Abstract
The machining of hard materials like titanium generate mechanical vibrations within the machining and tooling mechanical systems resulting in reduced optimum cutting conditions. Productivity and tool life are inversely proportional in these materials unless vibration can be reduced and the cutting zone properly cooled. Makino has developed its new AdvanTige technology for milling Titanium. Our latest solutions for titanium include new 5-axis machining centers designed specifically for titanium applications, and a series of new technology developments that will both improve productivity and increase tool life.

1.0 INTRODUCTION
Every mechanical system has one or more natural frequencies at which it will vibrate more readily than at other frequencies. Every rotating cutting tool has its own natural frequency as well and also creates cutting frequencies due to the physical engagement of the cutting edges rotating into and out of the material being machined. This combination of cutting frequencies exciting other natural frequencies is normally referred to as vibration or in higher frequencies, chatter. Makino has developed new machine technologies called AdvantTige™ which help inherently reduce, monitor and counteract machine vibrations as well as monitor and counteract tool vibrations.

2.0 ANALYSIS OF THE MACHINING SYSTEM
2.1 Machine Rigidity
Each system has frequency ranges that are more ‘stable’ than others meaning the likelihood of generating vibration or chatter are less likely. Analysis of a frequency response function through tool tap testing can determine these ‘lobes’ of stability for the machine and tool.

Figure 1: Stability lobe diagrams showing low and high rigidity effect on depth of cut.
Figure 1 shows the results on depth of cut that having a more rigid system can provide. For the same given cutter RPM (or cutter frequency), a larger axial depth of cut is possible without the risk of vibration or chatter both enhancing productivity and tool life.

As shown in figure 2, even in a rigid setup, but with additional damping of vibrations, for all frequencies (RPMs) the depth of cut can be increased once again. This allows an even greater and substantial improvement in those ranges determined stable.

Machines possessing large way structures, heavy, rigid bases and columns increase the amount of inherent rigidity of the machine itself. Machine tools built with this concept already have an advantage in taking heavier cuts. This has been proven throughout the history of machine design.

In addition to a rigid machine design, if the design incorporates methods to damp any remaining vibration that occurs, deeper axial cuts are possible.

**2.2 Active Damping**

One of Makino’s new machine technologies is the ability of the machine tool to sense and respond to machine structure vibration. Called ‘Active Damping’, this feature uses faster processor technology (2X-4X faster) in the control along with stiffer control members and lubrication control to increase or decrease the amount of way friction to allow the machine structure to absorb more vibration on demand.

This has been implemented on all 5 axes of the machine tool thereby limiting vibration from any of the 5 axes of the machine. This technology is based on previous load compensating technology Makino developed in the 1980s. As vibration is sensed by the control system, the amount of oil in the way systems is modified thereby changing the stick-slip friction factor of the components. This causes the machine to remain stable even though cutting vibration wants to move the machine axes.
Figure 3a: Additional friction in the machine tool ways can further reduce vibration.

Figure 3b: Active damping of the machine tool can further enhance an already stable frequency range.

Figure 3b shows an example of the dynamic forces in 3 axes measured by a Kistler plate during machining. As illustrated, Active Damping reduces the X and Y vibration considerably. Per these graphs, X forces of 0-6kN (0-1348lbf) are reduced to just around 2kN (450lbf). Those in the Y axis range from 0-10kN (0-2,248lbf) but with active damping are held to around -5±1kN (1124±225lbf). This excitation at these strengths and low frequencies (~20Hz) can cause severe cutting edge damage and machine vibration which will reduce productivity, break tools or at least reduce tool life.

Tool frequencies can be calculated by (RPM/60) x (# cutting edges). For example, a 2” (50.8MM) cutter running 131SFM (40M/MIN) at 250RPM with 4 edges would yield 250/60(rev/sec) x 4(edges) = 16.7Hz (cycles/sec).
2.3 Spindle Vibration Monitoring and Correction

In addition to the machine structure vibration due to machining frequencies, the tool assembly including the spindle, due to close proximity to the origin of these vibrations, is much more readily excited, and at higher amplitudes. Using this information, Makino has designed an Autonomic™ spindle capable of detecting these frequencies and included control software to determine if they are of a detrimental nature and correct for them. The software evaluates if the frequencies are out of phase (vibration/chatter) and if so, calculates a best higher or lower cutting frequency (RPM) and readjusts the feed rate to maintain the same chip load.

![Autonomic Spindle](image)

*Figure 6: The Autonomic spindle, using accelerometers can detect vibration and automatically adjust speed and corresponding feed to eliminate the vibration detected.*

3. SUMMARY

The machining of hard metals like titanium have raised new issues with productivity and tool life in low RPM machining applications. Makino has studied the effects of vibration on productivity and tool life and determined that rigidity in the machine tool structure as well as new technology to detect and react to these vibrations can help to enhance productivity and reduce tool wear simultaneously. This combination allows for a combination of both better productivity and tool life.

ACKNOWLEDGEMENTS

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Counteracting Cutting Vibration in Machine Tools

Author: Mark W. Larson
Titanium – Why is its importance growing?

- Boeing 787, Airbus A350WXB, JSF F35 Lightning II are all using more Titanium than previous designs
- There are industry estimates of 1 million pounds of titanium to be machined per month!
  - At about 0.160 lbs per cubic inch, that is 6,250,000 IN$^3$ per month!
  - Based on currently around 0.6 IN$^3$ average overall removal per minute, requires about 173,611 machining hours per month!
  - At 20 days per month, 24 hours a day, 85% efficiency, that would be 426 spindles
- There is obviously a building demand for titanium machining capacity
Counteracting Cutting Vibration in Machine Tools

- So, what is Makino doing about it?
  - New Machine Designs
  - New Technologies

- These pursuits have led to a better understanding of the needs for machining titanium
Counteracting Cutting Vibration in Machine Tools

- **What are the issues?**
  - Titanium is a hard metal requiring high cutting forces to machine the material
  - Titanium, due to its resistance to heat, requires relatively slow cutting speeds, resulting in a lower RPM (or very poor tool life results)
  - Vibration – high force at low frequency
Counteracting Cutting Vibration in Machine Tools

What are the results of vibration?

- Harmonics – based on the frequency of the vibration, other natural frequencies may be excited within the machine, the spindle or the tool assembly
  - The machine bed, column, table, fixture, spindle, tool holder and tool body all determine the amount of impact these cutting frequencies have on the tool/part interface
- Undetected effects – at low surface speeds, the RPM is low resulting in very low cutting frequencies – these are not obvious like high frequency chatter and quite often go undetected
  - Lower tool life due to tool damage
- Higher per part cost
  - Both tool costs and machine operation costs increase
Why Is A Rigid Structure Required?

A rigid structure increases the machine’s capability for higher productivity.

**Rigidity:** low

- unstable area
- generation of chatter vibration

**Rigidity:** high

**Stable area**

**Stable limit line figure**

TITANIUM 2010

Orlando, Florida

3-6 October 2010
New Makino T-series Machine

- Example of a rigid machine - the Makino Aerospace T-series – T4 and T2
  - Rigid, heavy duty box way machine (248,000 lbs) to allow for heavy cutting – 12.2” wide and 2.4” thick, deep-quenched ways!
  - Rigid twin gear driven spindle - HSK-125A, 100kW / 1000Nm (133 HP / 740 ft-lbs) spindle with A/C axes
New Makino T-series Machine

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www.makino.com
T-Series Rigid Construction

T2 Bed Castings

Large way surfaces

2.4” (60mm)

Table casting

12.2” (310mm)
New Makino T-series Machine
Deep-quenched Large Slide Ways
High Speed & High Torque Rotary Axes

Rigid Twin Gear Driven A-axis Unit
Advance drive train on A-axis

- Mechanically and thermally balanced twin drive train
- Full scale feedback systems
- Pre-loaded A-axis slide ways reduce cutting vibration
- Simple and high torque reduction system with dual helical gears

Patent pending
www.makino.com
What Does the Damping Ratio Provide?

A higher damping ratio characteristic of a machine further increases productivity.
Makino’s Active Damping System

Constructed primitives
- Rigid structure
- Stiff spring connection between motor and mechanism
- Controlled mechanical damping factor
- Advanced servo control
Makino’s Active Damping System

- Controlled Mechanical Damping
  - All 5 axes have the functionality to change the friction to balance the cutting force - the friction reduces cutting vibration
Makino’s Active Damping System

Output - time domain (Channel 1)

Active Damping System: OFF

Output - time domain (Channel 1)

Active Damping System: ON
Cutting Force Measurement Result by KISTLER

Active Damping System
Off

Active Damping System
On

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Surface Quality Comparison

Active Damping System
Off

Chattered surface

Active Damping System
On

Clean surface
Makino’s Autonomic™ Spindle Technology

- Spindle detects, thinks, decides and reacts by itself
  - Level 1: Alarm history log recording and review
  - Level 2: Vibration and temperature monitoring
  - Level 3: Cutting force monitoring
Autonomic Spindle Technology (Level 4)

Autonomous Sweet Spot Search and Approach

Cutting Force [N]

Spindle speed [rpm]

Stability lobe diagram

Unstable cutting

Stable cutting

Chatter

sweet spot

Stable

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Evaluation Test in MAG1

Evaluation Test in Aluminum Application

MAG1 with AST4
Surface Quality Comparison

Autonomic Spindle Off

Autonomic Spindle On

Cutting direction

Chattered surface

Clean surface

Initial speed: 15000 rpm

Controlled speed: S13050 rpm
New Processing Methods for Titanium

- Based on advances with this new Makino technology called ADVANTiGE, new process advances are made possible
  - Heavy hogging
  - One-shot finishing
  - Extended tool life
Heavy Hogging

Pump spec.
- 200L/min (53 gallon/min)
- 7MPa (1,000psi)

Real measured
- 175L/min (48 gallon/min)
- 6.9MPa (986psi)

<table>
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<tr>
<th>Tool</th>
<th>Spindle speed ( [\text{min}^{-1}] )</th>
<th>Feed rate ( [\text{inch/min}] )</th>
<th>( a_p / a_e ) [inch]</th>
<th>MRR ( [\text{inch}^3/\text{min}] )</th>
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<td>Dia. 3.15&quot; 5 Flute, porcupine cutter</td>
<td>245</td>
<td>5.9</td>
<td>1.32 / 3.15</td>
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One Shot Wall Finisher

- Chatter-free, long-edge endmill
- Works fine for tall walls and pocket corners
- No step mark on the wall
- Can take large radial depth of cut

.63” carbide EM 5 flutes
One Shot Finish (with long flute end mill)

- Shorter cycle time
- Beautiful surface finish (no step)

One shot finish - Depth: 2.4” (61mm)
Conclusions

- Titanium machining demand is on the rise
- One large limitation to machining titanium is vibration, caused by cutting forces and both cutting and natural frequencies
- A rigid machine design, active damping of vibration and automatic spindle detection and corrections for vibration are beneficial
- With these capabilities, productivity and tool life can both be increased reducing overall part cost
Thank You