High Speed Machining of Aluminum
OVERVIEW

• High Speed Machining (HSM): High Speed Machining Theory
  – Understanding tool chatter
  – How to find the “Sweet Spot” of a cutting tool
  – Understanding Part Chatter
  – High Speed Programming Approaches
  – Typical Machining Plans

• HSM: Cutting Tool Considerations
  – Controlled Cutting Tool Specifications
  – Advanced Cutting Tools and Holders
  – Long Reach Tools
  – Consistency Requirements

• HSM: Spindle Growth at High Speeds
  – How much can a spindle grow?
  – How to control Spindle Growth

• HSM: Kinematic Modeling of Machine Tools
  – Siemens 840D control
  – Improved accuracy

• High Speed Machining (HSM): Review of Advantages
  – Improved Machining Capability
  – Lower Costs through Unitization

• Lower Speed Machining (LSM): Increasing Productivity throughout the Shop
  – LSM Roughing Approaches:
    – Shallow Applications - Crestkut and Greenfield
    – Deep Applications - Plunge Milling
    – Deep Applications - High Feed Mill
  – LSM Finishing Approaches:
    – Deep Applications - Indexable Finisher
    – High Flute Count Carbide Tools for Ribs and Webs
• Understanding Vibration & Chatter
  • What is chatter?
  • How to avoid tool-chatter and part-chatter?
    – Tool geometry
    – Cutter Paths
    – Part Fixturing Approaches
• **Vibrations are a major limitation in HSM**

• **We care about dynamic stiffness**
  – Between the tool tip and work piece

• **Balance is of some concern**
  – Cutting force >> Run out force

• **Major emphasis on chatter**
  – What is chatter?
  – How do we eliminate chatter?
• **Chatter is a self-excited vibration**
  
  – Vibration between the tool and the work piece
  
  • Creates large cutting forces
  • Accelerates tool wear
    – Often causing catastrophic tool failure
  • Creates unacceptable surfaces
    – Often requiring part rework or rejection
  • Affects life of machine components
• **Controlling Chatter in HSM**
  
  – Highly speed (RPM) dependent
    
    • Want optimum chatter free spindle speeds
    
    • Want optimum depths of cut for EACH tool set-up
      
    - Maximize MRR

• **Selection of the optimum spindle speed**
  
  – Stability lobes
    
    • Function of the machine/tool dynamics
    
    • Dynamics are different for each tool set-up and machine!
Testing for Cutting Parameters

Modal analysis is used to determine Machine Dynamics using MetalMax system.
$$b_{\text{lim}} = -\frac{1}{2\mu^*K_s^*\text{Re}(G(\omega))_{\text{min}}^*m}$$
• **Analytical stability lobes provide an estimate of the optimum process parameters:**
  – Spindle speed, DOC

• **Experimental verification is often necessary**
  – Simplifying assumptions in chatter prediction
  – Variations in the system dynamics at speed

• **Verification is done through cutting tests**
  – Cutting tests using actual production machine, tool, holder, set length
  – Changes with Speed make offline prediction difficult
• **Cutting tests performed by measuring the chatter frequency**

  – Sound (microphone) can be used to measure chatter
    • Sound is proportional to displacement of the tool tip
    • Sensors at the base of the spindle may be ineffective
      - Tool vibrations are usually very small in this area

• **Spindle speed is chosen as a multiple of the chatter frequency, $f_c$**

\[
RPM = \frac{f_c \times 60}{n \times \# \text{Teeth}} \quad \text{where } n = \text{multiple}
\]
Sweet Spot Speed Calculation

- **2000 Hz chatter frequency**
  - 2-flute tool
- **Requires 60,000 RPM**
  - 30,000 RPM for 40,000 RPM spindle
    - 2 waves between subsequent teeth
  - 20,000 RPM for 24,000 RPM spindle
    - 3 waves between subsequent teeth
  - 15,000 RPM for 15,000 RPM spindle
    - 4 waves between subsequent teeth
- **All cases maintain “constant” chip thickness**

\[ \text{RPM} = \frac{f_c \times 60}{n \times \# \text{Teeth}} \]
What About Feed rates?

• **Weak chatter control**
  - Affects amplitude (and volume) of chatter

• **Feed does not strongly affect onset of chatter**
  - Chatter is a function of the phase relationship between passing of subsequent teeth

• **Rambaudi example:**
  - 24,000 RPM, 240 IPM, .750” RDOC, .125” ADOC
    • Chatter free
  - 20,000 RPM, 40 IPM, .375” RDOC, .250” ADOC
    • Severe chatter in corners
Feed rate Considerations

• Boeing-St. Louis typically uses 100\(^\text{th}\) of the tool diameter as a starting point (inch/tooth)

\[
IPT = \frac{1}{100} \times \text{Diameter}
\]

• Feed rate is increased until surface finish degrades or machine power limits are exceeded
Testing for Cutting Parameters

Iterative machining trials in material block are performed:
Starting IPT = Tool Diameter/100

Final Speed is refined through audio feedback and system analysis, various ADOC’s are tested, surface finish examined, and final feedrates determined.

All parameters are captured and recorded in cutting database showing, tool extension length, setlength, type of holder, RPM, feedrate and ADOC.
• Dynamics are unique for spindles, tool holders, and tools

• Machine specific programming is essential to obtain competitive advantage

• Different spindle means different maximum depth of cut

• Otherwise, programs must be based on the weakest machine
Power Limitations

- **Emphasis is often placed on spindle power**
  - Most tool set-ups don’t allow effective use of this power
  - Usually limited by stability and chatter
  - Example, Ingersoll 40,000 RPM, 40 kW, HVM at Boeing, St. Louis
    - Approximately 40 Tools
    - Only 3 tools are Power Limited
\[ \text{Power} = \text{Torque} \times \text{RPS} \times 2 \times \pi \]

- For Aluminum,

\[ \text{Power} \approx \frac{\text{ADOC} \times \text{RDOC} \times \text{Feed}}{3} \]

Where, Feed (in/min), ADOC (in), RDOC (in), Power (Hp)
Video Of High Speed Aluminum Machining
• **Chatter definition:** “Chatter is a self-excited vibration between the tool and the work piece in metal cutting.”
  
  – Chatter is not only a function of tool/spindle dynamics
  
  – May be a function of the work piece dynamics

• **Work piece chatter virtually impossible to eliminate by speed regulation**
  
  – Natural frequency constantly changing during machining
Effect of Varying Rib Height on Chatter Frequency
• Avoiding work piece vibrations/chatter
  – Support work piece with back-up tooling
    • Vacuum Fixtures
  – Use “Smart” tool paths to maintain part stiffness
  – Correct choice of cutter geometry
Step Cutting (Waterline) Approach

Correct choice of tool path maintains part stiffness throughout cutting process.
Step Cutting (Waterline) Approach

Traditional Two-Sided HSM Web Cutting Approach

- Large Thickness Variations for Large Pockets
- Vibrating Floor
- Striking Cutter
- Each Level Is Milled Before Stepping Down for Next Pass

Modified Two-Sided HSM Web Cutting Approach

- Small Thickness Variations for Large Pockets
- Thick Material Adds Stiffness to Cutting Area
- Entire Pocket Depth Is Step Cut Before Cutter Indexes Out
Improved Machining Capability

- All cutters have a maximum depth of cut they can take before they will chatter.

- Traditional cutting techniques result in large thickness variations due to cutter and part deflections.
Typical Machining Plan

- **Picture Frame fixturing**
  - Plate bolted/held directly to machine tool bed
  - Excess material is used as tooling
  - Tabs machined on edge of part hold it in material
  - Part cut from “picture frame,” and tabs are removed when machining complete

- **No vacuum fixture necessary**
  - Avoid cost of fabrication, maintenance, and tracking of vacuum fixture
  - Use special programming strategies for second side of part
Typical Machining Plan

Roughing

1.) For best Metal Removal Rates use largest tools available and maximize toolpath for:
   • stepovers
   • axial depths
   • feedrates

2.) Always leave enough excess on features to stabilize them during finishing operations!
Typical Machining Plan

**Finishing**

Minimize tool axis movement for 5-axis features when practical
Use 3+2 tool axis control instead (fixed axis kelling) when possible

**Finishing**

In HSM no difference in climb versus conventional motion for surface finish
Rules of Thumb on Thickness

THE KEY TO CUTTING THIN RIBS IS TO CONTROL THE AMOUNT OF UNCUT MATERIAL SUPPORTING THE FEATURE TO BE FINISHED

IN ALUMINUM WE TRY TO MAINTAIN A 4:1 HEIGHT TO WIDTH RATIO PRIOR TO FINISHING

FOR A RIB 4 INCHES TALL WE WOULD ROUGH THE RIB TO BE AT LEAST A TOTAL OF 1 INCH THICK :: DURING FINISHING OF AN .060” THICK RIB WE WOULD NOT MACHINE ANY DEEPER THAN .24” PER AXIAL DEPTH FOR THE FIRST 3.0” OF DEPTH
WHEN USING THE 6.0” LONG TOOL THE AXIAL DEPTH LIMIT PER TESTING WAS .100” AND EACH RIB WAS SIZED TO .05” EXCESS AT EACH .24” DEPTH BEFORE A FINAL FINISHING PASS
Cutting Underneath Flanges

FIXED AXIS KELLERING MOTION USING EXTENSION HOLDERS TO MACHINE CLOSED ANGLES UNDER LEADING EDGE BETWEEN RIBS

ROUGHER 322 IPM AND .110” ADOC
BALLNOSE FINISHER 275 IPM AND .110” ADOC
**Eliminating Cutter Ramps**

Boeing Technology | Phantom Works

**Advanced Manufacturing Research & Development**

**FIXED AXIS KELLERING MOTION USING .50" DIAMETER PENCIL CUTTER WITH .125" RADIUS IN EXTENSION HOLDER TO REMOVE EXCESS MATERIAL AT RIB AND WEB INTERSECTIONS**

170 IPM FEEDRATE WITH .02" ADOC and .02" STEPOVERS
Unsupported Machining

FINISHING 2ND SIDE M/L SURFACES

“DOWN AND OVER” TECHNIQUE
UNCUT STOCK SUPPORTS LOCAL AREA OF MACHINING
3-AXIS ROUGHING PASSES ARE AT .30” MAXIMUM AXIAL DEPTH OF CUT RUNNING AT 460 IPM
WITH .030” LEFT FOR 5-AXIS FINISHING PASS AT 300 IPM
Unsupported Machining

Fast Patch Paste for Holding Problems

Unattached ribs at floors vibrated causing undercuts in prototype
Unsupported Machining

Ribs at floors held in place using "red stuff"
• Length to diameter ratio
• Cleaning out corners
• Inserted cutters
• Cutter substitution
## Controlled Cutting Tool Specifications

All cutting tools are designed and bought to specification:

- Two flute solid carbide
- Shortened flute lengths about equal to diameter
- Shank above is relieved to holder grip
- Flutes are “feather blended” to shank

### Inserted Cutting Tools are not Used!
• When corner radii and flange height drive a large length to diameter ratio, consider the following:
  – Use a larger diameter cutter (smaller L/D ratio) to machine part
  – Come back in with smaller diameter cutter to clean out corners

Possible Manufacturing Scenario:
1. Cut part complete w/ .500” dia. x 1.5” (3D cutter)
2. Finish corners w/ .250” dia. x 1.5” (6D cutter)
Substitution of cutters when running a part is **NOT recommended**!

- Using a high speed steel cutter or a longer cutter in place of the programmed cutter for a part can result in the following:
  - Poor part surface finish/quality
  - Broken or damaged cutters
  - Excessive vibrations which can damage or break the spindle
• **Shrink-Fit, Hydraulic, Schunk “TriBos”** are precise.

• **Colleted** have less gripping force and more run-out.

• **Set-Screw holders** are imprecise, inconsistent and not balanceable.

• **HSK** required above 15krpm
• **Consistent Optimized performance requires attention to details**

• **Tool geometry**

• **Same tool holders**

• **Same spindles/spindle maintenance**

• **Consistent tool set length**
Tool Length must be held to .010in for consistent optimized performance.

.5in diameter tool example
Blue curve is 2.1in long tool
Green curve is 2.0in long tool

2.0in long
2.1in long
Performance without consistency
Cutting Data on .5 inch diameter X 2.7 vs. 2.6 in Extension

Stable vs. Unstable
Small tools cut better in small spindles

Large Diameter - Highly Damped

Small Diameter - Lightly Damped
Spindle Growth After Tool Change

Position

Temperature

Speed related growth

50 µm

Spindle Growth After Tool Change

Position (m)

Time (min)

Temperature (°C)
Spindle Growth Errors

100μm = .004in (.008inch for 2-sided part)

Spindle Growth (μm)

- Speed Related: 15
- After Tool Change: 35
- Spindle Shaft During Warmup: 50
- Total Spindle Growth: 100

100μm = .004in (.008inch for 2-sided part)
Controlling Spindle Growth?

- Cooled spindles reach steady-state
- Heat comes from speed (not from cutting)
- Laser tool-setter is cheap ($1300) : probe without stopping spindle
- Wait for steady-state spindle temperature

probe tool length before finishing cuts

![Renishaw Laser Tool Setter](image)

Graphs:
- Cooled Spindle
  - Length vs. time

- No Spindle Cooling
  - Length vs. time

OR

??
Lower Costs through Unitization

Monolithic components become cost effective

- Reduced part count
- Reduced assembly times
- Fewer assembly fixtures
- Increased strength
- Reduced weight
- Increased accuracy

- New complex features
  - Return flanges
  - Enclosed corners
  - Unsupported flanges
Replaced Bonded Aluminum Honeycomb with Ultra-thin Unitized Aluminum Machining for BSS

7 Feet X 8 Feet X 1 Inch ~ 33 lbs
Minimum Gage .020 +.005/-000

- .020 Minimum Gauge
- Only 5% Price Increase for Ultra-Thin Part as Compared to Conventional Gages
Observing Errors in Machine Construction
Required for accurate 5-axis parts
Observing and correcting errors in Machine Construction
Shallow Applications  
Crestkut and Greenfield

CAT 50 holders on 25 HP spindle  
Gantry style machine  
Two sided detail with .06” - .08” walls and .05” webs 1.42” deep  
with largest pocket 22” x 30”

<table>
<thead>
<tr>
<th>Standard Rougher</th>
<th>CrestKut Rougher</th>
<th>Greenfield Rougher</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three .48” ADOC’s</td>
<td>Two .71” ADOC’s</td>
<td>One 1.42” ADOC</td>
</tr>
<tr>
<td>21 IPM @ 1200 RPM</td>
<td>90 IPM @ 3000 RPM</td>
<td>54 IPM @ 3000 RPM</td>
</tr>
<tr>
<td>6.3 IN³ MRR</td>
<td>63 IN³ MRR</td>
<td>71 IN³ MRR</td>
</tr>
<tr>
<td>2 HP</td>
<td>21 HP</td>
<td>24 HP</td>
</tr>
</tbody>
</table>
Deep Applications – Plunge Milling

Iscar High Feed Mill
RPM=3000
IPM=120
ADOC=8.75”
RDOC=.30”
72 in³ MRR
24 HP Cut
Video of high feed milling in aluminum
Video of high feed milling in aluminum
Deep Applications – Indexable Finisher and High Feed Mill

**Stellram Finisher**
- RPM = 3400
- IPM = 120
- ADOC = .400
- RDOC = .2

**Iscar High Feed Mill**
- RPM = 3000
- IPM = 300
- ADOC = .080”
- FULL SLOT
- 48 IN³ MRR
- 16 HP Cut
**Higher Flute Count Carbide Tools for Ribs and Webs**

**1.0” Dataflute 5 Flute**

**Rib Finishing**
Leave .20 to .30 excess on ribs

Can cut 1.0” deep taking up to .3” radial depth of cut at 3000 RPM & 300 IPM = 90 Cubic Inch MMR

Must stay out of corners – NO SLOTTING!

**Web Finishing**
Leave .20 to .30 excess on web

Finish web using “down-and-over” to rib excess leaving .05” for last pass at web running 3000 RPM & 150 IPM

Finish corners to web and tangency of eventual rib finisher

**Dataflute or Fullerton**

1.0” 10 Flute or .75” 8 Flute
Questions About Aluminum???