Today, February 25th

- HW#2 due before the class, #3 out on the web after the class.
- Math Formulae, handout
- Lab groups fixed, and thank you.
  - group report!!!
- Metal cutting demo
- Cutting physics

A lathe of pre WWII

Material removal processes

- Cost: 🌩
  - Expensive $100 - $10,000
- Quality: ☁
  - Very high
- Flexibility: ☁
  - Any shape under the sun
- Rate: ☁
  - Slow

Surface roughness by machining

Machined Surface

<table>
<thead>
<tr>
<th>Surface Roughness</th>
<th>µ inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough</td>
<td>1000</td>
</tr>
<tr>
<td>Medium</td>
<td>500</td>
</tr>
<tr>
<td>Avg.</td>
<td>125</td>
</tr>
<tr>
<td>Better than Avg.</td>
<td>63</td>
</tr>
<tr>
<td>Fine</td>
<td>32</td>
</tr>
<tr>
<td>Very Fine</td>
<td>16</td>
</tr>
<tr>
<td>Extremely Fine</td>
<td>8</td>
</tr>
</tbody>
</table>
Cutting processes

- Why do we study cutting physics?
  - Product quality: surface, tolerance
  - Productivity: MRR, Tool wear
- Physics of cutting
  - Mechanics
  - Force, power
  - Tool materials
  - Design for manufacturing

Cutting process modeling

- Methods: Modeling and Experiments
- Key issues
  - How does cutting work?
  - What are the forces involved?
  - What affect does material properties have?
  - How do the above relate to power requirements, MRR, wear, surface?

Orthogonal cutting in a lathe

Assume a hollow shaft

- Shear plane
- Depth of cut
- Rake angle

Cutting tool and workpiece.

Varying rake angle $\alpha$:

- $\alpha$
- $\alpha = 0$
Basic cutting geometry

- We will use the orthogonal model

Continuity

\[ V_t = V_c \]

- chip thickness
- depth of cut

Cutting ratio: \( r < 1 \)

\[ V_c = V_t \cdot \sin(\phi) \cdot \cos(\phi - \alpha) \]

Continuity

\[ V_c = V_t \cdot \sin(\phi) \cdot \cos(\phi - \alpha) \]

### Forces and power

- **FBD at the tool-workpiece contact**
- **What are the forces involved**
  - Thrust force, \( F_t \)
  - Cutting force, \( F_c \)
  - Resultant force, \( R \)
  - Friction force, \( F \)
  - Normal Force, \( N \)
  - Shear Force, \( F_s, F_n \)

**FBD of Forces**

\[
\begin{align*}
F &= R \cdot \sin(\beta) \\
N &= R \cdot \cos(\beta) \\
\mu &= \tan(\beta) \\
F_t &= R \cdot \sin(\beta - \alpha) \\
F_c &= R \cdot \cos(\beta - \alpha) \\
F_s &= F_c \cdot \cos(\alpha) \\
F_n &= F_c \cdot \sin(\alpha)
\end{align*}
\]

Typically: \( \mu < 2 \)

### Velocity diagram in cutting zone

**Law of sines**

\[
\begin{align*}
\frac{V_c}{\sin(\phi - \alpha)} &= \frac{V_t}{\sin(\phi)} \\
\frac{V_c}{\cos(\phi - \alpha)} &= \frac{V_t}{\cos(\phi)} \\
V_c &= V_t \cdot \sin(\phi) \cdot \cos(\phi - \alpha)
\end{align*}
\]

### E. Merchant’s cutting diagram

**Analysis of shear strain**

- What does this mean:
  - Low shear angle = large shear strain
  - Merchant’s assumption: Shear angle adjusts to minimize cutting force or max. shear stress
  - Can derive:

\[
\phi = 45^\circ + \frac{\alpha}{2} - \frac{\beta}{2}
\]
Shear angle

\[ F_c = R \cdot \cos(\beta - \alpha) \]
\[ F_t = F_c \cdot \cos(\phi) - F_f \cdot \sin(\phi) = \text{Rame}(\phi + \beta - \alpha) \]
\[ F_c = F_x \cdot \cos(\phi - \eta) + \cos(\phi + \beta - \eta) \]
\[ F_t = A \cdot s \cdot (\text{area of shear plane: shear strength}) \]
\[ F_c = \frac{A}{\text{se}} \cdot \cos(\eta - \alpha) + \cos(\eta + \beta - \alpha) \]
\[ \frac{df}{d\phi} = 0 \quad \phi = 45^\circ + \frac{\alpha}{2} - \frac{\beta}{2} \]

Things to think about

- As rake angle decreases or friction increases
- Shear angle decreases
- Chip becomes thicker
- Thicker chip = more energy dissipation via shear
- More shear = more heat generation
- Temperature increases!!!

\[ \phi = 45^\circ + \frac{\alpha}{2} - \frac{\beta}{2} \]

Power

Power input: \( F_t \cdot V \) => shearing + friction

Power for shearing: \( F_t \cdot V_s \)

Specific energy for shearing: \( \eta_s = \frac{F_t \cdot V}{W \cdot t_o \cdot V} \)

Power dissipated via friction: \( F \cdot V \cdot u_f \)

Specific energy for friction: \( \eta_f = \frac{F \cdot V}{W \cdot t_o \cdot V} \)

Total specific energy: \( \eta_t + \eta_f = \frac{F \cdot V}{W \cdot t_o \cdot V} + \frac{F \cdot V}{W \cdot t_o \cdot V} \)

Experimental data

Specific energy (rough estimate)

Approximate Energy Requirements in Cutting Operations (at drive motor, corrected for 90% efficiency; multiply by 1.25 for dull tools).

<table>
<thead>
<tr>
<th>Material</th>
<th>W/s/mm³</th>
<th>hp·min/in²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloys</td>
<td>0.4-1.1</td>
<td>0.15-0.4</td>
</tr>
<tr>
<td>Cast iron</td>
<td>1.6-3.3</td>
<td>0.16-3.2</td>
</tr>
<tr>
<td>Copper alloys</td>
<td>1.4-3.3</td>
<td>0.5-1.2</td>
</tr>
<tr>
<td>High-temperature alloys</td>
<td>3.3-8.5</td>
<td>1.2-3.1</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>0.4-0.6</td>
<td>0.15-0.2</td>
</tr>
<tr>
<td>Nickel alloys</td>
<td>4.5-6.8</td>
<td>1.8-2.5</td>
</tr>
<tr>
<td>Refractory alloys</td>
<td>3.8-9.6</td>
<td>1.1-3.5</td>
</tr>
<tr>
<td>Stainless steels</td>
<td>3.0-5.2</td>
<td>1.3-4.0</td>
</tr>
<tr>
<td>Steels</td>
<td>2.7-9.3</td>
<td>1.0-3.4</td>
</tr>
</tbody>
</table>

Example

- Consider the turning with a rod, from 1.25 inch diameter to 1.0.
- \( d \); depth of cut, 0.005 inch
- \( f \); feed rate, 0.025 inch/rev
- \( n \); spindle speed, 1000 rpm
- \( u_f \); specific energy for friction
- \( u_s \); specific energy for shearing, 0.35 hp min/in²
- 1 hp = 550 ft.lbf/s

- How many passes?
- Time to make this part?
- \( V \); max?
- Max power needed?
- Initial cutting force?

Cutting zone pictures

- Continuous
- Secondary shear
- BUE

- Serrated
- Discontinuous