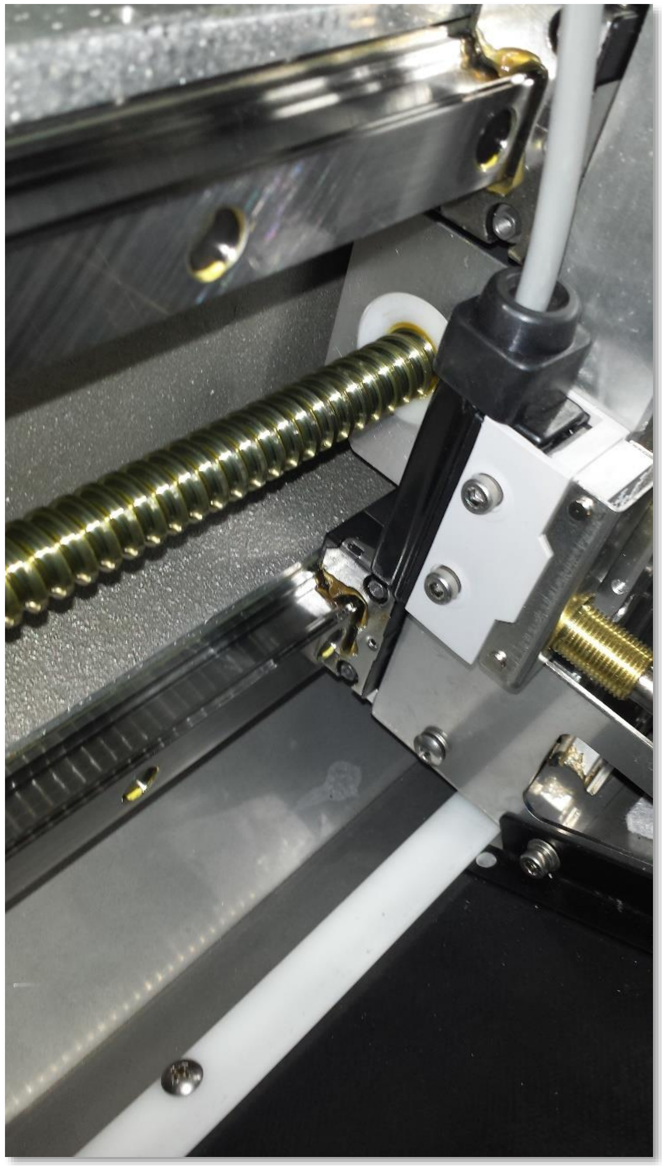


CNC Machine Vibration

CAUSES AND EFFECTS ON DENTAL RESTORATION QUALITY

Axsys Dental Solutions

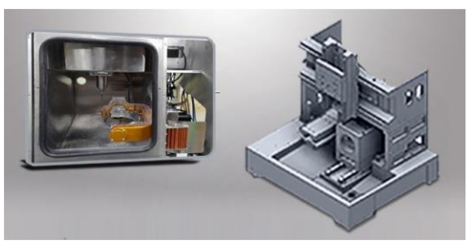
Abstract

The objective of every machining operation is to remove material within tolerances as quickly as possible. The challenge for every lab, milling center or dental practice is, for a given material and restoration type: determining the optimum machining conditions that will produce highly accurate restorations, in the shortest time-frame while maintaining high-quality gingival margin, fine surface finishes, minimum post-machining hand work and long cutting tool life while meeting their individual production, quality, reliability and profitability requirements.

Knowing machine construction elements and how they affect operation, reliability, quality of output and cost of ownership allows dental professionals to make educated decisions in the selection of a machining center that will meet their needs and requirements.

FOUR KEY ELEMENTS

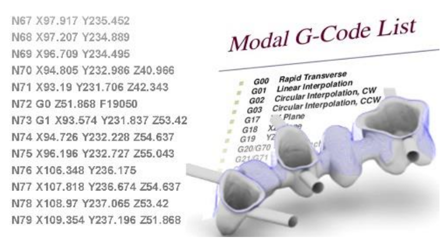
There are 4 key elements that determine reliability, performance, restoration quality and operational costs. These elements are:



1. Machine construction.

2. Part fixturing.

3. CAM Software.



4. Machining templates.

The Dental Machining Center

There are many interrelated factors that affect a DMC's (Dental Machining Center) power, speed and accuracy.

It's the balance between these critical areas (power, speed, accuracy) that must be evaluated against your needs to get the best buy for your money.

POWER, SPEED, AND ACCURACY

The basics include the machine frame, spindle drive system, machine operating system (CNC control), and the axis drive system.

The spindle drive system provides power to the cutting tool to remove material.

The machine control or "machine operating system" is the brain of the DMC and coordinates machine motion.

The axis drive system determines how smooth the motion of the DMC is and how that translates into restorations that are consistently accurate with the required fit, margin and surface finish quality.

The quality of the axis drive system is a function of the construction of the frame and the machine axes way system. This aspect of the machine determines rigidity, vibration damping capacity, and resistance to side thrust.

It's the balance between these critical areas (power, speed, accuracy) that must be evaluated against your needs to get the best buy for your money.

The key is selecting a small footprint machine that offers the best features and benefits of full-frame industrial high-speed CNC machine tools – one that is reliable, easy-to-operate and requires minimum maintenance. This requires adherence to strict design standards, incorporating construction techniques and components that are:

- Of high precision.
- High-quality.
- Rigid.
- Heat-dissipating.
- Vibration-absorbing.

THE HEART OF A DIGITAL DENTAL MANUFACTURING SOLUTION

The milling machine stands at the heart of a reliable and effective digital dental manufacturing solution requiring high productivity and accuracy.

The high-speed machining of dental materials necessitates the need for higher feed rates and spindle speeds, which increases the heat and cutting forces in the system.

These high-speed machining rates lead to higher deflections, thermal deformations and vibration of the machine, which results in accuracy deterioration.

To achieve the required high operating bandwidth while maintaining relatively high accuracy, the structure of CNC machine tool must be rigid.

Machine Vibration and Chatter

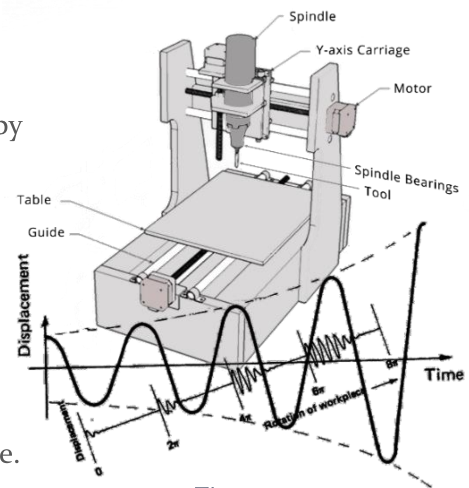


Figure 1

Machining vibrations are also referred to as chatter.

Chatter is a self-excited vibration induced and maintained by forces generated in the cutting process.

More than vibration, in machining chatter is vibration that feeds on itself as the cutting tool moves across the part.

The cutting tool, tool holder, spindle, bearings and machine components vibrate at some natural frequency or frequencies (Figure 1) leaving waves in the machined surface. This "waviness" can cause the subsequent tools cutting edge to experience a variable load. This variable load feeds the vibration.

Chatter results from the momentary separation of the tool and workpiece and the immediate banging back into contact. It is a danger signal of impending possible chipping or fracture.

Gearing and a ballscrew nut fit may introduce backlash. Machine way motion becomes jumpy at slow speeds ("slip-stick" motion), even with heavy lubrication. A milling cutter at slow feed may actually rub until pressure builds up. It then may dig into the work and surge ahead. Adding to the difficulty, the sudden change in cutting torque adds to the pounding caused by the tools cuttng flutes entering the cut.

The remedy is to eliminate uneven motion and loose fits. As an extreme simplification, chatter can be combated with lower cutting forces while looseness and backlash cannot. Like all other problems in machining, chatter can be greatly reduced by proper fixturing, rigid machine construction, appropriate cutting parameters and proper tool design.

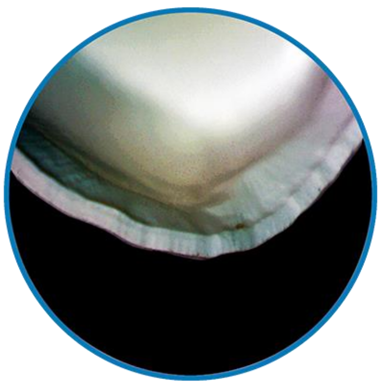
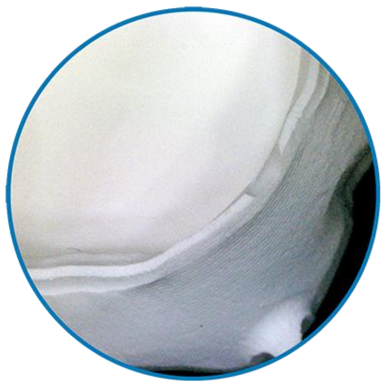
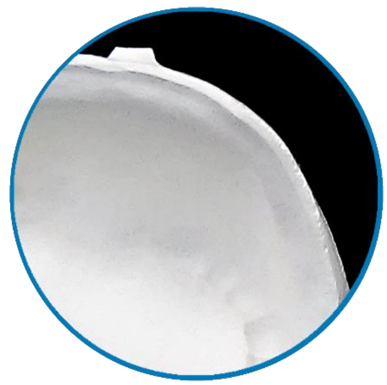
The effects of vibration and chatter include:

- Increased machine maintenance.
- Reduced machine life.
- Decreased cutting tool life.
- Broken tools.
- Reduced production rate.
- Decreased dimensional accuracy.
- Poor surface finish quality.
- Bad fits.
- Chipped or open margins.
- Excess hand-finishing.
- Increased material cost

EXAMPLES: POOR FIT AND FINISH



EXAMPLES: GINGIVAL MARGIN INEGRITY

SAFTEY IN NUMBERS: MARGIN REINFORCEMENT

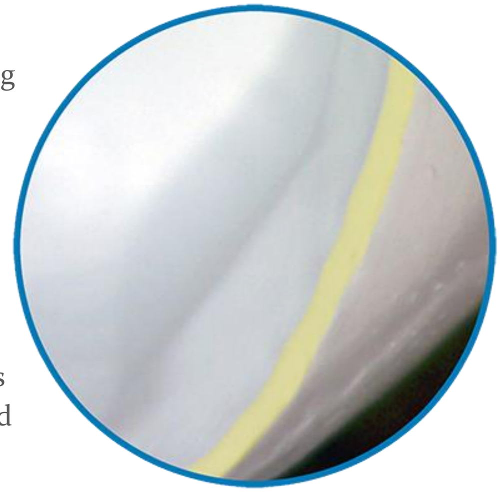
The popular “Band-aid” for increasing the quality of gingival margins is one that tries to make up for the REAL causes behind chipped margins and one that the majority of sub-$20,000 (to even as much as $40,000) mill solutions utilize. Sadly, practitioners, laboratories and milling centers have come to accept this problem as the norm and typical for all dental milling machines.

But in reality, it doesn't have to be this way!

To preserve the integrity of restorative margins, these inferior solutions must reinforce the margin area with additional stock that must later be removed by manual methods.

Some of the available solutions recommend a minimum of 200 microns of additional material be added in the restoration design phase to "reinforce" the margin in order to be reasonably confident in maintaining its integrity.

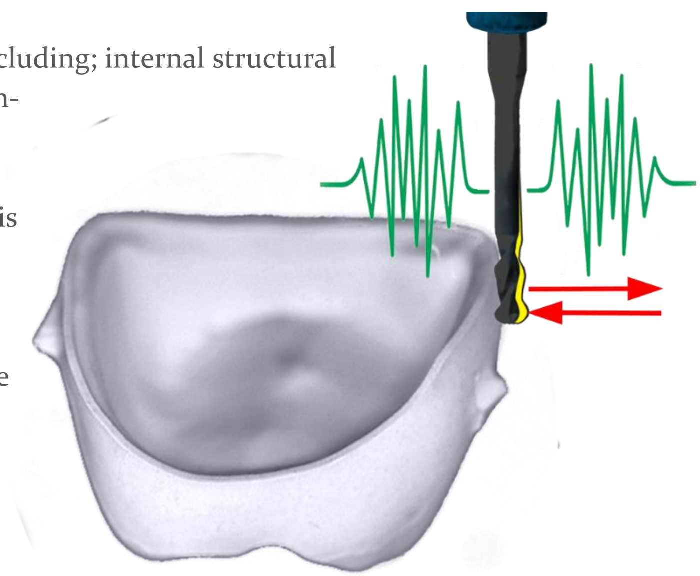
The Real Story



The margin is the area most prone to damage during the milling process. To preserve the integrity of the margin, additional thickness is added to the margin in software to strengthen it during milling and provide additional stock in anticipation of violation

While the margin reinforcement feature (which can be as much as 200µm in less capable systems) is helpful during milling, it must be manually removed afterward as part of the margin-finishing process.

Worn tooling aside, the primary reasons for margin violations and the subsequent requirement for margin reinforcement include:



- Lack of machine rigidity.
- Machine spindle performance including; internal structural quality, excessive cutting tool run-out, tool deformation etc.
- Weak fixture rigidity including lack of quality machine rotary axis gear reducers.
- Lack of available robust machining strategies or poor output generated from within the CAM software.
- Improper toolpath "processing" from within automated CAM machining templates.
- Combination of any of the above.

The structural integrity of the machine and fixture coupled with precision, high-torque spindles, robust CAM software and expert machining templates enable users to reliably produce high-quality restorations with clean, thin gingival margins and minimal margin reinforcement — as little as 40µm.

**Notice the difference between the margin quality and amount of margin reinforcement between the two crowns pictured above.*

Machine Construction

When performing a milling operation, there is a total "force-loop" that must be taken into account. This loop starts from cutter-to-part contact, and then all the way back through the machine tool. Meaning, from the part, to the table, to the guide-ways, to the bed-casting, to the column, to the headstock casting, to the spindle housing, through the spindle bearings, through the spindle-taper, to the tool-holder, down through the cutting tool, and finally back into the cutter-to-part contact.

It is important to remember: Heat and vibration are the enemy and must be eliminated in every way possible. The ability of a machine to accomplish this is dependent on several factors, Including:

- Quality and geometry of available tooling.
- Spindle: driver, construction, torque and power.
- Capability of the internal machine structure to dissipate heat, dampen vibration and absorb forces induced by the machining process
- Machine axes drive system.
- Ability to properly and securely hold the material being machined.

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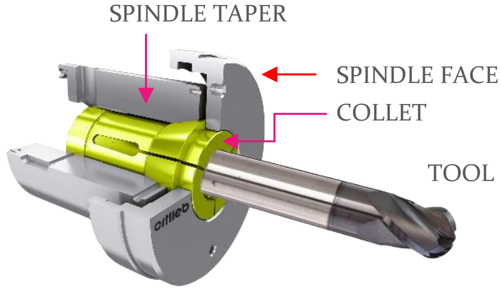
SPINDLE

The spindle is heart of any high-quality dental machining center. The design of the spindle and the quality of the parts buried within the spindle are vital to its performance and its lifespan. Quality components not only determine longevity of the spindle, they determine how the spindle handles speed, torque and vibration.

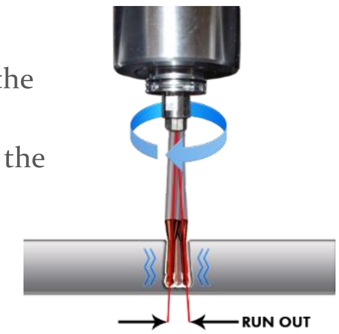
The spindle's speed, torque, bearing type/configuration, run-out and clamp diameter specifications largely influence production rates, materials that can be processed, and restoration quality.

Runout



Runout refers to the inaccuracy of rotating mechanical systems, where the tool or shaft does not rotate exactly in line with the main axis.

Dynamic runout originates in the spindle and the collet. Any errors in the production of the spindle, tool holder and cutting tool, or debris within any of these components can also be the source of runout and induce vibration.

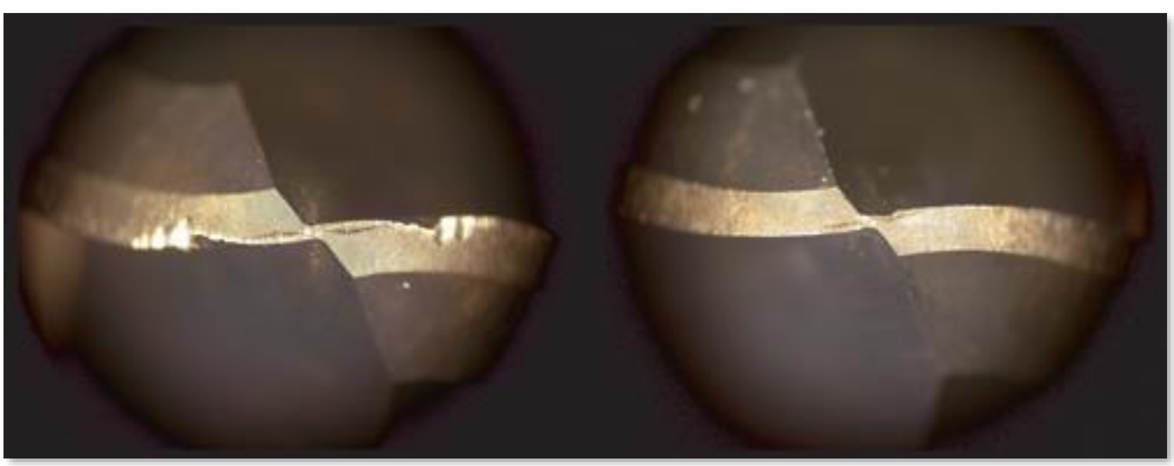


Spindle rotation errors can originate from thermal deformation of the spindle components, imperfections in the spindle taper or support bearings, wear, and imperfections in the squareness and flatness of the spindle face.

Runout causes interrupted cuts which are tough on tools. Runout and static vibration results in reduced tool life as well as decreased restoration accuracy and poor surface finishes.

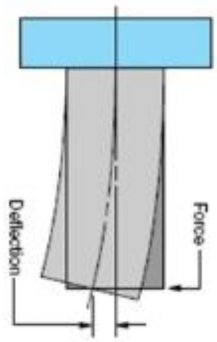
Spindle vibration, a function of spindle (type, bearings, etc.) and machine construction varies with rpm as a result of centrifugal and thermal expansion which itself induces chatter. This vibration can be easily measured by a dial indicator, smart phone app, or even felt by hand while the spindle is running.

The pounding tools take during interrupted cutting frequently leads to severe edge wear that cuts tool life, affects restoration fit and produces chipped margins.



Compare image of worn tool on the left with a new, unused tool on the right.

Deformation



Heat has critical influences on machining as it causes thermal deformation in the cutting tool and induces vibration and chatter which in turn results in increased tool wear, reduced tool life poor fits and decreased restorative margin integrity (i.e. chipped or open margins).

Smaller diameter cutting tools and those with small tool shank diameters are less rigid and particularly susceptible to deformation.

Smaller tool shank diameters will typically present long tool lengths with high tool length to diameter ratios. As tool rigidity decreases by a power of 4 relative to tool diameter, machines with smaller clamp diameters (which typically run from 3.0 – 6.0mm) and their associated tool are subject to significant tool deflections and deformations.

MACHINE STRUCTURE

To achieve better stiffness and rigidity of structure, several factors should be considered in the design. Weight is an excellent indicator of rigidity however it must be evaluated with other considerations, including;

- Contact area between the machines moving and stationary components.
- The amount of mass in the machines stationary parts.
- The ratio of width to length for continuous unsupported members of the machine.

Increasing mass reduces vibration amplitude and resonant frequency, while dampening reduces amplitude by dissipating vibratory energy as frictional heat. Since each part of the cutting system (i.e. the machine, the fixture, the tool and the workpiece) can affect the mode and amount of vibration, most should be made oversize and broadly supported.

To achieve optimum performance machine frames, the foundation of the machine on which all components are attached, should be constructed of precision machined cast aluminum-alloy (Figure 3), hybrid stone or heavy gage steel or aluminum plate (Figure 4).

Fabricated sheet-metal enclosures (Figure 4) provide no rigidity nor dissipate heat in any meaningful way.

Figure 2

Figure 3

Figure 4

AXIS DRIVE SYSTEM

The DMC's axis drive system contains all the components necessary to quickly and accurately drive and position each machine axis in the machining process (Figure 5). Key components include:

- Axis drive motors that drive the linear motion drive mechanisms
- Linear motion drive mechanisms
- Rotary motion drive mechanisms
- Axes guide system—including the load-bearing components that support the spindle and table and guide their movement

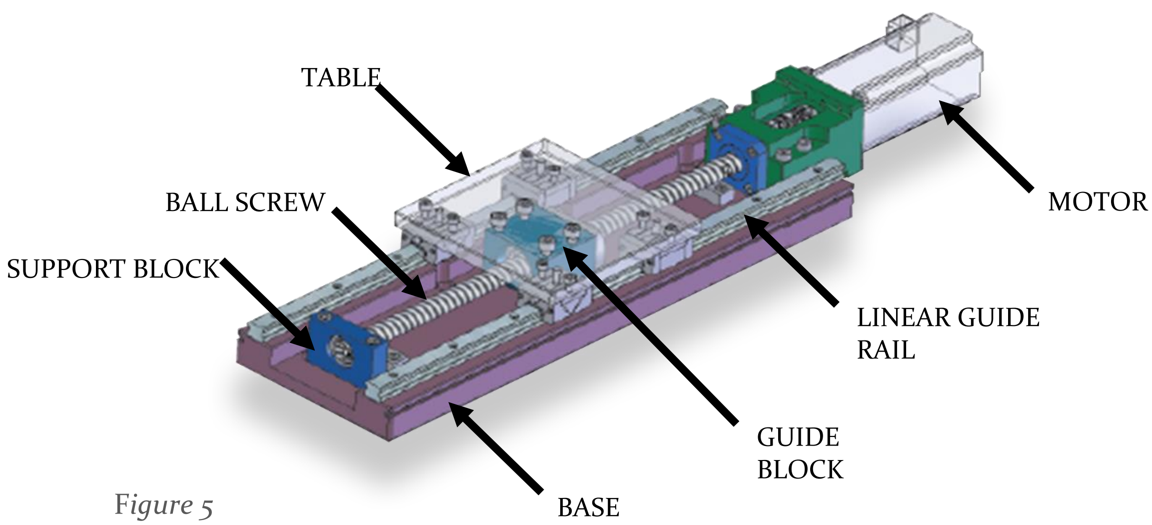


Figure 5

These systems convert the rotary motion of the axis drive motor into linear motion. In the case of screw driven actuators, the axis drive motor rotated a ball screw which drives a ball nut which is mounted to the axis “carriage” (Figure 6).

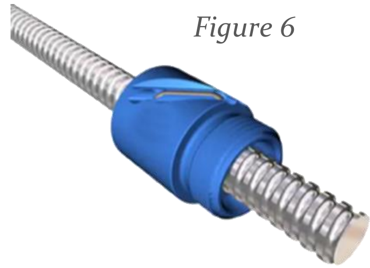


Figure 6

zThe interface between the stud and ball screw is a ball bearing system where hardened steel balls in the nut roll along the raceway of the stud (Figure 7).

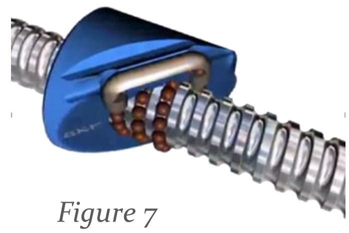
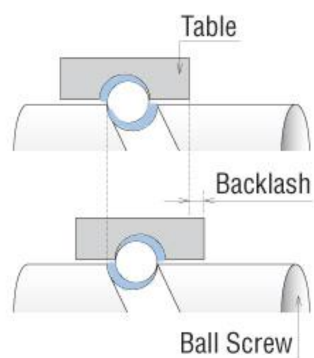


Figure 7

Ball screws are preferred for applications requiring high degrees of reliability and repeatability over extended time periods as they provide superior positioning accuracy and are less susceptible to vibration. It is important however the ball screw be fully support on each end through the use of a support block.

Backlash

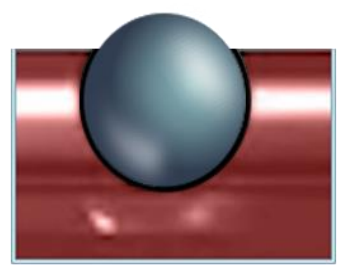
Backlash is any non-movement that occurs when an axis reverses direction. This “play” or “lost-motion” occurs between loosely fitting machined parts—like the ball screw and the ball nut for example.



The space between the ball screw and the ball nut is typically provided to allow for a film of lubricant, binding from heat expansion and eccentricity or manufacturing inaccuracies.

Backlash is a measurable quantity which to a degree, can and must be compensated for within the machine control. Regardless of “compensation”, backlash causes positioning errors and vibration in the positioning system.

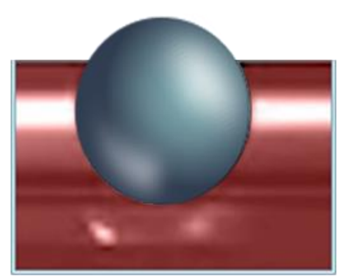
Eliminating Backlash



No preload

Backlash occurs when the diameter of the rolling element is less than the space within the track. Backlash is eliminated when the diameter of the rolling element is larger than the space within the track.

Preloading, or imposing a load on both sides of the screw thread simultaneously, even while it is not moving eliminates backlash.



Preload

Preload is the amount of force exerted against the rolling elements in a screw, without the application of any external forces.

Preload influences accuracy, speed limits and rigidity. Proper preload maximizes drive system life and optimizes machine performance.

AXIS LINEAR GUIDE SYSTEM

The guide system is the system used to move a load along a straight path with as little resistance to the direction of motion as possible absorbing static and dynamic forces.

Liner Guideways

Linear guideway systems (the preferred system in high-end CNC milling machines) are composed of two primary components. The linear rail, which guides the guide blocks and provides a smooth and durable surface for linear motion, and the Guide Block which rides on the rail and supports the load that is to be moved. One of the primary aspects of linear guide blocks and rails that set them apart from other linear bearing systems is that they are fully supported along the length of travel.

Linear guide systems are very robust and accurate. Since most guide block systems use ball bearings to roll the load along the rail, they are highly offer high accuracy, and are highly efficient with great vibration dampening characteristics.

Cylindrical Guideways

In this system, balls are not forced by a groove to move in a linear fashion and therefore cannot transmit torque. Perhaps the biggest disadvantage of cylindrical guideways is that, since they can only be supported on each end, they are less rigid and therefore subject to vibration enduring flex.

It is widely recognized that linear guideways with fully supported precision ball screws (10mm diameter minimum) with anti-backlash nuts for linear axis is the superior system for reliability, accuracy and repeatability.

ROTARY DRIVE SYSTEM

A rotary reduction drive assembly or system is utilized to provide the required power to the rotary axes— A-axis and B-axis in a 5-axis DMC.

The interface between the motor and the axis rotary assembly must be of high precision and made of high strength materials with high resistance to wear and slippage.

Factors affecting optimum dynamic response, quality and positioning accuracy include:

- Gear/reduction ratios.
- Rotary transformation.
- Gear materials.
- Backlash reduction.
- Mass inertia.
- Acceleration and velocity.
- Losses and efficiency.
- Torque.

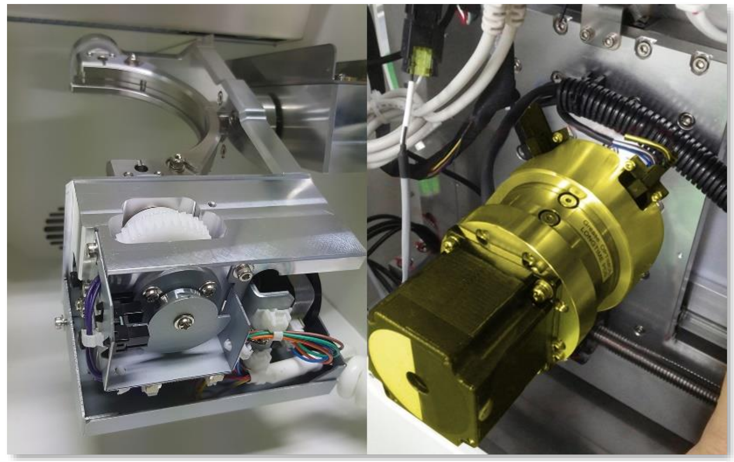


Figure 2 Comparison of rotary reduction drives between two different dental machining centers.

PROPER WORK HOLDING

Fixtures should be fully-supported to provide complete stability. If the part is not properly secured, the part itself can vibrate and induce chatter.

Set-up rigidity is vital to the maintaining dimensional accuracy of the cut surface, since the tool shifts into or out of the cut with the accumulation of static deflections and take-up of loose fits. Rigidity also maintains surface-finish quality, avoiding the marks made by elastic vibration and free play of loose fits and backlash.

In the control of vibration, rigidity of the part and cutting tool can make the difference between success or failure of the machining operation.

Good jigs and fixtures provide:

- A higher degree of positioning precision and repeatability.
- A greater accuracy for the positioning of precise hole centers.
- Tighter tolerances at micron levels with higher-quality surface finishes.
- Increased cutting tool life.

Example of proper fixturing: workpiece & fixture held securely on both ends.

Example of vibration enducing workholding : workpiece & fixture held on only one end.

Example of proper fixturing: workpiec & fixture held securely on both ends.

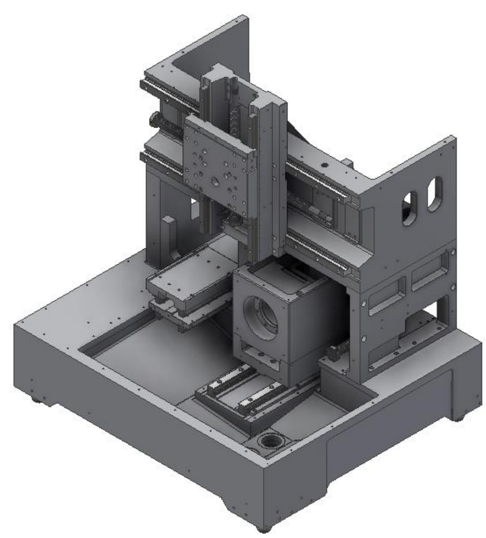
Example of vibration enducing fixturing: fixture held on only one end.

Conclusion

The dental machining center is the heart of an effective digital dental manufacturing system.

The ability of the DMC to dissipate eat and dampen vibration are key to long, effective cutting tool-life, production rates and quality dental restorations.

Interrupted cuts, whether caused by machine, fixture, cutting tool, CAM software or machining template failings must be avoided.



Key considerations in the selection of the most effective dental machining centers include:

- Ability dissipate heat, absorb vibration while maintaining rigidity and accuracy at high programed feed rates.
- Heavy, rigid frame and fixturing.
- Spindle specifications (bearings, torque, clamp Ø).
- Guideways.
- Linear and rotary motion actuators

- Axis drive system.
- Fixturing.

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