BOEING

Boeing Technology
Phantom Works

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

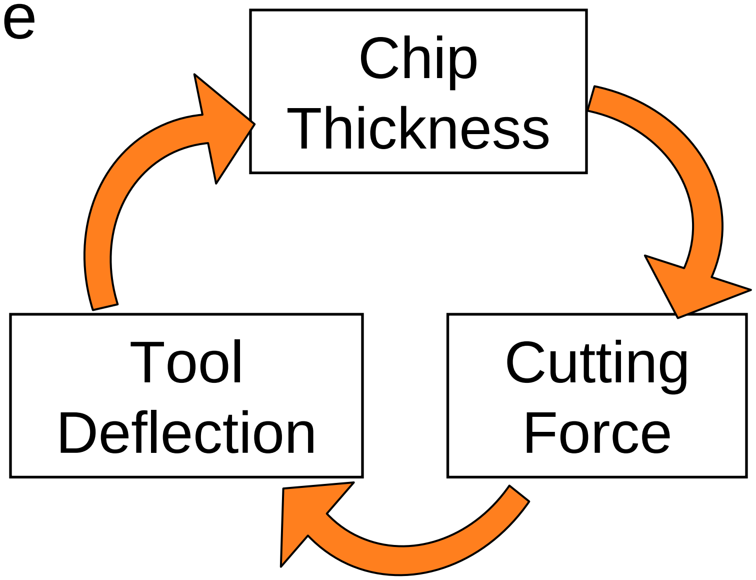
Theory

- Understanding Vibration & Chatter
  - What is chatter?
  - How to avoid tool-chatter and part-chatter?
    - Tool geometry
    - Cutter Paths
    - Part Fixturing Approaches

Vibrations in HSM

- 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?

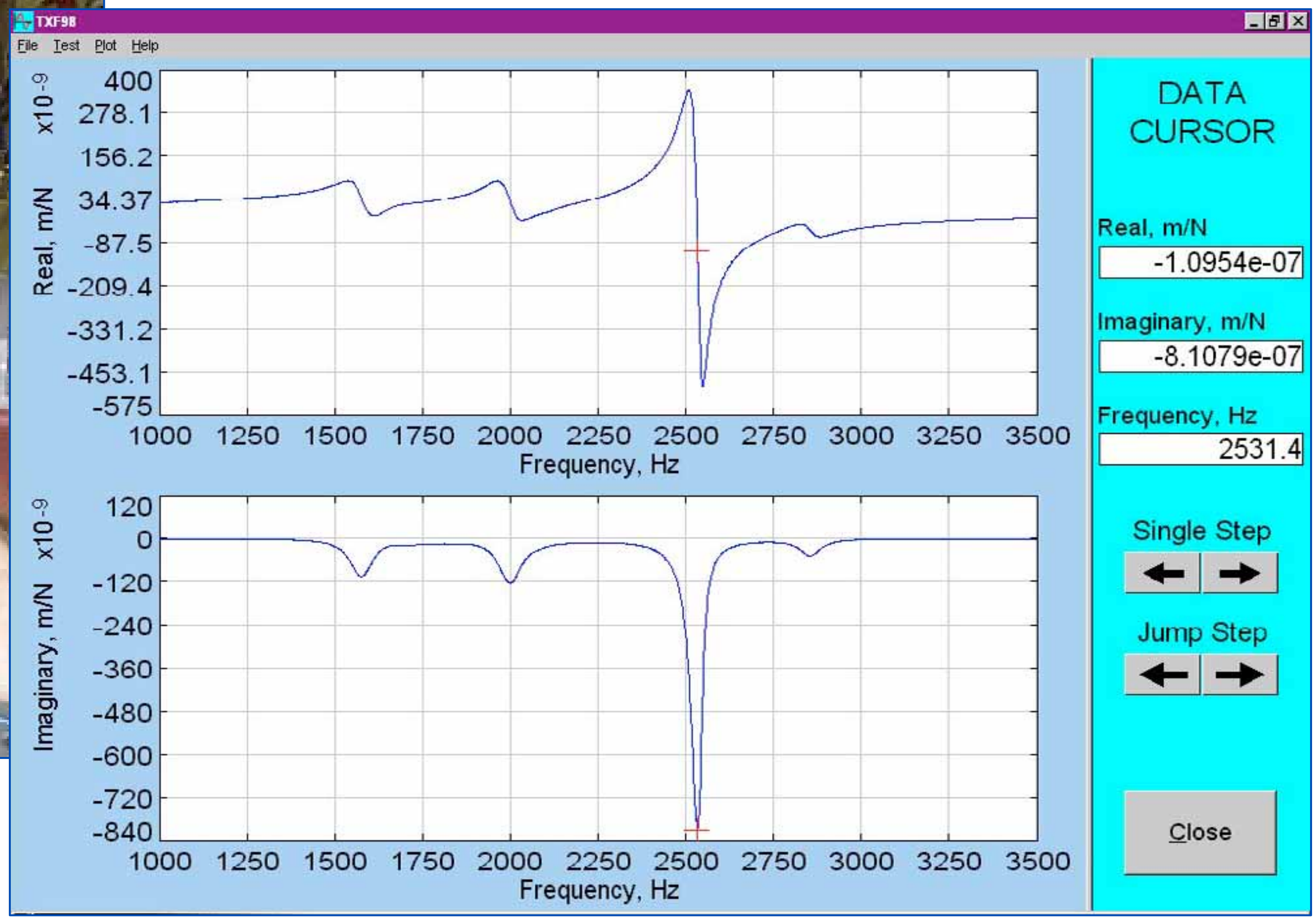
- Chatter is a self-excited vibration
  - Vibration between the tool and the work piece
    - Creates large cutting forces
    - Accelerates tool wear
      - Often causing catastrophic tool failure
    - Creates unacceptable surfaces
      - Often requiring part rework or rejection
    - Affects life 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!

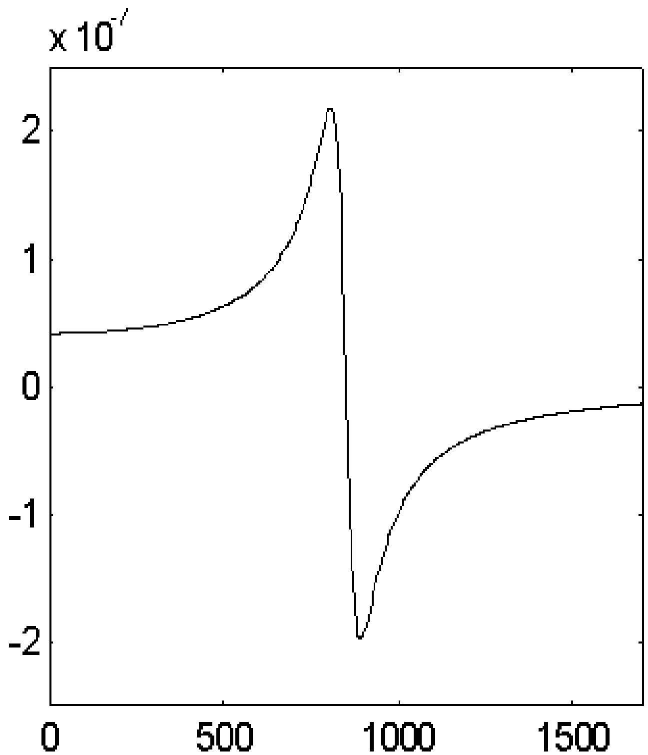
Testing for Cutting Parameters

Modal analysis is used to determine Machine Dynamics using MetalMax system.



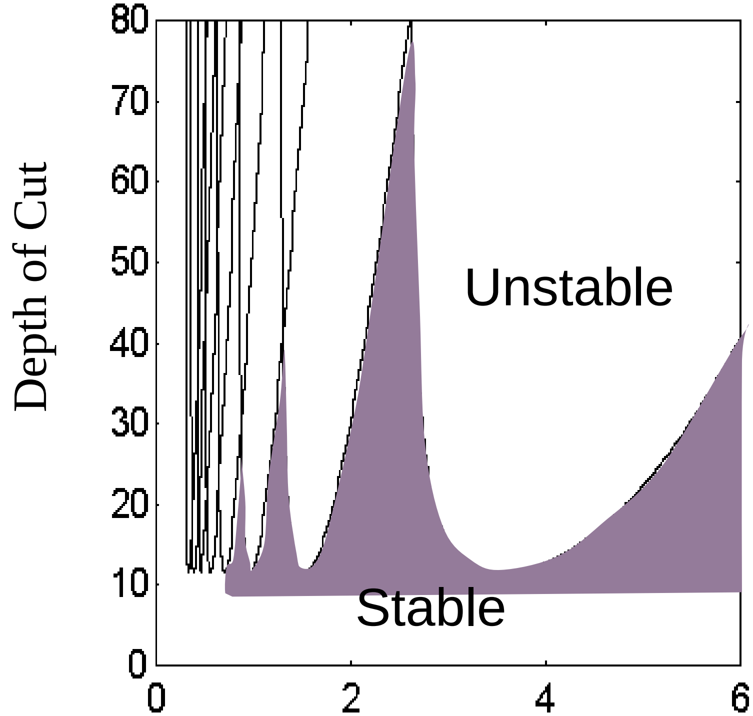
Stability Prediction

Real Transfer Function



Frequency (Hz)

Stability Lobe Diagram



RPM x10,000

$$b_{\lim} = -\frac{1}{2 * \mu * K_s * \mathrm{Re}(G(\omega))_{\min} * m}$$

Stability Prediction

- 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

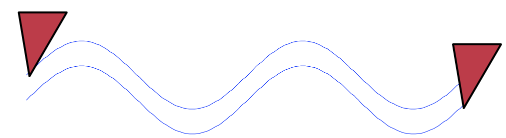
$$RPM = \frac{f_c * 60}{n * \# Teeth} \quad where\ n = multiple$$

Sweet Spot Speed Calculation

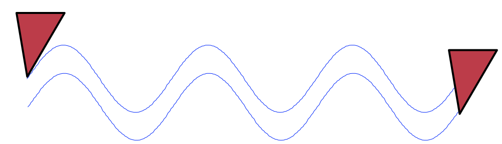
- 2000 Hz chatter frequency
  - 2-flute tool

$$RPM = \frac{f_c * 60}{n * \# Teeth}$$

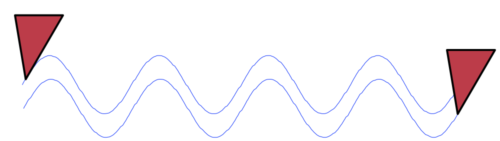
- Requires 60,000 RPM
  - 30,000 RPM for 40,000 RPM spindle
    - 2 waves between subsequent teeth



  - 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

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^{th} of the tool diameter as a starting point (inch/tooth)

$$IPT = \frac{1}{100} * Diameter$$

- Feed rate is increased until surface finish degrades or machine power limits are exceeded

NC Programming Process Parameters

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

2	Forest Line'		Job Number:				Material:	
3		Date:	2/26/2008 Lockcode:				Programmer:	
5			Operations / Cutters					
7	Seq.	Tool No.	Description	Mat'l Code	Tool Ext.	Set Length	Holder	Parameters
129			EndMill Parameters for the 24K Spindle:					
130								
131		22	End Mill callout (Dia x Neck Lgth x Rad.) Ref. Only					
132			1/4" 0.2500 End Mill: (.25 x .75 x .010)	T7520701	1.035	3.91	Marquart 04701627070	23,150 rpm 230 ipm MaxADOC=.050
133			1/4" 0.2500 End Mill: (.25 x 1.25 x .01)	-7521201				
134			1/4" 0.2500 End Mill: (.25 x 1.25 x B/N)	T7521291	1.54	4.41	Marquart 04701627070	20,000 rpm 100 ipm MaxADOC=.020
135		34	1/4" 0.2500 End Mill: (.25 x 1.50 x .01)	T7521501				
136			3/8" 0.3750 End Mill (.375 x 1.25 x .01)	T7531101	1.325	4.285	Marquart 04701627071	24,000 rpm 180 ipm MaxADOC=.130
137			3/8" 0.3750 End Mill (.375 x 1.5 x B/N)	T7531591	1.785	4.66	Marquart 04701627071	22,500 rpm 165 ipm MaxADOC=.018
138		23	3/8" 0.3750 End Mill (.375 x 2.25 x .12)	T7532231	2.535	5.41	Marquart 04701627071	20,000 rpm 150 ipm MaxADOC=.006
139			1/2" 0.5000 End Mill: (.50 x 1.5 x .010)	T7541501	1.785	4.66	Marquart 04701627072	24,000 rpm 240 ipm MaxADOC=.180
140		36	1/2" 0.5000 End Mill: (.50 x 1.5 x .090)	-7541521	1.785	4.66		
141			1/2" 0.5000 End Mill: (.50 x 1.5 x .120)	T7541531	1.785	4.66	Marquart 04701627072	24,000 rpm 240 ipm MaxADOC=.080
142			1/2" 0.5000 End Mill: (.50 x 2.0 x .120)	T7542031	2.285	5.16	Marquart 04701627072	23,500 rpm 235 ipm MaxADOC=.065
143			1/2" 0.5000 End Mill: (.50 x 2.0 x .190)	T7542041	2.285	5.16	Marquart 04701627072	23,500 rpm 235 ipm MaxADOC=.065
144			1/2" 0.5000 End Mill: (.50 x 2.5 x .010)	T7542501	2.785	5.66	Marquart 04701627072	21,500 rpm 215 ipm MaxADOC=.050
145			1/2" 0.5000 End Mill: (.50 x 2.5 x .010)	T7542531	2.785	5.66	Marquart 04701627072	21,220 rpm 210 ipm MaxADOC=.035
146			1/2" 0.5000 End Mill: (.50 x 2.5 x B/N)	T7542591	2.785	5.66	Marquart 04701627072	24,000 rpm 211 ipm MaxADOC=.020
147			1/2" 0.5000 End Mill: (.50 x 3.0 x .120)	T7543031	3.285	6.16	Marquart 04701627072	20,500 rpm 205 ipm MaxADOC=.024
148		24	1/2" 0.5000 End Mill: (.50 x 3.0 x B/N)	T7543091	3.285	6.16	Marquart 04701627072	18,500 rpm 185 ipm MaxADOC=.015
149			3/4" 0.7500 End Mill: (.75 x 2.2 x .010)	T7562201	2.535	5.41	Marquart 04701627073	20,000 rpm 300 ipm MaxADOC=.300
150			3/4" 0.7500 End Mill: (.75 x 2.2 x .190)	T7562241	2.535	5.41	Marquart 04701627073	20,000 rpm 300 ipm MaxADOC=.300
151			3/4" 0.7500 End Mill: (.75 x 2.2 x B/N)	T7562291	2.535	5.41	Marquart 04701627073	20,823rpm 300 ipm MaxADOC=.150
152			3/4" 0.7500 End Mill: (.75 x 3.0 x .010)	T7563001	3.285	6.16	Marquart 04701627073	21,330 rpm 220 ipm MaxADOC=.260
153			3/4" 0.7500 End Mill: (.75 x 3.0 x .120)	T7563031	3.285	6.16	Marquart 04701627073	20,700 rpm 310 ipm MaxADOC=.300
154			3/4" 0.7500 End Mill: (.75 x 3.0 x B/N)	T7563091	3.285	6.16	Marquart 04701627073	21,000 rpm 315 ipm MaxADOC=.150
155			3/4" 0.7500 End Mill: (.75 x 3.75 x .01)	T7563701	4.035	6.91	Marquart 04701627073	16600 rpm 250 ipm MaxADOC=.100
156			3/4" 0.7500 End Mill: (.75 x 3.75 x B/N)	T7563791	4.035	6.91	Marquart 04701627073	18,000 rpm 245 ipm MaxADOC=.090
157			3/4" 0.7500 End Mill: (.75 x 3.75 x .12)	T7563731	4.035	6.91	Marquart 04701627073	17,200 rpm 260 ipm MaxADOC=.080
158			3/4" 0.7500 End Mill: (.75 x 4.5 x .010)	T7564501	4.785	7.66	Marquart 04701627073	14,400 rpm 216 ipm MaxADOC=.028
159			3/4" 0.7500 End Mill: (.75 x 4.5 x .120)	T7564531	4.785	7.66	Marquart 04701627073	14,400 rpm 216 ipm MaxADOC=.028
160		25	1.0" 1.0000 End Mill: (1.0 x 2.0 x .190)	-7582041	1.285	5.16	Marquart 04701627074	21,000 rpm 420 ipm MaxADOC=.300
161			1.0" 1.0000 End Mill: (1.0 x 3.0 x .010)	T7583001	3.285	6.16	Marquart 04701627074	18,200 rpm 364 ipm MaxADOC=.350
162			1.0" 1.0000 End Mill: (1.0 x 3.0 x .120)	T7583031	3.285	6.16	Marquart 04701627074	18,200 rpm 364 ipm MaxADOC=.350
163			1.0" 1.0000 End Mill: (1.0 x 3.0 x B/N)	T7583091	3.285	6.16		

7	Seq.	Tool No.	Description	Mat'l Code	Tool Ext.	Set Length	Holder	Parameters
153			3/4" 0.7500 End Mill: (.75 x 3.0 x .120)	T7563031	3.285	6.16	Marquart 04701627073	20,700 rpm 310 ipm MaxADOC=.300

Spindle Specific Programming

- 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

Power Calculations

$$Power = Torque * RPS * 2 * \pi$$

- For Aluminum,

$$Power \cong \frac{ADOC * RDOC * Feed}{3}$$

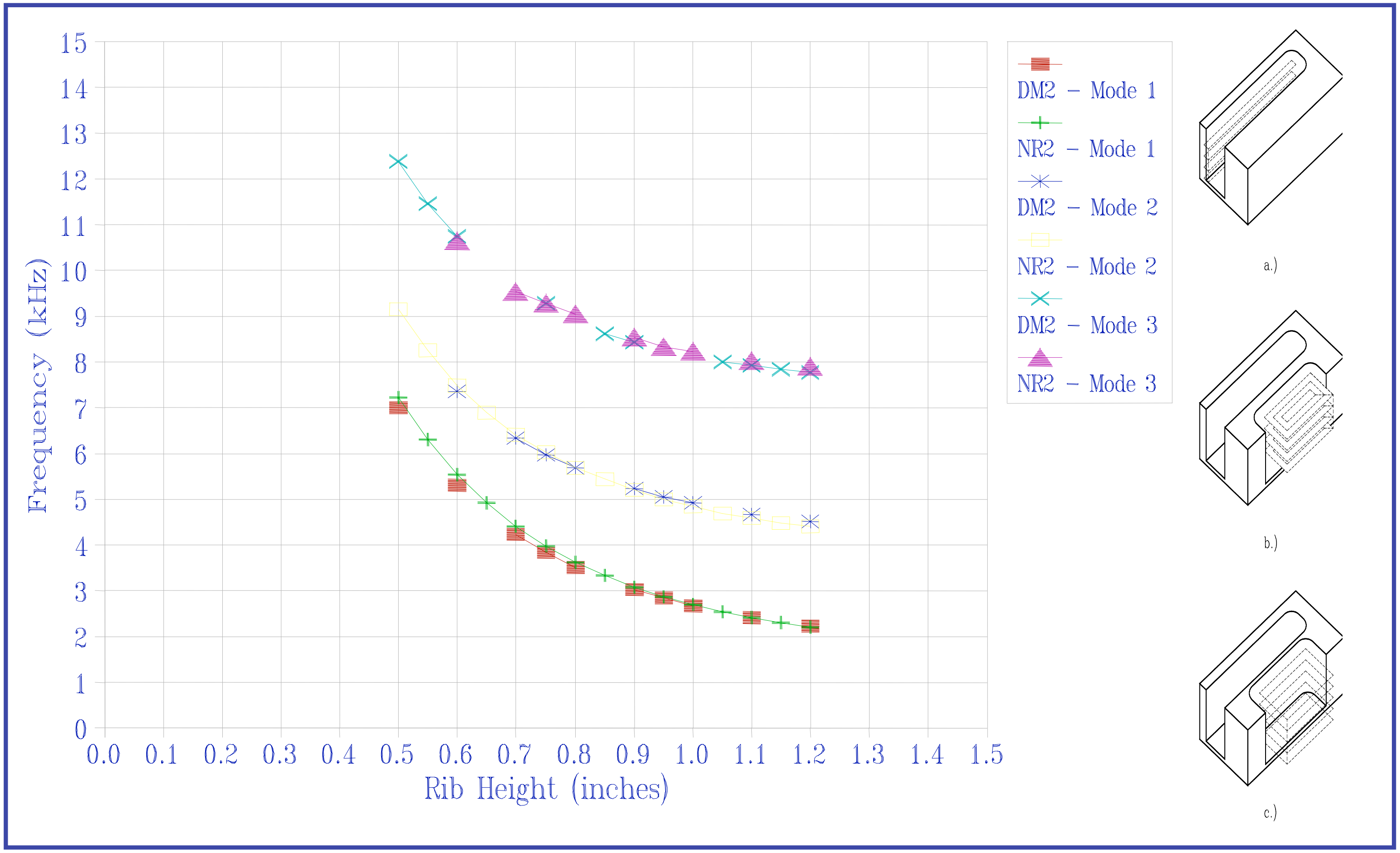
***Where*, Feed (in/min), ADOC (in), RDOC (in), Power (Hp)**

Video Of High Speed Aluminum Machining

Work piece Stiffness

- 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

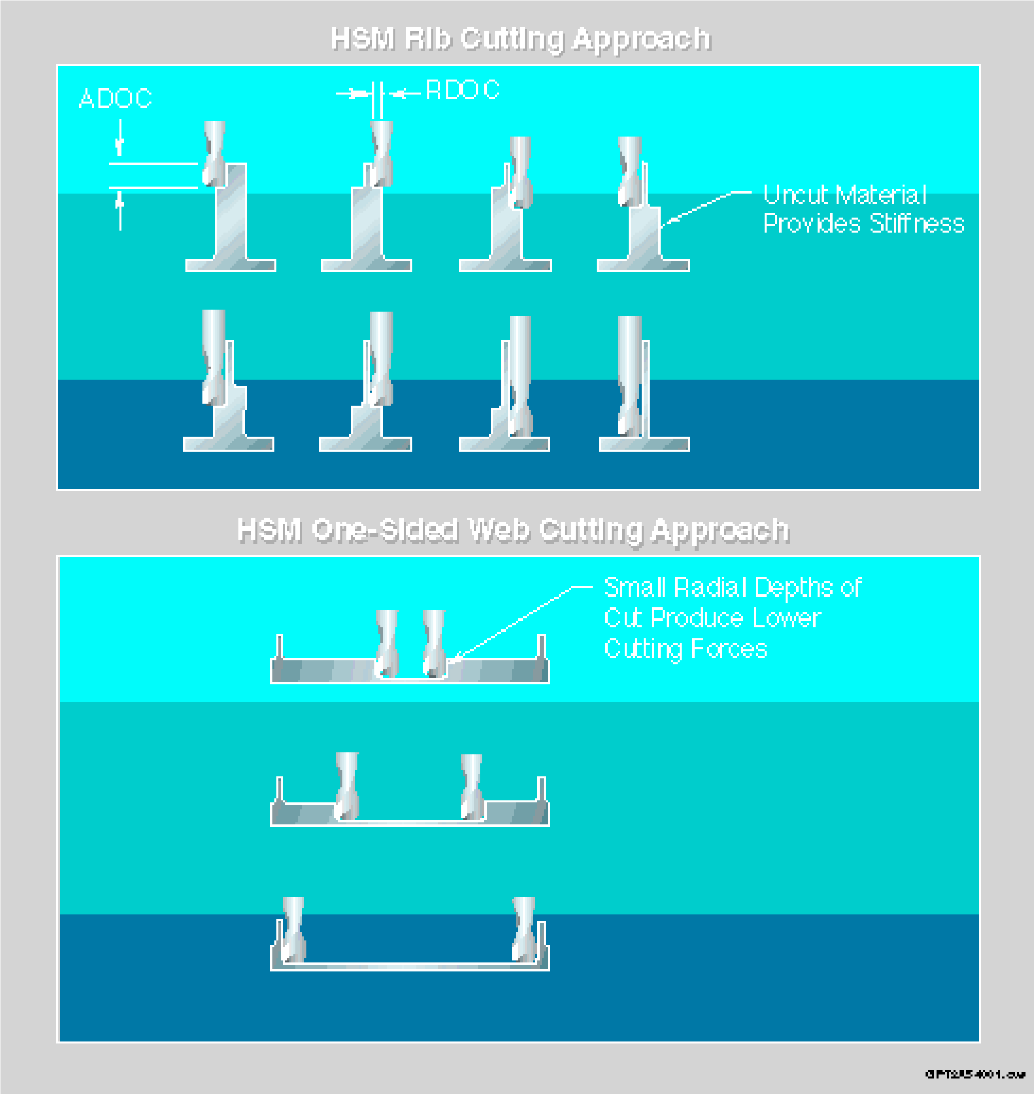
Effect of Varying Rib Height on Chatter Frequency



Work piece Chatter

- 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



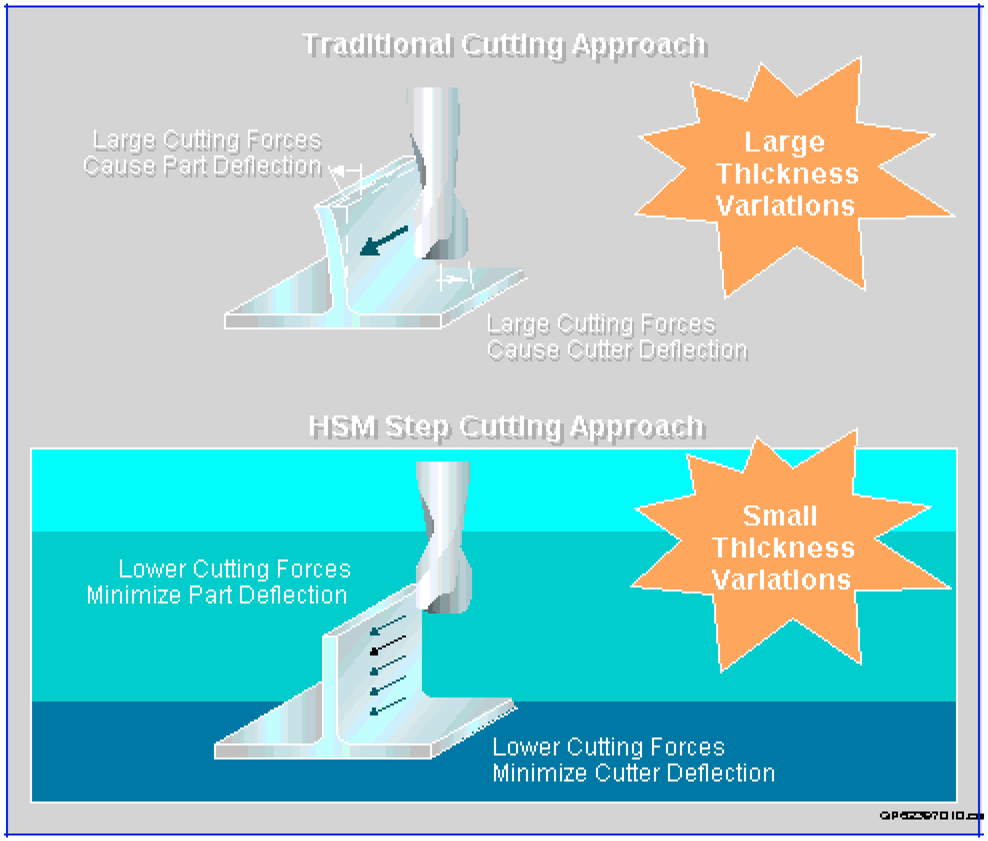
Correct choice of tool path maintains part stiffness throughout cutting process.

Step Cutting (Waterline) Approach

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

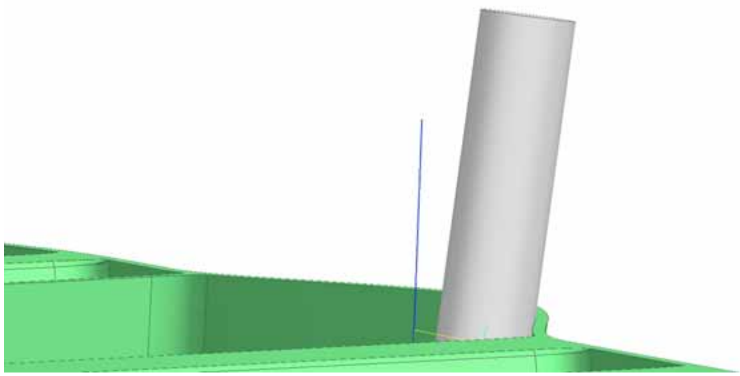
1.) For best Metal Removal Rates use largest tools available and maximize toolpath for:
- stepovers
- axial depths
- feedrates

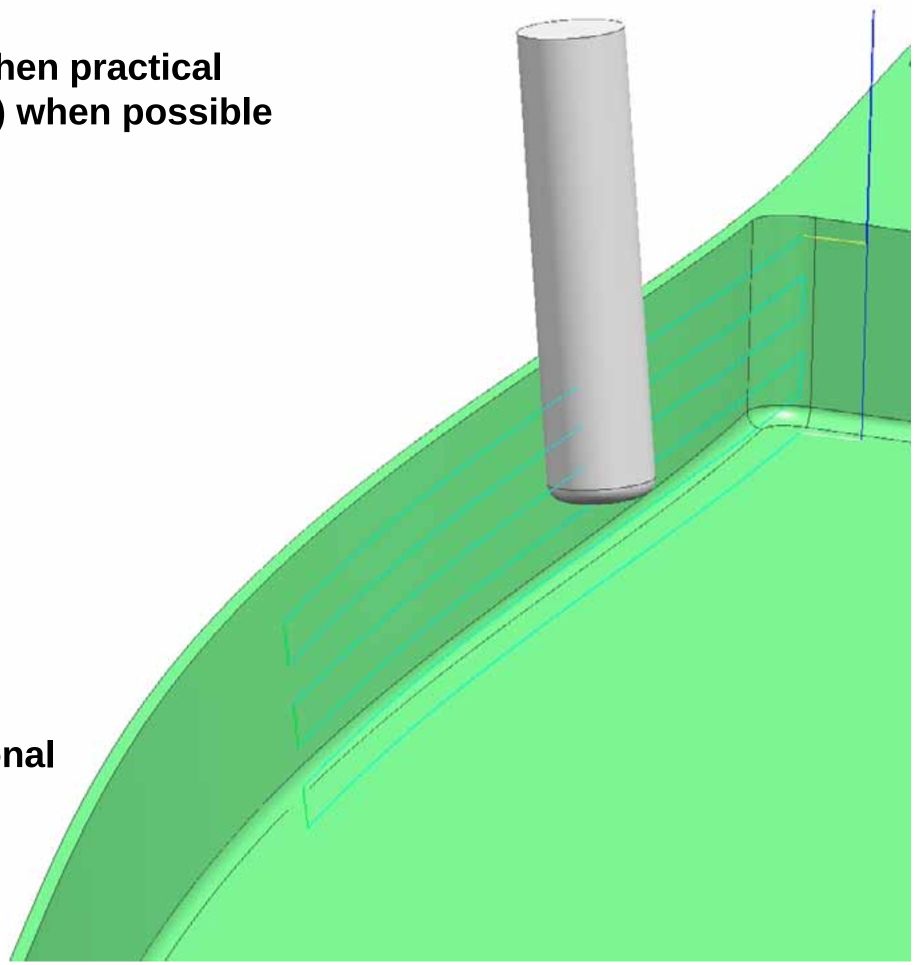
2.) Always leave enough excess on features to stabilize them during finishing operations!

Typical Machining Plan

Finishing

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

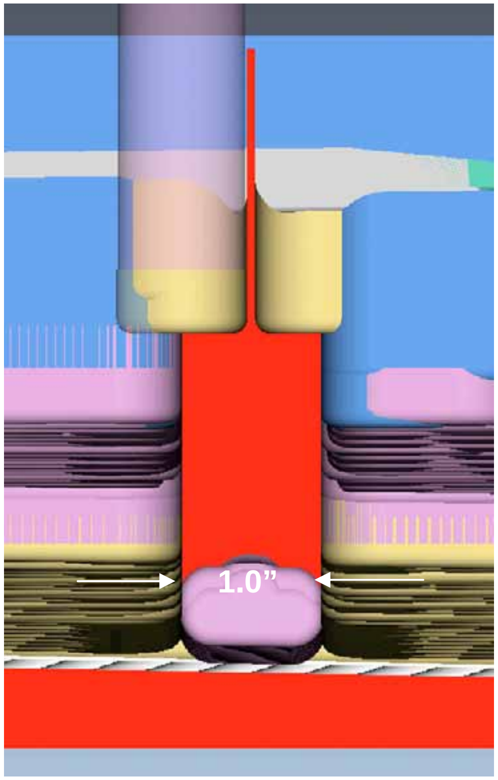




Finishing

In HSM no difference in climb versus conventional motion for surface finish

Rules of Thumb on Thickness

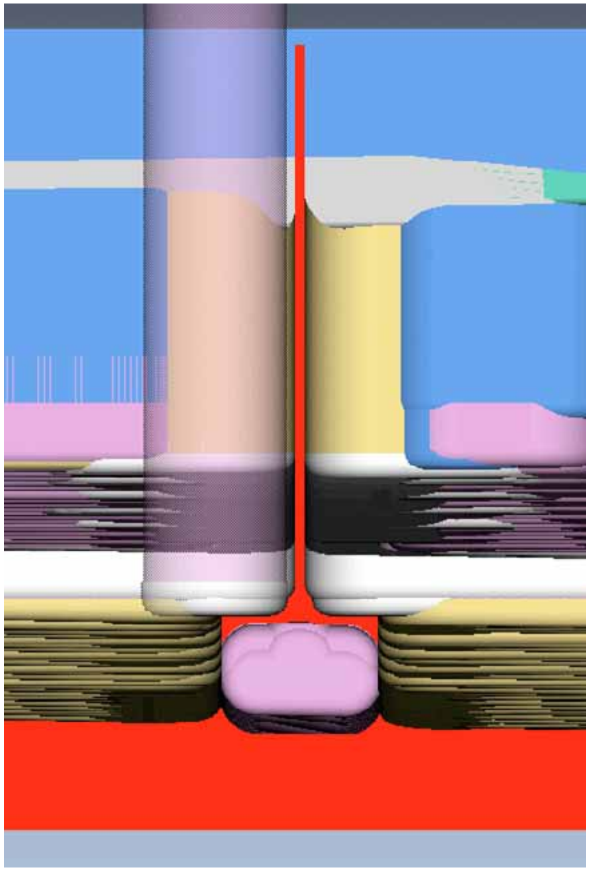


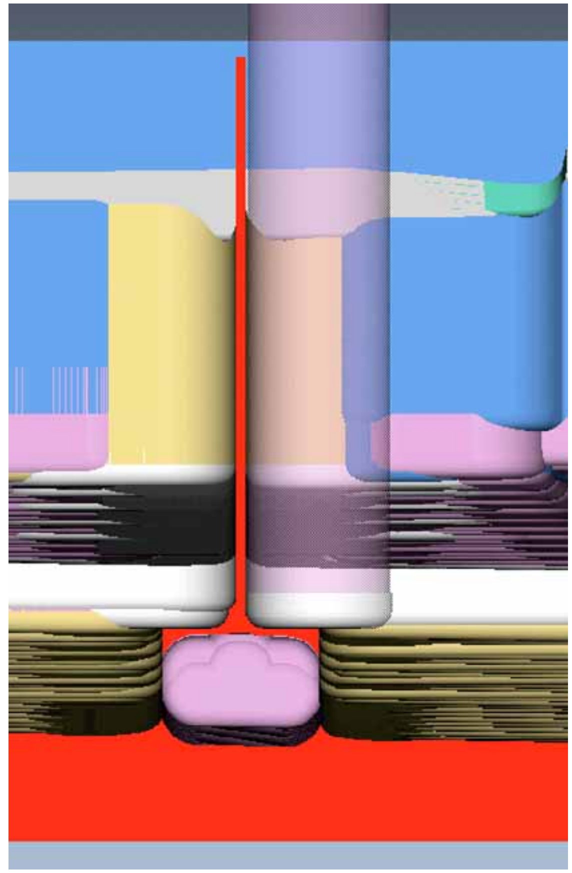
THE KEY TO CUTTING THIN RIBS
IS TO CONTROL THE AMOUNT
OF UNCUT MATERIAL SUPPORTING
THE FEATURE TO BE FINISHED

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

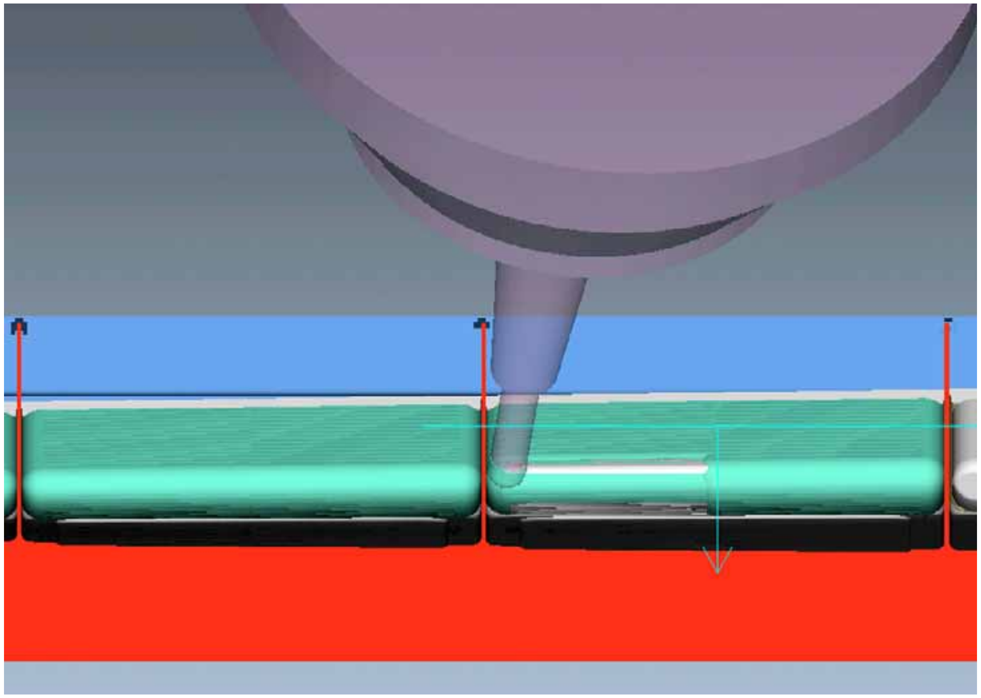
Rules of Thumb on Thickness





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

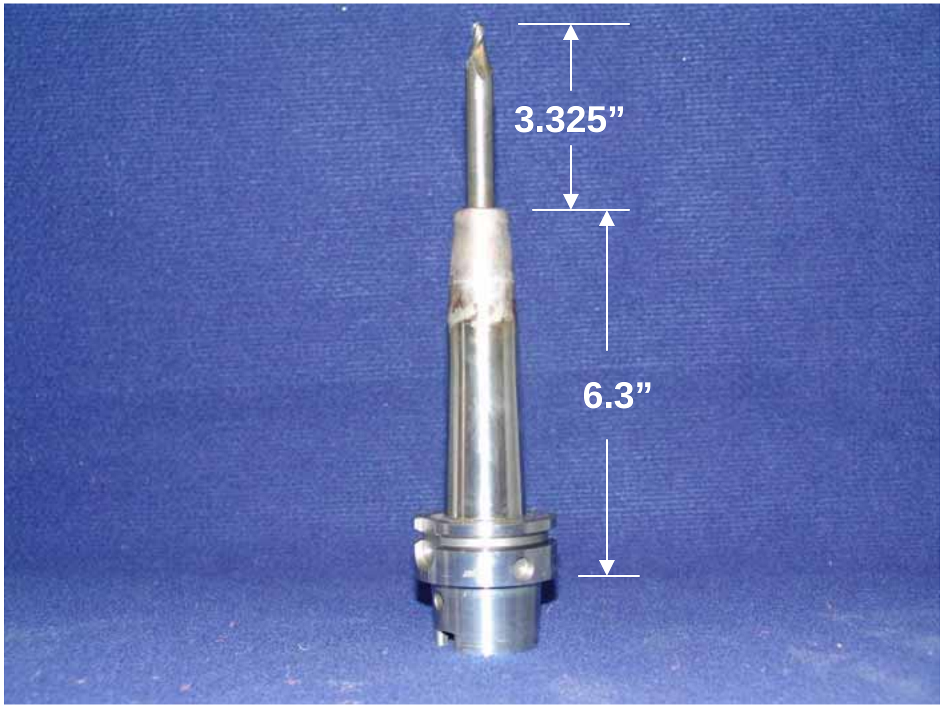
Cutting Underneath Flanges

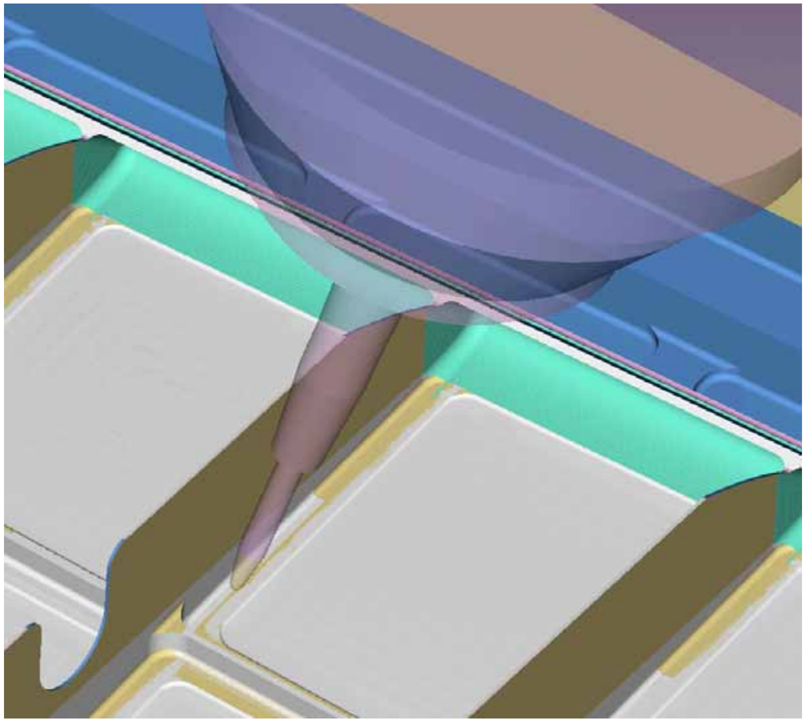


FIXED AXIS KELLERING MOTION USING EXTENSION HOLDERS TO MACHINE CLOSED ANGLES UNDER LEADING EDGE BETWEEN RIBS

ROUGHER 322 IPM AND .110” ADOC
BALLNOSE FINISHER 275 IPM AND .110” ADOC

Eliminating Cutter Ramps



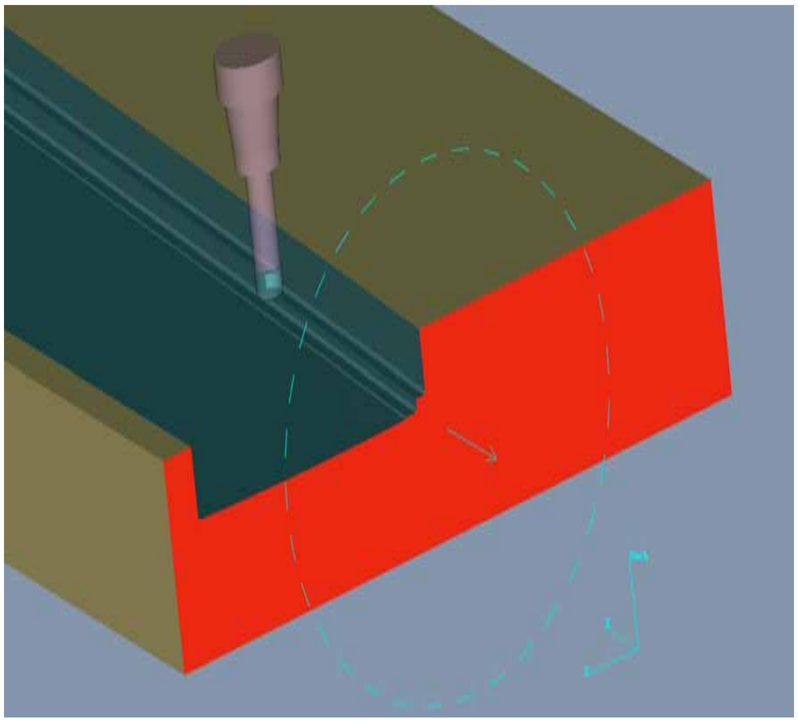


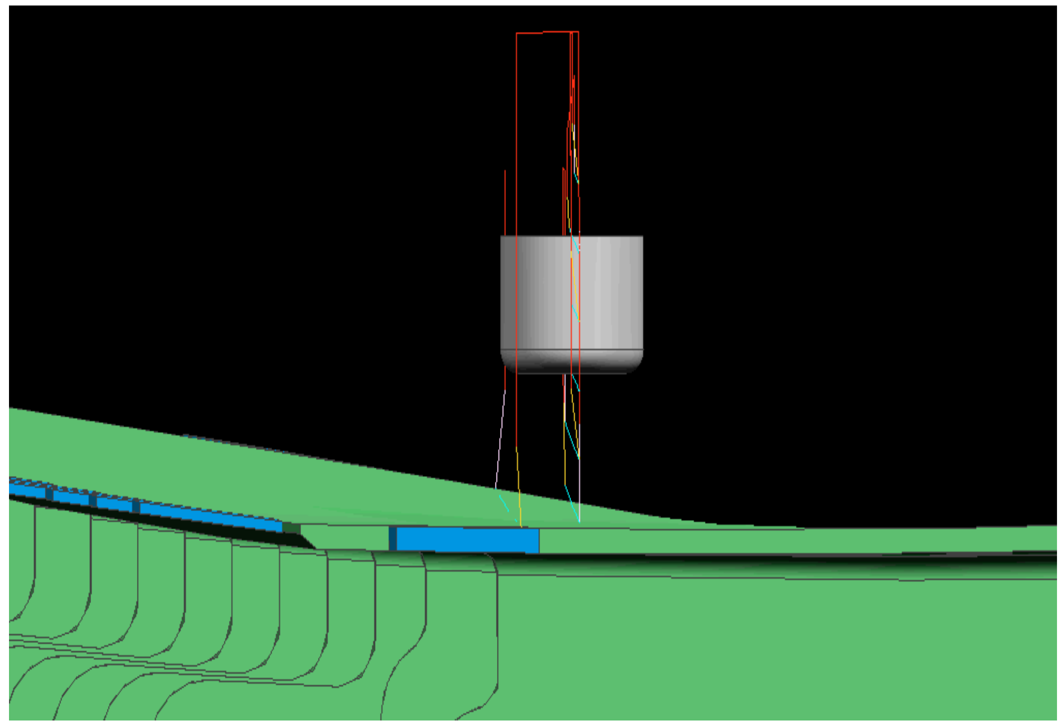
FIXED AXIS KELLERING MOTION USING .50" DIAMETER PENCIL CUTTER WITH .125" RADIUS IN EXTENSION HOLDER TO REMOVE EXCESS MATERIAL AT RIB AND WEB INTERSECTIONS

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

Unsupported Machining

FINISHING 2ND SIDE M/L SURFACES





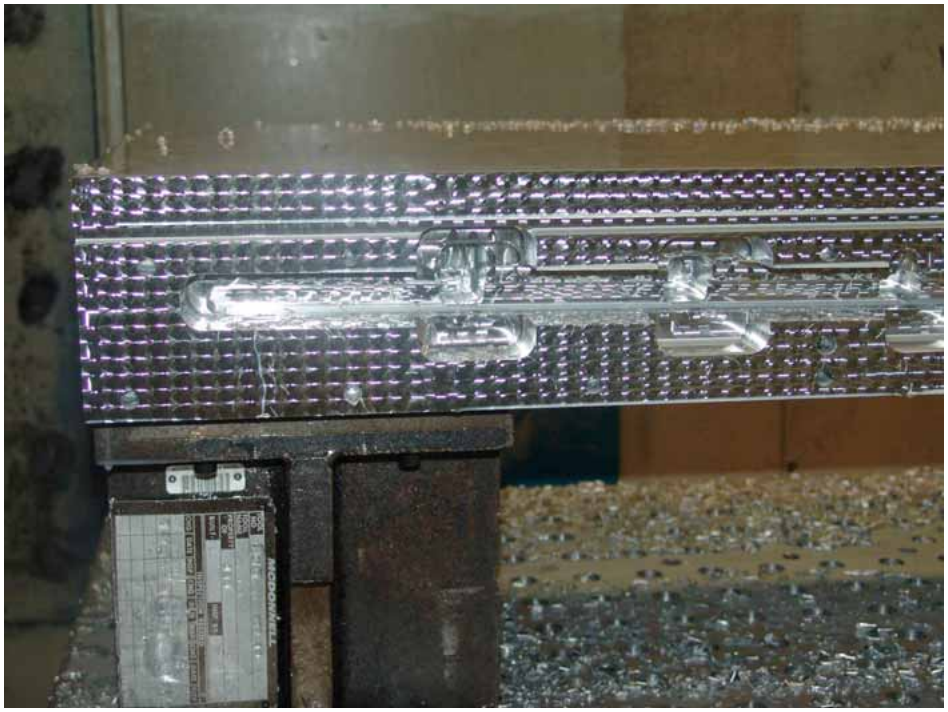
"DOWN AND OVER" TECHNIQUE

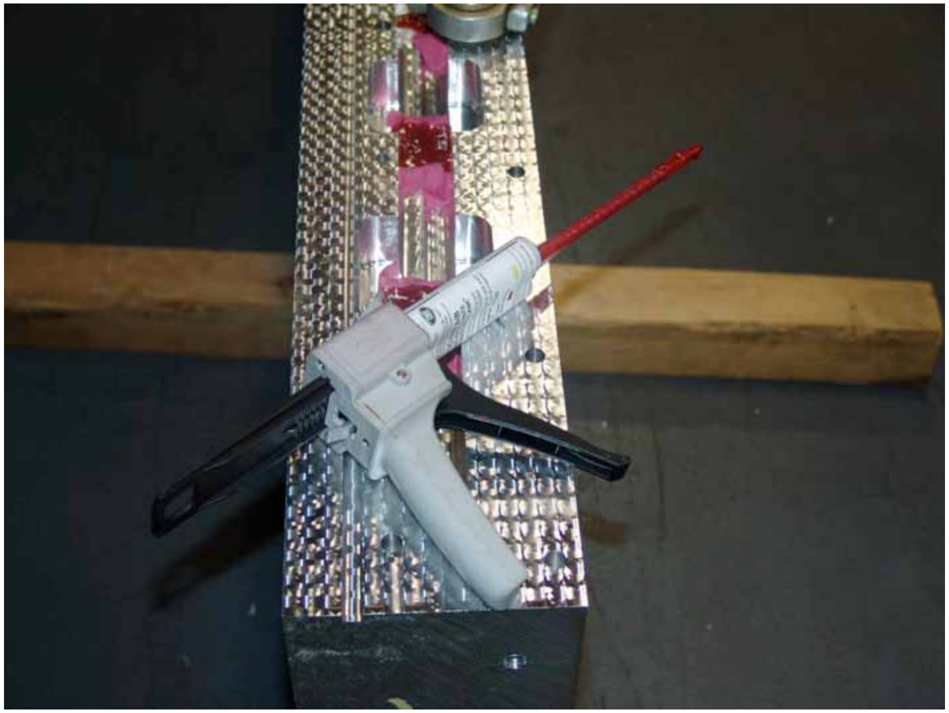
UNCUT STOCK SUPPORTS LOCAL AREA OF MACHINING

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

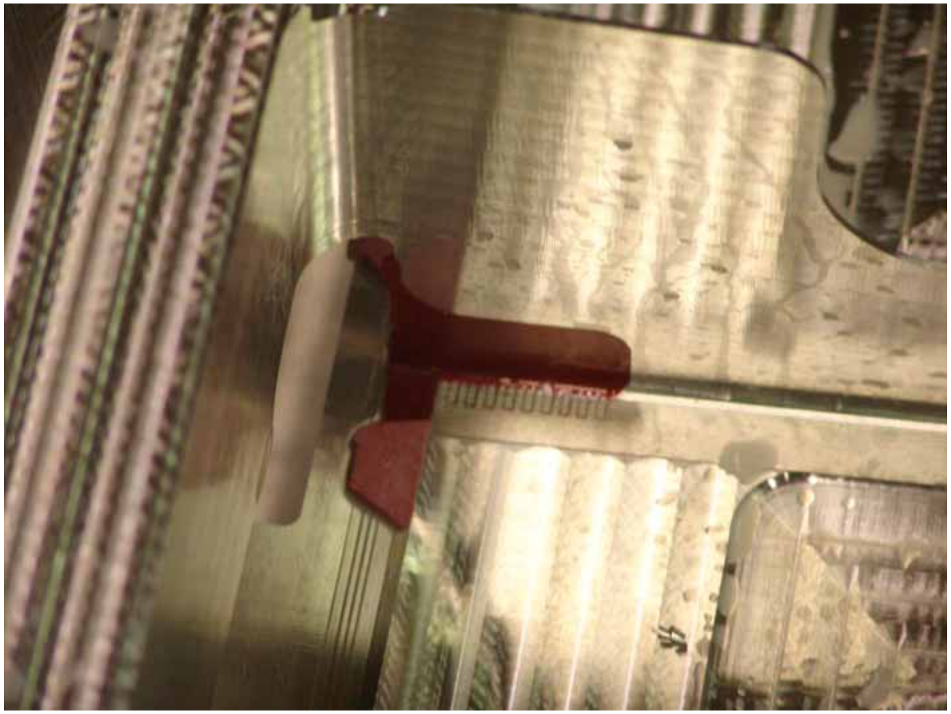
Fast Patch Paste for Holding Problems





Unattached ribs at floors vibrated causing undercuts in prototype

Unsupported Machining



Ribs at floors held in place using "red stuff"

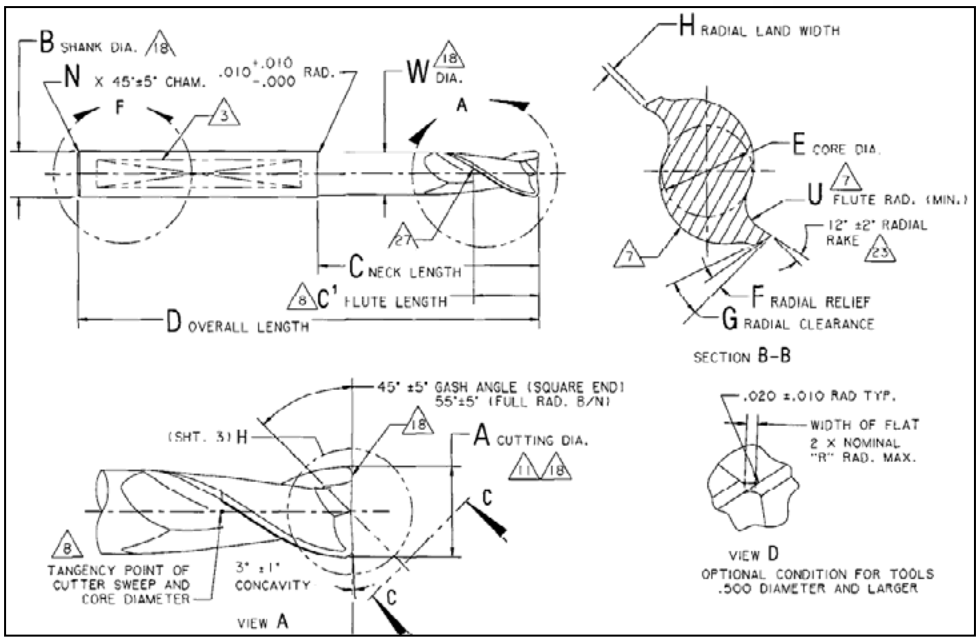
Cutting Tool Considerations

- 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



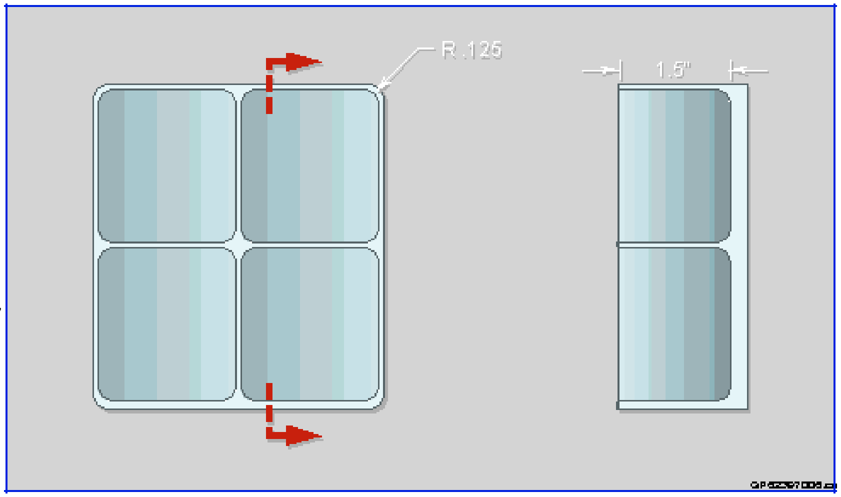
All holders are HSK style
Shrinkfit for endmills
Precision collets for drills and reamers

Inserted Cutting Tools are not Used!

Cleaning Out Corners

- 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

Or reverse the order



Finish corners then ribs

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)**

Cutter Cautions

- 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

Tool Holder Considerations

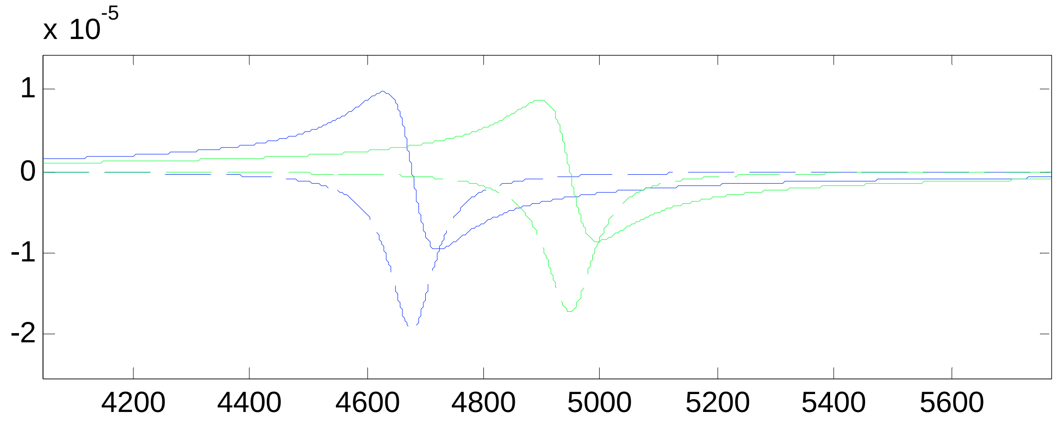
- Shrink-Fit, Hydraulic, Schunk “TriBos” are precise.
- Colleted have less gripping force and more run-out.
- Set-Screw holders are imprecise, inconsistent and not balanceable
- HSK required above 15krpm

Consistency Requirements

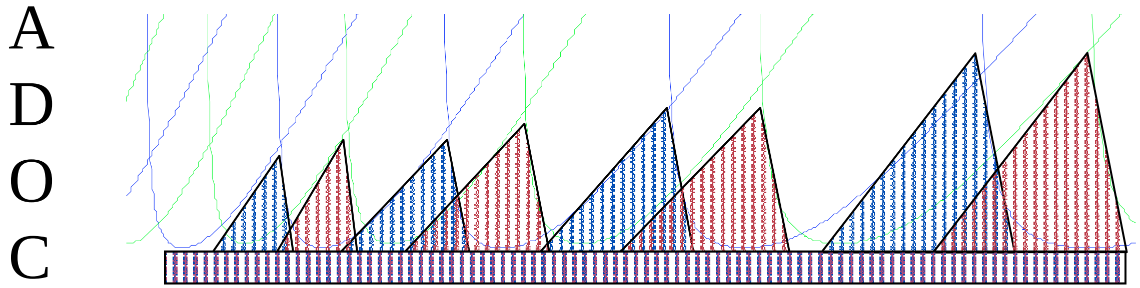
- Consistent Optimized performance requires attention to details
- Tool geometry
- Same tool holders
- Same spindles/spindle maintenance
- Consistent tool set length

Effect of Tool Length Change

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



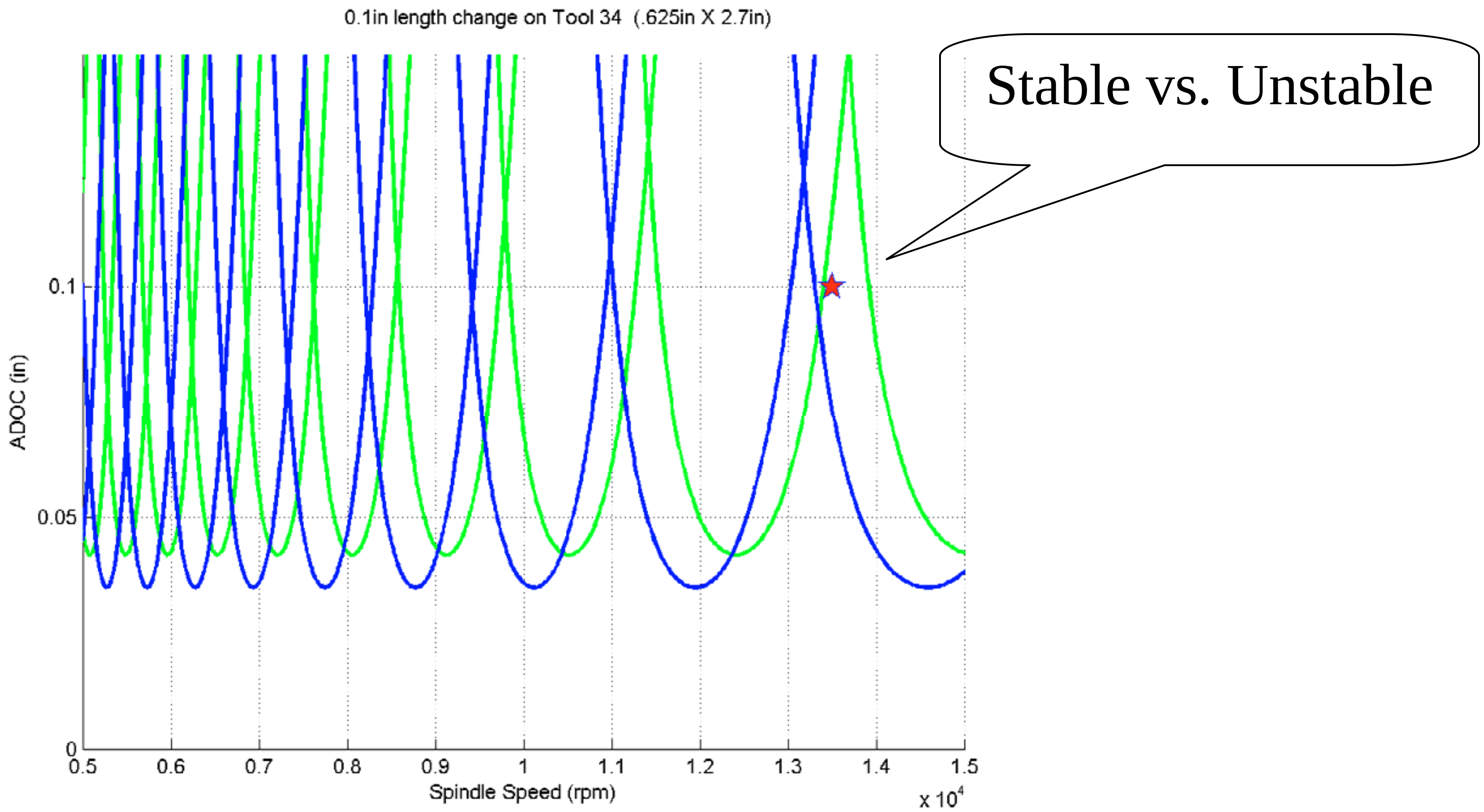
2.0in long

2.1in long

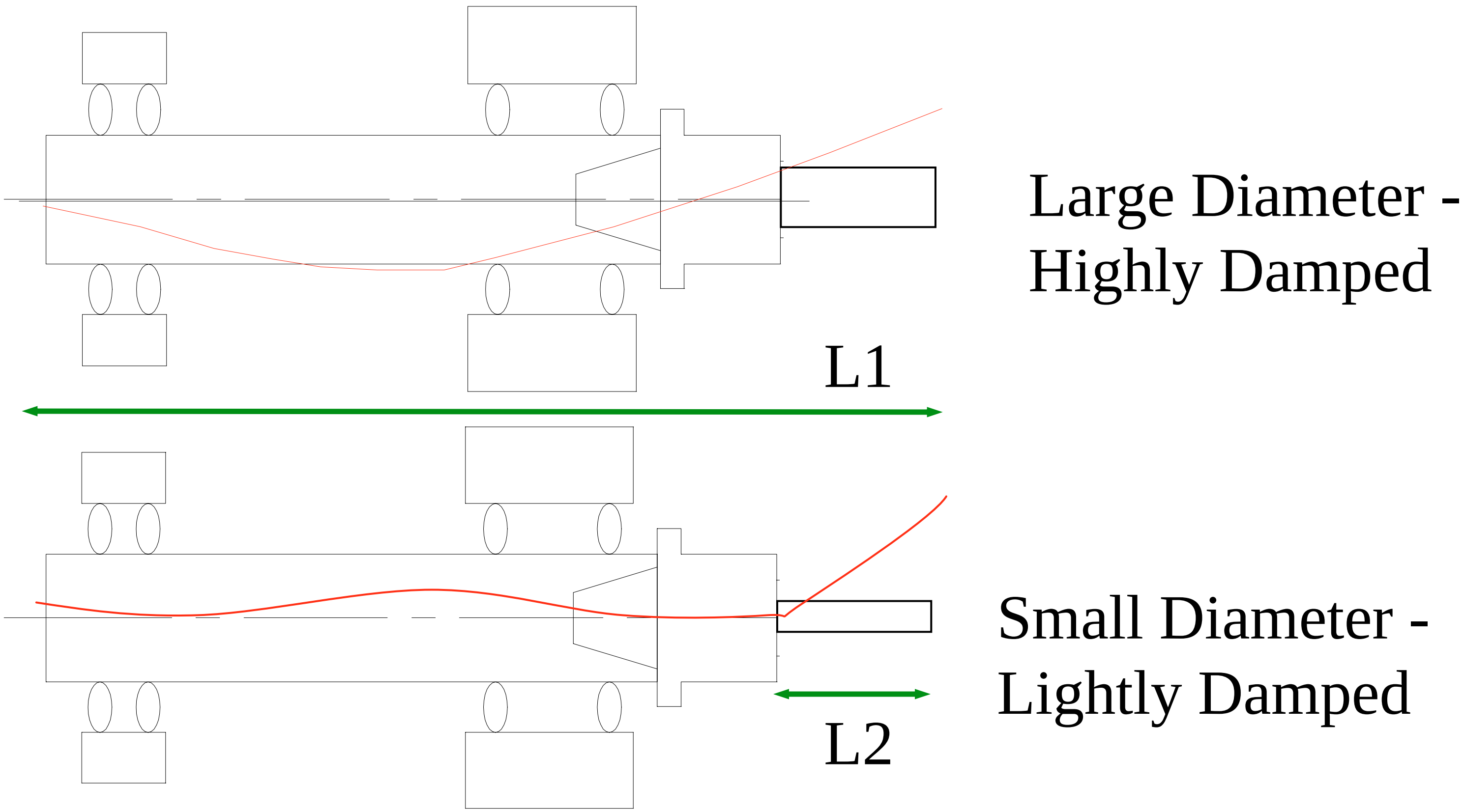
Performance without consistency

Effect of Tool Length Change

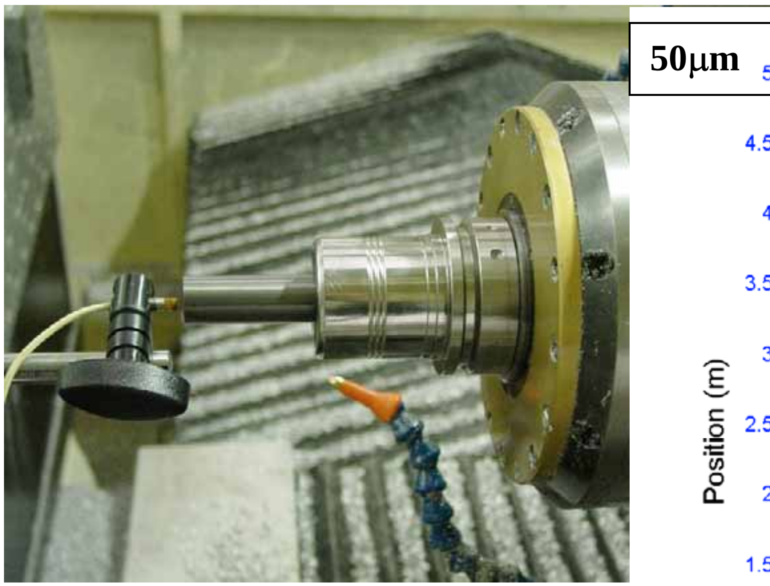
Cutting Data on .5inch diameter X 2.7 vs. 2.6 in Extension

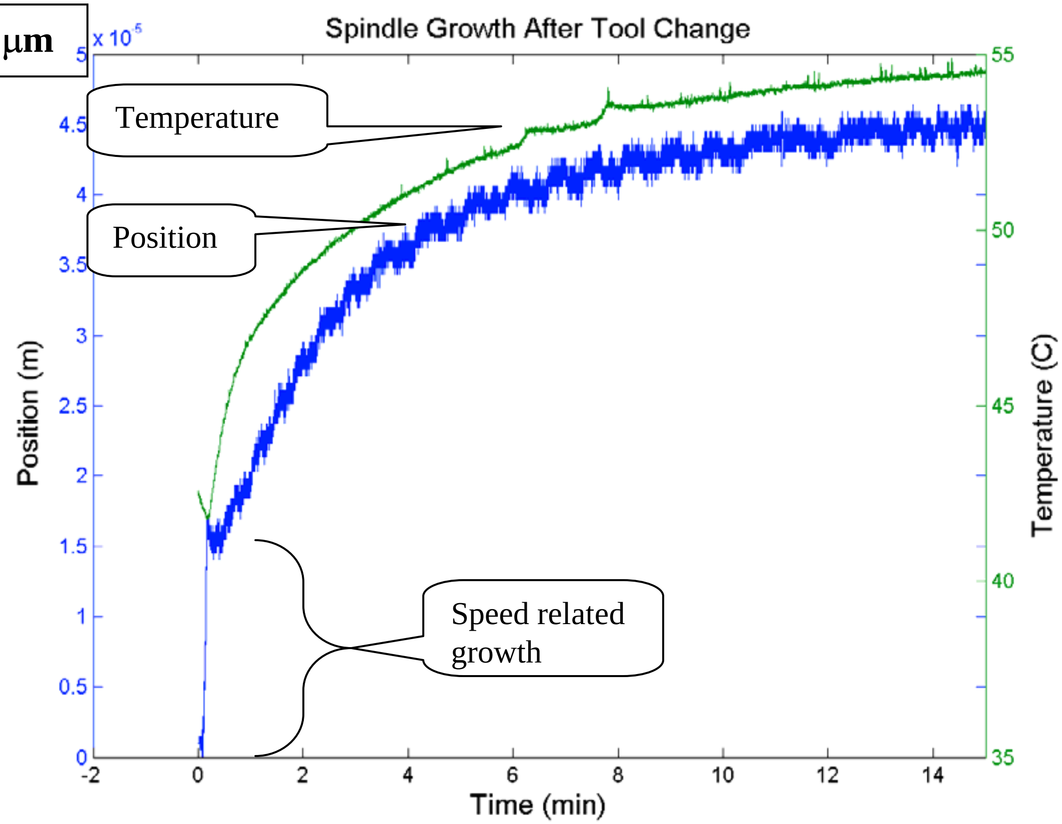


Small tools cut better in small spindles



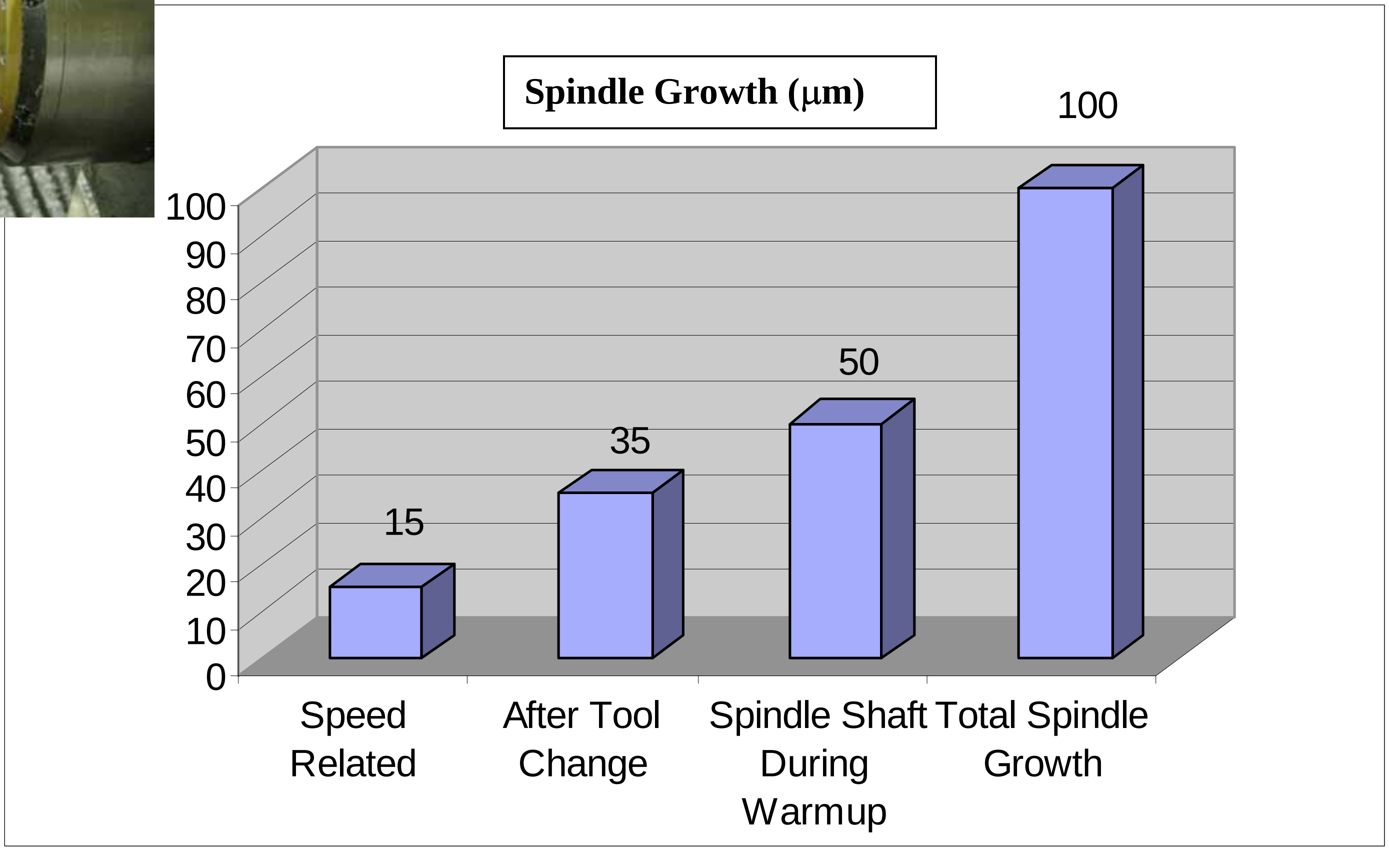
Spindle Growth After Tool Change





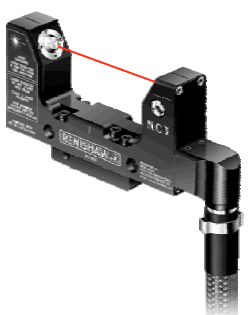
Spindle Growth Errors

100µ**m** =.004in (.008inch for 2-sided part)



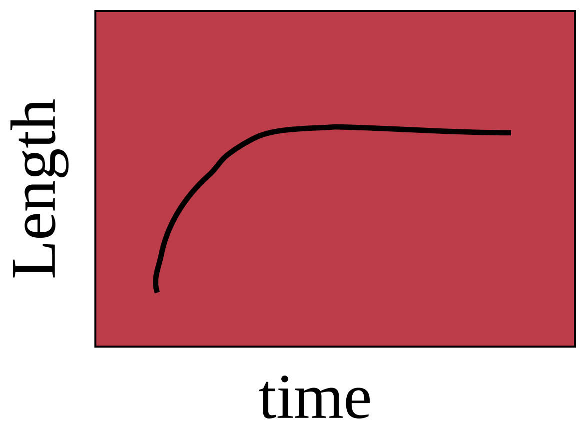
Controlling Spindle Growth?

Renishaw Laser Tool Setter



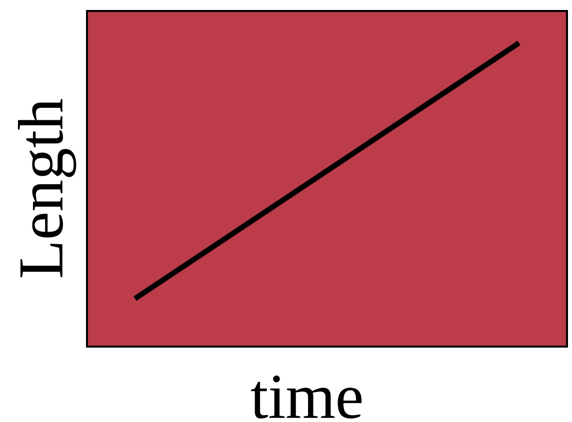
- Cooled spindles reach steady-state
- Heat comes from speed (not from cutting)
- Laser tool-setter is cheap ($1300) :probe without stopping spindle
- Wait for steady-state spindle temperature probe tool length before finishing cuts

Cooled Spindle



OR

No Spindle Cooling



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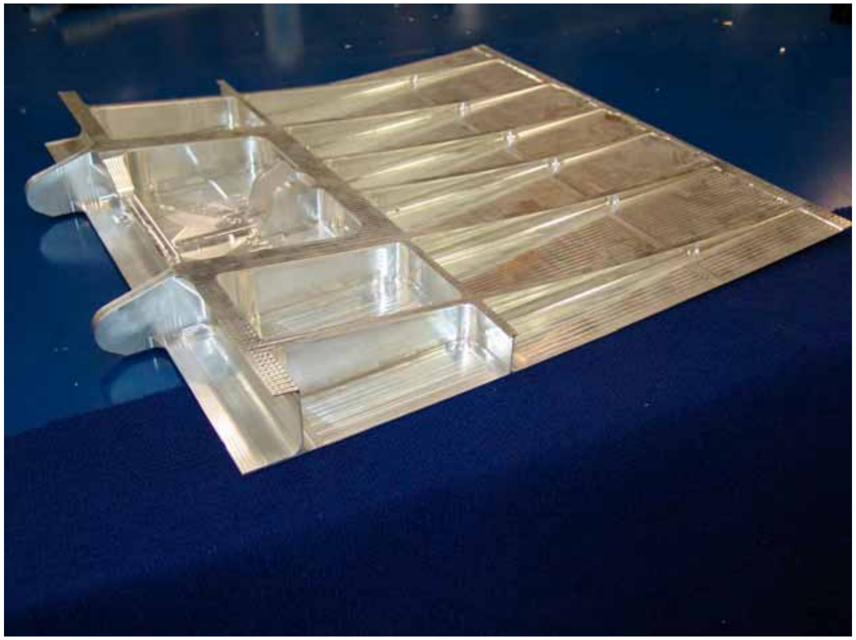
Lower Costs through Unitization

Monolithic components become cost effective

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



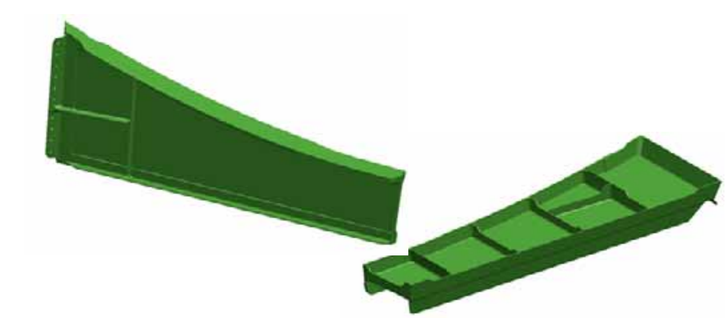
- New complex features
  - Return flanges
  - Enclosed corners
  - Unsupported flanges

Ultra-thin Structure – Light/Efficient

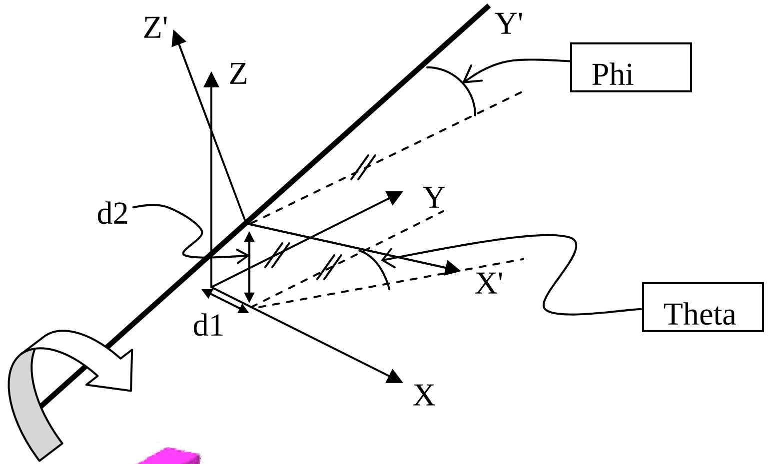
Replaced Bonded Aluminum Honeycomb with Ultra-thin Unitized Aluminum Machining for BSS

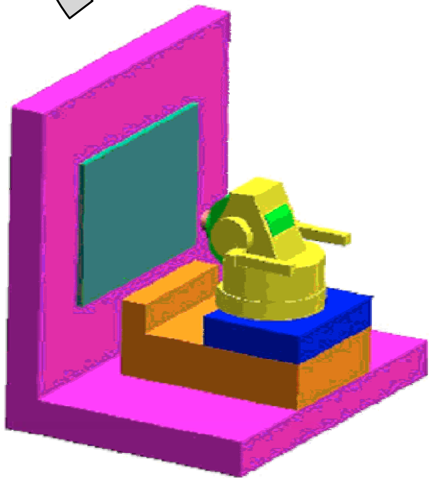
7 Feet X 8 Feet X 1 Inch ~ 33 lbs
Minimum Gage .020 +.005/-.000

- .020 Minimum Gauge
-Only 5% Price Increase for Ultra-Thin Part as Compared to Conventional Gages

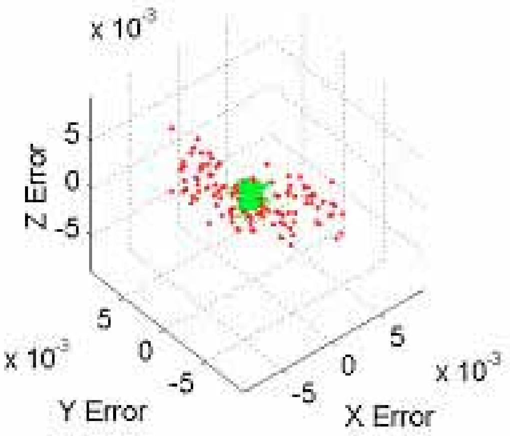


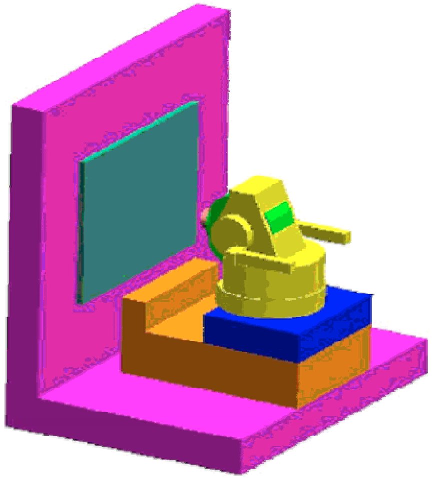
Observing Errors in Machine Construction Required for accurate 5-axis parts





Observing and correcting errors in Machine Construction





LSM ROUGHING APPROACHES

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”

Standard Rougher

Three .48” ADOC’s
21 IPM @ 1200 RPM
6.3 IN^3 MRR
2 HP

CrestKut Rougher

Two .71” ADOC’s
90 IPM @ 3000 RPM
63 IN^3 MRR
21 HP

Greenfield Rougher

One 1.42” ADOC
54 IPM @ 3000 RPM
71 IN^3 MRR
24 HP

Deep Applications – Plunge Milling

Iscar High Feed Mill

RPM=3000

IPM=120

ADOC=8.75”

RDOC=.30”

72 in^3 MRR

24 HP Cut

Video of high feed milling in aluminum

Video of high feed milling in aluminum

LSM: ROUGHING AND FINISHING APPROACH

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”

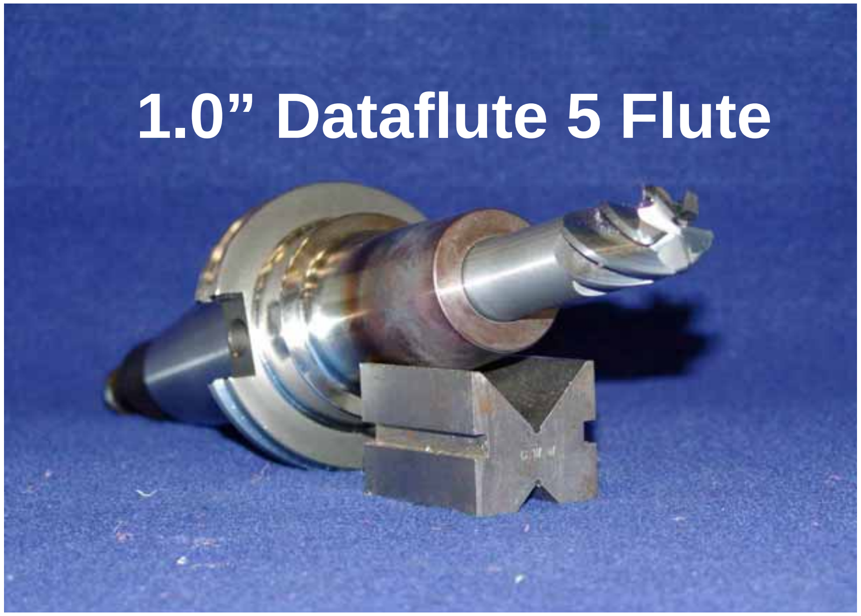
FULL SLOT

48 IN^3 MRR

16 HP Cut

LSM: FINISHING APPROACHES

Higher Flute Count Carbide Tools for Ribs and Webs



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

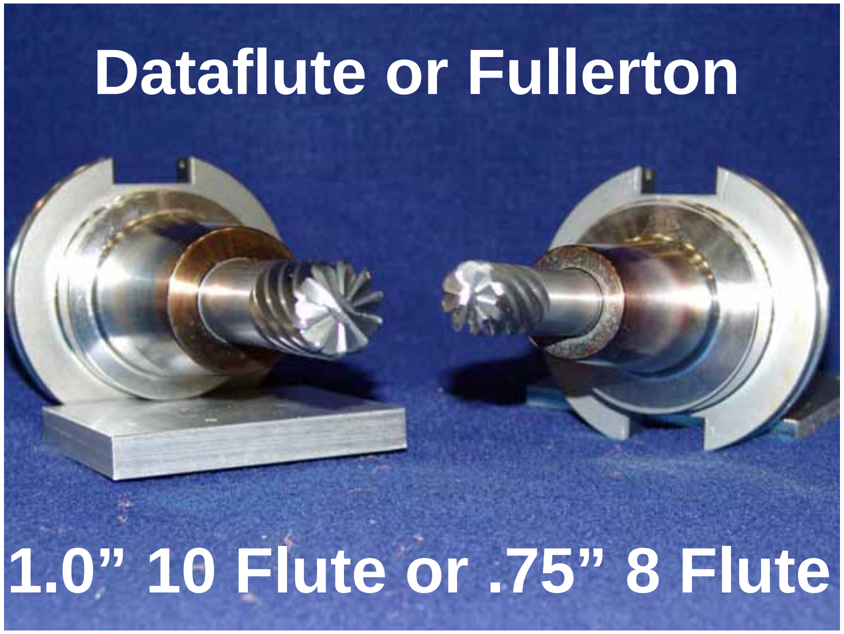
Finish corners to web and tangency of eventual rib finisher

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!



Questions About Aluminum???