Cutting Processes I

Reading assignment:

- 20.1 – 20.3, 20.5

Cutting processes I

Cutting processes
- Process planning, Cost, Quality, Rate and Flexibility

Modeling: Orthogonal cutting
- Video, geometry, forces and power

Demonstration

Cutting equipment/tools

Design for Manufacturing: Cutting

Process variation

Material removal processes

Mechanical removal processes
- Milling
- Turning
- Shaping
- Grinding
- Broaching

Others
- Thermal
- Electrochemical
- Chemical

In general:

<table>
<thead>
<tr>
<th>Cost</th>
<th>Flexibility</th>
<th>Quality</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expensive</td>
<td>Complex shapes</td>
<td>Depends</td>
<td>Slow</td>
</tr>
</tbody>
</table>
Understanding what is going on

Key issues
- How does cutting work?
- Linking the Cost, Flexibility, Quality and Rate to process parameters

Available methods to design process parameters:
- Analytic
- Numerical
- Experimental

Process planning & cutting process

Step I:
- Geometry & Motion
  - Tool and material

Step II:
- Forces
  - Cutting, shearing, friction

Step III:
- Material & Power
  - Specific energy
  - Cutting, shearing, friction

Geometry & Motion -> Forces -> Material & Energy/Power

Steps we will take to get there

Basic cutting geometries

Orthogonal (2D) → Provides insight for understanding
Oblique (3D) → Complex, diminishing returns

Geometry & Motion -> Forces -> Material & Energy/Power
Orthogonal cutting in a lathe

**Geometry & Motion → Forces → Material & Energy/Power**

### Orthogonal cutting zone geometry

**Important Angles**
- Shear angle: $\phi$
- Rake angle: $\alpha$
- Relief angle: $\varepsilon$

![Shear plane diagram]

**Motion**

**Geometry & Motion → Forces → Material & Energy/Power**

### Cutting Video

**Key issue:**
- Motion and material flow
- Types of chips
- How chip type relates to material

**Velocity diagram of cutting zone**

Need velocities to obtain power estimates

**Geometry & Motion → Forces → Material & Energy/Power**
Cutting ratio, $r$

From mass conservation:
$$\rho \cdot t_c \cdot w \cdot V = \rho \cdot t_w \cdot w \cdot V_c$$

From velocity diagram:
$$\frac{V}{\cos(\phi - \alpha)} = \frac{V_c}{\sin(\phi)}$$

Cutting ratio:
$$\frac{V}{V_c} = \frac{t_w}{t_c} = r = \frac{\sin(\phi)}{\cos(\phi - \alpha)}$$

Analysis of shear strain

What does this mean:
$$\phi \downarrow \rightarrow \gamma \uparrow$$

Cutting forces and power

Why do we need to know the cutting force/power?
- Designing parts / machine tools (power and stiffness)
- Part, machine and tool deflection
- Trade offs in process planning, CFQR...
- Equipment suitability
- Others....

Cutting forces

Forces:
- Thrust $F_t$
- Cutting $F_c$
- Friction $F_f$
- Tool normal $N$
- Shear $F_s$
- Chip normal $F_n$
Merchant’s diagram: Force relationships

**Shear plane forces:**

\[ F_t = F_c \cos(\phi) - F_f \sin(\phi) \]

\[ F_n = F_c \sin(\phi) + F_f \cos(\phi) \]

**Tool-chip forces:**

\[ F_t = F_c \sin(\phi) + F_f \cos(\phi) \]

\[ N = F_c \cos(\phi) - F_f \sin(\phi) \]

\[ \mu = \frac{F_f}{N} = \tan(\beta) \]

Typically: \( 0.5 < \mu < 2 \)

Geometry & Motion → Forces → Material & Energy/Power

Cutting and thrust forces

\[ F_t = F_c \tan(\beta - \alpha) \]

- \( \beta < \alpha \) tool is pulled into part
- \( \beta > \alpha \) tool is pushed away
- \( \beta = \alpha \) no thrust force

Use high \( \alpha \) for thin cuts?

Geometry & Motion → Forces → Material & Energy/Power

\[ \phi \] and \( \tau_s \)

Magnitude of shear stress varies with angle of shear plane

\[ \tau_s = \frac{F_c \cdot \cos(\phi) - F_f \cdot \sin(\phi)}{A_w} \]

\[ \phi \] [degrees]

\[ \tau_s \] [psi]

Shear stress along shear plane

Geometry & Motion → Forces → Material & Energy/Power

Merchant’s relationship

**Merchant’s assumption:**

- Shear angle adjusts to maximize \( \tau_s \)

\[ \tau_s = F_c \cdot \cos(\phi) - F_f \cdot \sin(\phi) \]

\[ F_c = \tan(\beta - \alpha) \]

\[ \frac{d\tau_s}{d\phi} = \frac{F_c \cdot \cos(\phi) - F_f \cdot \sin(\phi)}{A_w} \cdot 2 \cdot \sin(\phi) \cdot \cos(\phi) \]

\[ \frac{d\tau_s}{d\phi} = \frac{\cos(2\phi) \cdot F_c}{\sin(2\phi)} - \frac{\sin(2\phi) \cdot F_f}{\sin(2\phi)} = \frac{\cos(\beta - \alpha) \cdot \sin(2\phi)}{\sin(2\phi) \cdot \cos(\beta - \alpha)} \]

\[ 2\phi + \beta - \alpha = \frac{\pi}{2} \rightarrow \phi = \frac{\pi}{4} \cdot \frac{\beta - \alpha}{2} \]

Merchant’s relationship [radians]

Geometry & Motion → Forces → Material & Energy/Power
The use of Merchant’s relationship

\[ \phi = \frac{\pi}{4} - \frac{\beta}{2} + \frac{\alpha}{2} \quad \text{Merchant's relationship [radians]} \]

As rake angle ↓ or as friction angle ↑
- Shear angle ↓
- Chip thickness ↑
- Energy dissipation via shear ↑
- Heat generation ↑
- Temperature ↑

Geometry & Motion → Forces → Material & Energy/Power

Power/energy requirements

What happens to energy you put in?
- Shear
- Friction
- Others?

Geometry & Motion → Forces → Material & Energy/Power

Specific energy (table from Kalpakjian)

\[ u_s = \frac{\text{Energy}}{\text{Volume}} \text{[certain conditions]} \]

Approximate Energy Requirements in Cutting Operations

Assumed for 80% motor efficiency

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy range (J/mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloys</td>
<td>0.40 – 1.10</td>
</tr>
<tr>
<td>Copper alloys</td>
<td>1.40 – 3.30</td>
</tr>
<tr>
<td>Cast irons</td>
<td>1.60 – 5.50</td>
</tr>
<tr>
<td>Steels</td>
<td>2.70 – 9.30</td>
</tr>
<tr>
<td>Stainless steels</td>
<td>3.00 – 5.20</td>
</tr>
</tbody>
</table>

Geometry & Motion → Forces → Material & Energy/Power

Power and specific energy

Specific energies to consider:

\[ u_s = \frac{F_s \cdot V}{w \cdot t_o \cdot V} \quad u_f = \frac{F_f \cdot V}{w \cdot t_o \cdot V} \quad \text{Others} = \frac{\tau_s \cdot \gamma}{\sin(\phi)} \cdot \frac{V}{V} \]

\[ u_s = \tau_s \cdot \gamma \]

-75% ~ 20% ~ 5% 100%

Geometry & Motion → Forces → Material & Energy/Power
Cutting Processes II

Reading assignment:

© 20.6 – 20.8
© 21.1 – 21.6, 21.13

Cutting processes II

Cutting processes
- Process planning: Cost, Quality, Rate and Flexibility

Modeling: Orthogonal Cutting
- Video, geometry, forces and power

Demonstration

Equipment and tools
Design for Manufacturing
Process variation

Process planning & cutting process

Market research → Conceptual design → Design for manufacture

Assembly → Unit mfg. processes
- Machining
- Injection molding
- Casting
- Stamping
- Forging
- Others...

Factory, systems & enterprise

Settings:
- Speed
- Tool orientation
- Feed/depth

Materials:
- Tool
- Coating
- Lubricant

Equipment:
- Tool geometry
- Machine tool
- Fixture

Inputs:
- Material
- Energy
- Others

Cutting Process

Outputs:
- Parts
- Chips
- Energy
- Others

Last
Today
Next
**Review: Cutting forces**

**Forces:**
- Thrust: $F_t$
- Cutting: $F_c$
- Friction: $F_f$
- Tool normal: $N$
- Shear: $F_s$
- Chip normal: $F_n$

**Merchant’s minimum energy assumption**

**Assumption:** $\phi$ adjusts to value that minimizes cutting energy

- If energy need to cut is minimized, $F_c$ is minimized for a given $V$
- $F_c$ is minimum when shear plane is plane of maximum shear stress
- $F_c$ is dependent on $\phi$

**Example:** $F_s$ minimum and $\tau_s$ maximum for $\phi = 35^\circ$ (for same $\alpha$ and $\beta$)

**Merchant’s relationship**

**Merchant’s relationship:**

$\phi = \frac{\pi}{4} \frac{\beta}{2} + \frac{\alpha}{2}$

- It is an idealization, not always accurate, BUT the trend is consistent

**Review: Power and specific energy**

**Specific energies to consider:**

<table>
<thead>
<tr>
<th>Shear energy +</th>
<th>Friction energy +</th>
<th>Others</th>
<th>Total energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_t = \frac{F_c \cdot V}{w \cdot t_o \cdot V}$</td>
<td>$u_f = \frac{F_f \cdot V}{w \cdot t_o \cdot V}$</td>
<td>$u_o$</td>
<td>$u = \frac{F_c \cdot V}{w \cdot t_o \cdot V}$</td>
</tr>
<tr>
<td>$u_s = \frac{\tau_s \cdot V}{\sin(\phi) \cdot V}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$u_s = \tau_s \cdot \gamma$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\approx 75\%$ $\approx 20\%$ $\approx 5\%$ $100\%$
Caution on modeling and reality

Our assumptions:
- Slow, orthogonal cutting
- Material properties invariant
- Constant temperature
- Simple sliding friction
- No strain hardening

Use our analysis for:
- Trends & building intuition
- Basis for detailed study

Chip types (source: Kalpakjian)

A) Continuous chip with narrow primary shear zone
- Ductile materials @ high speed
- Bad for automation (use chip breakers)

B) Secondary shear zone at chip-tool interface
- Secondary shear zone -> increased energy dissipation

D) Continuous chip with build up edge (BUE)
- High plastic working and bad for automation

E) Serrated chip:
- Low thermal conductivity materials

F) Discontinuous chip (good chips)
- Low ductility materials and/or negative rake angles
**Example**

**Given:**
- $t_o$
- $w$
- $P_{lathe}$

**Find:**
- Velocity at which lathe stalls
- Cutting force

**Cutting tool requirements**

**Maintain:**
- Hardness at operating temperature
- Toughness
- Low wear rate

**Should be easy to repair/sharpen**

**Tool-part combination should be chemically inert**
- Diamond and steel....
Cutting tool characteristics

Why do we worry about tool wear?
- Tool can cease to cut
- Surface finish
- Cost
- Dimensional accuracy
- Cutting force/power
- Flexibility
- Rate
- Quality

Is a function of many parameters
- Coolant
- Geometry
- Lubricant
- Process parameters

Cutting tools: Geometry

Tooling hardness and temperature

Things to note:
- Performance ↑
- Rate of change ↓

Source: Kalpakjian
Temperature and wear

Diffusion is thought to dominate crater wear
This is a function of temperature

Tool wear up close

Crater wear affected by same parameters as flank wear
In addition:
- Material affinity and temperature

Taylor’s wear relationship (flank wear)

Relationship between tool life and cutting speed
- Use to set optimum cutting speed for CFRQ
- Represents a given wear condition
- Define wear condition for failure

Defining tool failure

Wear “snowballs” to set limit
- Force/power increase to set limit
- Surface finish becomes unacceptable
- Wear land size for given process
Taylor’s wear relationship (flank wear)

C = constant & n = exponent (from experimental data)

\[ v \cdot t^n = C \]

v = cutting velocity (fpm)  
t = time to failure (min)

Coefficient n varies from:

<table>
<thead>
<tr>
<th>Material</th>
<th>Steels</th>
<th>Ceramics</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>0.1</td>
<td>0.7</td>
</tr>
</tbody>
</table>

As n ↑, wear is less sensitive to cutting speed

Preventing tool failure with coatings

Tools may be coated for many reasons:

- Chemically inert
- Temperature resistance
- Surface energy/specific energy
- Low friction

Common coatings

- Titanium nitride (TiN)
- Cubic boron nitride (cBN)
- Multi-phase coatings

Common coatings

Multi-phase coating

Layers ½ – 10 µm thick

CUTTING PROCESS

DFM
DFM for cutting: Surface roughness

Surface roughness:
- Definition

Depends on:
- Mass removed
- Size of tool
- Cutter
- Speed

A face milling operation will render a smooth finish.

DFM for cutting: Part geometry

Thin sections and tubes (vibration)

Overhanging parts

Inclined planes and drilling....

DFM for cutting: Ala features

Use common dimensions / parts / shapes / sizes
- Proper tolerance
- Use common/important datums
- Standard features (i.e. don’t use octagon shaped holes)

Finish by process (source = machinery handbook)

<table>
<thead>
<tr>
<th>Process</th>
<th>ROUGHNESS AVERAGE, R_a-MICROMETERS &amp; (MICRONCHIS &amp; in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flame Cutting</td>
<td></td>
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<tr>
<td>Snaking</td>
<td></td>
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<tr>
<td>Sawing</td>
<td></td>
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<tr>
<td>Planing, Shaping</td>
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<tr>
<td>Drilling</td>
<td></td>
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<tr>
<td>Chemical Milling</td>
<td></td>
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<tr>
<td>Electro, Discharge Mach.</td>
<td></td>
</tr>
<tr>
<td>Milling</td>
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<tr>
<td>Broaching</td>
<td></td>
</tr>
<tr>
<td>Reaming</td>
<td></td>
</tr>
<tr>
<td>Electro Beam</td>
<td></td>
</tr>
<tr>
<td>Laser</td>
<td></td>
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<tr>
<td>Electro-Chemical</td>
<td></td>
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<tr>
<td>Boring, Turning</td>
<td></td>
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<tr>
<td>Barrel Finishing</td>
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<tr>
<td>Electrolytic Grinding</td>
<td></td>
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<tr>
<td>Boiler Burnishing</td>
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</tr>
<tr>
<td>Grinding</td>
<td></td>
</tr>
<tr>
<td>Honing</td>
<td></td>
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<tr>
<td>Polishing</td>
<td></td>
</tr>
<tr>
<td>Lapping</td>
<td></td>
</tr>
<tr>
<td>DFM for cutting: Ala tooling</td>
<td>DFM for cutting: Ala equipment</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td><strong>Avoid deep pockets and holes</strong></td>
<td><strong>Beware of fixturing needs</strong></td>
</tr>
<tr>
<td></td>
<td>- Minimize number of fixture cycles</td>
</tr>
<tr>
<td></td>
<td>- Design an interface for part-fixture</td>
</tr>
<tr>
<td><strong>Design should include real shape tool makes</strong></td>
<td><strong>Machine and tool access to create features</strong></td>
</tr>
<tr>
<td>- Tapped holes</td>
<td></td>
</tr>
<tr>
<td>- Pocket corners</td>
<td></td>
</tr>
</tbody>
</table>