failure time (min)

Log normal distribution of failures

$\sigma_T = \text{standard deviation}$

Tool life or time to failure $\mu_T$

FIGURE Tool life viewed as random variable has a log normal distribution with a large coefficient of variation.
Economics of Machining

50% $V \uparrow \rightarrow 90\% \downarrow$ Tool life

50% $f \uparrow \rightarrow 60\% \downarrow$ Tool life

50% $d \uparrow \rightarrow 15\% \downarrow$ Tool life

FIGURE: Cost per unit for a machining process versus cutting speed.
Reconditioning of the cutting tools.

Whenever possible, re-sharp

Recoating: Cost ~ 1/5 the cost of the tool

Performances of the tool may be reduced

Machinability: ease to perform machining task

Relative evaluations with respect to a standard material cut at a specific speed at the same tool life

FIGURE 22-19 Machinability ratings defined by deterministic tool life curves.
Reconditioning Cutting Tools

• Resharpen to original tool geometry (CNC grinding machines for tool sharpening)
• Grind cutting edges and surfaces to a fine finish (recoat ground surfaces)
• Remove all burrs
• Avoid overheating, burning or melting the tool
Cutting Fluids

*Cooling* → increases the cutting speed by two or three-fold → Cutting fluids

Cutting fluids:

- coolant
- lubricant → reducing friction (tool-chip interface & workpiece-tool flank)
- helps remove the chip from cutting region
- friction reduction in other regions other than cutting edge-workpiece friction (drilling, sawing, reaming, etc.)
- temperature reduction → hot hardness issue → increased tool life or increased cutting speed for equal tool life
- better dimensional control of the machined workpiece

*Water* → good coolant (thermal capacity and conductivity), also oxidant, not a good lubricant

*Oil* → less effective coolant, not an oxidant, some lubrication

Coolants are recycled through restoration
Shaping and Planning:

- single point machining

Shapers Horizontal:  Push-cut

pull-cut or draw-cut shaper

Vertical:  Regular (slotters)

Keyseaters

Special
Stroke ratio: $R_s = \frac{\text{cutting stroke angle}}{360^\circ}$

$$V = \frac{2LN_s}{R_s}$$

$$\text{MRR} = \frac{(L \cdot W \cdot t)}{\text{CT}}$$

$$\text{CT} = \frac{W}{f_c} \cdot N_s$$
FIGURE Details of a horizontal, push cut shaper.
**Work-holding devices**

**Planers:** Tool is fixed, work is reciprocating

---

**FIGURE**  
Methods of clamping workpieces in a shaper vise.

**FIGURE**  
Schematic of planers. (a) double-housing planer; (b) open-sided planer; (c) interchangeable multiple tool holder for use in planers. (Photograph courtesy Gebr. Boehringer GMBH.)