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Addressing Machine Tool Errors

To make the first part correct, machine volumetric positioning accuracy is key

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At TechSolve Inc. the Smart Machine Platform Initiative (SMPI) program is working with various technologies to reach the objective of "First Part Correct." Independent Quality Lab (IQL) was enlisted by TechSolve to perform an initial measurement of the SMPI test bed, then perform a super tuning of the machine and measure the performance difference.

What is machine tool metrology? A practical definition of machine tool metrology is the process of gaining insight into a machine's accuracy via measurement. The accuracy of a machine tool is a direct result of how true each individual axis moves, as well as the relationships between the axes. Those knowledgeable in the field focus on *"Volumetric Positioning Performance"*, which provides insight into overall machine capability. This approach to evaluating machine tools considers the performance within the entire work zone, providing a more comprehensive view of a machine's behavior than other techniques. A concept used since 1985 in the CMM industry, it's now being slowly adopted by machine tool manufacturers. At the end of the day, a machine's positioning accuracy determines its ability to achieve desired feature tolerances—in other words, its productivity.

In many shops, quality and productivity problems take on a life of their own within the plant. They become a part of the background when it comes to scheduling, machine selection, and employee assignment. Many shops accept that a machine will not be able to meet certain tolerances, or that certain tricks are needed to make good parts. Some manufacturers have even accepted that a machine is only capable within certain areas of its work volume, and they limit their work to those areas.

It is very common for manufacturers to unknowingly expend significant resources and costs when addressing machine-accuracy issues. Productivity improvement opportunities rooted in machine tool accuracy can provide significant advantages to manufacturers with the right applications. Any manufacturer struggling to shorten first-part verification, improve process yields related to feature tolerances, or eliminate unnecessary secondary operations can make significant productivity gains by focusing on machine tool metrology.

With a better understanding of the errors of the machine tool and the technologies available to address those errors, many machine shops will not only see an improvement in their part quality, but also will enjoy overall increased part production and the benefits of operating a more flexible shop.

The ideal case for a machine tool would be for every axis to be perfectly straight and square with the world. The machine would be able to move to predictable points in space along all axes. The operator would be able to load a program into the control, and know that all metal would be removed in precisely the area that was intended, producing geometries that are completely consistent with the part print or solid model. Under these conditions we could safely assume that any nonconformances in the part are solely a function of improper setup, stock issues, or programming errors.

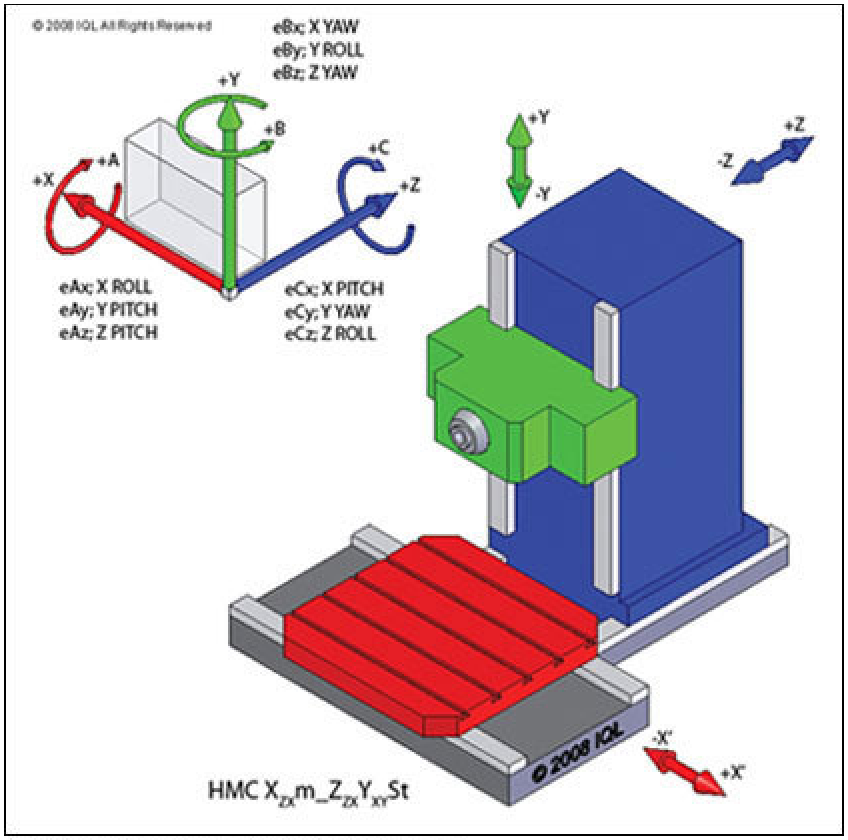


Diagram of a three-axis machine tool and angular errors.

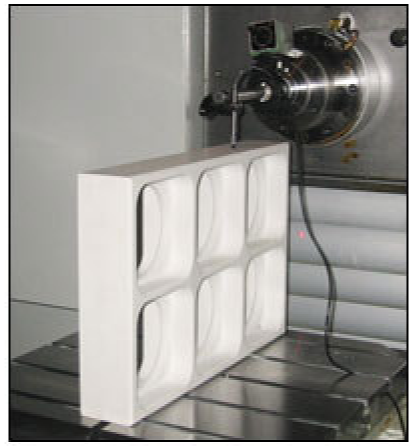
In reality, however, machining involves many variables that stand between the ideal case and what actually happens on the shop floor. Many shops deal with bored holes that are not round, surfaces that are not flat, and features that are not located at the proper distance. With experience and skill, these issues can be addressed by making compensations in the cutter paths, modifying part programs, slowing the feeds and speeds, adjusting the depth of cuts, and various other methods. In effect, machine errors are addressed after the fact to make acceptable parts.

In production environments, it's generally accepted that there will be errors in the machining process, and consequently tools are developed to deal with those errors. But these tools only address the symptoms of machine errors, not their root causes, which continue to be widely misunderstood.

Methods of measuring errors rely upon various theories and methods to gather information that is used to calculate the 3-D accuracy of a machine tool. The methods differ with regard to levels of complexity and the completeness of the information gathered.

Many people have a working knowledge of machine tool errors that's based on what they have dealt with in the past, but tend to be unaware of other, less-direct errors, or mistakenly attribute a nonconformance to the wrong metrological error. In fact there are as many as six errors that can be attributed to each machine axis: three transitional and three rotational, as well as errors in the squareness between the axes as they relate to each other (*XY, YZ, ZX*). For a three-axis machining center, that means there are 21 potential sources of error. This is the most widely accepted view of volumetric accuracy, and measuring these errors involves using a laser interferometer to take measurements at predetermined points along each axis, and then comparing the measurements to a nominal.

The net effect of all of these errors is that the tool tip removing material is not actually where the controller commands it to be. In some cases, the difference between the programmed and the actual dimension is so small that it is negligible, but when you machine a part with particularly tight tolerances (such as bolt-hole patterns or other mating features), these errors can be the difference between making a part that brings in money for your shop and generating scrap that will erode your profit margin.



Master ceramic square for pitch error is shown. Angular and straightness errors can be detected by use of a ceramic square, electronic levels, and laser interferometers.

If the machine is repeatable, making cutter path corrections is straightforward and quick. The question is, how much do these adjustments/iterations cost in labor, material, and machine capacity, in addition to extending lead times? How many sample parts are machined? How many hours of additional programming are needed? How much machine time/capacity is used? How much calendar time is lost? If the answers to any of these questions represent significant annual costs or are creating capacity constraints on key machine tools, then focusing on the root cause by using machine metrology needs to be considered. As low-hanging lean manufacturing opportunities decrease, eliminating less-obvious, non-value-added waste within the production process can provide significant advantages.

No machine tool is perfect, and all machine tools have twisting and alignment errors that will create inconsistent results throughout the work zone. The challenge to most machine shops is to find those areas in the work zone that can successfully make good parts. *Super tuning* focuses on optimizing key angular errors based upon the machine's specific structural design, resulting in consistent positioning performance throughout the entire work zone.

Preparation for the use of epoxy to anchor the machine to the floor.
Photo courtesy EOS

At TechSolve Inc. the Smart Machine Platform Initiative (SMPI) program is working to use various technologies to reach the objective of "First Part Correct". One of the thrust areas under investigation is machine tool metrology. Metrology can identify and help correct machine-tool errors that have a significant influence on the ability to make a part correctly the first time. Independent Quality Lab (IQL) was enlisted by TechSolve to perform an initial measurement of the SMPI testbed, a HMC 35 Milltronics machining center, then carry out a super tuning of the machine, and measure the difference in performance achieved.

What is super tuning? Super tuning adjusts the actual geometry of the machine on the micron level after the machine tool is secured to the floor with an extremely strong epoxy. Once the machine is anchored, several tools (e.g., a laser interferometer, master ceramic square, and electronic levels) are used to mechanically and electronically determine the errors within the machine tool. Those measurements make it possible to adjust the machine to reduce the errors.

The first step in the process is setting the machine. It's critical to make sure the spot the machine will be anchored to is analyzed in terms of material handling, access to electrical panels, and other rigging concerns. Once the position of the machine has been decided, the floor should be cleaned and prepared, old OEM pads must be replaced with new ones, and molds are placed around each pad. The epoxy is then mixed and poured in the molds, and allowed to set overnight.

Once the machine has been set into place, machine measurements need to be taken. Independent Quality Labs used the ASME B5.54 standard to perform the entire test. During this work, information is collected on all of the geometric errors of the machine, including backlash and reversal errors. After this step is completed, decisions can be made on the quality of the machine tool, not only in terms of tuning, but regarding major components that may not be performing as specified.

The machine can be adjusted to reduce or eliminate errors once they are quantified. Although the procedure for the adjustments is very precise, the concept is straightforward. The adjustments are all made from the floor at the pads. An industrialgrade epoxy holds the pads firmly in place, but all have adjustment screws that can be used to literally twist the frame of the machine into position. A well-trained technician should be able to make adjustments to the machine tool that will significantly reduce many of the errors found in the initial measurement. After the super tuning process is complete, a periodic ballbar test can be performed to identify changes, as a part of the machine tool's regular preventative maintenance schedule.

Before the SMPI testbed was super tuned, a ball-bar test was performed to baseline the state of the machine. Test findings showed that there were significant squareness issues between the *X* and *Y* axes of the machine, and that the straightness of the *X* and *Y* axes were also in great need of improvement. These issues influence the ability to machine a part within the required specifications, which is essential to the "First Part Correct" philosophy. However, this machine was in no worse condition than the thousands of new machine tools that are bought and sold in the US, and put into production making components for major manufacturers. Allowing the machine tool to remain in its as-is condition would have ensured that all of the struggles being dealt with by any other manufacturer would become a part of daily life with the TechSolve testbed.

In the pre-supertuned state, a part on the testbed that is over 300-mm long would have trouble maintaining any features that require position specifications any tighter than ±0.037 mm. For a production machine shop, this variation would be the reason for a high scrap rate, tailoring of the CNC program, and constant adjustment of the workholding to get a part within the specification.

In the case of the testbed at Tech-Solve, Inc., super tuning improved the volumetric positioning performance of the machine by 230% (±0.016 mm) and decreased the effects of angular errors in the work volume by 270%. After super tuning, therefore, the machine can position 2.3 times better than it could previously. Repeatability and reversal (backlash) were also improved by 170% and 270% respectively, resulting in a significantly more stable and precise machine.

Machine productivity is a measure of that machine's ability to create the desired geometry within the required tolerance over some period of time. The machine must first be capable of creating the desired geometry. Then that geometry must be within the tolerance requirements. Achieving the desired tolerance requires a combination of both accuracy and repeatability. In most cases, machine tools have better repeatability than positioning accuracy. However, missing the target by a similar amount every time can lead to the wasteful industry practice of modifying feature offsets and cutter paths to obtain the desired result. Lacking a formal justification for correction/improvement, many machinists and process engineers continue to work around the poor accuracy of their machines. Yet improvements made to the accuracy of machines can have a cascading effect on productivity.