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Final Report: PSP #14402-10-02 Improved Manufacturing of MC4531 Mold Bodies Using High-Speed Machining

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Abstract

Document is the final report for PSP project # 14402-10-02 entitled "Improved Manufacturing of MC4531 Mold Bodies Using High-Speed Machining (HSM)". The basic physics of high speed machining is discussed in detail including multiple vibrational mode machining systems (milling and turning) and the effect of spindle speed regulation on maximizing the depth of cut and metal removal rate of a machining operation. The topics of cutting tests and tap tests are also discussed as well as the use of the HSM assistance software "Harmonizer". Results of the application of HSM to the machining of encapsulation molds are explained in detail including cutting test results, new tool speeds and feeds, dimensional and surface finish measurements and a comparison to the original machining operations and cycle times. A 38% improvement in cycle time is demonstrated while achieving a 50% better surface finish than required.

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1. INTRODUCTION

PSP project # 14402-10-02 entitled "Improved Manufacturing of MC4531 Mold Bodies Using High-Speed Machining (HSM)" was awarded on 10/31/01 for $94K of funding over a one-year period. The project's purpose was to develop an improved machining strategy for the right and left halves of the MC4351 encapsulation mold bodies (MT70874T01-201 and MT70874T01-202 – Figure 1) by applying existing methods of high speed machining (HSM). Using HSM techniques, it was anticipated that the machining time would be reduced by about 25% while generating parts with a better surface finish that would require less secondary processing (hand polishing).

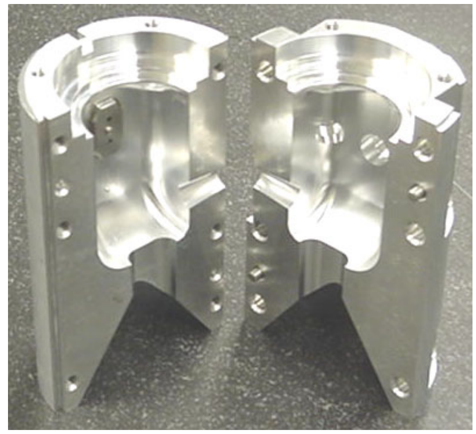


Figure 1 – MC4531 encapsulation molds.

Four primary benefits were anticipated to result from this project:

(1) Show HSM to be a viable technique for producing aluminum molds and fixtures for WR product faster and less expensive at SNL.
(2) Build internal capabilities to utilize HSM machine tools and techniques to improve product and decrease cycle time.
(3) Supply product needed in FY02 for MC4531 production normally costing $110K unloaded.
(4) Has direct application to other NG and WR production FY02 and beyond.

The project team consisted of the following people:

Table 1 – List of project team members and their roles.

Customer	Mark Sloane	14402	Customer
Project Lead	Bernie Jokiel	14184	HSM Technical Advisor
Machining Group	Doug Abrams	141862	Machining Team Leader
	Daryl Reckaway	14184	Technologist
	Jim Paustian	141862	Machinist
	Jim Metzler	14184	Machinist
Measurement Group	Monico Lucero	141861	Metrologist
	Tony Bryce	14186	Metrologist

The sections are organized as follows:

Section 2: Program plan
Section 3: Introduction to High Speed Machining
Section 4: Original process description and baseline
Section 5: HSM Mazak FJV-250 UHS cutting tests
Section 6**:** Application of HSM parameters to molds
Section 7: Improving machining strategy and path plan
Section 8: Conclusion

2. PROGRAM PLAN

Table 2 shows the original project plan with the original and modified time lines. The modified time line reflects delays caused by personnel changes along with planned and unplanned machine repair and maintenance.

Table 2 - Process steps with proposed and modified timelines.

Task	Sub Tasks	Original Timeline	Modified Timeline
Characterize Current Process	1. Machining steps (tools, time, number and type of operations) 2. Identify secondary processes (bead blast, burr removal, etc.) 3. Examine inspection data 4. Identify problem areas	Nov-01	Feb-02
HSM Cutting Tests	1. Examine tooling, purchase new tooling if needed. 2. Define cutting test experiment specifications (cutters, chip load, spindle speed, tool path). 3. Run full mold cavity (1 ea) on Mazak and Fadal. 4. Setup and conduct cutting test experiments. 5. Perform a DOE to identify new cutting test specifications. 6. Analyze test results (chatter, MRR, surface finish) 7. Pick three most promising parameter sets for mold test parts.	Nov-01 thru Feb-02	Feb-02 thru Apr-02
Machine MC4351 Mold Cavities	1. Mill cavities and fill sprue in 24 mold bodies (12 left, 12 right) using the three experimentally determined set of HSM parameters (8 parts per set). 2. Inspect the cavities for form and finish. 3. Compare measurement results to design specifications. 4. Compare HSM results to previous inspected mold body cavities.	May-02	May-02
Report Results	1. Create written report. 2. Compile results. 3. Comment on results. 4. Suggest machining parameters.	May-02	Jul-02

Some changes to this plan did occur - mainly during the "HSM Cutting Tests" stage. It turned out that the rigor in the original project plan was not required. Once the HSM methods were mastered, it became obvious that a particular set of cutting parameters was the best and therefore the redundant sets of parameters were abandoned. Although it took less time in the experimental stage, it took longer than expected to come up to speed on the HSM methods and software training, which in the end made the duration of that particular stage as long as planned.

3. INTRODUCTION TO HIGH SPEED MACHINING

3.1. Relating Metal Removal Rate to Spindle Power

The metal removal rate (MRR) is the rate at which material is removed from a workpiece and is defined in Equation (1).

$$MRR\left(\frac{\text{in}^3}{\text{min}}\right) = b(\text{in})*w(\text{in})*v\left(\frac{\text{in}}{\text{min}}\right) \tag{1}$$

where:
b – depth of cut
w – width of cut
v – tool feedrate

The spindle power required to achieve a certain MRR can be calculated from Equation (2).

$$P(\text{Hp}) = K_s\left(\frac{\text{lb}}{\text{in}^2}\right) * MRR\left(\frac{\text{in}^3}{\text{min}}\right) * C \tag{2}$$

where:
K_s – material specific cutting stiffness
C - conversion factor from metric to English units

The cutting stiffness (K_S) is an experimentally determined parameter that varies with material and the cutting tool geometry. Some typical values for K_S in end milling appear Table 3.

Table 3 – Cutting stiffness values for end milling [1].

Material	**K_s N/mm^2**
Grey Cast Iron	1500
302 Stainless Steel	2700
Inconel	3500
7075-T6 Aluminum	850

In light of equations (1) and (2) it is tempting to think that one could maximize MRR by increasing b, w and v up to the power limit of the spindle or until the tool breaks. However in practice other factors take over that limit the useable spindle power available. Typically before spindle saturation and even before tool breakage, a condition of *regenerative chatter* develops.

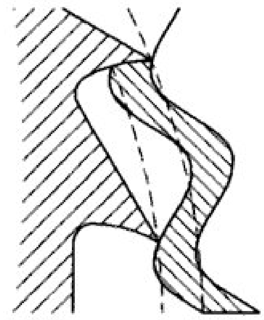
3.2. Principles of Regenerative Chatter

Regenerative chatter (or "chatter") is a self-excited vibration that develops between the milling system (spindle-tool-tool holder) and the workpiece. Chatter is extremely detrimental to the surface finish of a workpiece, and very serious to tool and spindle life. For instance injection molds and stamping dies are used to replicate shapes machined into them. Unwanted marks in the molds will be replicated that are at least unsightly, or worse will not allow the molded part to function correctly. Potentially the dies themselves may not function properly. Typically chatter marks will require a great deal of secondary processing by grinding and polishing to remove them which makes the parts more expensive and slows the manufacturing process.

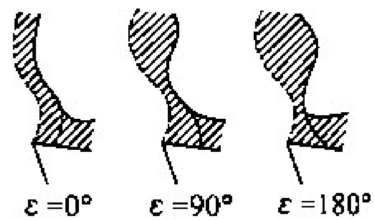
A tool allowed to chatter puts excessive stress on the edges of the cutting tool, which leads to tool breakage in a very short amount of time. During chatter the spindle too is subjected to excessive stress from chatter as forces generated during chatter are ultimately reacted in the spindle bearings leading to premature and potentially catastrophic spindle failure.

Chatter forms by a process of regeneration and occurs in the following manner:

1. During the cutting process, the vibrations in the machine tool are imprinted on the workpiece (waviness).

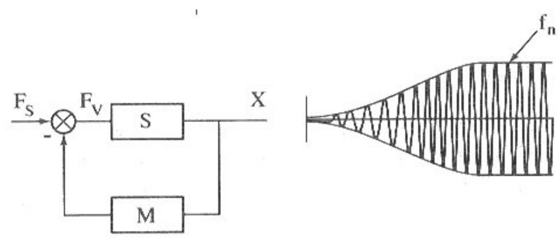


2. Subsequent passes of the tool re-cut the imprinted surface that produces a chip of varying thickness, which consequently imparts a time-varying force on the cutting tool.



Chip thickness variation h

3. The time-varying force excites the vibrational modes of the machining system. If the conditions are right, the vibration induced by the varying force on the cutting tool will grow uncontrolled (unstable).



(Above pictures may be found in [1].)

Machinists have typically tried to eliminate chatter in two ways:

1. Slow down spindle speed, and increase feedrate.

   This causes more intimate contact of backside of the tool with the workpiece. The extra friction effectively increases the damping of the machine tool. This is called "*process damping*".

2. Use chatter belts, add mass, and/or fill part with other material.

   This changes the mass, damping or stiffness of the machine tool slightly, which changes the natural frequency of the system enough so that surface waviness does not regenerate in a destructive manner.

However another way to eliminate or avoid chatter altogether exists which is to run at an extremely high spindle speed to escape the regenerative chatter frequencies.

3.3. The Limit of Stability – A Single Vibrational Mode

Consider a machine tool that has a single vibrational mode. If the machining system's modal stiffness (k), mass (m), damping coefficient (c) are known one can calculate the maximum chatter-free depth of cut or *limit of stability* (b_{lim}) for a particular spindle speed (n) and material cutting stiffness (K_s) (Equation 3) [1].

$$b_{\lim}(\text{mm}) = \frac{1}{2K_s \operatorname{Re}(G)}$$

$$\operatorname{Re}(G)\left(\frac{\text{mm}}{\text{N}}\right) = \frac{1000}{k}\left(\frac{(1-p^2)}{(1-p^2)^2 + 4\zeta^2 p^2}\right) \tag{3}$$

$$p = \frac{f}{f_n} \quad f(\text{Hz}) = \frac{n\left(\frac{\text{rev}}{\text{min}}\right)}{60} \quad f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad \zeta = \frac{c\left(\frac{\text{kg}}{\text{sec}}\right)}{2\sqrt{k\left(\frac{\text{N}}{\text{m}}\right)m(\text{kg})}}$$

The *critical limit of stability* ($b_{lim,cr}$) is the depth of cut below which the cutting process is always stable and can be calculated from Equation 4 [1].

$$b_{\lim,cr} = \frac{1}{2K_s(\operatorname{Re}(G))_{\min}} = \frac{2k\zeta(1+\zeta)}{K_s} \tag{4}$$

Previously it was stated that chatter was caused by the re-cutting of waves imprinted on the workpiece surface resulting from machine vibrations. The number of waves (w) imprinted on the workpiece between subsequent passes of the tool (in the case of turning) or between cutter teeth (in the case of milling), can be expressed as a number of integer (N) plus a partial wave (ε), which equates to the ratio of the chatter frequency (f) to the tooth passing frequency ($n*n_T$), where n_T is the number of teeth on the cutter (Equation 5) [1].

$$w = N + \frac{\varepsilon}{2\pi} = \frac{f}{nn_T}$$

$$\varepsilon = 2\left(\pi - \tan^{-1}\frac{\operatorname{Re}(G)}{\operatorname{Im}(G)}\right) \tag{5}$$

$$\operatorname{Im}(G) = -\frac{1000}{k}\left(\frac{2\zeta p}{(1-p^2)^2 + 4\zeta^2 p^2}\right)$$

By plotting b_{lim} versus *n* and incorporating *N* a *stability lobe diagram* results (Figure 2). A stability lobe diagram clearly shows the spindle speed and depth of cut combinations that are chatter-free, stable cutting parameters and unstable cutting parameters that produce chatter. In the example case presented in Figure 2 the region above the lobing curve is the unstable region. Any depth of cut and spindle speed combination in this area will produce chatter. The region below the lobing curve is the stable region, any combination of depth of cut and spindle speed will not produce chatter. Notice in Figure 2 that there are gaps between the lobes – most notably between lobes N=0 and N=1. These *stability gaps* are regions where a large increase in the depth of cut is possible while simultaneously avoiding chatter. In the case of the N01 stability gap a 6X increase in the depth of cut is possible over $b_{lim,cr}$ without inducing chatter. Stability lobe diagrams are extremely useful to the machinist or CNC programmer to select machining parameters (depth of cut, width of cut, and spindle speed) for a particular machine, tool and workpiece material.

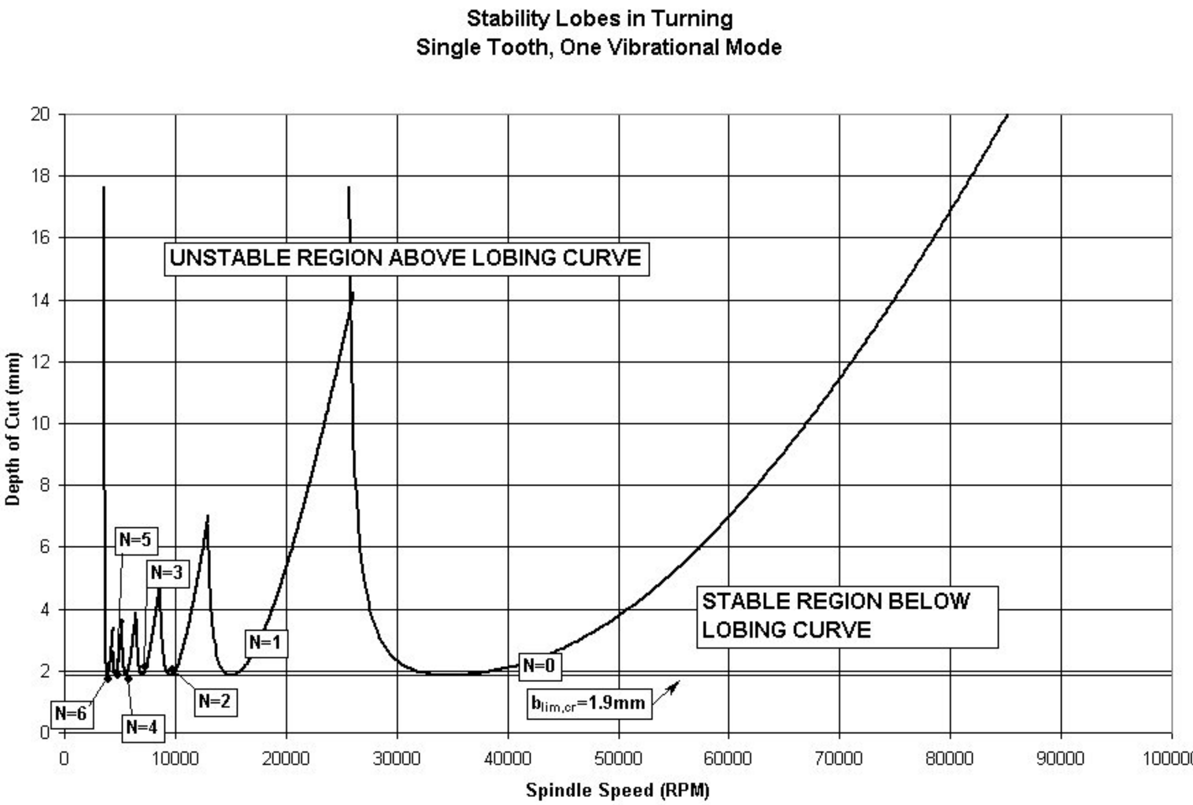


Figure 2 – Turning system modal properties.

By selecting appropriate parameters to keep the cutting process in the stability gaps, chatter is avoided and depth of cut can be maximized. Once the depth of cut is maximized the feedrate of the machine can be increased which will better utilize the available spindle horsepower and increase MRR, making the overall machining process faster and more efficient.

3.4. The Limit of Stability – Multiple Vibrational Modes

Machine tools typically have more than one vibrational mode. Usually only the first two or three are significant in chatter (but not always), which correspond to the vibrational modes of the tool, tool holder and spindle combinations. Consider a turning system that has two dominant vibrational modes who's properties are given in Table 4.

Table 4 – Turning system modal properties

Property	Units	Mode 1	Mode 2
n_T	Teeth	1	1
K_s	N/m^2	1.5e+09	1.5e+09
m	kg	4	3
k	N/m	2.80e+07	3.80e+07
c	kg/sec	1000	2000

Using Equations 3, 4 and 5 the stability lobes for each vibrational mode may be plotted (Figure 3).

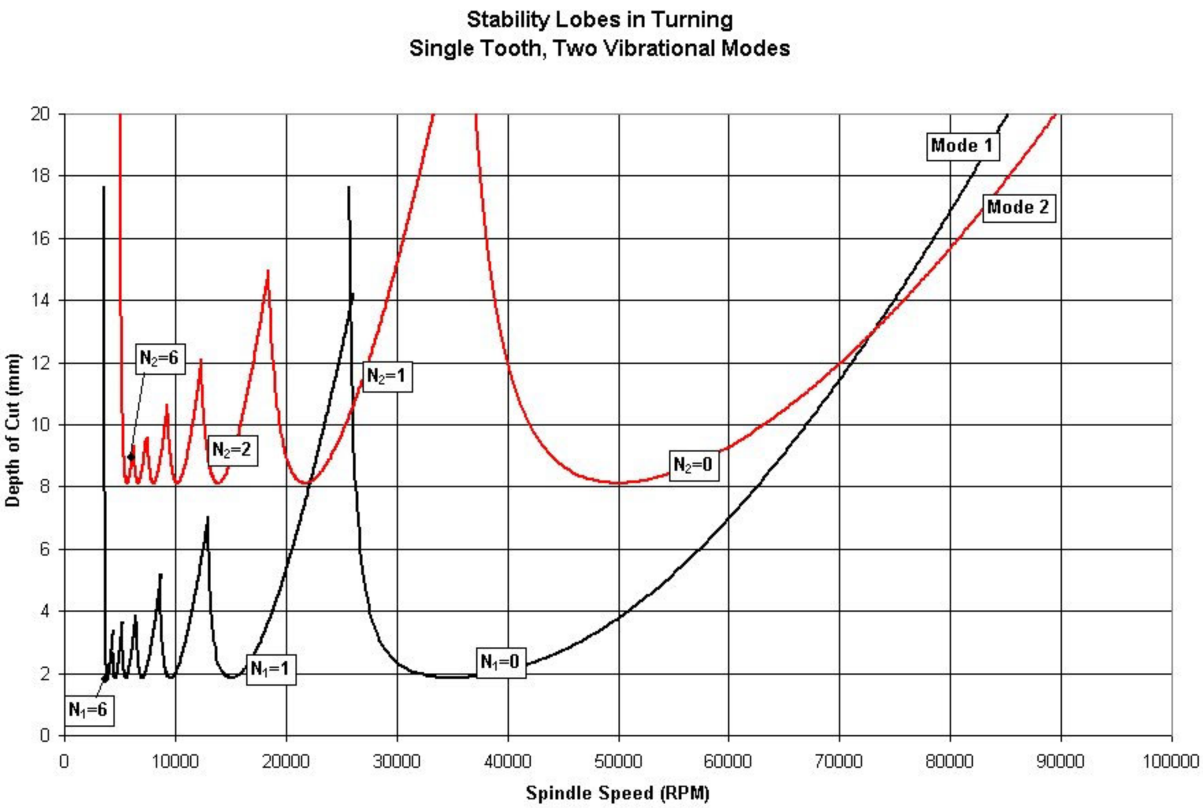


Figure 3 – Stability lobes for turning system with two vibrational modes.

In Figure 3 Mode 1 is represented by the black line and is the same as that of Figure 2. Mode 2 is represented by the red line – which has a higher stiffness, lower mass and greater damping than that of Mode 1 and correspondingly has a higher natural frequency. Notice that the lobing curve for Mode 2 crosses Mode 1 between stability gap $N_1$01 and to the right of N_1=0. The area above the curve is the unstable region and still applies**;** however**,** in the case of multiple vibrational modes one must look at the lowest parts of the curves.

Now that Mode 2 is being considered it can be seen that the spindle speed and depth of cut must be reduced to avoid chatter in Mode 2 and consequently one can achieve a 4X improvement in the chatter-free depth of cut.

3.5. The Effect of Multiple Cutting Teeth on Spindle Speed - Milling

In the previous examples the examples were based on a single-point turning operation. Looking back at Figures 2 and 3 it is apparent that the spindle speeds are rather high for turning (20000+ RPM). Due to part geometries, cutting speeds and tool materials turning is typically done under 10000RPM. In the case of the

Table 5 – Modal parameters of fictitious milling system in Figure 4.

Property	Units	Mode 1	Mode 2
n_T	Teeth	2	2
K_s	N/m^2	8.50e+08	8.50e+08
m	kg	1.5	1
k	N/m	2.80e+07	4.50e+07
c	kg/sec	500	1000

fictitious turning scenarios there would be little or no advantage to trying to find the stability gaps below 10000RPM since they are too narrow and close together, which is typically the case in turning.

However in milling there is typically more than one tooth involved in cutting. More cutting teeth has the effect of compressing the whole stability lobe graph down the spindle speed axis toward the depth of cut axis. Consider the stability lobe diagram in Figure 4 of a fictitious milling system that has the modal properties used in Table 5.

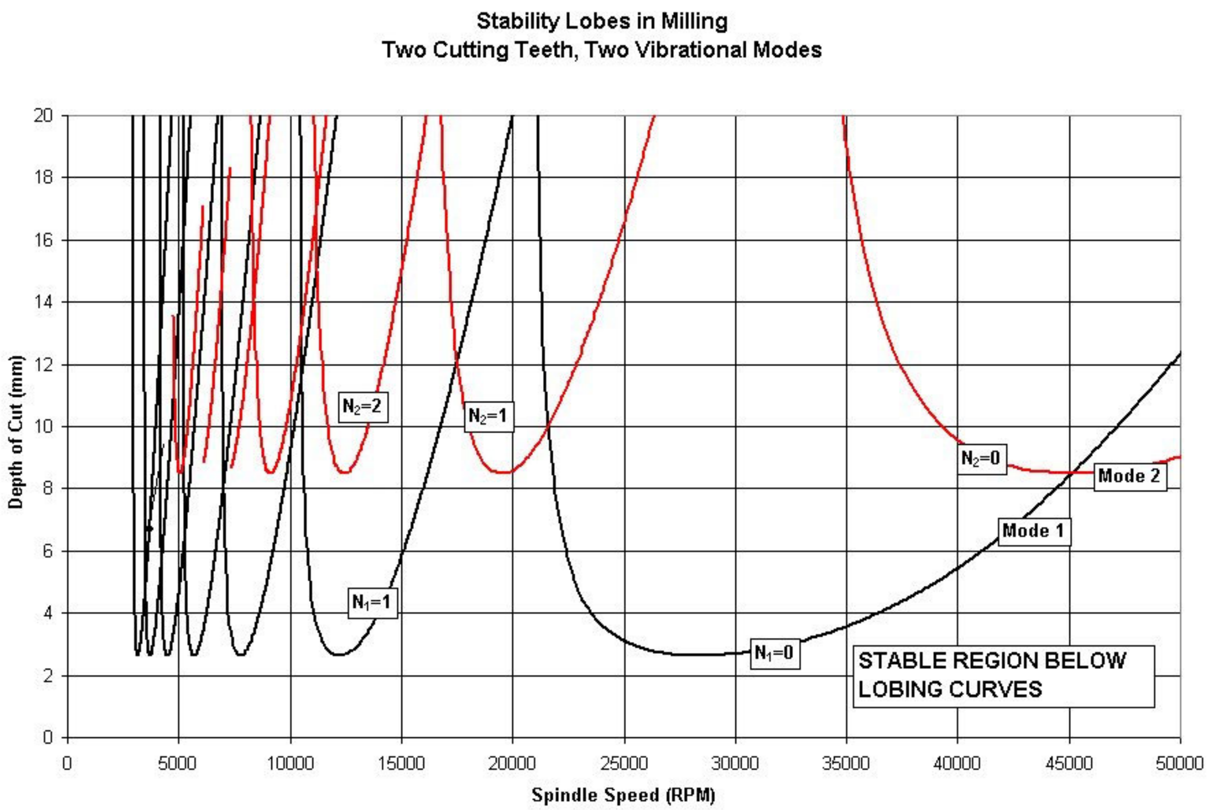


Figure 4 – Stability lobes for milling system with two vibrational modes.

In Figure 4 a large stability gap occurs between lobes N1=0 and N1=1. Notice that the speed range between two lobes is well within most high-speed, high-power milling spindles.

3.6. Example: HSM by Maximizing MRR Using Stability Lobes

HSM can be defined as a process to maximize the metal removal rate (MRR) and avoid tool chatter *for a particular combination of material, machine, tool, spindle and tool holder* by taking advantage of the vibrational characteristics of the machining system.

You are cutting a pocket in 6061-T6 aluminum with a ¾ inch, 2-fluted end mill. Based on past experience, you decide to mill out the bulk of the material with a depth of cut b=0.25” and width of cut w=.563" using a feed per tooth of 0.004" at 5000RPM. Your machine is equipped with a 25,000RPM, 30kW (40HP) spindle.

1. What are the MRR and the power required for the cutting parameters you have chosen?

$$v = f_T n_T n = \left(0.004\frac{\text{in}}{\text{tooth}}\right)\left(2\frac{\text{teeth}}{\text{rev}}\right)\left(5000\frac{\text{rev}}{\text{min}}\right) = 40\frac{\text{in}}{\text{min}}$$

$$MRR = bwv = (0.25\text{in})(0.563\text{in})\left(40\frac{\text{in}}{\text{min}}\right) = 5.6\frac{\text{in}^3}{\text{min}}$$

$$P = K_s MRR = \left(850\frac{\text{N}}{\text{mm}^2}\right)\left(5.6\frac{\text{in}^3}{\text{min}}\right)\left(25.4\frac{\text{mm}}{\text{in}}\right)^3\left(\frac{\text{min}}{60\sec}\right)\left(\frac{\text{m}}{1000\text{mm}}\right)\left(\frac{1.341\text{HP}}{1000\text{W}}\right) = 1.7\text{HP}$$

2. In light of the stability lobe diagram in Figure 2 (which jut happens to correspond to the tool setup you are using) is there a better choice of milling parameters given the power and speed rating of the spindle you are using?

$$v = f_T n_T n = \left(0.004\frac{\text{in}}{\text{tooth}}\right)\left(2\frac{\text{teeth}}{\text{rev}}\right)\left(17000\frac{\text{rev}}{\text{min}}\right) = 136\frac{\text{in}}{\text{min}}$$

$$MRR = bwv = (11.5\text{mm})\left(\frac{\text{in}}{25.4\text{mm}}\right)(0.563\text{in})\left(136\frac{\text{in}}{\text{min}}\right) = 34.6\frac{\text{in}^3}{\text{min}}$$

$$P = K_s MRR = \left(850\frac{\text{N}}{\text{mm}^2}\right)\left(34.6\frac{\text{in}^3}{\text{min}}\right)\left(25.4\frac{\text{mm}}{\text{in}}\right)^3\left(\frac{\text{min}}{60\sec}\right)\left(\frac{\text{m}}{1000\text{mm}}\right)\left(\frac{1.341\text{HP}}{1000\text{W}}\right) = 10.8\text{HP}$$

Or better yet:

$$v = f_T n_T n = \left(0.004\frac{\text{in}}{\text{tooth}}\right)\left(2\frac{\text{teeth}}{\text{rev}}\right)\left(22000\frac{\text{rev}}{\text{min}}\right) = 176\frac{\text{in}}{\text{min}}$$

$$MRR = bwv = (9.5\text{mm})\left(\frac{\text{in}}{25.4\text{mm}}\right)(0.563\text{in})\left(176\frac{\text{in}}{\text{min}}\right) = 37\frac{\text{in}^3}{\text{min}}$$

$$P = K_s MRR = \left(850\frac{\text{N}}{\text{mm}^2}\right)\left(37\frac{\text{in}^3}{\text{min}}\right)\left(25.4\frac{\text{mm}}{\text{in}}\right)^3\left(\frac{\text{min}}{60\sec}\right)\left(\frac{\text{m}}{1000\text{mm}}\right)\left(\frac{1.341\text{HP}}{1000\text{W}}\right) = 11.5\text{HP}$$

3. Does the MRR go up or down?

Up… way up! By using the stability lobes, stable milling speeds were found that allowed the depth of cut to increase substantially and thereby improving the MRR by *six times*. Using these parameters 29% of the spindle power to make chips versus 4% - clearly a more economical and improved process over the initial choices for milling parameters.

3.7. Finding the Stability Lobes By "Tap Test"

Previous sections demonstrated how Equations 3-5 are used to directly plot the stability lobes from modal stiffness (k), mass (m) and damping (c) parameters from a series of system vibration modes. However it was not explained how these parameters are determined. These parameters can be experimentally determined by a "tap test". A "tap test" involves the use of a force-sensing hammer and an accelerometer or series of accelerometers (Figure 5). The rudimentary steps to perform a tap test are as follows:

1. A tool holder containing a tool is mounted in the spindle.
2. An accelerometer is placed at the tip of the tool. The leads are connected to a data acquisition system.
3. A force-sensing hammer (a special hammer with a proof mass on an accelerometer) is connected to the data acquisition system. The experimentalist taps the hammer against the tool. The data acquisition system reads the force and vibration signals from the hammer and accelerometer. The data acquisition system computes the fast Fourier transform (FFT) of the signals and calculates the *transfer function*, which relates the mount of vibration per amount of input force over a range of frequencies. This is also called the *frequency response of the system* (Figure 5).
4. From the frequency response k, m and c can be calculated for the different vibrational modes observed in the system. (Figure 6).

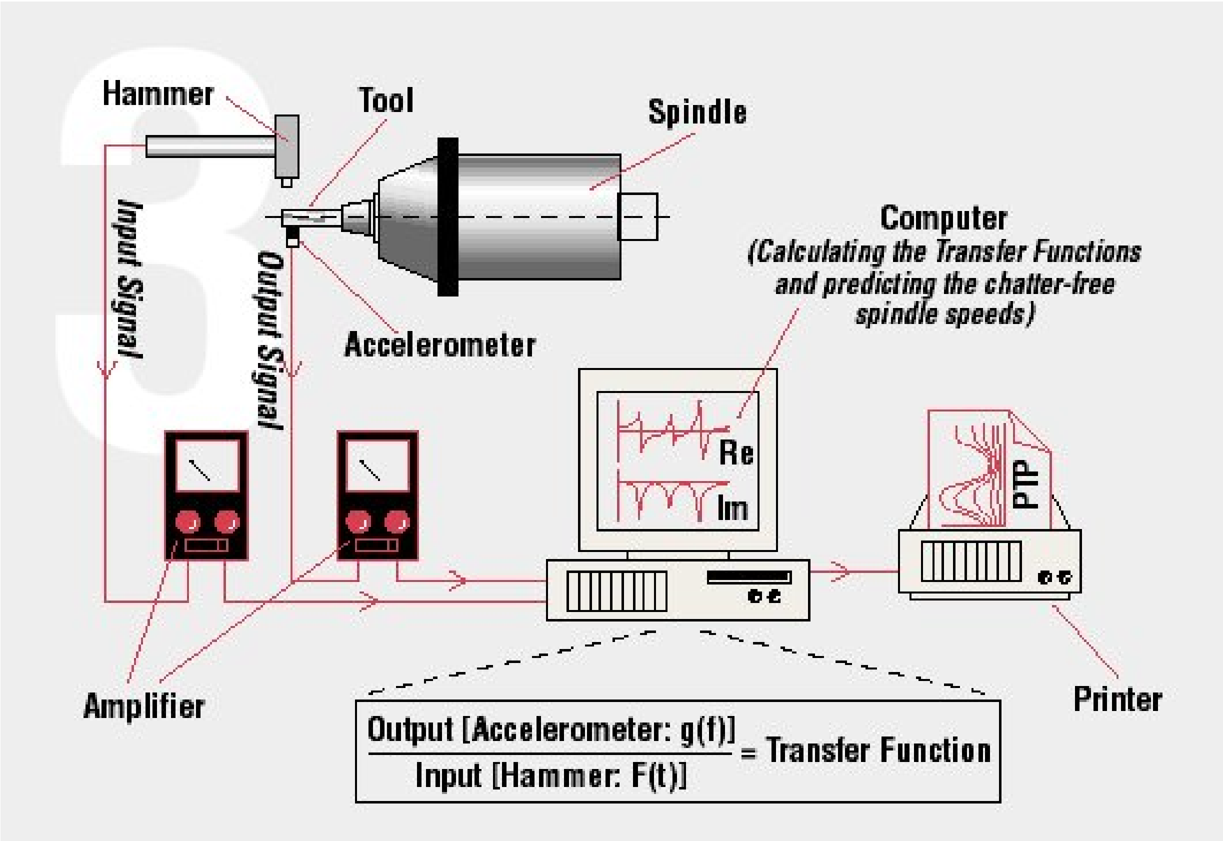


Figure 5 – “Tap Test” setup [3].

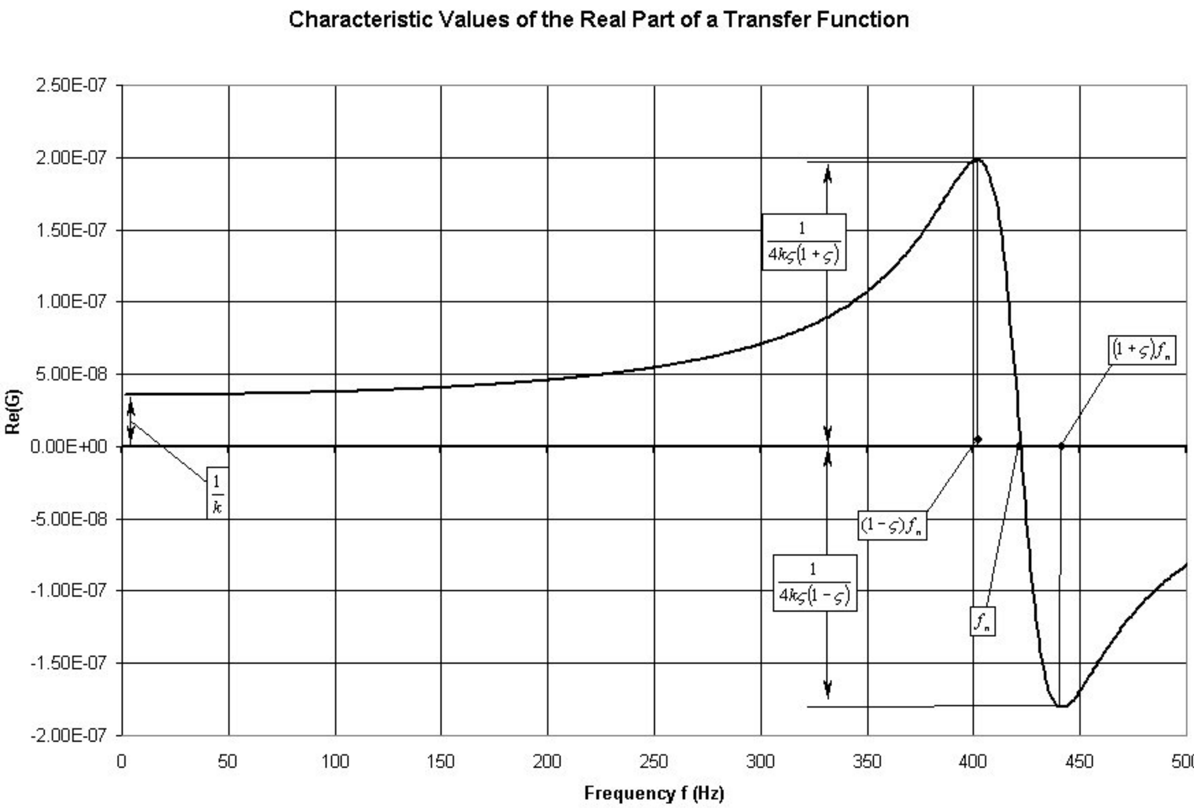


Figure 6 – Characteristics of the real part of a transfer function.

3.8. Finding the Stability Lobes By Cutting Tests

The limit of stability for a particular tool, tool holder, spindle and material combination can be found by systematically cutting a series of slots in a workpiece material varying the depth of cut and radial immersion. This process will determine under which conditions chatter occurs. Cutting tests are commonly used with an acoustic sensor (microphone) in conjunction with a computer and software that will perform an FFT on the signal coming in from the microphone. One such software program is the "Harmonizer" by Manufacturing Laboratories Inc. which is available for use in building 840.

A series of slots are cut at varying depths. When chatter occurs, the Harmonizer software determines a new spindle speed. The cutting of slots continues until speeds chosen by the Harmonizer do not yield a stable spindle speed. This method is not recommended for use on materials tougher than aluminum.

Experimental Setup:

1. Pick tools and tool holders to be tested.
2. Mount tools in tool holders. Record the following:
    A. Which tool is in which tool holder – note if a tool or tool holder is replaced during the experimental process.

B. The extension length from the tool tip to datum on tool holder – be consistent from tool holder to tool holder!
C. The exact cutting diameter of the tool – use a micrometer or other gage.
D. The lock nut torque if using collet tool holders.

3. Balance the mounted tools. Use a two-plane balancer.
4. Warm up machine.
5. Mount a block of the workpiece material in the machine using a vice or other clamping means. Skim cut the top of the block to true the top of the block to the machine table.

Experimental Procedure:

1. Pick a spindle speed between 15K-22K RPM. Make sure it is below the spindle redline. <u>Make sure the spindle can be run continuously at the chosen speed!</u>
2. Pick a feed per tooth. Calculate the feedrate and cutting power. <u>Compare to spindle power curve for the chosen spindle speed.</u>
3. After performing all of the steps in the "Experimental Setup" section, mount the tool in spindle.
4. Perform cutting test:
   A. Start the Harmonizer recording.
   B. Cut a slot (full radial immersion of the tool), 0.05" deep into the workpiece.
      I. Start off of the material at least ½ the tool diameter (do not plunge into material).
      II. Cut a slot that is at least twice at long as the cutter diameter.
      III. Feed up and stop.
   C. Stop the data collection on the Harmonizer. Let it analyze the cutting audio data and report its findings. In the cases of chatter the Harmonizer will recommend a new spindle speed. Dial it in exactly (do not round off).
   D. Increment the depth 0.05" and repeat steps 4A-C.
   E. Continue to increment the depth of cut by 0.05" per pass until the Harmonizer is unable to calculate a stable cutting speed.
   F. For each cut, record: (1) radial immersion of the cutter, (2) the depth of cut, (3) spindle speed, and (4) the presence of chatter. It may also be wise to not re-cut surfaces in order to measure surface roughness at a later time. In this case make sure the test piece is clearly marked.
5. Repeat the steps in #4 above for 100%, 75%, 50% and 25% radial immersion.
6. (optional) To find other stability lobes, start at a lower spindle speed and repeat steps 4-5.
7. Repeat the process steps 4-5 for each tool to be tested.

4. ORIGINAL PROCESS DESCRIPTION AND BASELINE

4.1. Mold Manufacturing and Processing Overview

Each mold body has five main processing steps (Figure 7):

1. Milling
   a. Rough internal cavities
   b. Rough external contours
   c. Finish internal cavities.
2. Turning - Pair mold halves, finish the external contour.
3. Milling - Finish the datums XX and XX.
4. Insert grinding and installation - Steel inserts and datums are ground and installed.
5. Hand finishing and polishing.

The operations targeted for improvement were the first milling operations (#1) and the hand polishing steps (#5). Process modifications were intended to greatly reduce time spent in the #1 milling operations while creating surfaces that did not require hand-polishing operations, thereby eliminating operation #5.

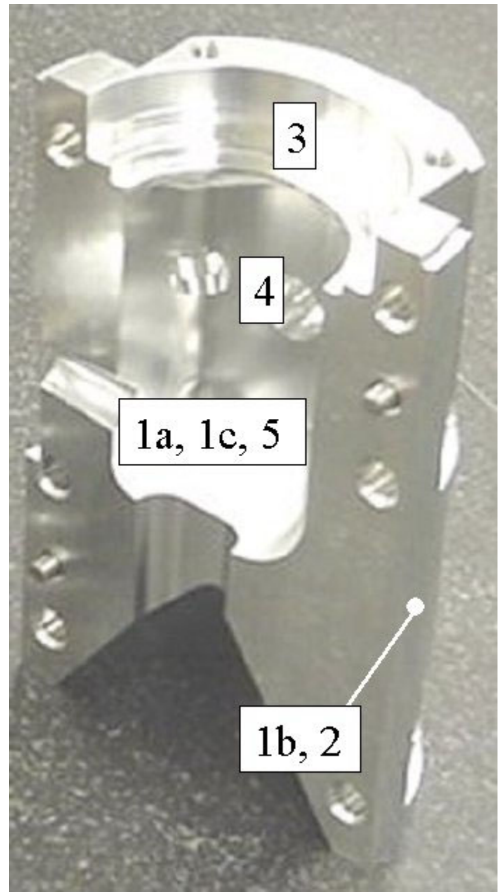


Figure 7 – Locations on mold body # MT70874T01-202 where machining operations take place

4.2. Original Equipment Specifications

Mold cavity machining operations have been successfully carried out on the Fadal 4020A CNC machining center – an industry recognized machining workhorse. Specifications for the particular machine in 840 are given in Table 6 and a picture in Figure 8.

Table 6 – Specifications of the 4020A installed in building 840.

Table Size	48" x 20"
Cutting Feed Rate (X/Y/Z)	.01"-400 ipm
Rapid Travel Rate (X/Y/Z)	900 (X,Y) 700 (Z) ipm
Ball Screw Size (X/Y/Z)	40 mm Dia. X/Y/Z
Axis Travels (X/Y/Z)	40"/20”/20” (Opt. 28”)
Accuracy, Axis Positioning	+/- .0002"
Accuracy, Axis Repeatability	+/- .0001"
Spindle	10000 RPM, No. 40 taper
Controller	128 bit, 1K block/second read ahead.
Spindle and Ball Screw Thermal Control	For consistent positioning repeatability.

Figure 8 – Fadal 4020A milling center.

4.3. Original Milling Process Description and Steps

The original machining process for MT70874T01-202 is outlined in Table 7. Note that fixture change over time and tool change time is not included in the estimates. Notice that setup #3 (cavity finish) accounts for 87% of the total machining time. The original machining process steps for MT70874T01-201 are very similar to MT70874T01-202 and for brevity will not be listed. The approximate machining time for the –201 is 57.2 minutes. These estimates do not take into account possible decreases or increases in feedrate override (adjustable in-situ by the machinist) that may have occurred during the machining operations.

Table 7 – Process steps for MT70874T01-202

Setup #	Step #	Tool Machining Parameters	Process Description	Time (Min)
1 - Rough internal cavities	1	3" Dia.5-flute Kennametal shell mill 3000 RPM 100 IPM .0066 in/tooth 2358 SFPM	Face top	0.50
	2	1" Dia.2-flute Data Flute carbide end mill 6000 RPM 100 IPM .0083 in/tooth 1572 SFPM	Square ends	0.82
	3	1/2" Dia.2-flute carbide end mill 8000 RPM 100 IPM .0063 in/tooth 1048 SFPM	Rough cavity and fill cone	2.07
2 - Flip over, rough external contour	4	3" Dia.5-flute Kennametal shell mill 3000 RPM 100 IPM .0066 in/tooth 2358 SFPM	Face bottom	0.72
	5	1/2" Dia.2-flute carbide end mill 7000 RPM 100 IPM .0071 in/tooth 1834 SFPM	Rough cavity and fill cone	2.70
3 - Flip back over, finish cavities	6	1" Dia.2-flute Data Flute carbide end mill 6000 RPM 100 IPM .0083 in/tooth 1572 SFPM	Square ends	0.73
	7	3/8" 2-flute carbide end mill 8000 RPM 100 IPM .0063 in/tooth 786 SFPM	Step out mold cavity	2.72
	8	3/8" 2-flute carbide ball mill 9000 RPM 100 IPM .0056 in/tooth 884 SFPM	Rough cavities	11.92
	9	1/4" 3-flute carbide ball mill 8000 RPM 100 IPM .0042 in/tooth 524 SFPM	Finish fill cone	6.77
	10	3/16" 3-flute carbide ball mill 8000 RPM 100 IPM .0042 in/tooth 394 SFPM	Finish cavity	17.48
	11	1/8" 2-flute carbide end mill 9000 RPM 50 IPM .0028 in/tooth 295 SFPM	Finish cavity	1.95
	12	3/16" center drill 6000 RPM 5 IPM	Center drill all holes	0.17
	13	0.281" HSSS M42 Stub drill 4000 RPM 5 IPM	Drill thru-holes	1.62
	14	0.180" HSS M42 stub drill 4000 RPM 5 IPM	Drill dowel pin holes	0.93
	15	3/16" HSS reamer 3000 RPM 15 IPM	Ream dowel pin holes	0.20
	16	45 degree HSS countersink 8000 RPM 20 IPM	Countersink holes	0.57
	17	3" Dia.5-flute Kennametal shell mill 3000 RPM 100 IPM .0066 in/tooth 2358 SFPM	Face bottom	0.23
TOTAL		***3 part setups, 17 steps***		***52.1***

4.4. Transfer of Original Milling Process to Mazak FJV-250 UHS

The first step to improve the process is to successfully demonstrate the original process on the new machine (Mazak FJV-250 UHS). The Mazak FJV-250 UHS (Figure 9) has better than twice the maximum spindle speed and horsepower than that of the Fadal and has a high performance control system for high speed, high acceleration motion axes (Table 8). The original process and tooling was successfully migrated to the FJV-250 UHS and demonstrated attaining approximately the processing time estimates listed in Table 7.

Figure 9 – Photograph of the Mazak FJV-250 UHS.

Table 8 – Mazak FJV-250 UHS 3-axis HSM CNC machining center features and specifications.

Table size	47.24" x 21.65"
Cutting Feed Rate (X/Y/Z)	>1000 ipm
Rapid Travel Rate (X/Y/Z)	1969 ipm
Ball Screw Size (X/Y/Z)	Not Available.
Axis Travels (X/Y/Z)	40"/20"/18"
Accuracy, Axis Positioning	+/- .0001"
Accuracy, Axis Repeatability	+/- .00003"
Spindle Speed	25000rpm, 40Hp, No. 40 Taper
Controller	Mazatrol Fusion 640
Spindle and Ball Screw Thermal Control	For consistent positioning repeatability.

5. HSM CUTTING TESTS ON THE MAZAK FJS-250 UHS

The first step to maximizing the MRR using HSM is to determine the spindle speeds for each tool that correspond with a stability gap and depth of cut. To do this the method of finding the stability lobes by cutting tests (Section 3.8) was used. Of the seven different tools that are used four of the tools (3/8”, 1/4”, 3/16” and 1/8” diameter end mills) are used in finishing of tightly-radiussed areas. Due to the nature of the finishing cuts, mold geometry and the small cutter diameters, these tools are not good candidates for MRR maximization. The other three cutters (3” face mill, 1” and 1/2”end mills) remove a great deal of material in roughing and preliminary finishing. These tools can stand higher MRR than the finishing tools and the geometry these tools affect makes them good candidates for larger depths of cut. Therefore only the three roughing and preliminary finishing tools were subjected to cutting tests. Daryl Reckaway and Jim Metzler using the Harmonizer software ran many trials on each of the three tools. Tables 9-12 show the best results they obtained.

Table 9 - Results of chatter avoidance cutting tests for 1/2", 2-flute carbide end mill

Date:	3/7/2002
Operators:	Daryl Reckaway and Jim Metzler
Cutter type:	End mill
Cutter diameter:	0.5 in
Cutter material:	Solid carbide
Number of flutes:	2
Tool length offset:	3.2681 in
Workpiece material:	7075-T6
Coolant:	NONE

Radial Immersion (in)	Depth of Cut (in)	Spindle Speed (RPM)	Feedrate (IPM)	Chipload (in/tooth)	Harmonizer message	Recommended Spindle Speed (RPM)
0.5	0.5	25000	350	0.007	Chatter detected - Lobe 1	22680
0.5	0.5	22680	318	0.007	Chatter detected - Lobe 1	20520
0.5	0.5	20520	287	0.007	Chatter detected - Lobe 1	19980
0.5	0.5	19980	280	0.007	Chatter detected - Lobe 1	19950
0.5	0.5	19950	274	0.007	Chatter detected - Lobe 1	19170
0.5	0.5	19170	268	0.007	Chatter detected - Lobe 1	18930
0.5	0.5	18930	265	0.007	Chatter detected - Lobe 1	18750
0.5	0.5	18750	262	0.007	Chatter detected - Lobe 1	18570
0.5	0.5	18570	260	0.007	No chatter detected	-

Final MRR:	65.0 in^3/min
Spindle horsepower used in cut:	20.2 Hp

Table 10 - Results of chatter avoidance cutting tests for 3", 5-flute carbide inserted face mill

Date: 3/8/2002
Operators: Daryl Reckaway and Jim Metzler

Cutter type: Face Mill
Cutter diameter: 3 in
Cutter material: Inserted carbide
Number of flutes: 5
Tool length offset: NOT RECORDED

Workpiece material: 7075-T6
Coolant: NONE

Radial Immersion (in)	Depth of Cut (in)	Spindle Speed (RPM)	Feedrate (IPM)	Chipload (in/tooth)	Harmonizer message	Recommended Spindle Speed (RPM)
1.385	0.1	7500	300	0.008	No chatter	-
1.385	0.2	7500	150	0.004	Chatter detected - Lobe 5	13481
1.385	0.2	13481	269	0.004	Chatter detected - Lobe 1	10740
1.385	0.2	10740	215	0.004	No chatter	-

Final MRR: 59.6 in^3/min
Spindle horsepower used in cut: 18.5 Hp

Table 11 - Results of chatter avoidance cutting tests for 1", 2-flute carbide end mill

Date:	5/23/2002
Operators:	Daryl Reckaway and Jim Metzler
Cutter type:	End mill
Cutter diameter:	1 in
Cutter material:	Solid carbide
Number of flutes:	2
Tool length offset:	NOT RECORDED
Workpiece material:	7075-T6
Coolant:	NONE

Radial Immersion (in)	Depth of Cut (in)	Spindle Speed (RPM)	Feedrate (IPM)	Chipload (in/tooth)	Harmonizer message	Recommended Spindle Speed (RPM)
1	0.2	12000	120	0.005	Chatter detected - Lobe 2	21000
1	0.2	21000	210	0.005	Chatter detected - Lobe 1	20340
1	0.2	20340	203	0.005	Chatter detected - Lobe 1	20100
1	0.2	20100	201	0.005	No chatter	-

Final MRR:	40.2 in^3/min
Spindle horsepower used in cut:	12.5 Hp

Table 12 - Results of chatter avoidance cutting tests for 1", 2-flute carbide end mill

Date: 5/23/2002
Operators: Daryl Reckaway and Jim Metzler

Cutter type: End mill
Cutter diameter: 1 in
Cutter material: Solid carbide
Number of flutes: 2
Tool length offset: NOT RECORDED

Workpiece material: 7075-T6
Coolant: NONE

Radial Immersion (in)	Depth of Cut (in)	Spindle Speed (RPM)	Feedrate (IPM)	Chipload (in/tooth)	Harmonizer message	Recommended Spindle Speed (RPM)
1	0.1	12000	120	0.005	Chatter detected - Lobe 1	24000
1	0.1	24000	240	0.005	Chatter detected - Lobe 1	11490
1	0.1	11490	115	0.005	No chatter	-
1	0.4	12000	120	0.005	No chatter	-

Final MRR: 48.0 in^3/min
Spindle horsepower used in cut: 14.9 Hp

Notice in each case the spindle speeds are much higher and the amount of horsepower used in the cut is a substantial percentage of the amount of spindle cutting power available – indicative of economical and efficient machine usage. In each case the depth of cut was maximized while avoiding tool chatter. Table 13 compares the original milling parameters for the three tools with the HSM parameters from Tables 9-12. Notice that the minimum improvement in MRR was 101%.

Table 13 - Comparison of optimized MRR.

Tool	Number of Flutes	Old Parameters Spindle Speed (RPM)	Old Parameters Feedrate (IPM)	HSM Parameters Spindle Speed (RPM)	HSM Parameters Feedrate (IPM)	MRR % Improvement
0.5" Dia. End Mill	2	8000	100	18570	260	***160***
3" Dia. Face Mill	5	3000	100	10740	300	***200***
1" Dia. End Mill	2	6000	100	20100	201	***101***

The actual spindle speeds and feedrates that were chosen for machining however differed slightly from those in Table 13. The actual machining parameters chosen appear in Table 14.

Table 14 – Actual machining parameters chosen.

		HSM Parameters		**Actual Parameters**		
Tool	**Number of Flutes**	**Spindle Speed (RPM)**	**Spindle Speed (RPM)**	**Spindle Speed (RPM)**	**Feedrate (IPM)**	**Change Justification**
0.5" Dia. End Mill	2	18570	18570	22920	289	Much less depth of cut used in program than in tests, which Allows a higher spindle speed and feedrate.
3" Dia. Face Mill	5	10740	10740	10187	382	Tool change, slight speed adjustment required for new setup.
1" Dia. End Mill	2	20100	20100	11490	190	Actual depths of cut closer to 0.1” than 0.2” therefore lower spindle speed selected.

6. APPLICATION OF HSM PARAMETERS TO MOLDS

Once the baseline part had been machined and the cutting tests of the three tools had been completed on the Mazak, the new speeds and feeds were developed for the remaining four tools and applied to the original machining program. At this stage of the experimental process it was desired to know how the original machining program (which we knew worked and yielded good results) would act under the higher speeds and feeds. To do this we concentrated on only the machining program for mold –202. A total of six test parts were machined. Results for each test part is not presented in the following sections. Only the final results (test part six) are presented.

6.1. New Parameters on Original Operation #1 – Roughing Cavity

Using the new HSM feeds and speeds for the roughing tools (Table 14) a 36% improvement in machining time for roughing operation #1 was observed. The original baseline parts (test parts #1 and #2) using the original speeds and feeds took a total time of 251 seconds (including tool change time). The test parts machined using the HSM feeds and speeds (test parts #4, #5 and #6) only took 160 seconds to complete (including tool change time) which yields the 36% improvement figure.

6.2. New Parameters on Original Operation #2 – Roughing External Contour

Using the new HSM feeds and speeds for the roughing tools (Table 14) a 49 % improvement in machining time for roughing operation #2 was observed. The original baseline parts (test parts #1 and #2) using the original speeds and feeds took a total time of 242 seconds (including tool change time). The test parts machined using the HSM feeds and speeds (test part #6) only took 124 seconds to complete (including tool change time) which yields the 49% improvement figure.

6.3. New Parameters to Original Operation #3 – Finish Internal Cavity

The finish operations were not as straightforward as the first two operations. The finish step used 12 tools and required extra test parts to wring out the process. Table 15 shows the final tool, speed and feed for operation #3. Using these machining parameters test part #6C was completed in 34 minutes 43 seconds (including tool change time). The baseline part was completed in 46 minutes 42 seconds (including tool change time) – a 25% improvement in processing time. The reason this operation did not show as great of an improvement in time as the other two operations has to do with the nature of the cavity geometry itself. There are many tightly-radii areas in the mold cavity. These areas require small diameter tools that cannot stand the higher chip loads as the large tools. Therefore more care must be taken with these operations, which is not always conducive to machining time reduction. This not withstanding a 25% improvement in machining time was observed.

Table 15 – New machining parameters for cavity finishing operations for MT70874T01-202.

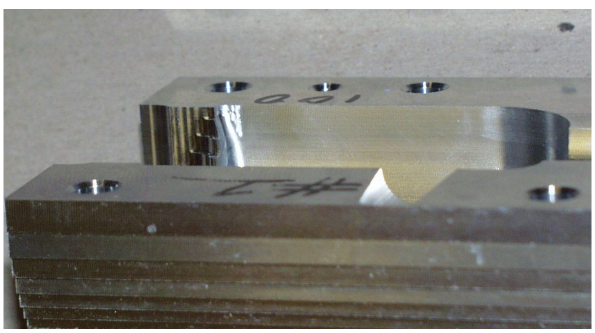
Tool			
Machining Parameters			
3" Dia.5-flute Kennametal shell mill			
10187 RPM	382 IPM	.0075 in/tooth	8000 SFPM
1" Dia.2-flute Data Flute carbide end mill			
11490 RPM	200 IPM	.0087 in/tooth	3000 SFPM
3/8" 2-flute carbide end mill			
25000 RPM	200 IPM	.004 in/tooth	2438 SFPM
1/4" 3-flute carbide ball mill			
25000 RPM	200 IPM	.0026 in/tooth	1637 SFPM
3/16" 3-flute carbide ball mill			
25000 RPM	100 IPM	.0013 in/tooth	1172 SFPM
3/8" 2-flute carbide ball mill			
25000 RPM	200 IPM	.004 in/tooth	2438 SFPM
3/16" 3-flute carbide ball mill			
25000 RPM	100 IPM	.0013 in/tooth	1172 SFPM
1/8" 2-flute carbide end mill			
25000 RPM	200 IPM	.004 in/tooth	813 SFPM
3/16" center drill			
20000 RPM	20 IPM		
0.281" HSS M42 Stub drill			
9000 RPM	25 IPM		
0.180" HSS M42 stub drill			
14000 RPM	25 IPM		
3/16" HSS reamer			
3000 RPM	15 IPM		
45 degree HSS countersink			
25000 RPM	220 IPM		

7. IMPROVING MACHINING STRATEGY AND PATH PLAN

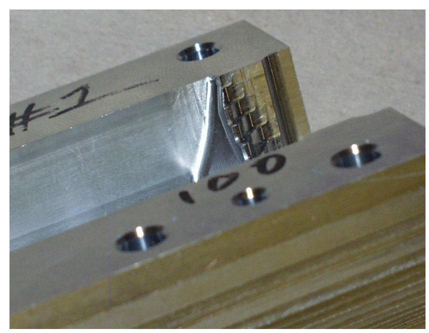
The application of higher speeds and feeds to the original machining program for the MT70874T01-202 demonstrated a significantly improved cycle time. It was determined however that there were several operations and steps that were no longer necessary due mainly to the speed and quality of the Mazak machine tool. It was found that these program sections could be deleted, modified or combined with other tool paths to create a much shorter and more efficient machining strategy.

The original machining strategy involved three different setups – one to rough the cavities, a second to rough the backside contours, and then a third to finish the cavities. Originally it was thought that these steps were necessary to control the stress relief and workpiece material warpage. This was successfully reduced to two setups – one to rough the backside and a second to rough and finish the cavities.

There were other areas of the cavities during finish that are extremely difficult to machine and leave a good surface finish. These areas are predominantly around the base of the mold where the 1/16” radius blends occur. A great deal of time was spent perfecting the machining strategy in these areas to completely eliminate chatter and gouging problems (Figure 10).



(a)



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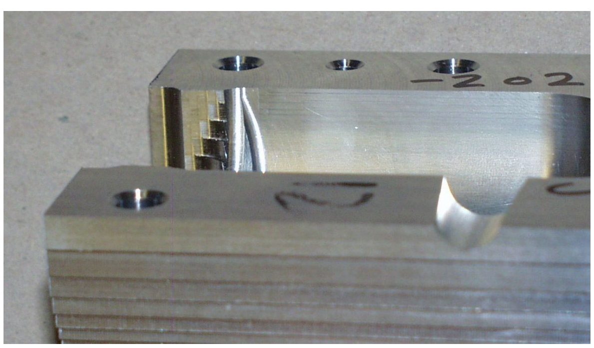
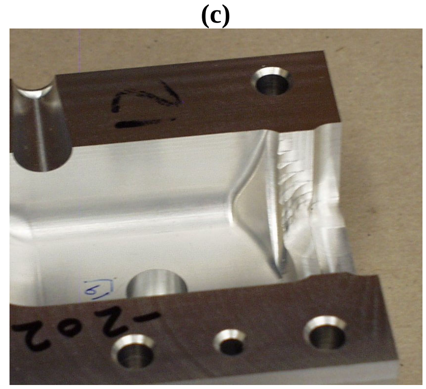


(b)



(d)

Figure 10 – Close-up of chatter and gouging in as-machined 1/16” radius blend area (a) original strategy left corner, (b) new strategy left corner, (c) original strategy right corner, and (d) right strategy left corner.

Six different test parts were machined using slightly different machining strategies (which will not be presented here) before the final machining strategy was developed. The final machining strategy, tool list, feeds and speeds are listed in Table 16.

The complete cycle time for the new machining strategy for the MT70874T01-202 was demonstrated to be 36 minutes 50 seconds versus the original machining strategy of 57 minutes 45 seconds – a 36% improvement in cycle time (figures include tool change time, but do not include fixture change-over setup time).

Table 16 – Improved process steps for machining the MT70874T01-202 mold body.

Setup #	Step #	Tool Machining Parameters	Process Description	Time (Min)
1 - Rough internal cavities	1	3" Dia.5-flute Kennametal shell mill 16000 RPM 600 IPM .0075 in/tooth 12480 SFPM	Face top	1.25
	2	1" Dia.2-flute Data Flute carbide end mill 25000 RPM 400 IPM .008 in/tooth 6500 SFPM	Square ends	
	3	1/2" Dia.2-flute carbide end mill 25000 RPM 300 IPM .006 in/tooth 3250 SFPM	Rough cavity and fill cone	
2 - Flip over, rough and finish cavities.	4	3" Dia.5-flute Kennametal shell mill 16000 RPM 320 IPM .004 in/tooth 12480 SFPM	Face bottom	35.58
	5	1" Dia.2-flute Data Flute carbide end mill 25000 RPM 400 IPM .008 in/tooth 6500 SFPM	Square ends	
	6	3/8" 2-flute carbide end mill 25000 RPM 200 IPM .004 in/tooth 2438 SFPM	Step out mold cavity	
	7	3/16" 3-flute carbide ball mill 25000 RPM 150 IPM .002 in/tooth 1219 SFPM	Finish cavity	
	8	1/4" 3-flute carbide ball mill 25000 RPM 225 IPM .003 in/tooth 1625 SFPM	Finish fill cone	
	9	3/16" 3-flute carbide ball mill 25000 RPM 100 IPM .0013 in/tooth 1219 SFPM	Finish cavity	
	10	90 degree spot drill 20000 RPM 20 IPM	Center drill all holes	
	11	0.281" HSSS M42 Stub drill 9000 RPM 25 IPM	Drill thru-holes	
	12	0.180" HSS M42 stub drill 14000 RPM 25 IPM	Drill dowel pin holes	
	13	3/16" HSS reamer 3000 RPM 15 IPM	Ream dowel pin holes	
TOTAL		***2 part setups, 13 steps***		***36.8***

Since the machining strategy for the other mold half MT70874T01-201 was very similar, the machining programs could be modified without too much difficulty to incorporate the improvements found for the MT70874T01-202 machining strategy. In doing so the complete cycle time including tool changes for the MT70874T01-201 was demonstrated to be 37 minutes 52 seconds versus 61 minutes 47 seconds for the original strategy – a 39% decrease in cycle time.

The machining cycle time for both mold halves up to this point is 74 minutes 42 seconds, which is a 37.5% improvement over the original machining strategy time of 119 minutes 32 seconds.

8. MEASUREMENT VERIFICATION

Each of the 24 mold halves was measured by a coordinate measuring machine (CMM) to verify basic dimensional tolerances (pocket width, length, and depth) and surface finish. The results of these measurements appear in Tables 17-18 and clearly show the exceptional dimensional quality and surface finish that HSM provides without secondary hand-finishing operations.

Table 17 - Measurement results (deviations from nominal) for each of the 24 mold halves.

Measured Feature	Tol (+/-)	1		2		3		4		5		6	
		-201	**-202**	**-201**	**-202**	**-201**	**-202**	**-201**	**-202**	**-201**	**-202**	**-201**	**-202**
Pocket Length (in)	0.005	.0006	.0008	-.0023	.0015	.0005	.0027	.0007	.0002	.0006	.0019	.0007	.0019
		.0006	.0008	.0032	.0013	.0004	.0024	.0006	-.0001	.0006	.0019	.0006	.0019
Pocket Width (in)	0.002	.0013	.0015	.0016	.0016	-.0002	.0016	.0019	.0018	.0019	.0015	.0017	.0018
		.0009	.0015	.0016	.0009	-.0004	.0015	.0017	.0016	.0016	.0011	.0017	.0016
Pocket Depth (in)	0.002	.0010	.0012	.0007	.0006	.0009	.0007	.0008	.0004	.0006	.0008	.0005	.0005
		.0008	.0010	.0006	.0004	.0008	.0005	.0007	.0002	.0006	.0006	.0005	.0003
Surface Finish (micro-in)	16 MAX	8	8	7	8	6	6	5	7	5	9	5	7

Measured Feature	Tol (+/-)	7		8		9		10		11		12	
		-201	**-202**	**-201**	**-202**	**-201**	**-202**	**-201**	**-202**	**-201**	**-202**	**-201**	**-202**
Pocket Length (in)	0.005	.0009	.0009	.0018	.0011	.0013	.0012	.0027	.0027	.0012	.0029	.0013	.0016
		.0008	.0009	.0016	.0009	.0011	.0011	.0025	.0027	.0008	.0027	.0012	.0015
Pocket Width (in)	0.002	.0014	.0012	.0009	.0013	.0013	.0017	.0015	.0013	.0014	.0010	.0012	.0017
		.0012	.0012	.0008	.0012	.0011	.0016	.0010	.0012	.0014	.0010	.0011	.0015
Pocket Depth (in)	0.002	.0009	.0010	.0014	.0012	.0010	.0006	.0011	.0011	.0007	.0011	.0006	.0004
		.0008	.0009	.0012	.0008	.0010	.0005	.0010	.0010	.0006	.0010	.0005	.0002
Surface Finish (micro-in)	16 MAX	7	13	6	9	8	12	9	12	5	9	9	14

Table 18 - Calculated statistical parameters for each measrued feature.

	Max	**Min**	**Max-Min**	**Mean**	**3*Std. Dev**
Pocket Length (in)	.0032	-.0023	.0055	.0013	.0029
Pocket Width (in)	.0019	-.0004	.0023	.0013	.0013
Pocket Depth (in)	.0014	.0002	.0012	.0008	.0008
Surface Finish (micro-in)	14	5	9	8	7.7

9. CONCLUSION

Modern High-Speed Machining (HSM) methods were successfully employed and demonstrated on Sandia WR product (MC4531 neutron generator encapsulation mold bodies

MT70874T01-201 and MT70874T01-202) using existing personnel and equipment on the machine shop floor in building 840. Using HSM techniques, it was speculated that the machining time would be reduced by about 25% while generating parts with a better surface finish that would require less secondary processing (hand polishing).

Results of the project clearly show that these initial projections were greatly exceeded by successfully demonstrating on 24 mold bodies a nearly 38% decrease in machining time while achieving on the average 50% better surface finishes than called for without the use of hand polishing or other secondary operations. Surface blemishes caused by tool gouging and chatter due to part geometry complexities were completely eliminated. The number of setups was also reduced from three to two allowing a faster, more streamlined process.

During the project a capability was generated in 840 in the proper use and application of tools to aid in HSM on aluminum parts including the use of software (Harmonizer), machining tests to optimize metal removal rates (MRR), stability lobes and optimization of spindle horsepower to generate the most efficient use of the Mazak FJV-250 UHS spindle power and feedrates.

In conclusion, based on the success of this study and its results, HSM is definitely a viable technique that can be applied to aluminum WR Sandia products and if applied appropriately can yield great reductions in machining time, number of set-ups and eliminate uncontrolled secondary operations such as hand polishing all of which lead directly to cost saving and product quality improvement. In addition these techniques are within reach of the existing equipment and personnel capabilities in the Manufacturing Enterprise.

10. FUTURE WORK

The surface in the applicability of HSM to WR part was only scratched by this brief study. Aside from high quality surfaces in aluminum, HSM has been proven to be very effective in other materials surface as cast iron, steel, hardened die and tool steels and even titanium. HSM has a proven reputation in the aircraft industry to consistently machine complex thin-walled, thin-floored parts (0.030”) from solid billets of aluminum, allowing for lighter, less expensive parts than conventional riveted sheet metal and allow for more streamlined and consistent manufacturing and production. Another virtue of HSM that was not fully explored in this study was the ability to cut directly to a finished surface during roughing operations. Due to geometrical constraints, a finish cut with a 1/8” diameter endmill was necessary on the encapsulation molds chosen for this study. However in the larger parts where the features do not require such tooling constraints, and where thin walls and floors are desired, it is possible to leave a perfect surface without finishing or “spring” passes. The final surface is cut to finish dimensions and tolerances directly without multiple passes.

HSM also fits well with quality paradigms such as ISO9000. Machining system dynamics are very sensitive to changes in tooling and tool holders. Therefore it is desirable to control these parameters as closely as possible including: milling cutter brands, tool setting, tool length, tool holder type (hydraulic, collet, or shrink-fit), even keeper-nut torque can cause inconsistencies in the application of HSM. Optimal use of HSM would require a standardize set of tools and tool setup for each machine that would provide consistently high MRR at consistent and reliable spindle speeds. This type of manufacturing control is ideally suited for incorporation into a quality system.

A number of types of parts produced by SNL's Manufacturing Enterprise could benefit from the application of HSM practices including: molds, fixtures, as well as rocket and satellite components. These parts can be made from a wide variety of materials (not only aluminum). The nature of HSM milling process stabilization by spindle speed and depth of cut modulation is not necessarily machine specific. There have been cases where very large machining centers with low speed spindles (<5000 RPM) have been better utilized through the application of HSM.

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