# HEIDENHAIN

Technical Information

Higher Precision for Machining Centers in Automated Large-Batch Production

Automobile customers demand a variety of vehicle types and engines in accordance with highly diverse framework conditions, asking about differing vehicle sizes, motor types or engine power within the individual markets, depending on fuel costs, emission standards and tax measures. For automobile manufacturers this hampers any estimation of quantity progressions or capacity planning and the design of production lines.

To meet customer needs, automobile manufacturers offer engines with the same number of cylinders but in differing performance classes, which also leads to an increase in variant diversity. Ever shorter vehicle product life cycles in combination with volatile markets therefore lead to changed production challenges for automobile manufacturers [1]. To meet such challenges, the aspect of flexibility is added to the classic production parameters such as quality, time and costs.

For production lines for the machining of vehicle powertrain components (engine, transmission and axle components), this means departing from classic transfer lines with fixed timing and high productivity, and adopting lines with linked machining centers and higher levels of flexibility. In addition to the challenge of responding to fluctuations in demand in automotive sales markets, the future will also bring increasing legislative and end-user requirements regarding the emission of pollutants and fuel consumption of vehicles. One approach to dealing with such a situation consists of reducing friction in the powertrain, which in most cases would lead to increased quality requirements for the components to be produced.

The interlinked machining centers used in production lines also have the task of implementing the demands of manufacturers in process-safe ways with large vehicle quantities (see Figure 1). The use of linear encoders in Closed Loop control in the feed axes of the machining centers contributes to meeting such diverse requirements.

Figure 1: Cylinder head machining in large-batch production (photo: MAG IAS GmbH)
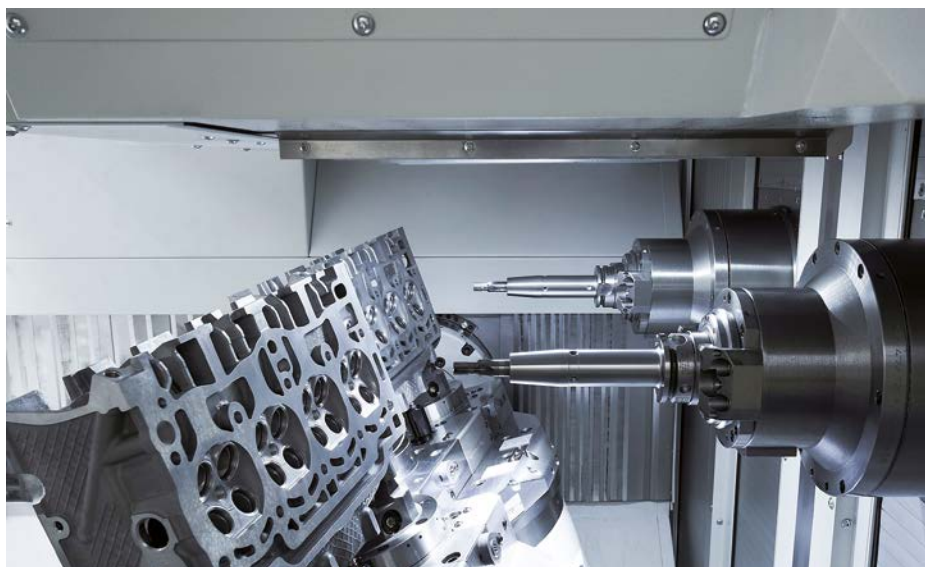
From transfer lines to linked machining centers
Greater flexibility for variants, machines and capacity

Transfer lines lack adaptability

Because individual stations within a transfer line are designed for machining specific workpieces, these fixed, chained lines cannot be simply expanded by adding additional stations. To make available the maximum planned capacity requirement, it is therefore necessary to implement the main part of production line investment at the start of production (SOP). Because quantities slowly increase (line ramp-up) at the beginning of production or fall away (line ramp-down) at the end of the product lifespan, excess production capacity is the result (Figure 2), and as a result the installed capacity is not fully exploited.

Additional challenges come about if capacity requirements during regular operation in the transfer line are larger than originally planned, and workpieces required by the market can no longer be produced with the installed line capacity. Duplicating a transfer line to absorb such quantity peaks, however, would lead to significant over-capacity.

Flexibility through linked machining centers

Production lines with smaller capacity ranges can be installed by using linked machining centers, enabling a wider spectrum of production tasks and therefore higher production flexibility. Adaptation to actual quantity needs during line ramp-up can then be achieved by integrating additional machining centers into the existing production line at free stations or by duplicating the complete line.

This method of approximating available capacity to capacity needs is aimed at expanding the production system with as much cost-efficiency as possible [2]. As a consequence, the large-batch production of vehicle powertrain components is now distancing itself from transfer lines and is increasingly adopting machining centers or transfer centers [3].

The increased flexibility of linked machining centers is directly related to the requirement for highly rapid and economic responses to fluctuations in demand. As an example, one demand is that differing variants of a workpiece should be machined on the same production line without needing to adapt the setup **(variant flexibility).**

Another approach is using additional machines to simply expand production lines. This could be called **reuse flexibility,** as the use of standard machines and their standardized linking enables simplified integration and reuse of such machines in other production lines.

If line capacity is seen with respect to the complete lifespan of a manufactured workpiece, the fluctuations in demand outlined above also lead to differences between capacity needs and capacity availability in the production line. While with transfer lines only comparatively large jumps in production capacity can be achieved, production lines with linked machining centers enable capacity to be increased in smaller steps at production ramp-up. Such production lines can also be decommissioned again thanks to their high flexibility at production ramp-down [4]. Figure 2 shows a step-by-step investment during the ramp-up phase of a workpiece to be produced, and the reduction in the ramp-down phase **(quantity flexibility).**

Figure 3 shows an example of a production line layout for the mechanical machining of a powertrain component. The machining centers are illustrated linked by gantry loaders and grouped into individual machining operations. A machining operation therefore consists of several machining centers operated in parallel with the same processing content.
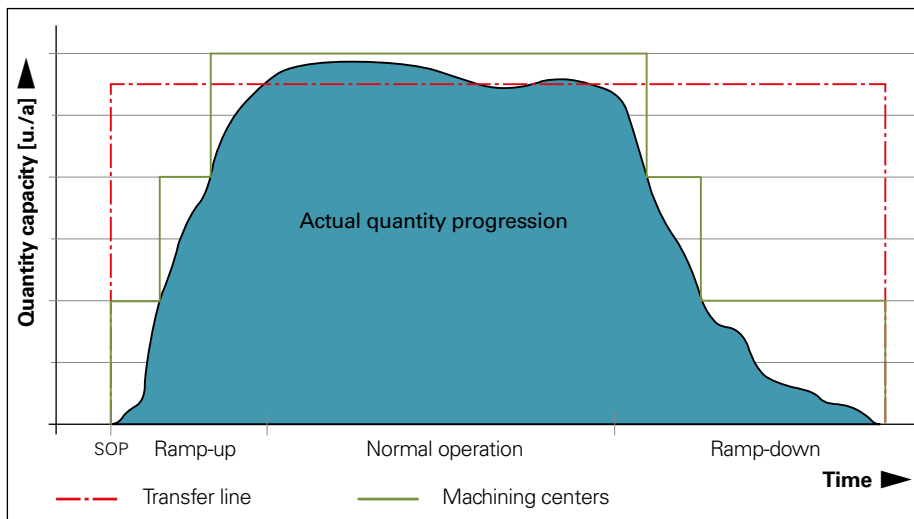

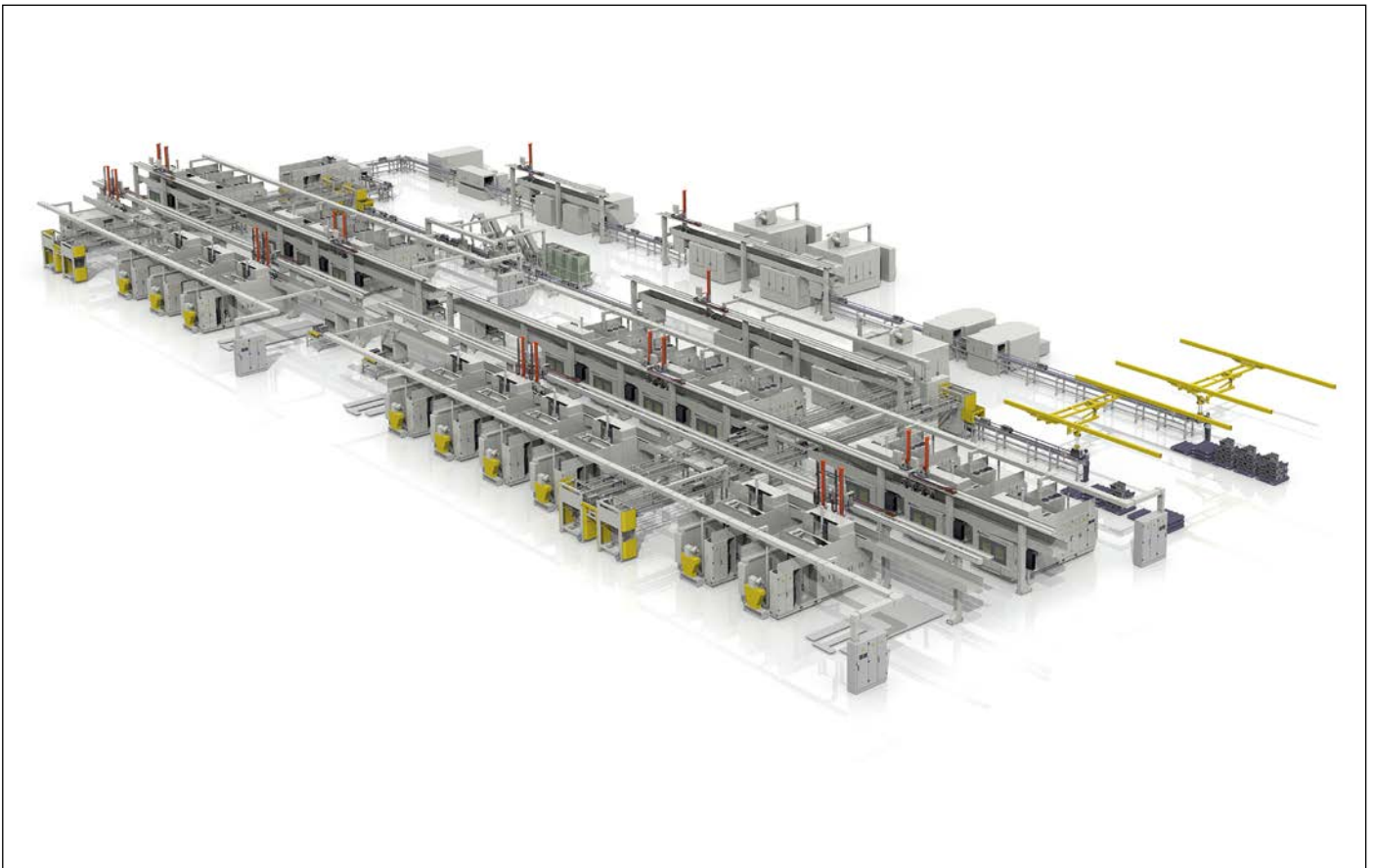Figure 2: Quantity flexibility—capacity availability vs. capacity needs [4]

Figure 3: Example of a production line for large-batch manufacturing (photo: MAG IAS GmbH)

Advantages of horizontal machining centers

Horizontal machining centers are usually used for production purposes, and they have an advantageous chip fall, whereby less cooling lubricant or even minimum quantities of lubricant (MQL) are used to wash chips. Such machines can also be variably automated via easy front or top loading for workpiece supply, enabling use of the same machine model for various production lines even with different loading systems. Double-spindle machines, with only slightly larger support base areas, are sometimes used due to their higher productivity (see Figure 1 on page 1).

Features of large-batch automotive production

In summary, the following characteristics for machining cubic workpieces in large-batch automotive production can be identified as follows:

- Automated production with linked horizontal machining centers
- One machine operator supervises eight to fifteen machines
- A machining operation usually consists of several identically built machining centers operating in parallel with identical processing content
- A workpiece is machined sequentially across several machining operations
- A single workpiece is produced with several machining centers, meaning that several centers are responsible for tolerance conformity of the workpiece

The last point in particular makes clear that the produced tolerances of a workpiece depend on the individual machines or sub-processes of the entire production system. In contrast to die and mold production where workpieces are produced on one machine and supervised by a single machine operator, with large-batch production dependencies exist between the individual machining steps in the process chain. This fact must be taken into account when designing the process as well as the production line.

Cubic powertrain components
Machining process and tolerances

The powertrain of a vehicle can be separated into engine, transmission and axle modules [1], and these modules in turn consist of further component groups such as the valve train and its components. The cylinder head, crankcase and transmission housing are examples of classic cubic components in powertrain production.

Because of high quantities and related cost-efficiency, workpieces are normally manufactured to near net shape before mechanical machining. This means that the primary geometry of workpieces is already predetermined by the casting or forging process, e.g. when forging connecting rods or crankshafts, and this is reflected in the machining operations for cubic workpieces [5, 6].

Focus on drilling
Figure 4 shows the machining operations for a cylinder head. Milling is relatively low compared to drilling or similar machining, and this is understandable because the primary geometry of the workpiece has already been cast, apart from a few areas.

Specified holes in castings, however, are manufacturable only at high cost or are not possible at all for complex geometries. They have to be integrated into the mechanical production line using drilling operations, so that their share of the machining process clearly predominates.
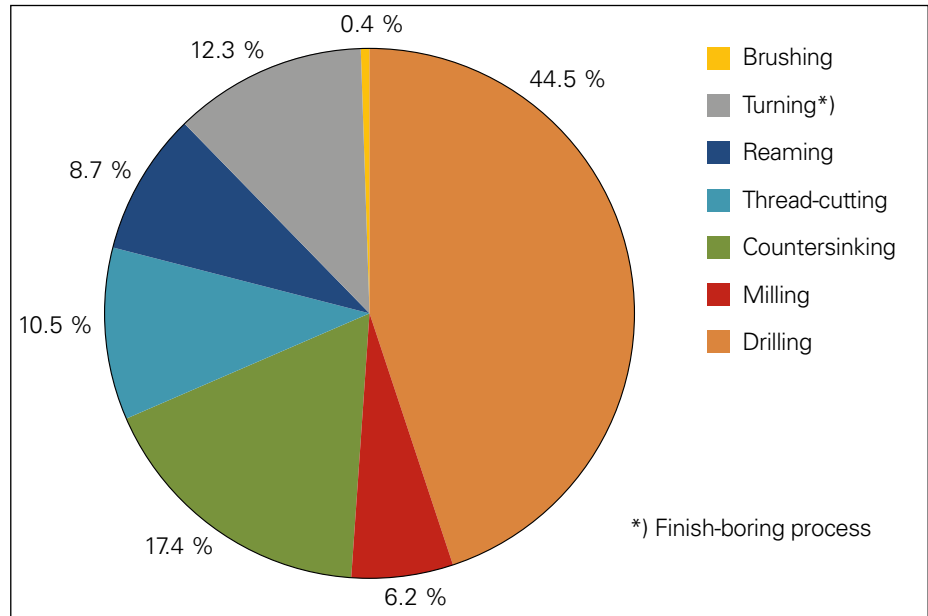

Figure 4: Machining operations and their share of the manufacture of a cylinder head [5]

The various machining operations also enable conclusions about the axis movements required for machining. Because of the drilling operations, most of the movements consist of positioning the tool to the workpiece and a single-axis feed and retraction motion. And because the workpieces usually have no free-formed surfaces, during milling operations the motion in the working plane (via traverse in two linear axes) is sufficient in addition to a positioning motion.

The predominant number of geometrical tolerances on the workpiece to be produced is therefore determined by the majority of drilling operations required. In addition to diameter tolerances mainly influenced by the dimensions of the tool, such as reamers, workpiece drawings also contain tolerance specifications for position, distance and hole depth.

Figure 5: HEIDENHAIN linear encoder in a horizontal machining center
(photo: GROB-WERKE GmbH & Co. KG)

Linear axes determine dimensional accuracy

Complying with specified tolerances is determined among other factors by the capability of the linear axes of a machine tool to achieve precise positioning (Figure 5). Depending on the workpiece or set of drawings, differing tolerance values and tolerance divisions for production features may exist.

Figure 6 shows the distribution of tolerance (position, distance and depth tolerances) for a crankcase. The example shows that somewhat more than 30 % of the tolerances analyzed are ≤ ±0.1 mm, and production features also exist on cylinder heads and transmission housings with tolerances of ≤ ±0.1 mm required by the designers. Examples are the position and depth tolerances of drill holes in the area of a cylinder head valve train as well as the bore axis distances of the main and neck bearing axes on a differential housing.

Reliably complying with tight tolerance values

To achieve the above-specified need for improved flexibility, producers make it their goal among other things to use standard machine tools in manufacturing, making it unnecessary to use additional specialized machines for individual production dimensions. This in turn means that, even if tolerance values are ≤ ±0.1 mm, they must still be complied with in a safe and reliable way with the machining centers installed in the production lines.
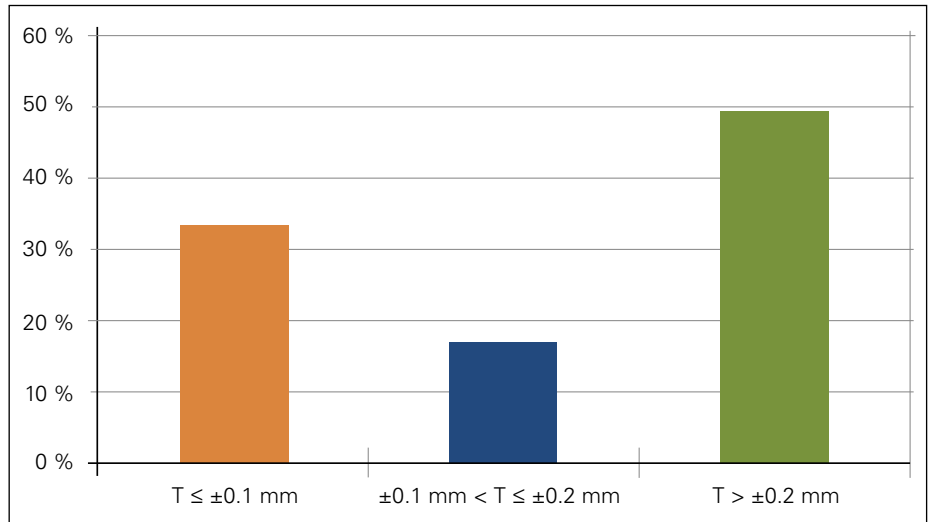

Figure 6: Distribution of position, distance and depth tolerances for a crankcase

Cubic powertrain components
Capability analyses supply specifications for machine capability and process capability

The tolerance values specified previously seem large compared to requirements in the die and mold production sector. It must be considered, however, that values for automotive workpieces initially correspond to the designer's drawing specifications. Automotive manufacturers carry out statistical capability analyses on the machining centers to make sure that the machine tools and implemented production processes are capable of meeting requisite drawing tolerances over a long period with a defined safety margin to the tolerance limits [7].

Capability tests for machine and process

For acceptance testing of the machine tools, 50 workpieces, for example, are produced on the system or single machines and the distribution of produced tolerances is then evaluated using statistical methods. Capability specifications or capability indices are defined for the capability tests.

To determine the **machine capability** the indices C_m or C_{mk} are defined, and for recording **process capability** the indices C_p or C_{pk}. The indices C_{mk} and C_{pk} take into account a non-central distribution of measured tolerance values captured on several workpieces.

Determining the machine capability provides knowledge about the temporary scattering behavior with tolerances produced by a machine tool subjected to constraints that are as constant as possible (≡ short-term testing). The process capability aims to determine the long-term scattering behavior of a machine under process constraints (≡ long-term testing). See [7] for equations for calculating the indices based on the measured tolerance values of produced workpieces, as well as for further information.

Equation 1 specifies the variables C_m and C_p:

$$C_m, C_p = T / (6 \cdot s) \qquad \text{(equation 1)}$$

T = tolerance range in accordance with drawing dimensions
s = standard deviation

Manufacturers specify capability indices for the quality-relevant tolerances, and production machines supplied by the machine tool builder must at least achieve these during acceptance testing. With regard to the acceptance test, determining the indices leads to a further limitation of tolerance values specified in the workpiece drawing. Figure 7 demonstrates this with the example of a tolerance of T = ±0.1 mm under consideration of the machine capability specification C_m. Automotive manufacturers also specify feature classes for tolerance that are critical (C_m = 2.00), important (C_m = 1.67) or less important (C_m = 1.33) in relation to component functionality.
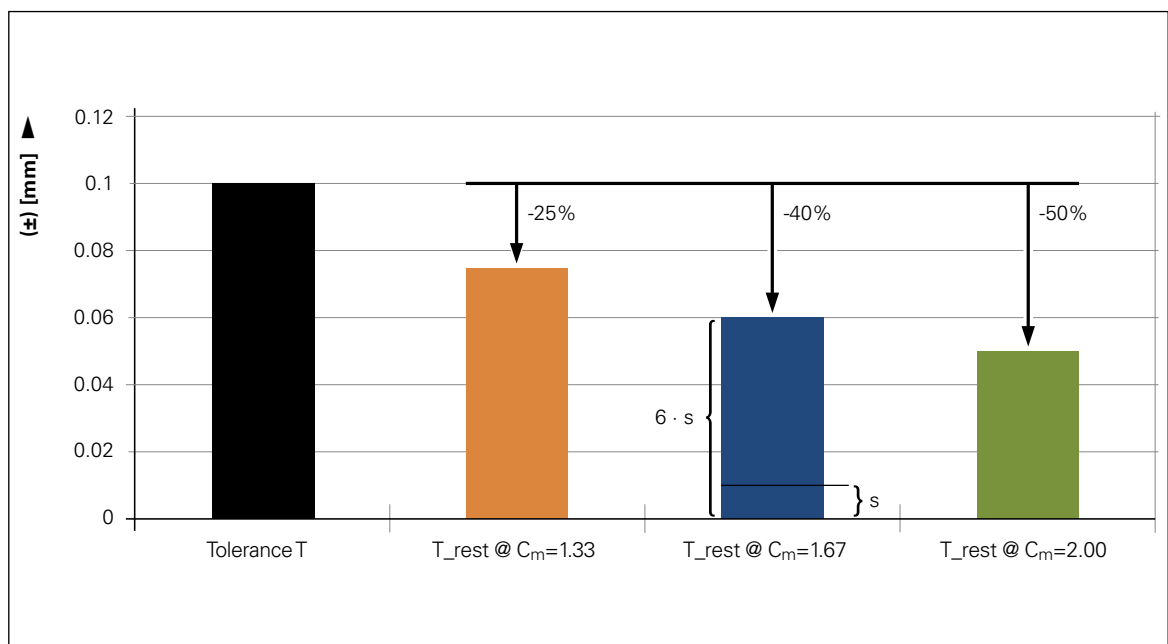

Figure 7: Correlation between the drawing tolerance specification and capability index C_m

Target: Minimum scattering

For uniformly high workpiece quality and minimum scrap rates, the target is to achieve lowest levels of scattering with tolerances produced, and therefore low deviations from the standard. Equation 1 can therefore be construed as follows:

$$C_{m,measured} = T / (6 \cdot s) \geq C_m \quad \text{(equation 2)}$$

or

$$6 \cdot s \leq T / C_m \quad \text{(equation 3)}$$

$C_{m,measured}$ corresponds to the index derived from measuring a tolerated dimension on e.g. 50 workpieces produced during machine acceptance and the standard deviation calculated from them.

Capability tests check compliance with maximum acceptable scattering

Equation 2 demonstrates that the capability index resulting from the measurements becomes greater the lower the standard deviation is. The value ($C_{m,measured}$) from measurements on the workpieces must be greater or equal to the value of C_m specified by the manufacturer. If this is taken into account, specifying a capability index corresponds to specifying the maximum acceptable standard deviation by the manufacturer for a tolerated dimension (equation 3 and Figure 7).

For the example in Figure 7, with $C_m = 1.67$ this means that for the original tolerance of ±0.1 mm, 99.73 % of all tolerance dimension values measured on various workpieces must be in the range of ±0.06 mm. As a consequence, the acceptable standard deviation must have a maximum value of only ±10 µm. Achieving such values is a significant challenge for the linked machining centers in large-batch production.

Error limits for machining
Flaw sizes in the process and their effects

The previous pages outlined the order of magnitude of tolerances on workpieces for vehicle powertrains. The question arises as to the percentage of available tolerance of a production feature that flaw size arising in the process depletes.

If the total flaws are greater than the available tolerance, the machine tool or process cannot fulfill the specified machining task. In the following, the error limits that can occur on a machine tool e.g. due to workpiece clamping or thermal drift behavior on axes are therefore estimated, and the aim is to estimate the residual tolerance reserve by comparing the available tolerance with the existing error limits. This reserve enables the machine tool or process to compensate for unpredictable or difficult-to-control production influences.

Index tolerance of workpiece clamping
The loading of machine tools is usually automatic, using special loading modules such as gantry loaders. Before a workpiece is machined, it needs to be positioned and fixed in the clamping fixture of the machine, and because this must be carried out without manual intervention, positioning is usually done by index pins in the clamping

fixture. This means that the mechanical fitting tolerance between the index holes of a workpiece and the index pins of the clamping fixtures in the production line must be considered.

According to the drawing specifications, identical tolerance for the index holes is available for each workpiece produced on the production line, but the actually produced dimension varies from workpiece to workpiece. This also applies to the individual index pins of the clamping fixtures. As a result, constantly identical indexing deviation cannot be expected. The specified maximum tolerance ranges for the index holes and index pins should, however, be complied with in each case as rejects will otherwise be produced. This makes it possible to estimate an error limit.

With the above-specified cubic automotive powertrain components (cylinder head, crankcase, transmission housing), index holes with a diameter of 12 mm are often drilled. Clamping of the workpiece within the indexing pins is not desired because this can lead to excessive loads on the loading systems or workpiece clamping errors, and therefore to possible idle times in the production line.

To avoid this, a transition fit of $\varnothing$ 12 H7/js6 is assumed in the following. These specifications achieve the following maximum error limit for workpiece indexing in the clamping fixtures:

Index hole
$\varnothing$ 12 H7 = $\varnothing$ 12 $^{+0.018}_{0}$ mm   (equation 4)

Index pin
$\varnothing$ 12 js6 = $\varnothing$ 12 $^{+0.0055}_{-0.0055}$ mm   (equation 5)

$\varnothing$ (12.018 – 11.9945) mm
$\equiv \pm 11.75$ μm (radial)   (equation 6)

To manufacture features with tight tolerances, the workpieces are sometimes moved in a defined direction using thrust cylinders in the clamping fixture prior to clamping. This means the workpieces are radially pressed onto the index pins, so that from the central drilling axes only a maximum of half the error limit occurs ($\equiv \pm 5.88$ μm). Because sliding units often make clamping fixtures more complex and therefore more expensive, they are not integrated in all machining stations.
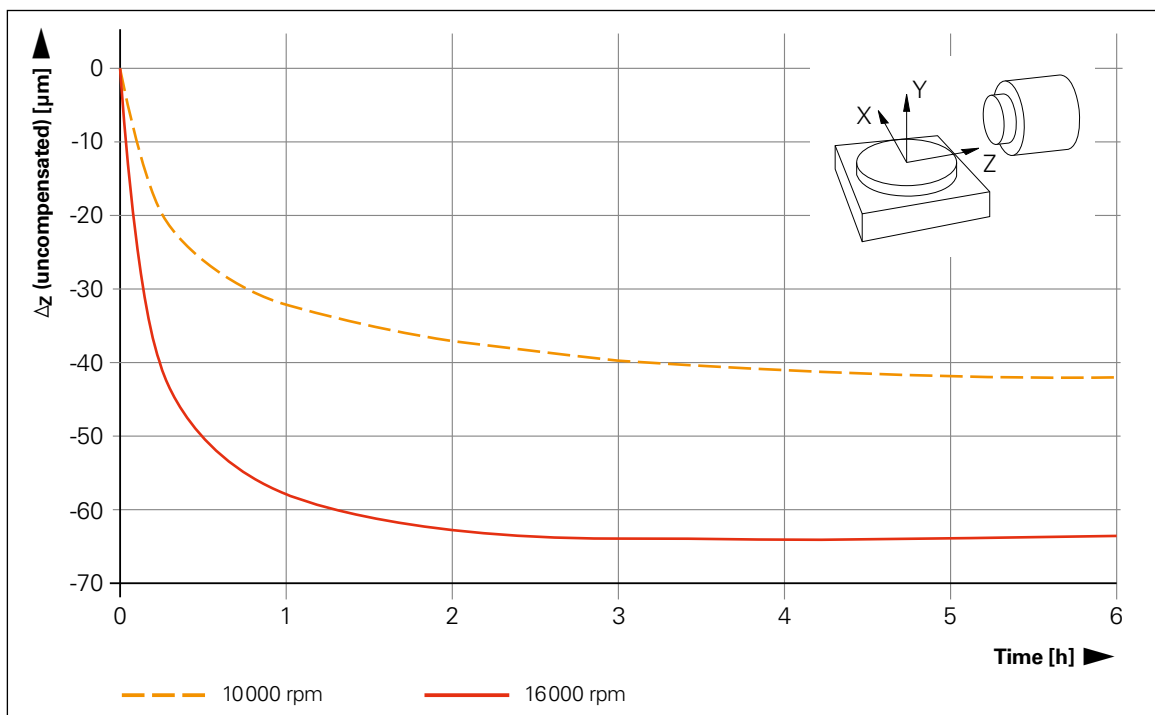

Figure 8: Measured, uncompensated Z axis drift due to heating of the main spindle

Tool change tolerances

On the tool side, inaccuracies also occur during tool changes and depending on the tool interface used. In the machining centers of the above-specified production lines, main spindles and tools with hollow taper shank interfaces are normally used. In [8], the predominant repeatability of the hollow taper shank connection is specified as < 1 µm (axial) and < 3 µm (radial) (≡ ±0.5 µm axial; ±1.5 µm radial).

Thermal drift of the spindle nose

Axial drift on the spindle nose during operation has an effect for holes with defined depth dimensions as well as on face milling if two plane-parallel surfaces must be machined with a defined distance, for example the combustion chamber and hood faces on cylinder heads. During operation, heat development of the main spindle strongly affects expansion of the spindle shaft and subsequently the Z axis structure. Motor spindles are usually implemented in the above-specified production machine tools. The various machining conditions lead to fluctuating performance constancy and therefore changeable thermal loads from the integrated spindle drive and spindle bearings. Because the motor spindle is highly integrated into the axis structure of the machine, heat is dissipated via the motor spindle housing and mounting surfaces onto the machine axis structure. The motor spindle is therefore usually connected to a cooling unit.

Figure 8 displays drift in the Z axis in the warm-up phase as a result of drift measurements taken from a machining center with motor spindle. The drift of the tool center point is shown relative to the machine tool table, at idle spindle speeds of 10,000 rpm or 16,000 rpm. The measurements do not include supplementary thermal loads and resultant drift due to spindle loads occurring during cutting. Depending on the load and speed of the main spindle though, significantly increased drift values compared to idle speed should be expected.

Based on the measurement curve shown in Figure 8 for load with an idle speed of 16,000 rpm, a thermal drift at the spindle nose of around 64 µm in the Z direction occurs relative to the machine tool table. Thermal drift is often reduced even further by use of compensation models saved in the control, achieving an expected reduction of the drift shown by around 80 %. When applied to the measurement curve shown this means a residual value of 12 µm (≡ ±6 µm).

Error limits for machining
Flaw size due to the position detection principle

The further considerations require a differentiation regarding determination of the actual position value on a feed axis with use of a ball screw drive. The main difference in this case occurs due to the mounting location of the axis encoder and its integration into the control loop of the feed axis. Figure 9 shows a feed axis design with Semi-Closed Loop control compared to an axis with Closed Loop control.

Semi-Closed Loop and Closed Loop
Semi-Closed Loop means the position control loop of the feed axis is closed via the encoder of the feed motor. The encoder measures the angular position of the feed motor shaft here, and not the position of the axis slide to be positioned. The slide position is calculated by using the measured angle and the pitch of the ball screw, and it is assumed that the correlation of angle position, spindle pitch and slide position while operating the feed axis or machine tool remains constant. If this correlation changes, e.g. due to thermal expansion or wear in the ball screw, then the calculated position value is erroneous. The control and encoder are "blind" to changes of the feed axis powertrain.

With Closed Loop operation of the feed axis, the slide position of the feed axis is measured with a linear encoder and returned to the position control loop of the axis as an actual position value. Any deviations occurring during operation, such as thermal drift of the ball screw drive, are detected on the slide and adjusted with axis control.

Systematic and random position deviations
Positioning inaccuracies result during positioning of the feed axes ([9], [10]). Systematic deviations occur that can be reproduced with identical boundary conditions and can therefore be compensated. Random deviations also occur that are not reproducible, but have more or less statistical behavior. The effect of random deviations on the positioning of a machine axis is specified as the position variation range.

If a machine is to drill a hole in a workpiece with position tolerance, then the position variation range as a non-reproducible factor of error must be considered. Measurements carried out demonstrate that typical values for position variation ranges with feed axis lengths of 500 mm to 800 mm are around 2 µm ($\equiv$ ±1 µm) if the axes are operated in Semi-Closed Loop.

Connecting a linear encoder to the axis slide and feedback of the actual position values into the position control loop reduces the effects of friction in the axis and of linear guides on positioning. Measurements show that the position variation range with Closed Loop control can typically be reduced by 40 % to 50 % compared to Semi-Closed Loop ($\equiv$ ±0.5 µm).

Reduction of thermally induced drift
Measurements specified in the "Accuracy of Feed Axes" and "Machining Accuracy of Machine Tools" Technical Information documents show that a feed axis operated in Semi-Closed Loop with a ball screw and traverse range of 800 mm can produce thermally induced drift of over 40 µm ($\equiv$ ± 20 µm) ([11], [12]). If the problem is approached by cooling the ball screw, a drift reduction of 50 % can be achieved by using a high quality cooling unit (with a temperature constancy $\leq$ 1 K).
As well as integrating the cooling unit, additional pipes for coolant fluid for the individual feed axes must be installed, together with rotary unions for the transmission of coolant to the rotating ball screw spindles.
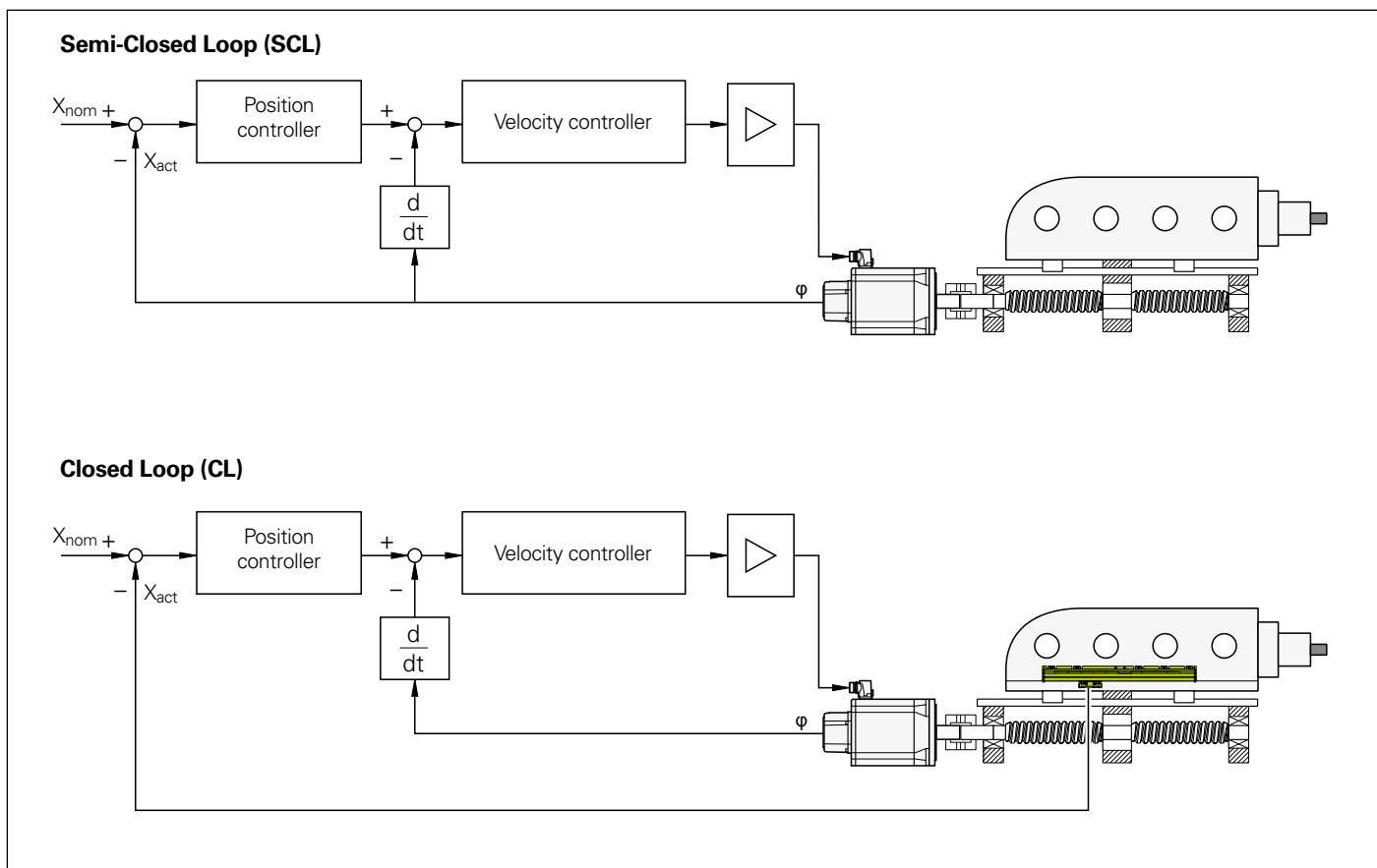

Figure 9: The principles of Semi-Closed Loop control and Closed Loop control

	Estimated error limits [µm]	
	Semi-Closed Loop	**Closed Loop**
Workpiece clamping indexation	±11.75 ±5.88 (with sliding unit)	
Tool change inaccuracy (hollow taper shank)	±0.5 (axial) ±1.5 (radial)	
Thermal main spindle axis drift (compensated)	±6	
Position variation range (500 mm < X ≤ 800 mm)	±1	±0.5
Thermal drift due to heating of ball screw	±20 ±10 (cooled ball screw spindle)	±1
Linear measurement deviation of coordinate measuring machine (CMM)	±1.5	

Table 1: Estimated error limits for Semi-Closed Loop and Closed Loop

A significantly higher reduction of thermally induced drift on a ball screw axis can, however, be achieved by using Closed Loop control. The linear encoder detects the drift of the ball screw spindle and this is adjusted by the axis control—residual thermal drift is then ≤ 2 µm (≡ ±1 µm) [11].

Table 1 lists the previously estimated error limits, comparing these for a feed axis with Semi-Closed Loop and Closed Loop. The position of the workpiece and the tolerated production features in the workspace must be taken into account when estimating which share of the tolerance to be produced the specified error limits will deplete. Thus, only those errors in the direction of the indicated tolerances require a share of the available tolerance budget.

Influences of workpiece measurement

Evaluation of the dimensional accuracy of workpieces is usually carried out in suitable measuring rooms with coordinate measuring machines. In its geometric construction a coordinate measuring machine is similar to a machine tool and is also subject to influences of error, with measurement deviations occurring when evaluating workpiece dimensions. The extent of measuring deviations is influenced by:
- Temperature fluctuations in the measurement room
- Geometry errors of the coordinate measuring machine
- Probing errors
- Measurement method selected
- Errors from workpiece clamping and operator errors
- ...

Because the residual measurement deviation must be significantly lower than the dimensional tolerance to be evaluated, coordinate measuring machines are usually operated in temperature-controlled measuring rooms. High precision is aimed for when producing and assembling the coordinate measuring machines, and linear encoders are used for Closed Loop control.

An additional reduction in residual deviations (e.g. from bending of the probe during probing) is achieved via computed compensations. To ensure reliable measurements with tolerated length dimensions, the linear measurement deviation of a coordinate measuring machine should be only approximately one tenth of the tolerance to be evaluated. So for a tolerance of ±0.1 mm as specified in a workpiece drawing this therefore means ±10 µm or less. However, to reliably measure smaller tolerances and to make available universally usable measuring machines, for example in central measuring rooms, in practice coordinate measuring machines are used that have linear measurement deviations in the range of ±1.5 µm.

Tool tolerance vs. error limits
Closed Loop increases the tolerance reserve

The comparison of required workpiece tolerance and estimated error limits specified on the previous pages is demonstrated in the following using an example geometry. Figure 10 illustrates the holes for the bearing assembly of a shaft in a transmission housing.

To reduce ancillary times and therefore the cycle time itself, both hole diameters can be produced using a combined tool. The tool edges for machining the diameters and Z dimensions are both located on one tool for this purpose. One of the index holes required for aligning the workpiece is also shown. The tolerance direction of the index hole is in the same direction as the tolerated production dimensions Z_1 and Z_2. This does not apply to the Y dimension.

Errors to be considered
The error that can occur due to indexing of the workpiece in the clamping fixture must therefore be taken into account when machining Z_1 and Z_2. Since other tools are used at other positions on the workpiece in the machine during this machining operation, the tool change inaccuracies must be integrated into the error budget. Furthermore, errors in the direction of the Z_1 and Z_2 dimensions, caused by thermal main spindle axis drift, position variation range during positioning of the Z axis in the machining direction, and thermal drift in the Z axis direction resulting from heating of the ball screw drive, should also be taken into account. The linear measurement deviations of the coordinate measuring machine are calculated into the error budget analysis independent of the clamping direction of the workpiece in the machine tool.
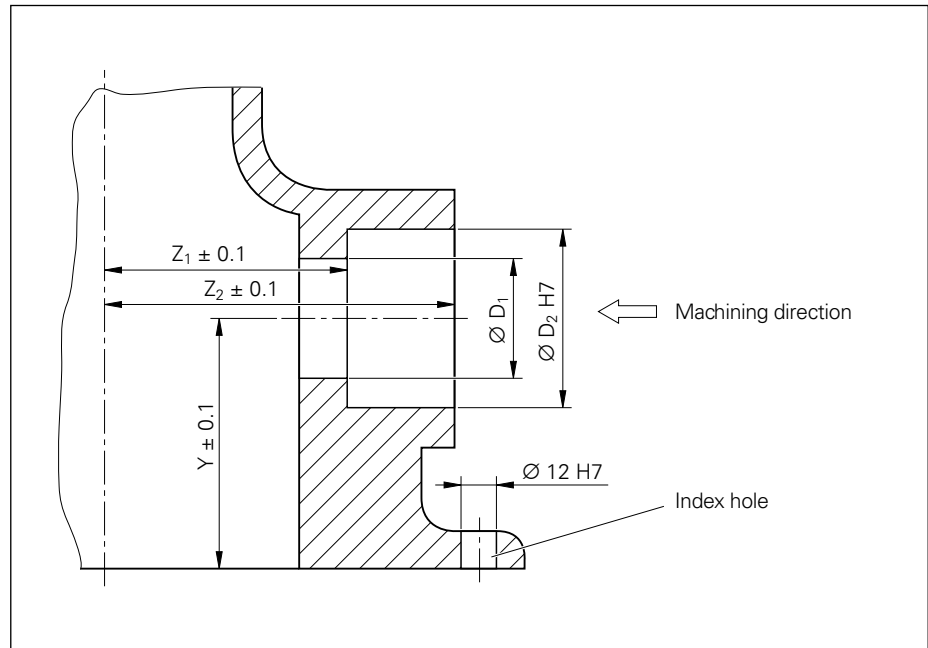

Figure 10: Bearing holes in a transmission housing (example geometry)

Under the assumption that tolerated production dimensions have a mean machine capability index of $C_m = 1.67$, it can now be ascertained how large the depletion of available tolerance is due to estimated errors in the worst case. Figure 11 demonstrates this for tolerances in the Z_1 and Z_2 dimensions with Semi-Closed Loop control.

It can be seen that the largest consumer of available tolerance is uncontrolled thermal drift of the ball screw spindle. The residual quantity of available tolerance (tolerance reserve) at the end of the analysis is only ± 19 μm.

Fewer errors and more tolerance reserve
It becomes clear that a reduction of error variables directly leads to an increase in tolerance reserve. The use of linear encoders on the linear axes, meaning operation in a Closed Loop, is able to specifically reduce thermally induced ball screw drift (Figure 12), and the result is a significantly increased tolerance reserve of ± 39 μm.

As outlined above, dependencies occur among individual production steps in the process chain with large-batch manufacturing. The error limits listed in Table 1 only indicate some of the potential error variables that can occur along the entire component production chain. The aim is therefore to achieve minimum flaw size in the individual machine tools, so as to maximize the tolerance reserves for difficult-to-influence errors within the process.
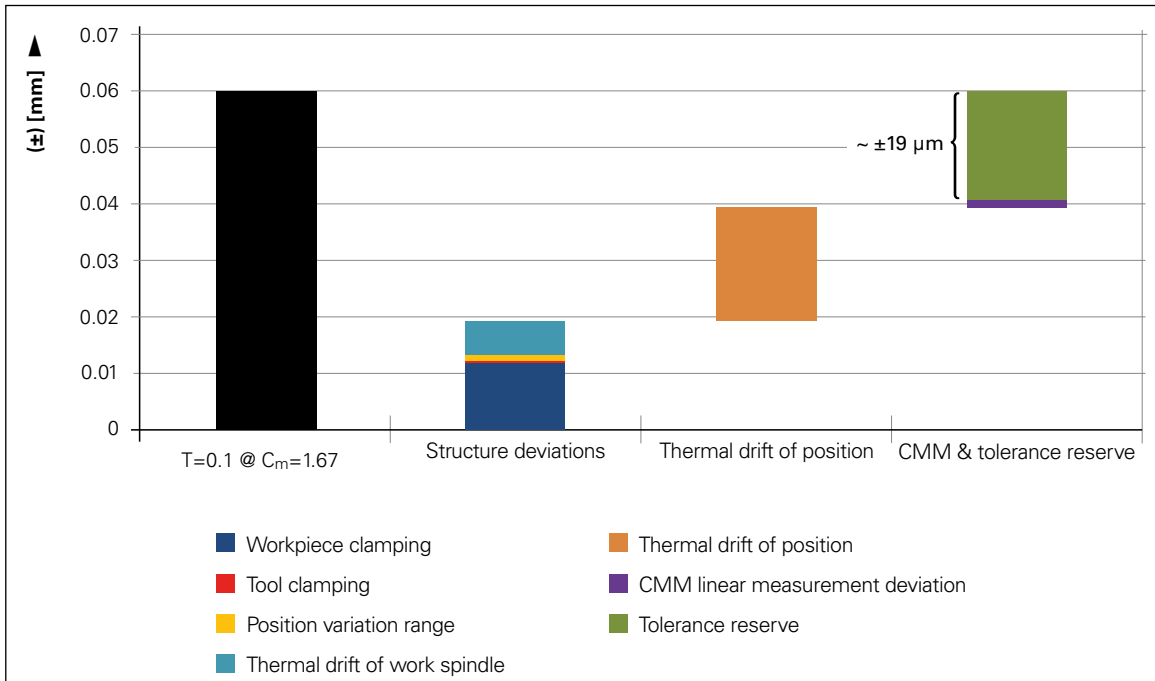
Figure 11:
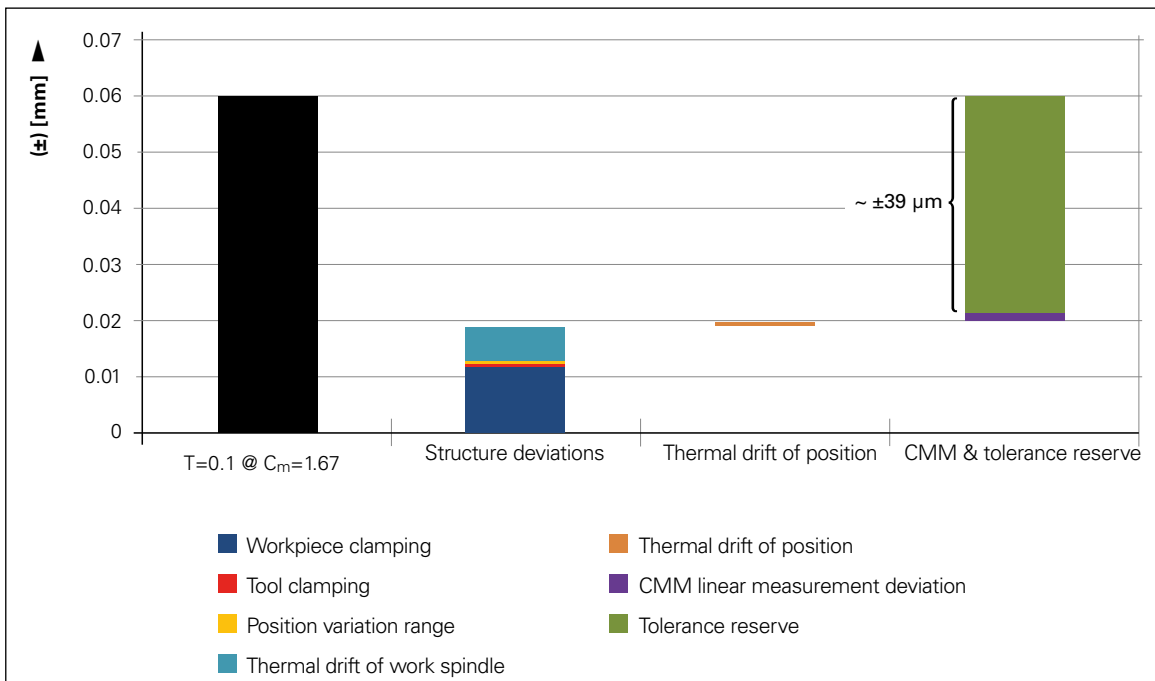Available tolerance (±0.1 mm) with $C_m = 1.67$ vs. error limits with Semi-Closed Loop

Figure 12:
Available tolerance (±0.1 mm) with $C_m = 1.67$ vs. error limits with Closed Loop

Factors of influence that are difficult to control in the production chain may consist of:
- Hall temperature fluctuations
- Coolant temperature fluctuations
- Workpiece temperature fluctuations and therefore thermally induced workpiece expansion during transport between machines
- Static distortions on workpieces due to varying clamping forces and clamping tolerances in individual clamping fixtures in the production line
- Thermal distortion of tolerance dimensions due to differing workpiece

temperatures in the individual machines (production of tolerance dimensions) and in the measuring room (evaluation of tolerance dimensions)
- Tool deflection due to inaccurate pre-machining (i.e. deflection of a reamer due to tolerance deviations in pilot drilling)
- Chips (i.e. stuck chips, chips from pilot drilling, etc.)
- Tool wear (i.e. variable cutting forces, tool deflection, etc.)
- …

This list is not comprehensive but clearly shows that designing a production process is not in any way trivial for the automated mechanical machining of vehicle powertrain components. Many possible error sources exist that are able to influence the quality, duration and costs of production.

Tool tolerance versus error limits
Tolerance reserves increase productivity

To gain a feeling of what tolerance reserves of ±19 μm in a Semi-Closed Loop or ±39 μm in a Closed Loop mean, the extent of tool wear is looked at closer below. With aluminum workpieces, burr formation on a workpiece often leads to a tool change despite the appearance of highly sharp cutting edges, whereas the machining of workpieces from cast iron (e.g. crank cases) or high-temperature resistant cast steel (e.g. exhaust gas turbochargers) causes higher levels of tool wear. This wear is usually seen as the increasing flank wear (VB) over time (Figure 13).

Tool wear must be permissible
Due to the tool edge geometry (clearance angle α, rake angle γ), a corresponding cutting edge offset (SV) occurs with increasing flank wear that then directly reduces the tolerance reserve. The cutting edge offset can be calculated according to [13], depending on the flank wear VB as well as α and γ as follows:

$$sv = \frac{VB \cdot \tan \alpha}{1 - \tan \alpha \cdot \tan \gamma} \qquad \text{(equation 7)}$$

Presupposing the latest linear layout incorporating linked machining centers, tool costs for the mechanical machining of cylinder heads, crank cases and transmission housings consist of 8 % to 12 %, which is a significant portion of the total system investment. This includes both non-wearing tool components (e.g. tool holder and boring bars) and the parts subjected to wear (inserts, drills, etc.). The proportion depends among other factors on the number of replacement tools used (sometimes up to three sets) and the cutting materials (e.g. PCD blades for aluminum machining).

To save on running tool costs the tool life should be as long as possible, and a certain level of tool wear must therefore be acceptable before carrying out tool changes or modifications. A flank wear VB of 200 μm to 400 μm is specified in [14] as a benchmark for carbide tools and for the finishing cycle relevant for generating tolerance. To gain a magnitude for the cutting edge offset, the typical cutting edge angles of α = 5° and γ = 4° are applied. Equation 7 then gives a cutting edge offset range of 18 μm to 35 μm.

Assuming a very sharp edge in the center of the tolerance zone, in a Semi-Closed Loop the targeted minimum tool wear values already require the largest part of the residual tolerance reserve. Under consideration of the larger tolerance reserves with the use of linear encoders, more workpieces can be machined before tool wear needs to be compensated, which in turn means less testing effort on the workpieces when detecting the right time to compensate or change the tool.

Tool changes interrupt production
Changing a tool used to produce a critical tolerance often requires a workpiece that needs to be directly tested and that was found to be in order (OK part). To prevent rejects, the machine sits idle while this first workpiece produced with the new tool is measured, and the machine tool is only approved if the produced and measured workpiece corresponds to an OK part. The waiting time until approval can be equated to a loss of parts because production time on the machine is lost.

Because the testing and compensation complexity can be reduced and machine run-times increased, a large tolerance reserve in large-batch production contributes to an increase in productivity levels. In analogy to automotive driving, this would correspond to driving in a wide lane where little correction effort by the driver is needed to stay within the lane—significantly more effort for correction is needed in narrower lanes.
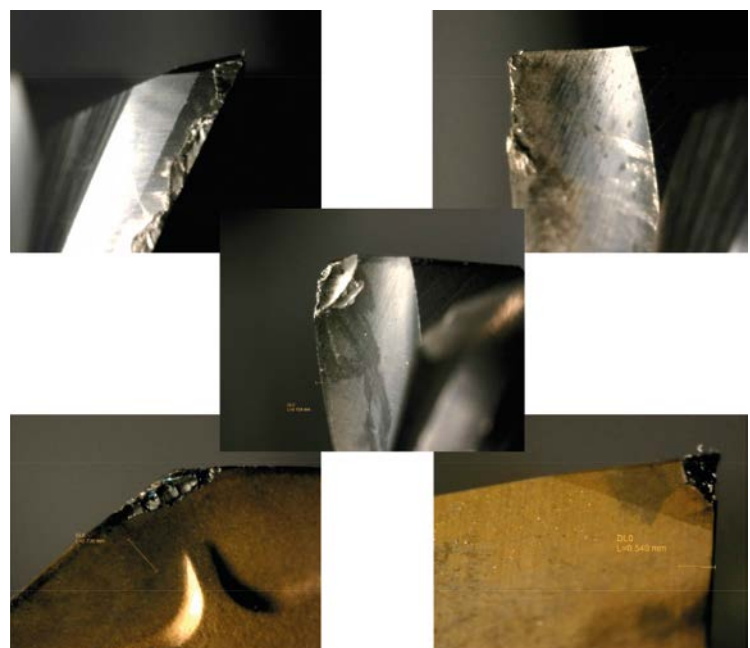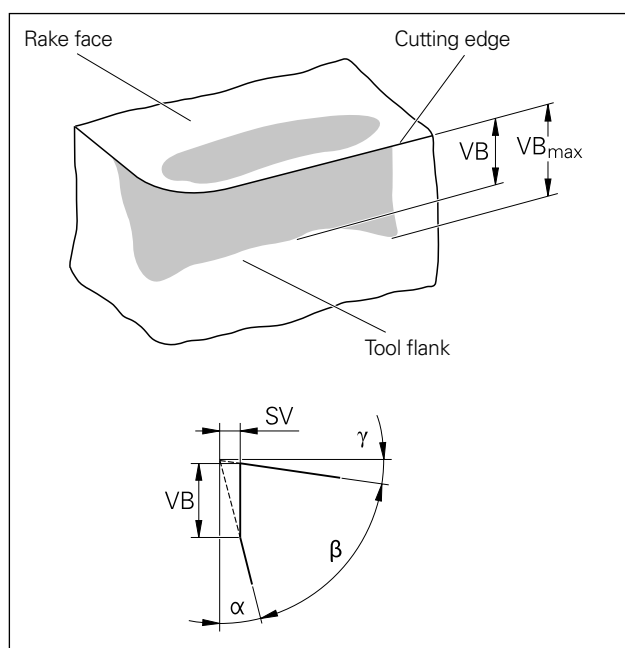

Figure 13: Flank wear (VB) and cutting edge offset (SV) – Drawings on the basis of [13] and [14]

Summary

In addition to the challenge of responding to fluctuations in demand in automotive sales markets, the future will bring increasing legislative and end-customer requirements concerning the emission of pollutants and the fuel consumption of vehicles. One possibility of meeting such a situation consists of reducing friction in the powertrain, which in turn requires narrow workpiece tolerances as well as higher quality surface parameters.

Because of the sequential workpiece machining implemented in automated large-batch manufacturing, dependencies occur between the individual production steps in the process chain. For reliable adherence to workpiece tolerances throughout the entire process, the aim is to expend a minimum of the available tolerances by the individual machine tools, with the remaining tolerance reserve being available for difficult-to-control factors that influence the process, meaning this reserve should be as large as possible.

Using linear encoders in the feed axes of the machining centers contributes to an increase in machine accuracy, and resulting from this an increase of the tolerance reserve as well. Inspection complexity and loss of parts can be reduced, leading to increases in productivity levels.

Literature

[1] Kasper, G.: Challenges for Future Powertrain Production – Insights to Global Manufacturing. 12th Powertrain Manufacturing Conference, Darmstadt, September 26th – 27th, 2013.

[2] Abele, E.; Hueske, B. and Kuhn, S.: Overall Equipment Flexibility – Entwicklung einer Methodik zur Messung der Gesamtanlagenflexibilität für die spanende Fertigung. ZWF 103 No. 5, 2008.

[3] Dörr, J.: Powertrain Machine Tool Concepts: Comparison from an Economic Point of View. 10th Powertrain Machining Conference, Fellbach, November 11th – 12th, 2009.

[4] Abele, E.; Wiegel, F.; Kuske, P. and Hueske, B.: Kleine Schritte für große Flexibilität – Eine Methodik zur monetären Beurteilung der Expansionsflexibilität von Fertigungssystemen. wt Werkstattstechnik online year 100, 2010.

[5] Stürenburg, B.: Optimierung der Spanbildung und Minimierung des Späneeintrages in das Werkstück für das Bohren von Al-Legierungen. Production reports from the FBK, Volume 02/2009.

[6] Abele, E.; Ellermeier, A.; Hohenstein, J. and Tschannerl, M.: Untersuchungen an langen VHM-Spiralbohrern – Einfluss der Werkzeuglänge auf das dynamische Verhalten von Vollhartmetallspiralbohrern. wt Werkstattstechnik online year 97, 2007.

[7] VDMA 8669 : 1999-01: Fähigkeitsuntersuchungen zur Abnahme spanender Werkzeugmaschinen. Verband Deutscher Maschinen- und Anlagenbau e. V. (VDMA), 1999.

[8] MAPAL: MAPAL Kompetenz – Spanntechnik. Corporate publication MAPAL Präzisionswerkzeuge Dr. Kress KG, Order No. 10138532 | V2.1.0, 2015.

[9] DIN ISO 230-2 : 2000-05: Testing Rules for Machine Tools – Part 2: Determination of Positioning Uncertainty and Repeat Accuracy of Positioning with Numerically Controlled Axes. DIN Deutsches Institut für Normung e.V., 2000.

[10] VDI/DGQ 3441: Statistische Prüfung der Arbeits- und Positionsgenauigkeit von Werkzeugmaschinen - Grundlagen. Verein Deutscher Ingenieure / Deutsche Gesellschaft für Qualität, March 1977.

[11] HEIDENHAIN: Technical Information – Accuracy of Feed Axes. March 2006.

[12] HEIDENHAIN: Technical Information – Machining Accuracy of Machine Tools. September 2011.

[13] Paucksch, E.; Holsten, S.; Linß, M. and Tikal, F.: Zerspantechnik – Prozesse, Werkzeuge, Technologien. Vieweg + Teubner Verlag, 12th edition, 2008.

[14] GARANT: GARANT ToolScout – Zerspanungshandbuch. ISBN 3-00-016882-6, modified ND 04/2013.

Linear encoders for machine tools

Linear encoders for position feedback are indispensable for high positioning accuracy of machine tools. They directly and immediately measure the actual position of the feed axis. Mechanical transfer elements therefore have no influence on position measurement—both kinematic errors and thermal errors or influences of forces are measured by the linear encoder and taken into account in the position control loop. This makes it possible to 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
- Kinematic errors through pitch error in the recirculating ball screw

Therefore, linear encoders are indispensable for machine tools on which high **positioning accuracy** and a high **machining rate** are essential.

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 servo loop, such as milling machines, machining centers, boring machines, lathes and grinding machines. The beneficial dynamic behavior of the linear encoders, their high permissible 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.

LC 485 up to 2040 mm

LC 185 up to 4240 mm

LB 201 up to 28040 mm

HEIDENHAIN

More information:
- Catalog: *Linear Encoders for Numerically Controlled Machine Tools*
- Technical Information: *Accuracy of Feed Axes*
- Catalog: *Measuring Devices for Machine Tool Inspection and Acceptance Testing*