High Speed Machining (HSM) & 5-Axis Machining

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**Introduction of HSM**

- High cutting speed machining, $V_c$
- High rotational speed machining, $n$
- High feed machining, $V_f$
- High productive machining

- Achieving high metal removal rates with quick milling passes
  - Leaving a surface finish good enough to call finished in one pass

**Conventional Milling**

**Climb Milling**
Introduction of HSM

- C. Salomon, 1931

- F.J. McGee, 1979

McGee's curve
Introduction of HSM

Fig. 2. Machining sequence when using the implanted workpiece thermocouple [12].

Sources of heat generation in the orthogonal cutting process.
Very high internal shear stress.
• Induces high temperature due to friction between dislocated molecules.
• High stress and high temperature has transformed the materials from elastic to plastic in a rapid manner, and so produces high deformation.
• The plastic deformed materials will pack up layer by layer and sliding along the tool geometry, and creating the chip.

Cutting metals at high speeds results in highly localized temperatures, stresses and strain rates, and so resulting in a decrease in chip thickness and a corresponding decrease in cutting forces.
• Machined surface temperature decreases at higher cutting speeds.
Introduction of HSM

Secondary Deformation Zone

- Work done in deforming the chip and in overcoming the sliding friction at the tool-chip interface.
- Temperature can be raised to 1200°C.

Tertiary Deformation Zone

- Work done to overcome friction which occurs at the rubbing contact between the tool flank face and the newly machined surface of workpiece.
- Escaped materials has spring-back at the clearance angle of the tool flank face.
- Wearing at flank face is occurred due to rubbing.
Introduction of HSM

- Heat absorption at HSM

![Pie chart showing heat distribution]

To chip: 80-90%
To cutter: 10-20%
5-10% To work

Advantages

<table>
<thead>
<tr>
<th>FEATURES</th>
<th>EFFECTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced heat transfer to the work piece</td>
<td>Minimal workpiece distortion</td>
</tr>
<tr>
<td></td>
<td>Eliminates the need of coolant</td>
</tr>
<tr>
<td>Reduction of cutting forces</td>
<td>Part accuracy</td>
</tr>
<tr>
<td></td>
<td>Surface quality</td>
</tr>
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<td></td>
<td>Machining of very thin walls</td>
</tr>
<tr>
<td>Increased cutting speed</td>
<td>Stability of rotating cutting tool feed rate</td>
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<tr>
<td></td>
<td>Increased material removal</td>
</tr>
</tbody>
</table>
## Disadvantages

<table>
<thead>
<tr>
<th>FEATURES</th>
<th>EFFECTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased cutting speed</td>
<td>High tool wear</td>
</tr>
<tr>
<td></td>
<td>Expensive tool materials</td>
</tr>
<tr>
<td></td>
<td>Balanced tooling</td>
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<td></td>
<td>Precision tool-holder tapers</td>
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<td>Expensive spindles</td>
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<td>Costly machine tools and control systems</td>
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</table>

## 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 (mm³/min)
Cutting Parameters

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

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**Cutting Parameters**

<table>
<thead>
<tr>
<th>Material</th>
<th>Cutting Speed ( v_c ) (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber Reinforced Plastics</td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Aluminum</td>
<td><img src="image" alt="Graph" /></td>
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<tr>
<td>Bronze, Brass</td>
<td><img src="image" alt="Graph" /></td>
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<tr>
<td>Cast Iron</td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Steel</td>
<td><img src="image" alt="Graph" /></td>
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<tr>
<td>Titanium</td>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>Nickel-Based Alloys</td>
<td><img src="image" alt="Graph" /></td>
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</tbody>
</table>

Source: PTW, Technical University Darmstadt

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Cutting Parameters

Determine Feeds & Speeds:
- **By experience, or use rules of thumb**
  - Judge feeds and speeds by sound and experience
  - Hand on the machine’s handwheels
  - Cutter engagement angle?
    - Difficult to maintain with handwheels
    - Feedrates were generally a lot slower
  - Today we have CNC ⇒ much higher speeds
    - CNC machines have no ability to sense much about what’s going on in the cut.
- **Rely on manufacturer’s recommendations**
  - Over aggressive (great MRR, lower tool life) / Over conservative (great tool life, lower MRR)?
  - Coupled with own environment / knowledge-base
    - Used machining strategy, CNC machines, clamping system, etc.
- **Rely on their CAM software**
  - Most CAM software have some sorts of feeds and speeds calculator
  - Coupled with own environment / knowledge-base
Cutting Parameters

- Cusp (scallops) height $s$ and Stepover $a_e$ can be related by:

$$s = \frac{d}{2} - \sqrt{\frac{d^2 - a_e^2}{4}} \quad [\text{mm}]$$

for $s << d$, $a_e \equiv \sqrt{4sd}$
### Cutting Parameters

- **Low radial cut width** (i.e. \( a_r \), 10-15% of TDU, or even 5%), allows better chip clearance.

- **Increase cut depth** (i.e. \( a_p \)), allows more flute length to come into play instead just wearing out the bottom of the mill.

- **Use toolpath strategy that avoid heavy tool load**
  - Trochoidal milling

### HSM Techniques

- Low radial cut width (i.e. \( a_r \), 10-15% of TDU, or even 5%), allows better chip clearance.

- Increase cut depth (i.e. \( a_p \)), allows more flute length to come into play instead just wearing out the bottom of the mill.

- Use toolpath strategy that avoid heavy tool load
  - Trochoidal milling
HSM Techniques

- Use toolpath strategy that avoid heavy tool load
  - Slicing or peeling of corners.

- Keeping an constant tool engagement angle
**HSM Techniques**

- Use toolpath strategy that avoid heavy tool load
  - Keeping an constant tool engagement angle

**HSM Techniques**

- Can see the chip appearance and tell the difference...
HSM Techniques

- Can listen to the sound and tell the difference ...

- Conventional
- Constant tool engagement angle

Maximize horsepower! In roughing, aim to take advantage of as much of the spindle’s horsepower as possible.
- Use high power cutting, i.e. heavy cutting, to increase materials removal rate
- Use plunge roughing for rigid machine

- Finishing pass
  - Use as many flutes as possible, so that the cutting speed can be increased, and so the removal rate.

- Machine internal corners prior to finishing ribs
Machine

- Spindle speed \( n > 20000 \text{ rpm} \)
- Spindle power \( (>10 \text{ KW}) \)
- Feed rate \( (V_f \sim 40-60 \text{ m/min}) \)
- Rapid travels \( (<90 \text{ m/min}) \)
- Block processing speed \( (1-20 \text{ ms}) \)
- High thermal stability and rigidity in spindle
- Air blast/coolant through spindle
- Advanced look ahead function in the CNC

Semi-Finishing Toolpaths

- To realize finishing operation that can produce an optimum surface quality, accuracy and cutting tool life:
  - **constant stock material** is required on all surfaces to be finished.

- Semi-finishing operation in more than one step of:
  - Various cutting tools with decreasing diameter
  - Specific toolpath strategies for rest roughing
Semi-Finishing Toolpaths

- Rest roughing:

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<thead>
<tr>
<th>Ø</th>
<th>z</th>
<th>υc</th>
<th>f</th>
<th>a</th>
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<th>υb</th>
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<tbody>
<tr>
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<td>[m/min]</td>
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</tr>
</tbody>
</table>

HSM versus HPM

Material: Hardened Tool Steel 52 - 56 HRc
HSM versus HPM

- Benefit of HPM versus HSM for faster roughing of
  - large cavities
  - cavities with steep walls
- Drawback of HPM versus HSM for roughing of
  - small cavities
  - cavities with shallow walls
- Semifinish operation is required after HPM to remove the excess material left after the roughing operation
- HSM roughing gets closer to the final geometry

Introduction of 5-Axis Machining

- Positional 5-Axis (i.e. 3+2-Axis)
Introduction of 5-Axis Machining

- Continuous 5-Axis
Types of 5-Axis Machines

- Table/Table
- Table/Head
- Head/Head

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Types of 5-Axis Machines

- Table / Table

- Head / Table
Types of 5-Axis Machines

- Head / Head

Advantages of 5-Axis Machining

- Improved surface finish
**Advantages of 5-Axis Machining**

- Reduce post-machining operation

![Image](image1.png)

- Auto tilting to avoid collision

![Image](image2.png)
Advantages of 5-Axis Machining

- Minimal setup

Advantages of 5-Axis Machining

- Machining of difficult areas
Advantages of 5-Axis Machining

- Polar machining