Challenges and methods of measurement process validation for machine integrated product inspection

Robert Schmitt, Maria Nau and Susanne Nisch

Chair of Metrology and Quality Management, RWTH Aachen University, Steinbachstr. 19, 52074 Aachen, Germany
Maria Nau / E-mail: m.nau@wzl.rwth-aachen.de, TEL: +49-241-80-28383, FAX: +49-241-80-22193

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The increasing product variety and shorter life cycles are challenges the manufacturing industry has to face. This requires an agile and transparent production which can be achieved by the application of production metrology within the framework of the management of measurement processes (MMP). The MMP requires the validation of the acquired data, its processing to usable performance indicators and feedback in closed control loops. An influencing factor on the response time of these control loops is the integration level of the measurement system.
By shifting measurements from an inspection room onto a machine tool, the control loop's response time to corrections is reduced as the time between manufacturing and inspection is reduced. Besides this advantage it has to be considered that the influence of disturbances on the measurement processes increases with the degree of integration in the production. This implies that the validation of measured data becomes essential. An approach to validate this data is to proof the capability of the measurement process. For this, different procedures are discussed and for one of them, ISO 155530-3, an example is given for measurements of a 50 and 120 mm diameter on a machine tool with a calibrated ring.

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NOMENCLATURE

MMP = Management of measurement processes
X_n = Input quantities
Y = Output quantity
CMM = Coordinate measuring machine
TCP = Tool center point
MPE = Maximum permitted error
WKS = Workpiece coordinate system
U = Extended measurement uncertainty

1. Introduction

Today's manufacturing industry has to meet the challenges of shorter product life cycles and small lot sizes due to an increasing product variety. Therefore an agile and transparent production is required in order to stay competitive on the global market. The application of production metrology within the management of measurement processes are key factors concerning this. They provide the acquisition of data and the feedback of relevant information to associated machines or departments which at the same time provides transparency of the production process and forms the basis for process improvement. As decisions e.g. about adjusting process parameters or about approving or rejecting parts are taken based on the acquired data, it is important to assure its validity as this reduces the risk of taking wrong decisions. Hence, the measurement data has to be acquired with an appropriate uncertainty. Initially, the importance of measurement uncertainty was considered by the automotive industry that continuously claims a proof of capability for measurement processes. The proof of capability shows that a measurement system is capable to carry out a measurement with an appropriate uncertainty under defined circumstances and specific boundary conditions. Since the capability is influenced by these boundary conditions, the level of integration of the measurement system into the production line has to be considered. The number and intensity of influencing factors increases with the integration level. As the reaction to process changes becomes faster and the through-put-time is reduced due to machine-integrated measurements, the efforts to integrate coordinate measuring techniques into the production increases [3]. In order to ensure the validation of these measurements the challenge of identifying and estimating the influence of relevant factors on the measurement uncertainty has to be faced. Different analytic and experimental approaches and methods are discussed in this paper.

2. Integration level of measurements

By shifting measurements from an inspection room or a measurement system close to the production line onto a machine tool, the control loop's response time to corrections is reduced as the time between manufacturing process and inspection is reduced. By manufacturing and measuring the workpiece in one fixture on the machine tool, deviations between the measured and the nominal value can be corrected directly.

This concept enables a directed reworking and the improvement of following process steps especially for large and heavy or limping workpieces. To move such parts from the machine tool to a measurement device and back is mostly impossible because the setting on the machine tool is not repeatable. Above all, the throughput time can be reduced and the product quality is assured.

In general, five integration levels of metrology in the production chain can be differentiated [1]:

- measurements distant-to-production
- measurements close-to-production
- inline measurements
- post-process measurements
- in-process measurements

If the measurement is shifted onto a machine tool, it is usually a post-process measurement. Therefore, besides the advantage of a shorter reaction time, it has to be taken into account that the influence of disturbances on the measurement processes increases with the degree of integration into the production (Fig. 1). This provokes an increasing measurement uncertainty as well. An in-process or post-process measurement is e.g. influenced by the conditions of the production line like changes in temperature or vibrations from other machines.

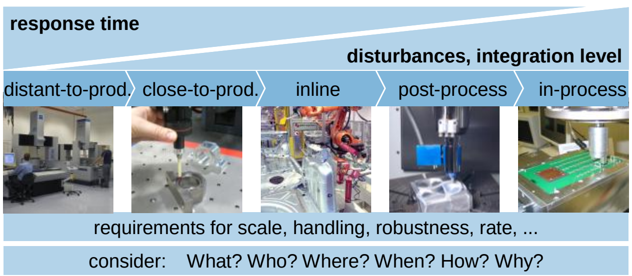


Fig. 1 Integration level of metrology [1]

Besides, several other aspects have to be taken into account when choosing the appropriate integration level such as the test frequency, sample size, cycle time, the robustness of the measurement and the time needed for the measurement.

If 100% of the produced parts have to be inspected, usually inline, post-process or in-process measurements are preferred. If only sample parts need to be inspected, generally distant-to-production or close-to-production measurements are chosen. For a workpiece that is taken out of the production and measured with e.g. a coordinate measuring machine (CMM) in an inspection room, it can take up to several hours for transferring it to the inspection room and back, cleaning it, measuring its relevant features, interpreting the results and adjusting the process parameters if necessary. The advantage is that the measurements have a very small uncertainty as the measurements are conducted in a stable environment. Especially for large parts this procedure is time and cost-consuming and can be simplified by measuring the part on the machine tool.

Any acquired measurement data is uncertain to the degree of influence of the surrounding. This means that a process variation that is monitored for process control is interfered with the measurement uncertainty. The resulting process variation is a superposition of the process variation and the measurement uncertainty (Fig. 2) [4].

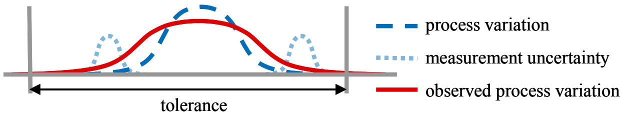


Fig. 2 Measurement uncertainty influences the observed process

Provided that the sampling size is big enough, a process can be recognized as capable if the observed process variation lies within the defined tolerance. Therefore the measurement uncertainty is of importance.

3. Management of Measurement Processes

3.1 General Approach

The model of the management of measurement processes (Fig. 3) is a systematic approach to the acquisition, validation, processing and feedback of information [5]. Its objective is to provide valid information considering the target variables quality, cost and time.

According to the management of measurement processes, the acquisition of data exceeds the classical approach of capturing signals with a sensor, as it includes all kinds of information along the process chain of design, planning, production and inspection. The acquired information can be diverse as the source of information is no longer limited to the workpiece. Not only are the results of the workpiece inspections considered but also e.g. the condition of the machine tools and tolerances. The required information depends on its application. In order to enable a decision about the conformity of a feature with its specifications, other information is needed than for the estimation of a machine tool's capability or for process control.

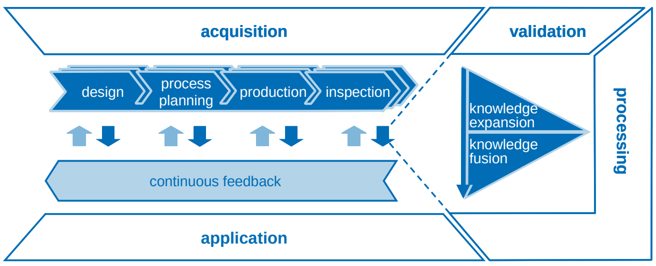


Fig. 3 Model of the Management of Measurement Processes

To avoid decisions based on invalid information, the validation of acquired data is essential. Wrong decisions can either cause the rejection of good parts (type I error) or the non-rejection of defected parts (type II error) [6]. If the data basis is valid, this risk is reduced and can be estimated.

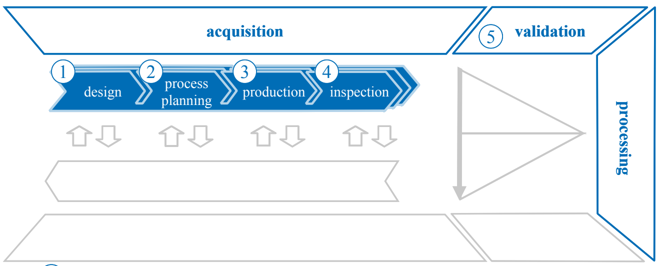
After validation, the measurement data is processed to provide useable key figures within the control loops. Therefore, the data is expanded e.g. to measurement series or different data sources to gain a wider knowledge about the workpiece or the production process.

Typical key figures are e.g. performance indicators such as the process capability or correction values for machine parameters. The feedback closes the control loop (Fig. 3) and therewith forms the basis for improvements of the production process.

The response time to improvements within the control loop is influenced by the degree of integration of the measurement system.

3.2 Application of measurements

Measurements can serve different purposes. The most common application is the measurement to ensure the quality and function of a workpiece. Hence, a specific feature of a workpiece is measured in order to determine its conformity with the specification. Therefore, information from different sources is needed (Fig. 4): Tolerances are set in the design phase (1). During process planning (2) the measurement system with which the feature is captured as well as its level of integration into the production line are chosen. Furthermore, the measurement uncertainty for this conducted measurement process (4) has to be estimated in order to prove the measurement process's capability. This proof of capability ensures that the acquired data is valid (5).



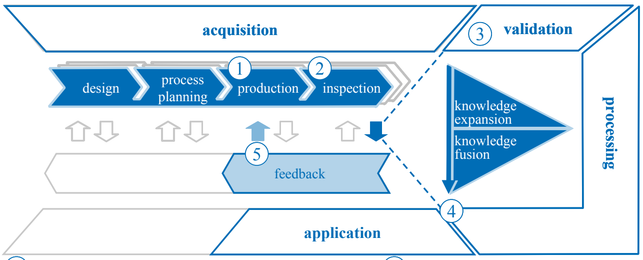
1 define characteristics and set tolerances
2 choose a measurement system and define the measurement process
3 produce the characteristics
4 carry out the inspections
5 estimate the capability of the measurement process

Fig. 4 Forward chain of the MMP model

Besides the workpiece inspection, measurements are applied to gain knowledge about a machine tool such as the machine tool's capability as well as its geometric characteristics [7, 8]. This knowledge about a machine tool can be used to compensate systematic errors in order to improve the production process (Fig. 5). The geometric errors of a machine tool are determined directly by calibrating the machine tool itself. Therefore, the tool is repeatedly repositioned within the working chamber of the machine (1b) whereby each position is measured (2b) to calculate the performance indicators.

To determine the machine capability sample parts are manufactured on the machine tool of interest (1a). Defined features of these parts are measured e.g. by a coordinate measuring machine (2a) and compared with their nominal values. Therewith, systematic as well as random errors are determined [9].

As the measurement of the workpieces is usually conducted in an inspection room, the necessary time is long compared to machine-integrated measurements because of the transport from the machine tool to the measuring device. To provide valid data (3) for the determination of the machine capability, it is important that the parts for testing are manufactured under the same conditions (e.g. temperature) as in the production line and the used measurement system has to be capable to measure the defined features with acceptable measurement uncertainty.



1a produce workpieces on the machine tool
1b reposition the tool
2a measure the workpieces' features
2b measure the positioning errors
3 ensure the capability of the measurement processes
4 estimate the machine tool's operation uncertainty
5 feedback the gained information to adjust parameters and to compensate geometric errors

Fig. 5 Application of information in the backward chain of the MMP model

The gained knowledge about the machine tool and the production process (4) can be used to improve the process which results in a decreased process variation (5).

Even for capable processes the improvement of the production process has advantages. On the one hand, a decreased process variation allows producing features with smaller tolerances and on the other hand it allows larger measurement uncertainty (Fig. 6). If the measurements are shifted onto a machine tool, the process improvement can be important when measurement uncertainty increases and the observed process capability must be provided.

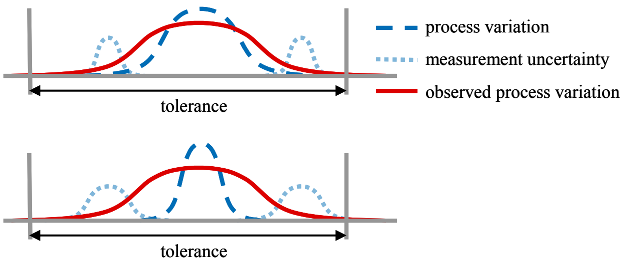


Fig. 6 The same observed process variation can result either from a large process variation combined with a small measurement uncertainty (above) or from a small process variation and a large measurement uncertainty (low).

4. Procedures for the validation of information

There are several approaches to ensure the validation of acquired measurement data. They all have in common that the measurement process needs to be modeled. Therefore factors that influence the measurement have to be identified. The influences and the resulting errors can be classified according to their cause and type [9].

The modeling of the measurement process can either be done analytically or experimentally. An analytic standard procedure to estimate the measurement uncertainty is the "Guide to the expression of uncertainty in measurement" [10]. Its basis is a mathematical model of the measurement process which describes the output quantity Y depending on the input quantities X_1 – X_n. Another analytic approach according to VDI/VDE 2617 part 11 [11] determines the task-specific uncertainty for measurements on coordinate measuring machines based on calculation tables.

The specific guidelines of the automotive industry [12, 13] to proof the capability of measurement processes take both approaches into account: The experimental determination of influences on the measurement and the determination of measurement uncertainties based on pre-knowledge.

An experimental approach is defined in ISO/TS 15530-3 [2]. It describes the determination of the measurement uncertainty of coordinate measuring machines using calibrated parts or measurement standards.

These different approaches form the basis for the validation of acquired data in the production. Thus, they are also applied to validate machine-integrated measurements.

5. Validation of measurements on machine tools

5.1 Challenges of machine integrated 3D measurements

By the application of tactile probing systems on machine tools, production integrated 3D measurements are feasible from a technological point of view. Nowadays, every new machine tool can be equipped with probing systems that are used to measure the workpiece position before manufacturing as well as geometric product features after manufacturing. The probing system, which is put in the machine's tool interface, detects the measurement position when touching the workpiece. The contact triggers the machine controller whereby the position of the tool center point (TCP) is measured by the hardware encoder of the machine axes (Fig. 7). Two types of interfaces are established to transfer the trigger signal, infrared and wireless connection. In grinding machines the transfer can be realized by cable, because the probing system does not need to be put in a variable tool interface.

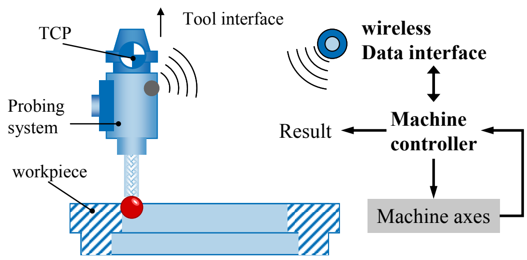
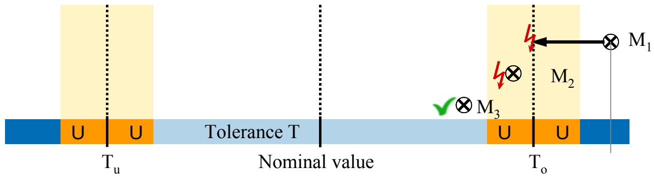


Fig. 7 Application of tactile sensors for machine integrated 3D measurements

Concerning the configuration of the measuring program and the data processing, different types of integration can be distinguished. Based on parameterized cycles, the NC program for the measurement is defined directly on the controller and the resulting value for the measured feature is saved in special parameter on the controller. The advantage of this method is the direct use of information on the controller for correction loops. To process data, simple calculations are used. Their results are not comparable with results from a CMM that are processed by optimizing algorithm. Besides, the measurement strategies are limited. Usually measurement points are probed in one direction of the machine axes [14]. The tangential probing in several axes compared to a CMM is not used. With external measurement software the configuration and displaying of results can be simplified for the user while providing the same result. Whereas, the configuration of a probing point based measurement program and the following data processing by external software is less common.



M1 Measured value exceeds the tolerance limit
M2 Measured value is inside the tolerance but close to the limits
M3 Measured value is inside the tolerance that is reduced by the uncertainty

Fig. 8 Influence of measurement uncertainty on correction for a two side limited feature

The validation of data and the estimation of the measurement uncertainty are essential for the application of the measuring results for an automated correction of process steps. Around the tolerance limits T_O and T_U a zone is set due to the measurement uncertainty in which it is impossible to decide clearly about features conformity (Fig. 8). If the measured value (M_2) is near the tolerance limit, closer than the value of the measurement uncertainty, the definite inspection of conformity of the feature is not possible. Considering the measurement uncertainty, this process has to be corrected to avoid exceeding a tolerance limit (M3). If the measured value (M_1) is outside of the tolerance zone, the process can be adjusted against the nominal value or against one of the tolerance limits considering the measurement uncertainty. To correct the production process against a tolerance limit can be useful for manufacturing processes that are strongly influenced by abrasion.

With this approach the uncertainty of measurements for detecting the coherences between deviation of product features and the control variables have to be considered. Consequently, the maximum acceptable measurement uncertainty is reduced dependent on the measurement process for the determination of coherences.

5.2 Influencing factors

The influencing parameters of integrated 3D measurements on machine tools are divided in four causes: Errors of the machine tool, the tactile probing system, the measurement strategy and the environmental conditions.

The results of manufacturing on machine tools are influenced by different factors. It can be differentiated between geometric machine errors, kinematic and dynamic behavior, process inherent forces as well as temperature deviations and drifts [15]. Compared to that, the measurement process is mainly influenced by geometric machine errors and temperature deviations. Geometric errors of machine axes can be detected by several direct and indirect methods. By the volumetric calibration of a machine tool based on multilateration with laser tracking interferometer and compensation, the volumetric positioning errors can be minimized up to a few micrometers [16]. To monitor the characteristics of machine tools, the diagonal test is proposed by ISO 230-6 [17], compared to the inspection of specification at CMMs [18]. However, there are no specifications defined for the evaluation of machine tools characteristic concerning integrated measurements, like MPE (Maximum permissible error) for CMMs. Another difference between a machine tool and a CMM is the stability of machine characteristics. Caused by forces in the manufacturing process the geometric machine characteristics change with time. Hence, the regular inspection of machine characteristics by standardized tests is necessary.

Producer of tactile probing systems specify the repeatability of probing at the confidence level of 2 σ. Compared to a probing system on a CMM whose geometry and stiffness is determined by probing a precise sphere, the probing system on a machine tool is characterized by single points probed in the direction of machine axes [14]. The trigger point and the diameter of the probe tip are determined using a dial ring or a precise sphere with known diameter and position in the Z direction. This information is used to correct the probed position. Hence, the tangential probing compared to CMMs needs the determination of the probe characteristics for tangential probing directions, too.

The measurement strategy has a big influence on the measuring results. If a value for a product feature is determined by simple calculation of differences between two points in the direction of machine axes the measurement result is very sensitive to positioning errors of the machine, surface characteristics and deviations of orientation (Fig. 9). By measuring several points and processing these data to reference elements such errors can be minimized.

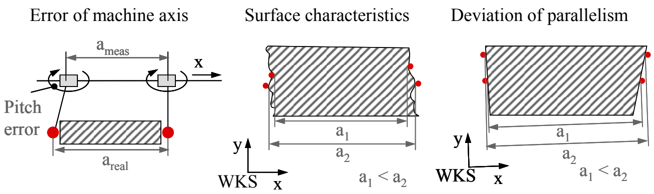


Fig. 9 Sensitivity of measurements by the probing strategy combined with errors of machine axes (WKS - workpiece coordinate system)

Besides inherent influences, the environmental conditions like temperature deviations, vibrations, air pressure, humidity and dirt like chippings and lubricants on the workpiece have to be considered. The conditions on a machine tool are not comparable to production integrated CMMs. To install a CMM, factors like sources of vibrations, air draft and dirt are considered and have to be minimized before use. These factors have to be regarded when preparing a measurement on a machine tool, too.

5.3 Inspections with calibrated workpieces or standards

According to ISO/TS 15530-3 [2], calibrated workpieces or standards can be used for a simplified determination of the measurement uncertainty of coordinate measuring machines. For this method, the similarity of dimension and characteristics of the workpiece as well as the features of interest has to be provided. The Test series need to be performed under the same conditions with the same measurement strategy.

The extended measurement uncertainty U with a coverage interval of 95 % (k=2) is calculated:

$$U = k \cdot \sqrt{u_{cal}^2 + u_p^2 + u_w^2 + b^2} \tag{1}$$

The standard deviation u_p is calculated based on test series with at least 20 measurements with the calibrated workpiece. The uncertainty due to the calibration of the workpiece u_{cal} is calculated based on the extended uncertainty U_{cal} documented in the calibration certificate. This uncertainty has to be less than the uncertainty of the regarded measurement process. U_W considers deviations and varying characteristics of the workpiece like temperature deviations from the nominal temperature of 20°. Process variations that result e.g. in roughness have to be estimated by u_W, too, because its impact needs to be considered in the measurement strategy [19]. The systematic deviation b is the difference between the calibrated value of the feature and the value indicated by the measurement system.

5.4 Design of Experiments

Based on two calibrated rings with nominal diameters of 50 mm (form deviation of 2.1 µm) and 120 mm (form deviation of 11.2 µm), the differences of measurements on a machine tool and a CMM concerning the uncertainty will be illustrated. Therefore the method of ISO/TS 15530-3 [2] is applied to estimate the uncertainty for of a measurement process on a machine tool with different strategies for data processing. The main advantage of this approach is the transferability to other machine tools or workpieces and the practical application. Only calibrated workpieces are required with known calibration uncertainty and comparable characteristics. This is less complex than e.g. the procedure of the GUM [10], as individual sources of deviations are not analyzed. A directed optimization of the measurement process needs to detect coherences between influences in the measurement process and deviations of the measurement result.

The rings are measured by 4 points, probed in the direction of the machine axes, and by 8 points in the XY plane of the machine tool. Afterwards, the center position and the diameter of the rings are calculated directly by determination of the diameter of a difference between two points and by using a reference circle. To calculate the reference circle, the method of Gauss is applied using external measurement software. The test series is repeated at several positions within the machine volume to consider the influence of the machine geometry. Temperature deviations are measured to correct the measured data. This correction of length deviation is considered with u_W in the uncertainty budget.

The specification for the probing repeatability of the probing systems, which is characterized by a dial with a diameter of 30 mm, is 1 µm. A test series of 20 repetitions in every direction of the machine axes without removing the probing system from the tool interface showed show a repeatability of 0.3 µm.

The measurements are applied on a machining center whose geometric errors where calibrated and compensated up to a residual positioning uncertainty of 4 µm [16].

5.5 Results

Previous activities like the compensation of geometric machine errors result in small measurement uncertainties for the test series with both calibrated rings (Fig. 10). The measurement uncertainty of the measurement set up on a machine tool is not much bigger than the uncertainty resulting from the set up on a CMM.

In fact, the uncertainty for measuring the ring with the diameter of 120 mm is 25% bigger than the results from the form deviation of this ring. However, it has to be considered that these test series were performed under very stable conditions. The measured temperature varied 0.4 K over the regarded time period.

Discrepancies to measurements with a CMM can be explained by the positioning uncertainty after volumetric compensation of the machine tool, to the method for determination of the probing system's characteristics and to temperature errors of second order or higher, e.g. temperature forced deflections of the machine.

Ring	Test series	Mean value	Standard deviation	Bias |b|	U
50 mm	MT/4 points/diff.	49.9977 mm	0.3 µm	2.8 µm	**5.7** µm
	MT/4 points/ref.	49.9978 mm	0.3 µm	2.7 µm	**5.6** µm
	MT/8 points/ref.	49.9981 [illegible]	0.3 [illegible]	2.4 [illegible]	[illegible]

Fig. 10 Results of the measurement uncertainty estimation with calibrated rings for several measurement strategies on machine tool (MT) and CMM.

6. Conclusions

The evaluation of measurement processes is important for the further use of measurement results. The measurement uncertainty therefore needs to be considered for all inspections, both for workpiece inspections and for measurements that result in a correction of process steps. Different methods for the estimation of these uncertainties are applied that require the modelling of the measurement process. Especially measurement processes close to the production are influenced by various variables that make the mathematical modelling very complex. Therefore practical methods originally defined for CMMs can be applied to production integrated measurement processes. The design of experiments for the estimation of uncertainties with calibrated workpieces requires the consideration of the variance of different features as well as the varying environmental conditions.

Machine integrated 3D measurements of calibrated rings illustrated the demands of the application of calibrated workpieces. When the results of measurements on a machine tool are used to monitor or to correct process steps, the measurement uncertainty needs to be an adequate fraction of the tolerance.

The results show the high repeatability of probing a workpiece with a machine tool under stable conditions. This indicates a high potential of machine-integrated measurements. The temperature behaviour of the machine tool with process heat was not considered in the test series yet. To determine the measurement uncertainty for real measurements, the temperature behaviour during production and the long term behaviour of the machine have to be investigated in further test series. Beyond that, methods to reduce the measurement uncertainty of machine integrated measurements will be part of further research.

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