Milling 101

CONTENTS

- Introduction of Milling
- Categories of Milling
- Cutting Parameters
- Horse Power at Cutter (HPC)
- Note on Low Speed Machining
- HSM versus HPM
- Cutting Tools
- Conventional vs HSM Machining
Introduction of Milling

• Material-removal operation:
  – Cutting and shaping materials by means of a rotating cutting tool.

• Cutting tool is the main interface between your machine and your work material.
  – Much like how custom tires on a high-end sports car ensure a peak driving experience.

• Maximum material-removal efficiency:
  – Selected cutting tool, employed machining parameters.

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Introduction of Milling

• Select all proper variables necessary for a successful milling operation, historically is:
  – Tribal knowledge / “our ways of doing things”
  – An art form
  – Not easily transferred to others

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Categories of Milling

- **Face milling**
  - Creating a flat surface on the workpiece
  - Cutting plane \( \perp \) axis of spindle

- **Periphery milling (Side milling)**
  - Cutting plane \( \parallel \) axis of spindle

- **Slot milling**
  - Disc mills and End mills

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11/8/2015 5
Milling 101

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Categories of Milling

- **Z-axis plunge milling**
  - Higher material-removal rate with long reach capability
  - Cutter forces are directed into the cutter axially

- **Ramping**
  - Creates angled surface
  - Used as lead in/out
  - Pocketing

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11/8/2015 6
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Categories of Milling

- Helical and Circular interpolation
  - Creating cylindrical surface
  - Creating entry points for later applications

- Trochoidal

Cutting Parameters

Conventional Milling

Climb Milling
**Cutting Parameters**

- Cutting stability ↑, if helix and normal rake angles ↑

![Diagram of milling process](image)

**Cutting Parameters**

- Feed per tooth, \( f_z \):
  - Linear distance traveled by the cutter during engagement of a single cutting tooth
  - Sometimes quoted as chip load

![Diagram of feed per tooth](image)

- Chip thickness:
  - Average chip thickness \( h_m \)
  - Maximum chip thickness \( h_{ex} \)
  - Amount taken by each insert as it advances through the arc of the cut.
  - Define a milling cutter’s performance

![Diagram of chip thickness](image)
Cutting Parameters

- $a_p$: Axial depth of cut or Stepdown (mm)
- $a_e$: Radial depth of cut or Stepover (mm)
- $n$: Spindle rotational speed (rpm)
- $V_c$: Cutting speed (m/min)
- $f_z$: Feed per tooth per revolution (mm)
- $z$: Number of tooth or flute or cutting edge
- $V_f$: Feed rate or table feed (mm/min)
- $Q$: Material removal rate ($\text{mm}^3/\text{min}$)

\[ Q = a_p \times a_e \times V_f \quad [\text{mm}^3/\text{min}] \]
\[ V_f = f_z \times n \times z \quad [\text{mm/min}] \]
\[ d_e = 2 \times \sqrt{a_p (d - a_p)} \quad [\text{mm}] \]
\[ V_c = \frac{\pi \times n \times d_e}{1000} \quad [\text{m/min}] \]
### Cutting Parameters

**General cutting data:**

<table>
<thead>
<tr>
<th>Work Materials</th>
<th>HSS</th>
<th>Carbide</th>
<th>Cutting Speed Vc (m/min)</th>
<th>Feed per tooth f (mm) for Tool Diameter Range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Aluminum</td>
<td>200</td>
<td>200</td>
<td>&lt; 3</td>
<td>0.050 - 0.127</td>
</tr>
<tr>
<td>Aluminum Alloy</td>
<td>75</td>
<td>200</td>
<td>4 - 6</td>
<td>0.127 - 0.152</td>
</tr>
<tr>
<td>Stainless Steel 304</td>
<td>140</td>
<td>140</td>
<td>12 - 25</td>
<td>0.152 - 0.177</td>
</tr>
<tr>
<td>Copper</td>
<td>75</td>
<td>75</td>
<td>&gt; 25</td>
<td>0.177 - 0.076</td>
</tr>
<tr>
<td>Steel 4140</td>
<td>120</td>
<td>120</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Manufacturers supplied cutting data:**

#### Milling Parameters

**Cutter:** Kwan Fung, End Mill, Solid carbide, with coating, z = 4, Helix angle = 30 deg

<table>
<thead>
<tr>
<th>Type of processing</th>
<th>ap [% or mm]</th>
<th>ae [% or mm]</th>
<th>f (mm)</th>
<th>d (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughing</td>
<td>25% - 50%</td>
<td>50% - 80%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi-finishing</td>
<td>5% - 4%</td>
<td>20% - 80%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finishing</td>
<td>0.1 - 0.2 mm</td>
<td>0.1 - 0.2 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Slot Cutting Parameters

**Material:** Aluminum or Copper

<table>
<thead>
<tr>
<th>Type of processing</th>
<th>ap [% or mm]</th>
<th>ae [% or mm]</th>
<th>f (mm)</th>
<th>d (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot Cutting</td>
<td>0.125 - 0.325</td>
<td>0.0125 - 0.025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slot Cutting</td>
<td>0.125 - 0.325</td>
<td>0.0125 - 0.025</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Cutting Speed Vc (m/min)**

<table>
<thead>
<tr>
<th>Vc (m/min)</th>
<th>d (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.05</td>
</tr>
<tr>
<td>75</td>
<td>0.02</td>
</tr>
<tr>
<td>140</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Feed per tooth f (mm)**

<table>
<thead>
<tr>
<th>f (mm)</th>
<th>d (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
</tr>
</tbody>
</table>

**Side Cutting Parameters**

**Material:** Aluminum or Copper

<table>
<thead>
<tr>
<th>Type of processing</th>
<th>ap [% or mm]</th>
<th>ae [% or mm]</th>
<th>f (mm)</th>
<th>d (mm)</th>
</tr>
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<tr>
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### Cutting Parameters

#### Manufacturer’s supplied cutting data:

<table>
<thead>
<tr>
<th>Material</th>
<th>Type of processing</th>
<th>Vc (m/min)</th>
<th>ap [% or mm]</th>
<th>ae [% or mm]</th>
<th>f (mm)</th>
<th>d (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unalloyed copper</td>
<td>Slot Cutting</td>
<td>600</td>
<td>60%</td>
<td>100%</td>
<td>0.025 - 0.150</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Type of processing</th>
<th>Vc (m/min)</th>
<th>ap [% or mm]</th>
<th>ae [% or mm]</th>
<th>f (mm)</th>
<th>d (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrought aluminium alloy 6%</td>
<td>Slot Cutting</td>
<td>1200</td>
<td>60%</td>
<td>100%</td>
<td>0.025 - 0.150</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Type of processing</th>
<th>Vc (m/min)</th>
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<th>Type of processing</th>
<th>Vc (m/min)</th>
<th>ae [% or mm]</th>
<th>ae [% or mm]</th>
<th>d (mm)</th>
<th>ae [% or mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side Cutting</td>
<td>80</td>
<td>60%</td>
<td>100%</td>
<td>0.015</td>
<td>0.020</td>
</tr>
<tr>
<td>Side Cutting</td>
<td>85</td>
<td>100%</td>
<td>50%</td>
<td>0.020</td>
<td>0.025</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of processing</th>
<th>Vc (m/min)</th>
<th>ae [% or mm]</th>
<th>ae [% or mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side Cutting</td>
<td>40</td>
<td>100%</td>
<td>50%</td>
</tr>
<tr>
<td>Side Cutting</td>
<td>45</td>
<td>50%</td>
<td>100%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of processing</th>
<th>Vc (m/min)</th>
<th>ae [% or mm]</th>
<th>ae [% or mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side Cutting</td>
<td>25</td>
<td>100%</td>
<td>50%</td>
</tr>
<tr>
<td>Side Cutting</td>
<td>30</td>
<td>50%</td>
<td>100%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of processing</th>
<th>Vc (m/min)</th>
<th>ae [% or mm]</th>
<th>ae [% or mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side Cutting</td>
<td>15</td>
<td>100%</td>
<td>50%</td>
</tr>
<tr>
<td>Side Cutting</td>
<td>18</td>
<td>50%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Impact of the cutting tool geometry on the effective cutting speed

Impact of the cutting tool geometry on the surface finish

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Horse Power at Cutter (HPC)

- **HPC = MRR / K:**
  - MRR: Material Removal Rate (inch\(^3\) / min) = \(Q / 16387\)
    - \(Q\): Material Removal Rate in mm\(^3\)/min
  - \(K\): K factor depends on hardness of materials

\[\text{MRR} = a_p \times a_e \times V_f\]

- \(a_p\): depth of cut (inch)
- \(a_e\): width of cut (inch)
- \(V_f\): feed rate (inch per minute, ipm)

- **Horse power at motor (HPm) = HPC / E**
  - \(E\): 0.75 to 0.9

K factor:
- A power constant represents the no. of in\(^3\) of materials per minute that can be removed by one horsepower.
- Materials, Hardness (HB), K factor:
  - Stainless Steel / Wrought Iron / Cast Iron, 135-275, 1.54-0.76
  - Stainless Steel / Wrought Iron / Cast Iron, 286-421, 0.74-0.50
  - Titanium, 250-375, 1.33-0.87
  - Iron-based, 180-320, 0.91-0.53
  - Aluminum alloys, 30-150, 6.25-3.33
  - Copper, 150, 3.33
  - Copper alloys, 100-150, 3.33
  - Copper alloys, 151-243, 2.00

Machines in EMF:
- Cincinnati Milacron: 5000 rpm, 14.5 kW
- Chevalier QP2040-L: 8000 rpm, 11 kW
- Hartford MVP-8: 16000 rpm, 7.5 kW
- Mikron VCP600: 24000 rpm, 13.5 kW
Cutting Parameters

• Case study 1 – Roughing:
  – Aluminum 6061; Pocketing, Roughing - Raster
  – HSS End Mill dia = 8 mm; 3 flutes
  – From “General Cutting Data”:
    • \( V_c = 75 \)
    • \( f_z = 0.060 \) (reduced from 0.12, as the tool overhang is too long)

General Cutting Data:

<table>
<thead>
<tr>
<th>Work Materials</th>
<th>Cutting Speed ( V_c ) (m/min)</th>
<th>Feed per tooth ( f_z ) (mm) for Tool Diameter Range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Alloy</td>
<td>HSS</td>
<td>Carbide</td>
</tr>
<tr>
<td></td>
<td>75</td>
<td>200</td>
</tr>
</tbody>
</table>

• \( a_p = 2 \text{ mm} \) (i.e. 25% of tool diameter)
• \( a_e = 4 \text{ mm} \) (i.e. 50% of tool diameter)

<table>
<thead>
<tr>
<th>Type of processing</th>
<th>( a_p ) [% or mm]</th>
<th>( a_e ) [% or mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughing</td>
<td>25% - 50%</td>
<td>50% - 80%</td>
</tr>
</tbody>
</table>

11/8/2015 21 Milling 101

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Cutting Parameters

• Case study 1 – Roughing:
  – Estimated cutting parameters are:
    • \( V_c = 538 \)
    • \( HPC = 0.0409 \)

Effective diameter of cutter:
\( d_{ef} (\text{mm}) = 8.0000 \)

If force spindle speed =:
\( n \text{ (rpm)} = 2985 \)
\( V_f, \text{eff} (\text{mm/min}) = 537 \)
\( Q, \text{eff} (\text{mm}^3/\text{min}) = 4,298 \)

11/8/2015 22 Milling 101

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Chinese
Cutting Parameters

- Case study 2 - Finishing:
  - Aluminum 6061; Pocket, Constant Z Finishing
  - HSS End Mill dia = 6 mm; 4 flutes
  - From “General Cutting Data”:
    - \( V_c = 75 \) and \( f_z = 0.040 \)

General Cutting Data:

<table>
<thead>
<tr>
<th>Work Materials</th>
<th>HSS</th>
<th>Carbide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Alloy</td>
<td>75</td>
<td>200</td>
</tr>
</tbody>
</table>

Feed per tooth \( f_z \) (mm) for Tool Diameter Range (mm)

<table>
<thead>
<tr>
<th>Type of processing</th>
<th>( a_p ) [% or mm]</th>
<th>( ae ) [% or mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughing</td>
<td>25% - 50%</td>
<td>50% - 80%</td>
</tr>
<tr>
<td>Semi-finishing</td>
<td>3% - 4%</td>
<td>20% - 40%</td>
</tr>
<tr>
<td>Finishing</td>
<td>0.1 - 0.2 mm</td>
<td>0.1 - 0.2 mm</td>
</tr>
</tbody>
</table>

Cutting Parameters

- Case study 2 - Finishing:
  - With the highest possible spindle speed \( n = 3000 \) rpm:
    - \( V_f = 480 \)
    - \( HPC = 0.021 \)

Effective diameter of cutter

\[ d_{eff} = 6.000 \]

If force spindle speed:

<table>
<thead>
<tr>
<th>Tool Type</th>
<th>End Mill</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d ) (mm)</td>
<td>6.000</td>
</tr>
<tr>
<td>( z )</td>
<td>4</td>
</tr>
<tr>
<td>( f_z ) (mm)</td>
<td>0.040</td>
</tr>
<tr>
<td>( a_p ) (mm)</td>
<td>3.00</td>
</tr>
<tr>
<td>( a_e ) (mm)</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Cutting Materials = Aluminum alloys; HB = 30-150

K factor = 4.20

\( HPC (hp) = 0.0037 \)

\( HPC (kW) = 0.0027 \)
### Note on Low Speed Machining

- Realizing high material removal rate $Q$ is the goal.
- High speed machining – leverage spindle speed
  - Speed is only the means.
- Low speed machining – cutting tool technology
  - Roughing with high feed mills
    - Cutting edge geometry that takes advantage of axial chip thinning to achieve a higher feed rate $V_f$
    - High horse power cuts
    - To make as much use as possible of the machine’s horsepower
    - Experimenting with different choice of tools in HPC, $Q$ and $f_z$
  - Solid carbide end mills capable of heavy depth of cut $a_p$ and feed per tooth $f_z$
    - For Al, $f_z > 0.25$ mm is possible
  - Finishing by high-flute-count (i.e. $z$) end mills
    - Higher $z$ can achieve better $V_f$ at lower $n$
  - Internal corners of part have to be machined first before the fast finishing passes are run.
HSM versus HPM

- HPM with improved strategy:
  - Tool overload cannot be tolerated at HPM.
  - Constant tool loading and engagement angle

HSM versus HPM

HPM cutting – slow motion illustration
Chip – color, size, and shape
Cutting Tools

- Two performance criteria
  - Thermal hardness (temperature stability)
  - Toughness or rupture strength
- Quality base material
  - Temperature resistance
  - Hardness
  - Wear resistance (stable cutting edges)
  - Toughness
- Appropriate coating
  - Resistance against oxidation, abrasion, adhesion
  - Thin layer (sharp cutting edges for finishing)
  - Thermal insulation
  - Reduced friction

\[ \delta = \frac{Fl^3}{3EI} \]
F = Force at end of cylinder
l = Length of overhang
E = Young’s Modulus of base material
\[ l = \frac{\pi d^4}{64} \quad ; \quad d = \text{Diameter of cutting tool} \]
\[ \delta \propto \frac{l^3}{d^4} \]
\[ \frac{1}{2} d \Rightarrow 16 \delta \quad \text{or} \quad 2l \Rightarrow 8 \delta \]
Cutting Tools

• Cutting tool materials:
  - Sorted from best toughness characteristics (top) to best thermal hardness (bottom).
    • HSS (uncoated and coated - not suitable for HSM)
    • Sintered hard carbide (uncoated and coated)
    • Ceramics
    • CBN
  
• Never use tools that have been used to machine metal to cut plastic.
  - HSS cutters work best for plastics.
  - Carbide cutters work better for aluminum and other metals.

1. Hardness < 42 HRC: TiN and TiCN coated Carbide
2. Hardness > 42 HRC: TiAlN coated Carbide
3. Hardness > 60: PCBN
4. Cast Iron: CBN and ceramic
5. Aluminum: Poly crystalline diamonds (PCD) and Cermet

• Physical vapour deposition (PVD)
  - Solid carbide
  - Results in sharper cutting edge
• Chemical vapour deposition (CVD)
  - Mass production of inserts
## Conventional vs HSM Machining

<table>
<thead>
<tr>
<th>Conventional</th>
<th>HSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>The contact time between tool and work is large</td>
<td>Contact time is short</td>
</tr>
<tr>
<td>Less accurate work piece</td>
<td>More accurate work piece</td>
</tr>
<tr>
<td>Cutting force is large</td>
<td>Cutting force is low</td>
</tr>
<tr>
<td>Low surface finish</td>
<td>High surface finish</td>
</tr>
<tr>
<td>Material removal rate is low</td>
<td>Material removal rate is high</td>
</tr>
<tr>
<td>Cutting fluid is required</td>
<td>Cutting fluid is not required</td>
</tr>
</tbody>
</table>

11/8/2015 33 Milling 101