

Machining Accuracy of Machine Tools

Productivity and accuracy of machine tools are important competition aspects. Rapidly changing operating conditions for machine tools, however, make it difficult to increase productivity and accuracy. In the manufacture of parts, increasingly small batch sizes have to be produced economically, and yet accurately. In the aerospace industry, maximum cutting capacity is needed for the roughing processes, whereas the subsequent finishing processes must be executed with maximum precision. For milling high-quality molds, high material removal rates are required during roughing and excellent surface quality must be obtained after finishing. At the same time, maximum contouring feed rates are necessary to realize the required minimum distances between the paths within acceptable machining times.

Thermal accuracy of machine tools is becoming increasingly important considering the strongly varying operating conditions in manufacturing. Especially with small production batches that require constantly changing machining tasks, a thermally stable condition cannot be reached. At the same time, the accuracy of the first workpiece is becoming very important for the profitability of production orders. Constant changes between drilling, roughing and finishing operations contribute to the fluctuations in the thermal condition of a machine tool. During the roughing operations, the milling rates increase to values above 80 %, whereas values below 10 % are reached during finishing operations. The increasingly high accelerations and feed rates cause heating of the recirculating ball screw in linear feed drives. Position measurement in the feed drives therefore plays a central role in stabilizing the thermal behavior of machine tools.

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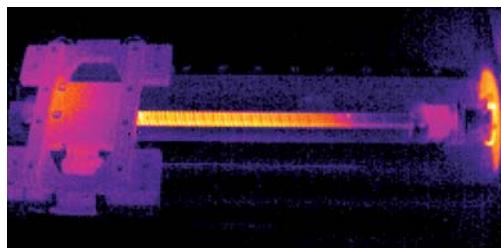


Figure 1
Heating of a recirculating ball screw during multipass milling at 10 m/min. This thermographic snapshot shows temperatures of 25 °C to 40 °C.

Thermal stability of machine tools

Solutions for avoiding thermally induced dimensional deviations of workpieces have become more crucial than ever for the machine tool building industry. Active cooling, symmetrically designed machine structures and temperature measurements are already common practice.

Thermal drift is primarily caused by feed axes on the basis of recirculating ball screws. The

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Did You Know...

...that HEIDENHAIN linear scales were the chosen components to enable high precision defense and aerospace parts to be made quickly and accurately off a mid-size VMC at **Votaw Precision Technologies** (www.votaw.com). This virtually new vertical machine center (VMC) underwent a linear upgrade when it was realized that its rotary measurement system was creating error and changes in the tolerances. Parts off this particular machine are of high tolerance and include those for satellites, Raptor fighter planes, the Aries 1 rocket and the Mars Land Rover among others, according to Richard Roy, Votaw maintenance manager.

"We had purchased this particular VMC used but it was less than a year old," explained Roy, "and soon found there to be cyclic error in the ballscrew/rotary system. We couldn't run the parts we needed to run and I knew we really needed a linear upgrade with HEIDENHAIN scales. I believe that all the top machines in the industry already come with scales on them and, in my 25 years of industry experience, believe that HEIDENHAIN scales are the best."

Votaw employed **A Tech Authority** (www.atechauthority.com) to arrange and handle the linear install on this three-axis system which only took a couple of days. "We're firm believers in the use of linear scales as the best method for machine measurement," said Craig D'Ambrosio, A Tech owner. A subsequent laser calibration of the VMC proved this to be correct for Votaw.

"This very busy machine is now extremely accurate since the retrofit," said Roy. "Even our operator who was originally skeptical has exclaimed 'what a positive difference!'"

This VMC employs three HEIDENHAIN scales (an **LB 382** and two from the **LS 100** series) with a 15-foot X axis, a 3-foot Z axis and an 8-foot Y axis. These sealed linear encoders are highly accurate and characterized particularly by high tolerance to vibration.



Richard Roy at Votaw with upgraded VMC

For more information, circle #1 on the reply card.

Machining Accuracy of Machine Tools *continued from cover*

temperature distribution along the ball screw can rapidly change as a result of the feed rates and the moving forces. On machine tools without linear encoders, the resulting changes in length (typically: 100 µm/m within 20 min) can cause significant flaws in the workpiece.

Position Measurement on Feed Drives

The position of an NC feed axis can be measured in principle through the ball screw in combination with a rotary encoder, or through a linear encoder. If the slide position is determined from the pitch of the feed screw and a rotary encoder (Figure 2, top), then the ball screw must perform two tasks: As the drive system it must transfer large forces, but as the measuring device it is expected to provide highly accurate values and to reproduce the screw pitch. However, the position control loop only includes the rotary encoder.

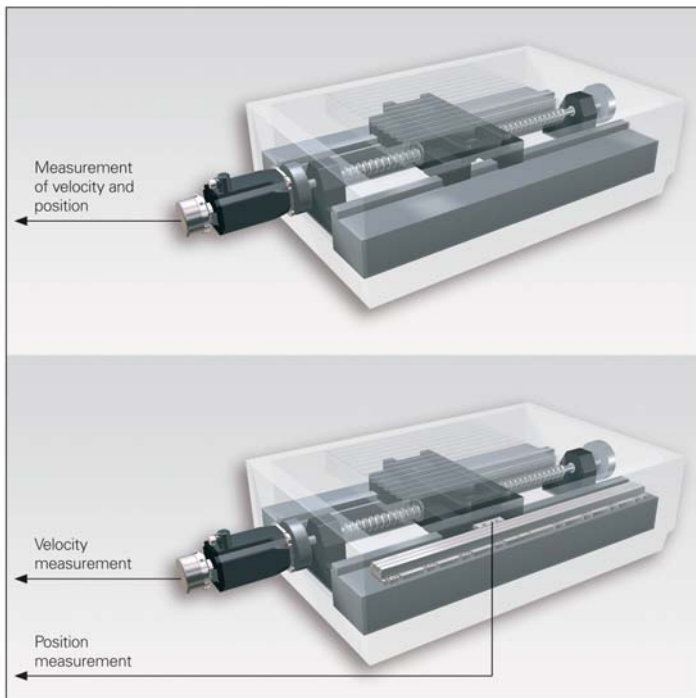


Figure 2
Position feedback control in semiclosed-loop mode (top) and in closed-loop mode (bottom)

Because changes in the driving mechanics due to wear or temperature cannot be compensated, this is called semiclosed-loop operation. Positioning errors of the drives become unavoidable and can have a considerable influence on the quality of workpieces.

If a linear encoder is used for measurement of the slide position (Figure 2, bottom), the position control loop includes the complete feed mechanics. This is therefore referred to as closed-loop operation. Play and inaccuracies in the transfer elements of the machine have no influence on the accuracy of

the position measurement. Measurement accuracy depends almost solely on the precision and installation location of the linear encoder.

This basic consideration applies both for linear axes and rotary axes, where the position can be measured with a speed reduction mechanism connected to a rotary encoder on the motor, or with a highly accurate angle encoder on the machine axis. Significantly higher accuracy grades and reproducibility are achieved if angle encoders are used.

Additional measures for semiclosed-loop operation

In order to prevent heating of the ball screw and the surrounding parts of the machine, some ball screws feature hollow cores for coolant circulation. In semiclosed-loop operation the positioning accuracy is affected by thermal expansion of the ball screw and thus depends on the temperature of the coolant. A temperature increase of only 1 K results in positioning errors up to 10 µm over a traverse range of 1 m. Common cooling systems, however, are often unable to restrict the temperature variations to values significantly below 1 K.

For drives in semiclosed-loop operation, thermal expansion of the ball screw is occasionally approximated using a model in the control. Because the temperature profile is difficult to measure during operation and is influenced by numerous factors – such as the wear of the recirculating ball nut, the feed rate, the cutting forces, the traverse range used, etc. – considerable residual errors up to 50 µm/m can occur when this method is used.

The ball screw is sometimes provided with fixed bearings at both ends in order to increase the rigidity of the drive mechanics. But even very rigidly designed bearings cannot prevent expansion caused by local heat generation. The resulting forces are considerable. They deform the most rigid bearing configurations and can even cause structural distortions in the machine geometry. Mechanical tension also changes the friction behavior of the drive, thus adversely affecting the contouring accuracy of the machine.

Due to these restrictions, the drive accuracy that can be attained by taking the described additional measures cannot be compared with closed-loop operation using linear encoders. Also, the additional measures for semiclosed-loop operation cannot compensate the effects of changes in the bearing preload due to wear, or elastic deformations of the drive mechanics.

Effect of Drive Accuracy on the Manufacture of Parts

In the machine building industry the demand for small parts manufactured in small production runs is increasing considerably. The accuracy of the first workpiece is therefore becoming an important factor for the profitability of manufacturing companies. Machine tools for high-accuracy production of small batches are facing a real challenge.

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HEIDENHAIN Introduces Innovative TNC 620 Contouring Control

With the TNC 620 with digital drive control, HEIDENHAIN Corporation introduces an exciting new control for use on both milling machines and machining centers with up to 5 axes plus spindle. This new TNC is based on an innovative software platform NC Kernel.

Once again proving its ability to offer a conversationally friendly control, HEIDENHAIN offers its TNC 620 equipped for handling even very complicated tasks, including those that use swivel and rotary axes. And for simultaneous machining with up to five axes, the TNC 620 offers special functions that produce optimal machining results. Dynamic look-ahead, algorithms for jerk limitation and intelligent motion control are the type of available functions that enable the TNC 620 to handle even very stringent requirements on the surface of a finished workpiece.



It is important to note that the main computer, controller unit, and other components of the HEIDENHAIN TNC 620 control system feature a new, powerful interface: HSCI (HEIDENHAIN Serial Controller Interface). HSCI is based on the 100BaseT Ethernet standard so well known in network connections. This helps make short cycle times for data transfer possible, considerably reduces cable costs and eases installation. Together with the new, purely digital EnDat 2.2 encoder interface, the TNC 620 has a uniformly digital design from the main computer to the encoder.

Unlike many of its competitors, the main computer of the TNC 620 is housed inside the operating panel, behind the TFT flat-panel display. Because of this, complicated wiring into the electrical box is a thing of the past.

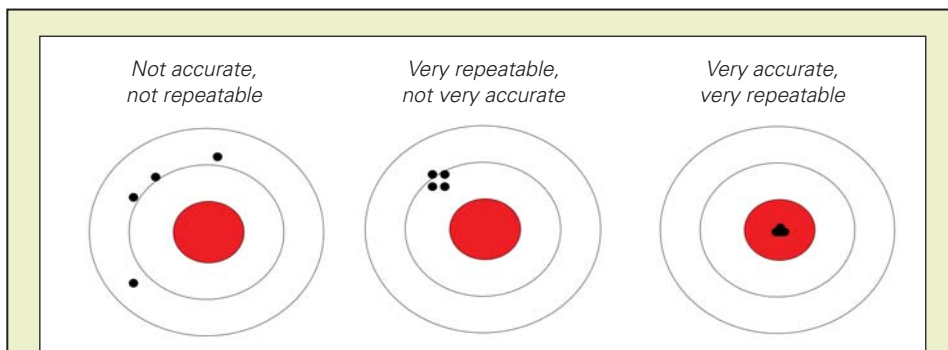
Lastly, this TNC 620 can be customized with select functions from many available options to meet the needs of the customer, from very simple to highly complex machine applications. ■

For more information, circle #2 on the reply card.

Dear Abbé...

Q: "Why does HEIDENHAIN talk about accuracy when many of your competitors talk only about resolution? What is the difference? How is repeatability related?"

A: Accuracy, Repeatability and Resolution, while related to each other, are separate issues.



Accuracy - Degree of conformity of a measure to a standard or true value.

Repeatability - The closeness of agreement among a number of consecutive measurements of the output for the same value of the input under the same operating conditions, approaching from the same direction, for full-range traverses.

Resolution - The least interval between two adjacent discrete details which can be distinguished one from another.

In the example on the left, the resolution is the size of the bulls eye and rings

• Not all applications require accuracy

- If you need to drill 10 holes then go back and tap them within .05", repeatability is more critical

• Resolution determines repeatability

- If your resolution is .0002", your repeatability cannot be better than .0002"
- If you increase your resolution (example: parameter setting on DRO) to .0001", your repeatability is now .0001"

Sincerely,
Abbé

If you have a question for Abbé, please send it to us by filling out the "Question for Dear Abbé?" section on the reply card.

Battery-free Infrared Touch Probe Now Available

For users looking for an alternative to battery-operated touch probes for machining applications, HEIDENHAIN Corporation offers the TS 444 infrared touch probe. The new TS 444 can be powered by an alternative energy source in the form of compressed air supplied through the spindle of the machine tool, and can be of use with all HEIDENHAIN control systems.

To operate the TS 444 touch probe, compressed air is introduced into the touch probe via the taper shank, and powers a turbine wheel inside the touch probe. The turbine wheel generates electrical energy through changes in the magnetic field, which is stored in high-power capacitors.

With fully charged capacitors, the touch probe is able to probe for two minutes. The charging time of the TS 444 touch probe varies depending upon the pressure: The higher the pressure, the shorter the charging time. A supply pressure of 5 bars or more is recommended to ensure that charging takes place in a reasonable time. For example, when a pressure of 5.5 bars is used, it takes around three seconds to completely charge the touch probe.

Like with conventional HEIDENHAIN touch probes, the exit air is used for cleaning the probing point on this TS 444. This means

that at the same time that the touch probe is charged with energy, the probing point is cleaned. The compressed air does not need to be specially cleaned.

Like other HEIDENHAIN touch probes, the TS 444 features a proven optical sensor technology for generating the trigger signal. This sensor endures a probing accuracy of $\pm 5 \mu\text{m}$ and a repeatability of $2 \sigma \leq 1 \mu\text{m}$. ■



For more information, circle #3 on the reply card.

See HEIDENHAIN at IMTS



HEIDENHAIN and its DIADUR symbols will be in full force come this September at the IMTS show in Chicago. The DIADUR is a significant metal etching process invented by HEIDENHAIN in 1950 that has come to be known as a representation of high precision measurement around the world.

This year, HEIDENHAIN will once again showcase its significance in the high precision motion control industry by having special booth displays and machine builder partnerships that demonstrate high accuracy and the importance of linear versus rotary measurement technology in that arena. These fixtures will be identified with a DIADUR symbol. Look for the DIADUR symbol in builder booths as well. They will serve as real-world examples of high precision applications utilizing HEIDENHAIN.

Other highlights at the HEIDENHAIN booth will include the newest ND 500 mid-level DRO which is now coupled with a HEIDENHAIN high quality LS linear scale, making this an extraordinary system offered at a value price. Also, many new HEIDENHAIN touch probe options will be on display, including the TS 444 battery-free probe, and the TS 740 probe, one of the most accurate probes in the world.

Adding to these exciting probing market introductions is HEIDENHAIN's UTI 192 interface and 3rd party macros. With these, more CNC machines than ever can connect with HEIDENHAIN's broad range of probing products. ■

Come see this and more for yourself in Chicago!

**HEIDENHAIN IMTS
Booth #D-4419**

For more information, circle #4 on the reply card.

Machining Accuracy of Machine Tools *continued from page 2*

Constant changes between setting up the workpiece, drilling, roughing and finishing cause constant changes in the thermal condition of a machine.

The typical feed rates for roughing a workpiece range from 3 m/min to 4 m/min, whereas feed rates from 0.5 m/min to 1 m/min are used for finishing. Rapid traverse movements during tool exchange also considerably increase the average velocities. The medium feed rates during drilling and reaming are negligible for heat generation in recirculating ball screws. Due to the strongly varying feed rates, the temperature distribution along the ball screws changes during the individual process steps. In semiclosed-loop operation the varying loads on the recirculating ball screw may cause the workpiece accuracy to suffer, even if the workpieces are completely machined in just one setup. Machine tools with linear encoders in closed-loop mode are therefore absolutely necessary for high-accuracy production of small parts.

Example of machining several parts from one blank form

An aluminum blank with a length of 500 mm is first drilled and reamed on a machine tool. The medium feed rates during the two machining operations are low, so the heat generation in the recirculating ball screws is negligible. In the next production step the contour is milled and the medium feed rate increases significantly, resulting in considerable heat generation in the ball screws (Figure 3).

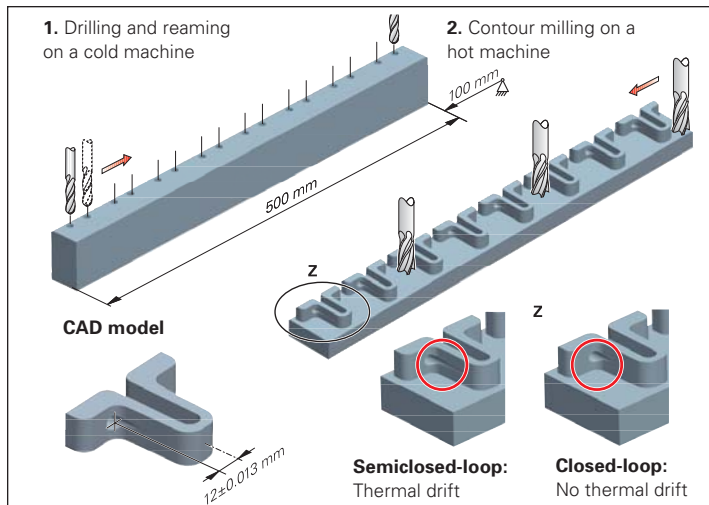


Figure 3
Effect of drive accuracy on the production of small parts
▲ Fixed bearing of the recirculating ball screw

If the milling machine is operated in semiclosed-loop mode, thermal expansion of the recirculating ball screws causes deviations between the drilling pattern and the milling pattern. The maximum deviations of 135 μm were measured near the loose bearings of the ball screw. In closed-loop operation these errors can be completely avoided (Figure 4).

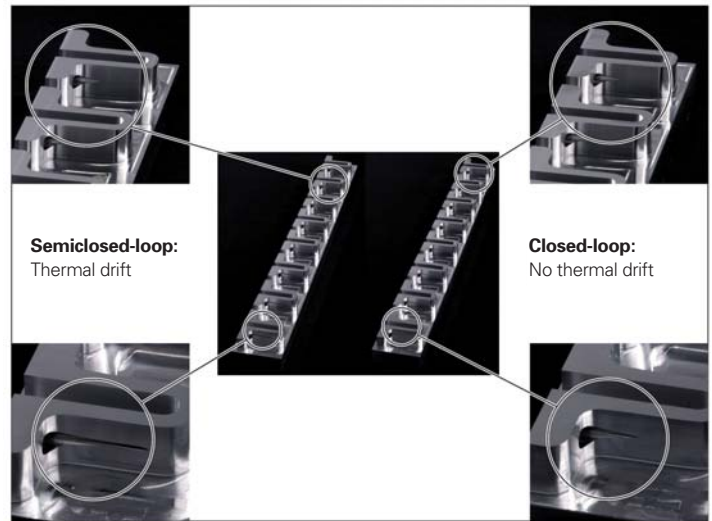


Figure 4
Effect of drive accuracy on the series production of small parts

The functional dimension between the position of the hole and the bisecting line of the individual workpiece is 12 mm and must meet tolerance grade IT8 in the illustrated example. This results in a permissible deviation of $\pm 13 \mu\text{m}$. All of the workpieces machined in closed-loop mode are significantly within this tolerance. Deviations up to 135 μm were measured in semiclosed-loop mode. Thus the workpiece only complies with tolerance grade IT13 instead of meeting the required tolerance grade IT8.

Integral Components with High Degree of Stock Removal for the Aerospace Industry

Using integral components in the aerospace industry provides the benefit of combining optimum utilization of the material characteristics with minimum weight. Typical integral components feature a degree of stock removal of 95% and more. Today high-performance HSC machine tools in conjunction with high feed rates and high cutting speeds are used in the manufacturing processes. The high material removal rates made possible by the remarkable degree of stock removal of the components are of great economic significance. But the resulting feed rates and machining forces also generate considerable frictional heat in the recirculating ball screws. Also, friction losses and the resulting thermal expansion of the ball screws vary during a machining process, for example because of different feed rates during roughing and finishing.

If the feed drives are operated in semiclosed-loop mode (without linear encoders), part dimensions differ for each single component manufactured in small production runs with short cycle times. Due to thermal expansion, the specified manufacturing tolerances might not be achieved. Such sources of errors can be prevented through the use of linear encoders,

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Machining Accuracy of Machine Tools *continued from page 5*

since thermal expansion of the ball screws is then fully compensated for in closed-loop operation.

Example of machining a coupling lever for an aerofoil

Figure 5 describes the manufacturing of a coupling lever, requiring the machining of two holes at distance of 350 mm from each other with a tolerance grade of IT7. The integral component is manufactured twice from the same blank form to permit evaluation of the accuracy that can be achieved in semiclosed-loop mode. The second workpiece is simply machined 10 mm below the first. Between the two machining operations, twenty machining cycles for the same part are executed above the blank.

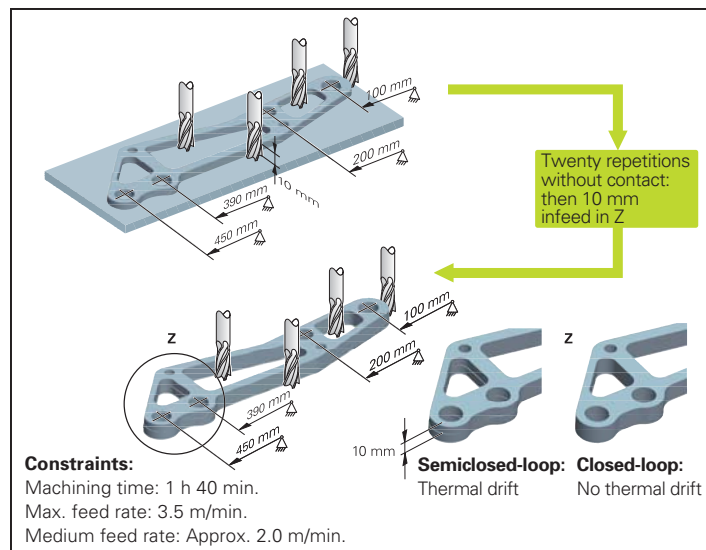


Figure 5 – Manufacturing of the coupling lever
 ▲ Fixed bearing of the recirculating ball screw

In semiclosed-loop operation, the contour of the second workpiece deviates from the contour of the first workpiece, as is shown by an edge (Figure 6). The farther the drives move away from the fixed bearings of the recirculating ball screw during machining, the more obvious the thermal expansion of the ball screw becomes.

The required functional dimension of 350 mm with a tolerance grade of IT7 corresponds to a permissible deviation of $\pm 28 \mu\text{m}$. The second workpiece machined in semiclosed-loop mode is unable to meet this requirement. The deviation is $44 \mu\text{m}$. With the use of linear encoders in closed-loop mode in this test, no edge results.

The residual deviations of $10 \mu\text{m}$ that occur in closed-loop operation are due to thermally induced, structural distortions of the machine geometry. The specified dimensions for the two bore holes can even be improved to IT5. A reproducible accuracy from the very first part is thus guaranteed.

Effects on Mold and Die Making

The manufacturing of molds or dies for injection-molded or die-cast components is a time-consuming task because it requires superior surface finish for sometimes very fine structures. Today many molds are directly milled in order to avoid the cost and time consuming eroding process. Increasingly small milling cutters with diameters as small as 0.12 mm are used. Mold and die making for milling is therefore characterized not only by high demands upon dimensional accuracy. It also requires high feed rates, including for hardened materials, to reduce the machining times. Typical machining times for molds and dies range from 10 minutes to several days. Dimensional accuracy, however, must not be sacrificed to fast execution. The first and last machining paths must be identical in order to ensure that the time previously gained is not lost to complex rework.

The heating of the recirculating ball screws in the feed axes substantially depends on the velocity profile specified for the individual axes by the NC program, and can cause changes in length up to $150 \mu\text{m/m}$ in the recirculating ball screws. These conditions make it impossible to guarantee dimensional accuracy in semiclosed-loop operation. Typical heating of the recirculating ball screw would cause an edge deviation of more than $20 \mu\text{m}$ in a mold with a length of only 150 mm. The expansion of the recirculating ball screw would result in so large a half of a die that the flaw can no longer be corrected by rework.

Example of 3-D milling of freeform surfaces

The following example illustrates the machining of a mold with the classic profile of the Watzmann – a legendary mountain in the German Alps. A 500-mm long workpiece is machined with multipass, climb and upcut milling cycles in the X direction, using a ball-nose cutter with a diameter of 12 mm and a maximum feed rate of 4.5 m/min. It takes around 60 minutes to machine the contour with an infeed of 0.2 mm in the Z and Y directions. The high feed rate of 4.5 mm/min together with the constant accelerations and decelerations generate heat in the recirculating ball screw and cause thermally induced linear deviations of



Figure 6 – Coupling lever, processed twice from one blank form

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Machining Accuracy of Machine Tools *continued from page 6*

130 µm in semiclosed-loop operation. Because the linear deviation with this mold component is difficult to visualize, machining was deliberately begun in the middle of the workpiece. Start and end paths therefore lie side by side and clearly show the thermal drift. The farther the workpiece position is away from the fixed bearing, the higher the thermal drift is.

In order to fulfill the high requirements of mold and die making, it is necessary to compensate the expansion of ball screws by using accurate linear encoders. In Figure 7 the high-accuracy workpiece with an excellent surface finish manufactured in closed-loop mode is compared with a workpiece manufactured in semiclosed-loop mode.

Summary

The successful fulfillment of manufacturing orders requires machine tools with high thermal stability. Machine accuracy must be maintained even under strongly varying load conditions. As a consequence, feed axes must achieve the required accuracy over the complete traverse range even with strongly varying speeds and machining forces. Thermal expansion in the recirculating ball screws of the linear feed axes adversely affects accuracy and varies depending on the velocity and load. Position errors of 100 µm and more may result within 20 minutes during a machining operation if the slide position is only determined from the spindle pitch and a rotary encoder. Because essential drive errors are not compensated in the control loop when this method is used, this is

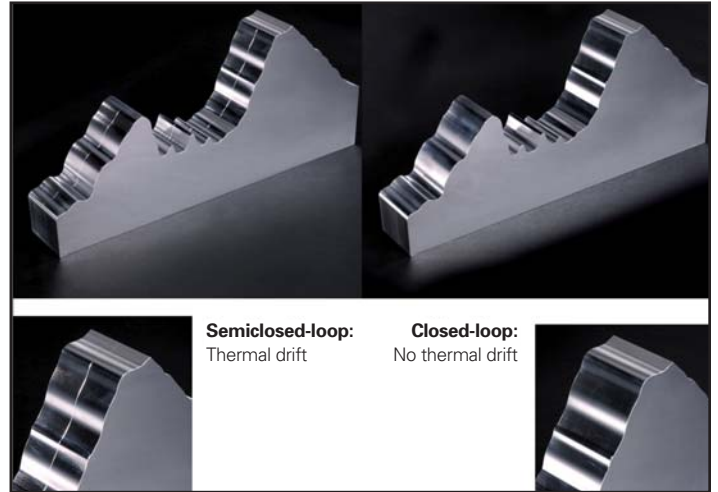


Figure 7
Watzmann profile with free-formed surfaces

referred to as semiclosed-loop operation of the feed drive. These errors can be completely eliminated by using linear encoders. Feed drives with linear encoders are operated in closed-loop mode because errors in the recirculating ball screw are considered in position measurement and compensated in the position control loop.

Angle encoders used on rotary axes provide similar benefits since the mechanical drive components are also subject to thermal expansion. Linear and angle encoders therefore ensure high precision of the components to be manufactured even under strongly varying operating conditions of the machine tools. ■

Linear Encoders for Machine Tools

Linear encoders for position feedback are indispensable for high positioning accuracy of machine tools. They directly capture the actual position of the feed axis. Mechanical transfer elements therefore have no influence on position measurement – both kinematics errors and deviations due to thermal influences or other forces are measured by the linear encoder and considered in the position control loop. This can eliminate a number of potential error sources:

- Positioning error due to thermal behavior of the recirculating ball screw
- Reversal error
- Errors due to deformation of the drive mechanics by machining forces
- Kinematics error through ball-screw pitch error

Linear encoders are therefore indispensable for machines that must fulfill high requirements for **positioning accuracy** and **machining speed**.

Linear encoders from HEIDENHAIN for numerically controlled machine tools can be used nearly everywhere. They are

ideal for machines and other equipment whose feed axes are in a closed loop, such as milling machines, machining centers, boring machines, lathes and grinding machines.

The beneficial dynamic behavior of the linear encoders, their highly reliable traversing speed, and their acceleration in the direction of measurement predestine them for use on highly-dynamic conventional axes as well as on direct drives. ■

For more information, circle #5 on the reply card.



Visit HEIDENHAIN on the Road

HEIDENHAIN will host exhibits at the following remaining 2008 trade shows. Come by and see what's hot! ■

SEMICON

July 15-17
Moscone Center – North
San Francisco, California

SEMICON®
West2008

IMTS

Sept. 8-13
McCormick Place
Chicago, Illinois

IMTS08

National Manufacturing Week

September 23-25
Donald E. Stephens Convention Center
Rosemont, Illinois

**National
MANUFACTURING
Week**

American Society for Precision Engineering (ASPE)

October 21-23
Marriott Downtown Waterfront Hotel
Portland, OR

 American Society for Precision Engineering

HEIDENHAIN's 2007 Distributor of the Year

In May, distributor Automation and Metrology, Inc. in Painesville, Ohio was presented with the prestigious 2007 HEIDENHAIN Distributor of the Year Award. This coveted annual award recognizes the HEIDENHAIN distributor who best represents excellence and commitment to the servicing industry, as well as HEIDENHAIN's highest standards. ■



Pictured here (from left to right) from Automation and Metrology are: Jennifer Bordelon (Customer Service), Dave Denman (Partner), Tom McManus (Sales/Service) and Mark Contorno (Partner). HEIDENHAIN Regional Manager Ron Hood on end. Look for a profile of Automation & Metrology in a future newsletter.

Technical Tidbit: Block Processing Speed

Many control manufacturers specify their block processing speed but few define what this means. Processor speed is one of the defining criteria for high speed machining but so are surface quality and tolerance accuracy. The HEIDENHAIN iTNC 530 offers processing speed of 3.7 ms and 0.5 ms, for example, but also makes separate provisions for accuracy and surface quality.

What impact does block processing speed have on feedrate?

Processing speed is the time required to execute one "block" or line of programming. *It is important to note that HEIDENHAIN specifies a block as a 3-axis simultaneous move without radius compensation)*

Example:

0.5ms means that a line of code can be processed in 0.5 milliseconds. As there are 1000 ms in a second, and 60 seconds in a minute, this control can execute 2000 blocks per second or 120,000 blocks per minute. To calculate theoretical maximum feed rate, we need to know the step per block. (*i.e., the linear distance for each subsequent axis move as defines in the part program*). If we assume .002" per step, we then can calculate:
.002" X 120,000 = 240 inches per minute maximum feed rate. ■

HEIDENHAIN Web Site Expands

In response to customer's requests and to better support our wide customer base, a new section called HESIS Public has been added to www.heidenhain.com that will facilitate easy access to information regarding older HEIDENHAIN products for OEMs, distributors and end users.

For example, just by administering a few clicks starting with the **Services and Documentation** tab, then **Technical Service**, all site users can access a Service Product Information page where a Product ID or Product Name field will come up allowing users to enter that information for even older product and receive mounting instruction, for example.

In the Member-Area, registered partners can be brought to HESIS-Web for even more information such as that of spare parts, testing equipment and repair descriptions for all HEIDENHAIN Products. ■

Check it out!

 **HEIDENHAIN**

HEIDENHAIN CORPORATION

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