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Capability of measurement with a touch probe on CNC machine tools

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ABSTRACT

Increasing the productivity of high-precision manufacturing requires efficient product inspection, for example, using integrated scanning systems on CNC machine tools (MT). However, measuring the dimensional and shape accuracy of workpieces using a touch probe (TP) on MT is negatively affected by the geometric accuracy setting of the MT, thermal stability of the MT and its surroundings, type of scanning system.

The aim of this paper was to examine the possibilities of assessing the capability of touch probe measurements on MT, to define the size of the permissible controlled tolerance of the workpiece and to assess the influence of the geometric accuracy of the machine on the size of the permissible tolerance parameter of the inspected workpiece. In the presented experiments, the calculation of the TP measurement capability is based on a new approach respecting the VDA5 standard extended by the minimum tolerance (TOLmin) conformity assessment procedure according to ISO 14253-1:2017.

1. Introduction

In all branches of industrial production, ever higher demands are placed on productivity and quality of production. Increasing production efficiency by introducing flexible production processes is one of the goals of research in the field of production technologies, especially for high value-added workpieces [1,2].

One of the ways of how to increase the efficiency of production on CNC machine tools is to perform a larger number of technological operations on one machine. These operations include inspecting the dimensional and shape accuracy of the final workpiece with integrated elements of automation and intelligent metrology [9].

Coordinate measuring machines (CMMs), which are regularly calibrated and operated mainly in a metrologically stable environment, are used as standard for this purpose. Thanks to the defined ambient conditions and long-term stable geometric accuracy, the CMM can be characterized by the MPE (Maximum permissible error) parameters according to ISO 10360-1: 2000 and ISO 10360-2: 2009, from which the suitability of the CMM for the inspected workpiece can be further assessed. The second variant is to use, for example, an integrated touch probe directly in the CNC machine tool and to inspect the workpiece directly in the machine. This makes it possible to achieve significant time savings and thus increase the productivity of a given production process. The main disadvantage of workpiece inspection using a touch probe in a machine tool are unstable ambient conditions, contamination of the machine workspace e.g., with process fluid and chips, static compliance of machine and changes in machine geometric accuracy related to static compliance and thermally unstable ambient conditions. A number of publications are devoted to determining the measurement uncertainty and defining the magnitude of the contributions of individual disturbances. For example, the study [3] dealt with the temperature effects on measurement uncertainty in the structure, which was extended by a comprehensive assessment of the uncertainty for on - machine measurements according to ISO 15530-3: 2004 [4].

It is necessary to view this inspection process not only in terms of accuracy and repeatability of the touch probe, but also in terms of accuracy and repeatability of the machine tool, which is a weak point in the process of inspecting the dimensional and shape accuracy of the workpiece. The overall summary of factors influencing the accuracy of a machine tool was given in detail in the publication [5] as early as in 2002. In terms of longitudinal dimensions, it is mainly a relative motion between machine parts, expansion of ballscrew and deformation of machine elements due to heat.

Implementing the procedures for touch probe measurements linked

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to the length standard [8] on machine tools will reduce the time required for the entire production process and thus increase work efficiency.

The dimensions obtained with the touch probe on the machining centre are usually indicative or relative, as there is no constant tolerance of the longitudinal dimension given by the machine tool [6,7]; therefore, the absolute dimensions of the workpiece cannot be declared with the touch probe.

The aim of this paper was to examine the possibilities of assessment of the measurement capability on machine tools, to define the size of the permissible controlled tolerance of the workpiece and to assess the influence of the geometric accuracy of the machine on the size of the permissible tolerance of the workpiece. For this purpose, capability tests were performed according to the VDA 5: 2010 standard, with calculation adjustments in accordance with ISO 14253-1: 2017. A solution to this problem has not yet been published. The proposed procedure is applied on a three-axis milling CNC machine tool

2. State of the art and research approach

The use of touch probes on CNC machine tools (hereinafter referred to as MT) is one of the standard operations for measurements during the machining process or after machining. However, in principle, the MT does not use a control mechanism that would determine for what minimum tolerance the MT can be used as a CMM. Standards such as VDA 5: 2010, ISO 14253-1: 2017, etc. can be used for CMM to determine the minimum workpiece tolerance. From the point of view of long-term geometric accuracy of CMM and MT, diametrical differences can be observed, especially in the environment in which machines operate and in the process of its exploitation, in particular in the mode of loading. Changes in working environment conditions are presented especially for MT, where these changes occur. These are, for example, changes in the ambient conditions and individual parts of the machine [10,11], setting up the workpiece in the process of measurement and static loading of the machine [12].

2.1. State of the art of workpiece measurement with a touch probe

A number of scientific papers are devoted to the identification of sources of errors by measuring with touch probes on the CMM. These are mainly errors caused by the compliance of the touch probes design, which include deformation of the shank, contact body, hysteresis of kinematic probes, etc. Mechanical and kinematic errors of touch probes range according to the studies in the range of 2 μm for mechanical errors and 1 μm for kinematic errors [13,14].

Another group of scientific papers focuses on the area of machine tool measurement. This area represents a relatively large potential for increasing the efficiency of the working process, where the touch probes are used to inspect the dimensional and shape accuracy of the workpiece [2,15].

The publication [1] provides a list of sources of errors contributing to the measurement uncertainty, based on the VDI guideline 2617-11:

- Geometric error of MT
- Touch probing system
- Temperature
- Measurement strategy
- Workpiece

These individual sources of error include systematic and random errors contributing to the resulting uncertainty value on the MT for a 95 % confidence level. The publication [4] presents a method for determining the uncertainty of on-MT measurements including the above-mentioned sources of errors.

The authors [1–3] deal with individual sources of errors comprehensively, but a possible change in the geometric accuracy of the machine during the long-term operation of the machine is not considered. The publication provides error budget estimates for small, medium size MTs and large size MTs. It is stated here that the proportion of error caused by a change in geometric accuracy is up to 10 μm.

The change in the geometric accuracy of the machine is subject to both short-term and long-term influences commonly occurring in the real operating conditions of CNC machine tools.

2.2. Research approach

There are two approaches to how to assess the capability of a measuring system and the process of measuring longitudinal dimensions. The first approach to assessing the measurement capability is based on the requirement to calculate the expanded uncertainty U and the requirement to calculate the minimum controlled tolerance T of the assessed length. The determination of this tolerance is based on statistical data processing and determination of measurement uncertainty according to ISO 15530-3: 2011.

The second possible approach is to use a combination of the method described in the ISO 22514-7: 2014 standard and to compare statistically processed measurements with a touch probe and a laser interferometer (length standard).

The system of validation of measurement system (MS) and measurement process (MP) has developed significantly in the last 40 years. Fig. 1 shows the result of this development on the basis of an error and uncertainty approach to the evaluation of the measurement results.

According to Fig. 1 on the left, the accuracy of the machine tool measurement is the closeness of agreement between the measured length value and its true value. Since we view accuracy as a qualitative concept, we can generally state that a measurement is more accurate when it offers less measurement error. This philosophy represents the classical so-called error concept of measurement accuracy.

For 21st century metrology, the theory of measurement uncertainty has been adopted, which we understand as a non-negative parameter characterizing the dispersion of values of quantities assigned to a measurement based on suitable information. Fig. 1 on the right explains the principle of expressing the measurement result by means of the expanded measurement uncertainty.

The procedure for assessing the suitability (VDA 5), capability (ISO 22514-7) of MP of a machine tool of the three-axis vertical machining centre type is processed according to VDA 5 and extended according to ISO 22514-7 in the following chapter.

3. Experimental setup

3.1. Theory of increase in capability of measurement on machine tools

The proposed procedure for assessing the suitability of the inspection process according to VDA 5 is described in the following chapter by Eqs. (1)–(9) and extended by ISO 22514-7 by Eqs. (10) and (11).

3.2. Suitability of the inspection process with one standard according to VDA 5

The procedure for determining this tolerance is as follows. After determining the vector of lengths, it is necessary to calculate the sample standard deviation of the repeatability s_g, see Eq. (1):

$$s_g = \sqrt{\frac{1}{K-1}\sum_{i=1}^{K}\left(L_i - \overline{x_g}\right)^2} \tag{1}$$

where K is the number of measured length values, L_i is the measured length of the i-th member of the length vector and $\overline{x_g}$ is the arithmetic mean of the measured values.

The next step is to calculate the tolerances for the measuring systems

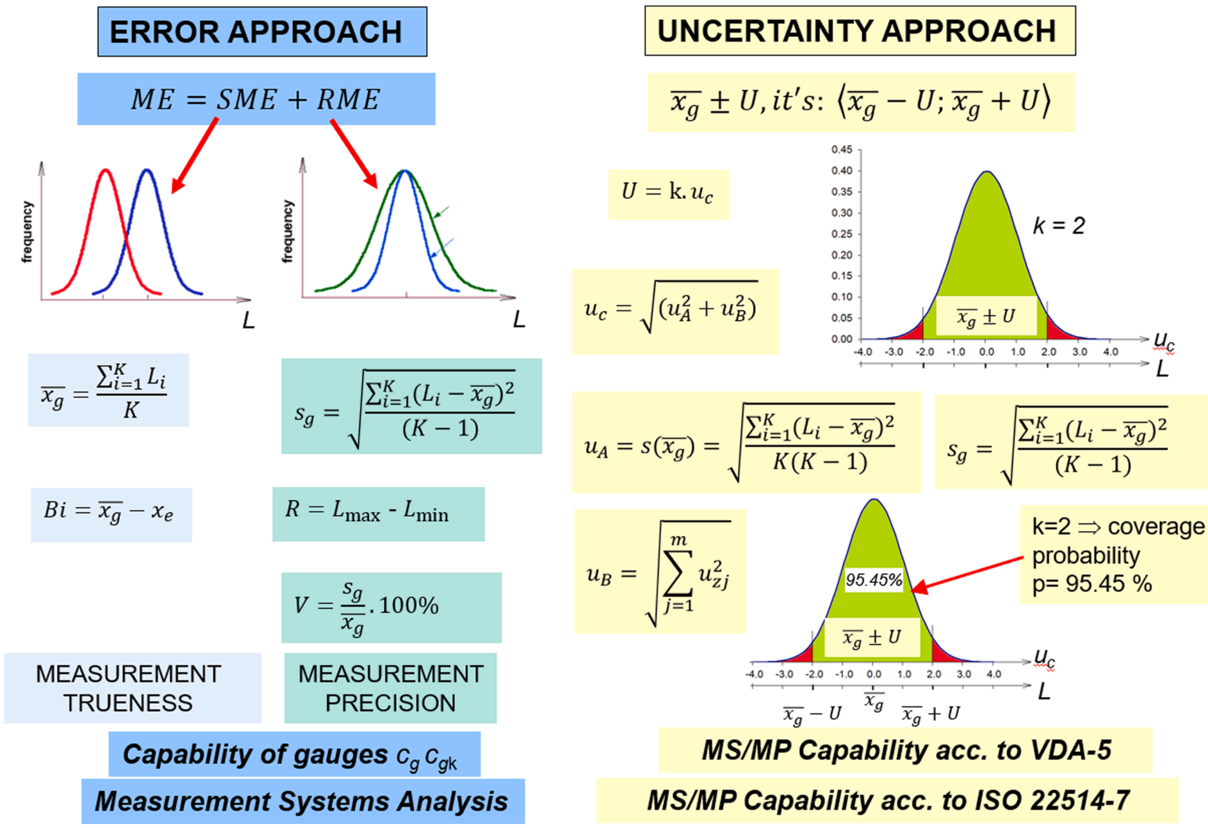

Fig. 1. Validation of measurement system (MS) and measurement process (MP) according to error and uncertainty approach.

T_{cg} of Eq. (2), using the capability coefficient $c_g \geq 1.33$ and T_{cgk} of Eq. (3), using the coefficient $c_{gk} \geq 1.33$ [16,17].

$$T_{c_g} = \frac{c_g \bullet 6 \bullet s_g}{0.2} \tag{2}$$

$$T_{c_{gk}} = \frac{c_{gk} \bullet 3 \bullet s_g + |\overline{x_g} - x_e|}{0.1} \tag{3}$$

In both cases, the capability coefficient was chosen to be 1.33 so that the resulting tolerance was as small as possible. The value of x_e is the reference length of the measured standard. The tolerance of the measuring system with the higher value was used to calculate the measurement tolerance itself. The main advantage of the procedure according to Eqs. (2) and (3) is the simplicity of assessing the accuracy of the gauge (by a single number) in relation to the tolerance fraction. The main disadvantage is "metrological conservatism" in the sense that the procedure does not take into account the measurement uncertainty.

To calculate the tolerance taking into account the measurement uncertainties, it is necessary to calculate the combined uncertainty. This is calculated using the calibration uncertainty, Eq. (4)

$$u_{cal} = \frac{U_{CAL}}{k_{CAL}}, \tag{4}$$

where U_{CAL} is the expanded calibration uncertainty and, for this case, it is chosen as $U_{CAL} = 0.0024$ mm and the expansion coefficient $k_{CAL} = 2$ [16]. Another component of the measurement uncertainty is the repeatability of the u_{EVR}, which is equal to the sample standard deviation of the measured values, see Eq. (5), where s_g is calculated according to Eq. (1).

$$u_{EVR} = s_g \tag{5}$$

Subsequently, it is necessary to calculate the component of measurement uncertainties caused by the resolution u_{RE}, using Eq. (6), where RE is the resolution of the machine, based on the properties of the measuring device.

$$u_{RE} = \frac{0.5 \bullet RE}{\sqrt{3}} \tag{6}$$

The last required component is the u_{BI} deflection uncertainty, which is calculated according to Eq. (7).

$$u_{BI} = \frac{|\overline{x_g} - x_e|}{\sqrt{3}} \tag{7}$$

From these uncertainty components, the combined uncertainty of the measuring system u_{MS} is then calculated, using Eq. (8), which, after the extension by the coefficient 2, can be used to calculate the minimum measurement tolerance TOL_{min}.

$$u_{MS} = \sqrt{u_{cal}^2 + max\{u_{EVR}^2; u_{RE}^2\} + u_{BI}^2} \tag{8}$$

The required minimum measurement tolerance can be calculated using Eq. (9):

$$TOL_{min} = \frac{4 \bullet u_{MS}}{Q_{MS\_max}}.100\%, \tag{9}$$

where Q_{MS_max} is the limit value of the suitability indicator and is selected as 15 % according to VDA 5. It should be noted that the resulting minimum tolerance indicates the total size of the tolerance field for which the MS is suitable, see Fig. 2.

Eq. (9) respects the requirement of ISO 14253-1:2013. In terms of ISO 14253-1:2017, it can be, provided that $TOL_{min}/u_{MS} \geq 4.93$, adjusted to Eq. (10).

$$TOL_{min} = \frac{2 \bullet 1.65 \bullet u_{MS}}{Q_{MS\_max}}.100\% \tag{10}$$

For $TOL_{min}/u_{MS} \in \langle 3{,}92;4{,}92 \rangle$, the general Eq. (11) applies:

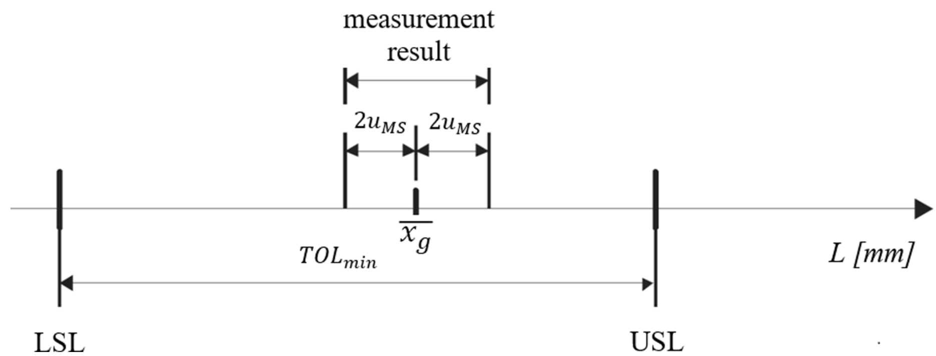

Fig. 2. Minimum measurement tolerance, taken from VDA 5, modified.

$$TOL_{min} = \frac{2 \bullet g_A \bullet u_{MS}}{Q_{MS\_max}}.100\%, \quad (11)$$

where g_A is the guard band factor, the value of which ranges from 1.65 to 1.96 depending on the value of the TOL_{min}/u_{MS} ratio in accordance with ISO 14253-1:2017.

3.3. Demonstrator

The experiment is carried out on a three-axis vertical milling CNC machining centre. A set of calibrated Johansson gauges is used as a reference gauge. The geometric accuracy of the machine tool is measured using a single-axis laser interferometer XL-80, a double ball-bar QC20-w and a laser tracking device LaserTRACER.

3.3.1. Three-axis vertical CNC machining centre

The three-axis vertical CNC machining centre (hereinafter MCV) (Fig. 3) was chosen in order to verify the effect of geometric deviation on the capability of measurement. It is a vertical machining centre with SINUMERIC 840Dsl control system from Siemens with VCS A3 option for volumetric compensation. The machine specifications are given in Table 1.

3.3.2. Johansson gauge

A set of six calibrated gauges according to Table 2 in the range of 100–500 mm with a measurement uncertainty of U=(0.2 + 2L) µm was chosen as the length measurement standard, where L is the nominal length of the end gauge in metres. The measurement uncertainty *U* is the product of the standard combined measurement uncertainty and the expansion factor *k*. In this case, k = 2, which corresponds to a coverage

Table 1
Classification of CNC machine tools based on technical parameters.

Item		
Travel of X axis		754 mm
Travel of Y axis		500 mm
Travel of Z axis		550 mm
Bi-directional systematic positioning error of an axis ISO 230–2:2014		0.008 mm
Touch trigger Probe OMP400	Unidirectional repeatability ± X, ±Y, +Z (2σ)	± 0.00025 mm
	2D deformation in axes X, Y (2σ)	
Linear encoder Y-axis Heidenhain LS487C	Accuracy grade	± 5 µm
	Coefficient of thermal expansion	8 µm/(m.K)
Temperature sensors uncertainty	Pt100, class A	0.25 °C
MPE (maximum permissible error)	Expert estimate	± 10 µm

Table 2
Results of calibration of Johansson gauges.

L [mm]	Deviation [µm]	Length range [µm]	Measurement uncertainty [µm]
100	0.15	0.11	0.4
150	0.69	0.33	0.5
200	1.95	0.21	0.6
300	2.24	0.28	0.8
400	−0.92	0.18	1
500	2.56	0.99	1.2

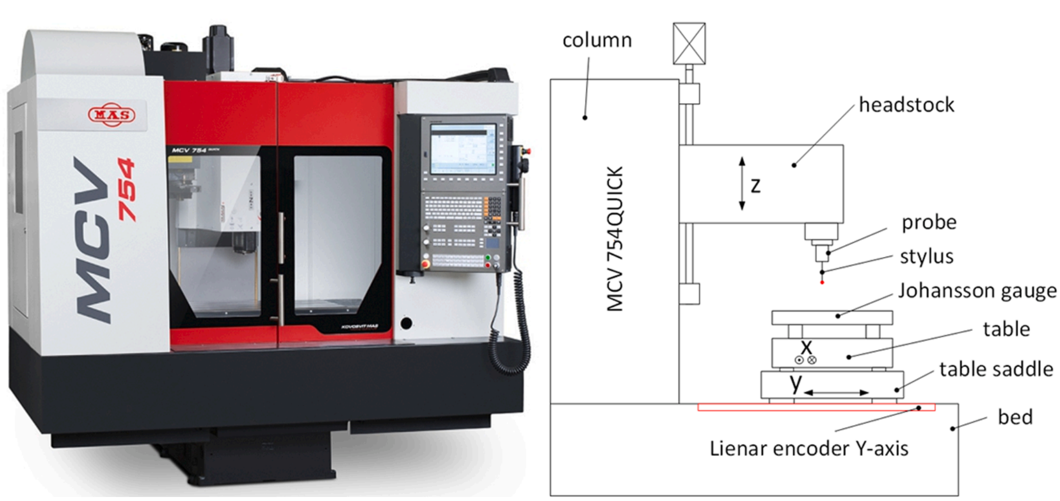

Fig. 3. Three-axis vertical CNC machining centre.

probability of approximately 95.45 %.

Fig. 4 shows the implementation of a set of Johansson gauges on an MCV machine. The whole set of gauges was aligned in the XZ and YZ planes to a slope error tolerance of 10 μm.

3.4. Design and implementation of measurement

3.4.1. Geometric accuracy of machine tool

The proposed experiment is based on the standard settings used for the geometric accuracy of CNC machine tools, which correspond to configurations A-C according to Table 3 and advanced settings in the form of volumetric compensation corresponding to configuration D, according to Table 3.

The suitability of the measurement by the touch probe on the CNC machine tool in the Y axis is assessed. Calibration and verification measurements were always performed within the settings of the individual B-D configurations. For each measurement, the temperature of selected sites on the machine and its surroundings was monitored to ensure the conditions of repeatability of measurements.

Configuration A – this is a machine setting where all software compensations are deactivated.

Configuration B – the Y axis is measured and compensated according to ISO 230-2: 2005 in both directions in the axis range of 5–495 mm with a step of 50 mm and five repetitions.

– XL-80 laser interferometer, RENISHAW (U ($_{(k=2)}$) = 0.5 μm/m) was used as the measuring device. The ENC (encoder compensation) table was used to implement the compensation.

Configuration C – based on the circularity test according to ISO 230-4 with the double ballbar device QC20-w ($U_{(k=2)} = 0.7 + 0.003{*}L$ μm) and the evaluation of the squareness error from the RENISHAW expert SW, cross errror compensation (CEC) was introduced. The test was performed with a radius setting of 150 mm and a feed rate of 1000 mm/min, angle of measurement of 220°. After activating the CEC tables, measurements and compensations were performed according to the settings described in configuration B.

Configuration D – in the range of axes X 5–745 mm, Y 5–495 and Z 400–0 mm with interpolated step of 10 mm, the measurement of volumetric accuracy was performed by uniaxial tracking device LaserTRACER ($U_{(k=2)}$ = 0.2 μm + 0.3 μm/m) from the ETALON company with subsequent activation of compensation VCS A3 (Siemens).

3.4.2. Method for determining the length of the Johansson gauge

Length measurement on a CNC machine tool is carried on using TP OMP400 (Table 1). Processing of measured positions of individual points from the machine is realized via communication protocol OPC-UA and the application created in Python SW. The entire touch probe measurement experiment runs in a fully automatic cycle.

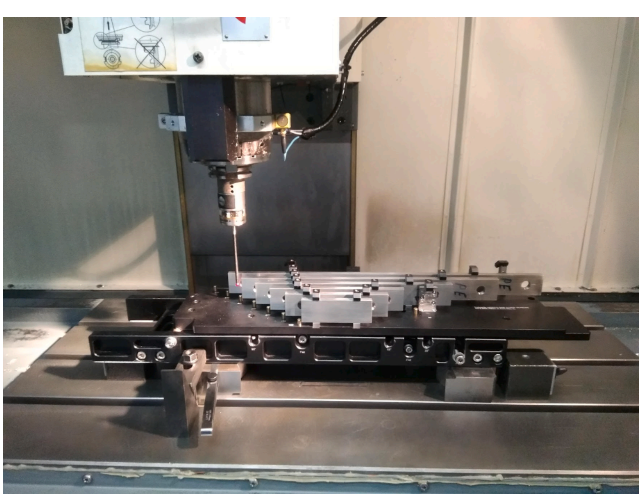

Fig. 4. Demonstration of measurement with a touch probe on an MCV machine using a set of Johansson gauges.

Table 3
Setting the compensated space of the MCV machine.

Configuration	Compensation	Measuring device
A	No compensation	–
B	Positioning compensation	XL-80
C	Squareness + Positioning compensation	QC20-w + XL-80
D	Volumetric compensation	LaserTRACER

The measurement cycle was selected based on the requirements of VDA 5 and ISO 14253-1:2017, where a minimum number of repetitions is defined 25 times. At the same time, three length measurement approaches based on point-point, point-straight line, point-plane measurements according to Fig. 5 were tested.

Due to the requirements for the number of repetitions (min. 25/point), a method for evaluating the point-to-point length was chosen. One of the reasons is the time-consuming measurement of one length and the elimination of temperature changes in the machine and its surroundings.

An example of the thermal stability of the machine measurement process on linear encoders is shown in Fig. 6. The temperature change during the individual measurements with the touch probe did not exceed 0.2 °C in the time interval of ca. 180 min. The position of the linear encoder on the MCV is shown in Fig. 3.

4. Results of investigation

4.1. Influence of machine tool setup

As part of the case study on a vertical CNC machine tool, various machine settings were made with the following comparison of results.

Fig. 7 shows the results of a 500 mm EYY error in the configuration A (without activated compensation table) and the configuration B (with activated compensation table). The error size according to ISO 230-2 is EYY = 8.6 μm for (conf. A) and EYY = 1.2 μm for (conf. B).

Fig. 8 shows the results of the circularity error according to ISO 230-4. The measurement was performed at a radius of 150 mm at a feed rate of 1000 mm/min. The resulting circularity error for conf. A is equal to 14.5 μm and for conf. B is equal to 6.7 μm.

Fig. 9 shows the results of volumetric deviations in space according to Table 4. The resulting volumetric deviation in the assessed space is for conf. A equal to 68 μm and for conf. D is equal to 12 μm.

.Table 5 summarizes the results of the individual parameters inspected according to the machine configuration settings A-D.

Table 6 presents a summary of the results of the tests performed in the A-D machine configurations and the assessed lengths of 100–500 mm respecting the machine temperature and the temperature of the inspection gauges.

The best results were achieved on an inspected dimension of 500 mm, namely the tolerance TOL_{min} = 0.0354 mm (see Fig. 10). The minimum tolerance of which the measuring system is still capable is at least 35.4 μm (500 ± 0.0177) mm.

From the above results, it is evident that the machine settings have a high weight for the possibility of using workpiece measurements on the machine tool. The further analysis revealed that the individual settings of the geometric accuracy of the machine are differently dependent on the inspected length. The individual curves represent the ratio of configuration A to configuration B/C/D and are shown in Fig. 11.

For the A/B and A/C setting ratios, the course of the improvement is almost constant for all assessed lengths, while the A/B improvement ratio is equal to 1.2 and for A/C it is approximately 1.7. For the A/D configuration ratio, it is the smallest at a length of 100 mm and is equal

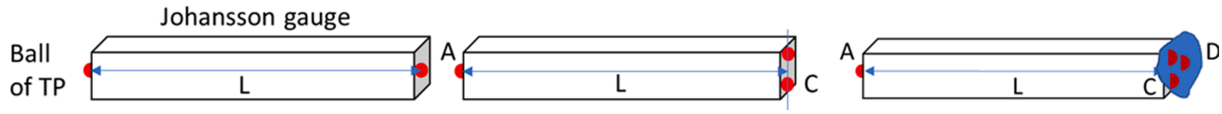

Fig. 5. Length measurement: point-point, point-straight line, point-plane.

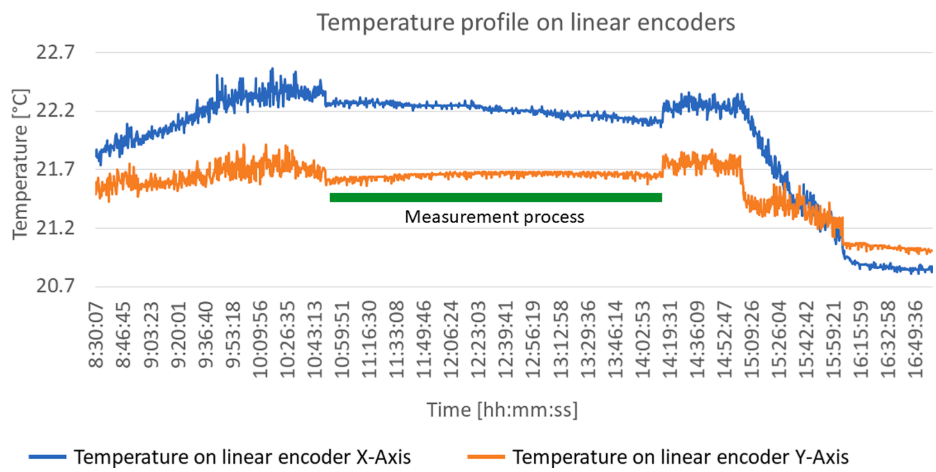

Fig. 6. Demonstration of the temperature profile on the linear encoders of the MCV machine.

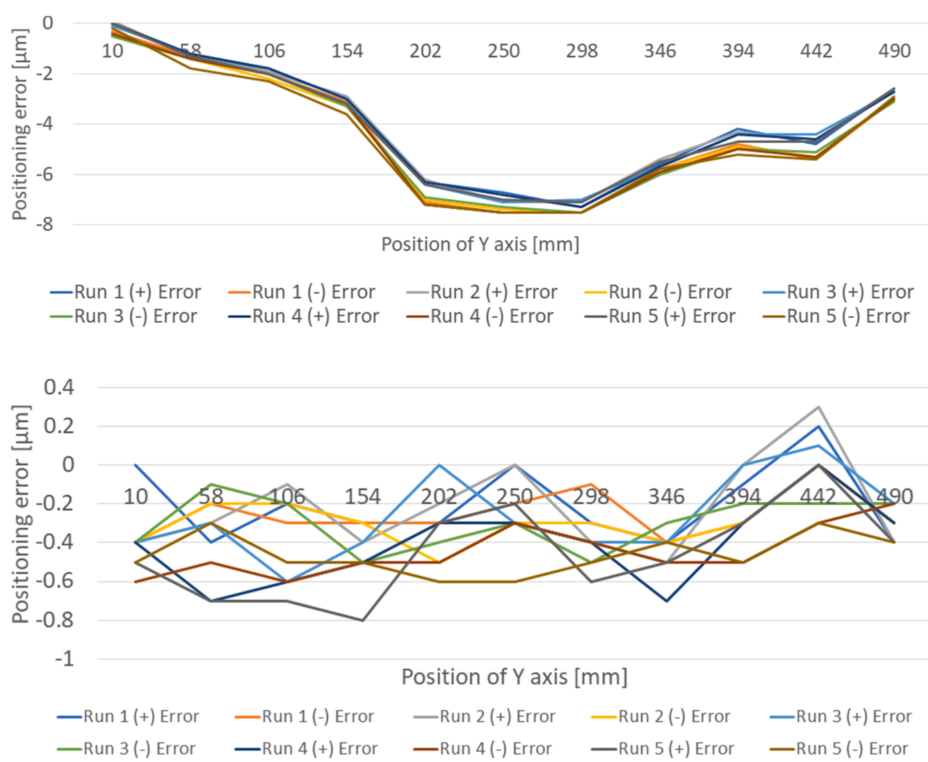

Fig. 7. Bi-directional positioning test Raw data. Configuration A – up. Configuration B – down.

to 1.3 and increases with distance to a value of 4.5 at a length of 500 mm. Thus, the best results were obtained by setting the geometric accuracy of the machine using the volumetric compensation at the maximum inspected length.

4.2. Capability of measurement

We will use a procedure respecting the ISO 14253-1:2017 standard to assess conformity with the TOL_{min} tolerance.

Let us assume that we can estimate the type B uncertainty as follows:

$$u_B = \frac{MPE}{\sqrt{3}}, \tag{12}$$

where MPE is the maximum permissible error of measurement of a machine equipped with a measuring probe. Furthermore, let us assume that the MPE CNC machine tool as a measuring machine is 10 µm. Then we can arrange the calculation for the conformity assessment with the

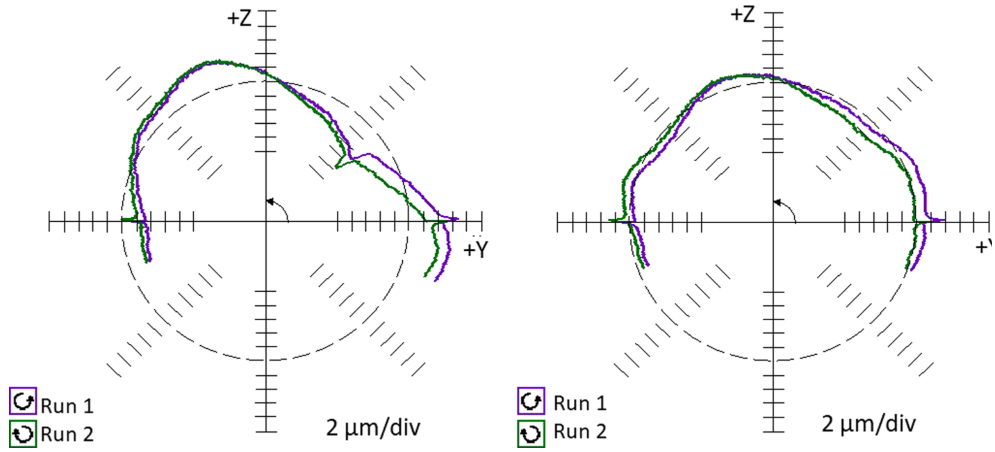

Fig. 8. Bi-directional circular test ISO 230-4:2005. Configuration A – left. Configuration C – right.

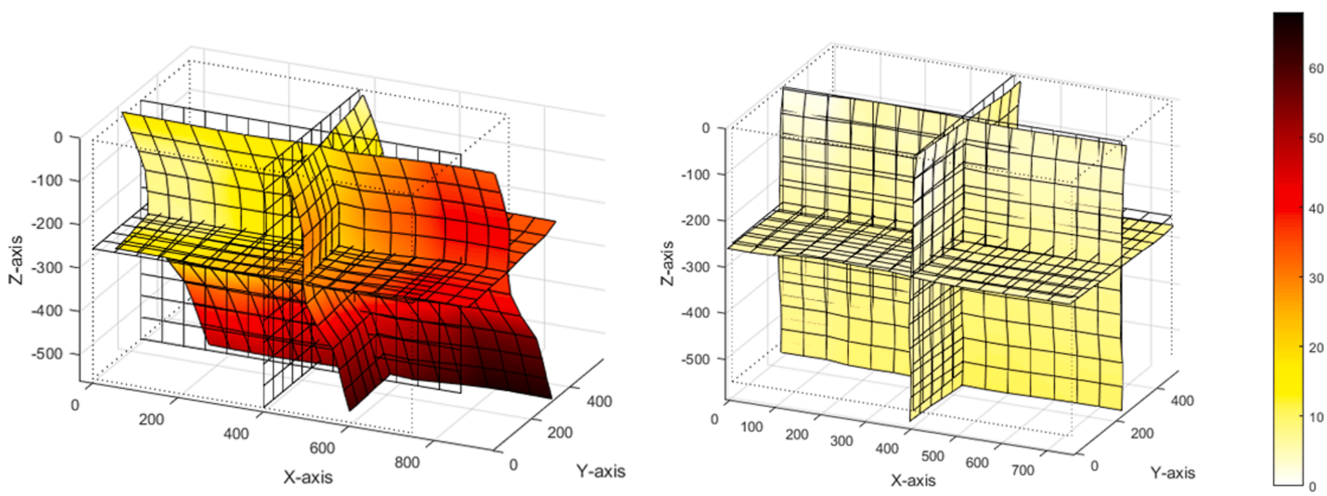

Fig. 9. Volumetric error map. Configuration A – left. Configuration D – right.

Table 4
Setting the compensated space of the MCV machine.

	Start of interval [mm]	End of interval [mm]	Size of step [mm]
Axis X	2	752	50
Axis Y	0	500	50
Axis Z	−500	0	50

Table 5
Results of geometric errors in various MCV machine settings.

Config.		ISO 230-4:2005 [µm]	ISO 230-2:2014 EYY [µm]	Straightness A0Z [µm/m]	Vol. error [µm]
A	ENC 0 CEC 0 VCS 0	14.5	8.6	52.1	68
B	ENC 1 CEC 0 VCS 0	14.5/**6.7**	8.6/**1.2**	–	–
C	ENC 1 CEC 1 VCS 0	9.9/**6.6**	7.8/**1.3**	52.1/**0.5**	–
D	ENC 0 CEC 0 VCS 1	–	–	–	68/**12**

TOL_{min} tolerance into a clear table (Table 7):

Fig. 12 shows the results of Table 7.

According to Fig. 12 we can state that the CNC machine tool is capable of measuring the length of 500 mm in the tolerance TOL_{min} = 0.0354 mm, because:

- the measurement result is 500.00119 ± 0.01155 mm,
- the acceptance zone is more than 16 µm,
- nearly the target value was reached (500.00119 mm instead of 500.00256 mm),
- the measurement process is only 1.41 µm below the target value (measured standard of length 500.00256 mm),
- it is probably not appropriate to propose improvements by centring,
- the measured values do not show any extremes,
- the uncertainty is reasonable, the measurement conditions are acceptable,
- the CNC machine tool is compliant as a gauge.

Table 6
TOL_{min} results for different inspected lengths and different states of the MCV machine.

	TOL_{min} [mm]					
	100 [mm]	150 [mm]	200 [mm]	300 [mm]	400 [mm]	500 [mm]
A	0.1253	0.1147	0.126	0.1144	0.1917	0.1524
B	0.102	0.0938	0.1121	0.103	0.1406	0.1305
C	0.0635	0.0688	0.0828	0.0741	0.0819	0.0874
D	0.0877	0.0578	0.0534	0.0363	0.0449	0.0354

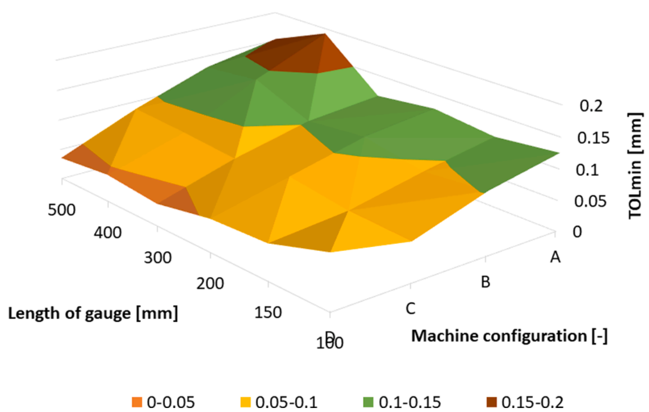

Fig. 10. Graphical representation of the distribution of the TOL_{min} result over the inspected distance and machine setting.

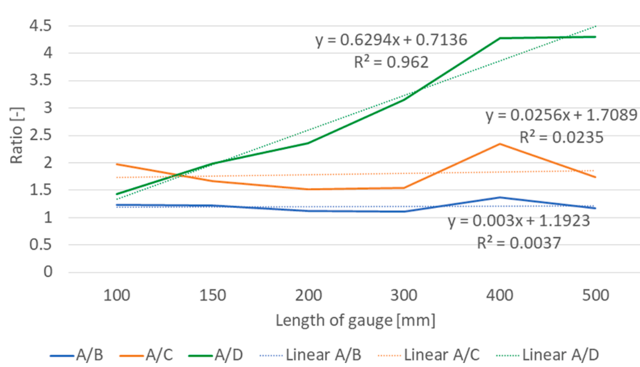

Fig. 11. Courses of the ratio of the result TOL_{min} to the initial state of machine A.

Table 7
Summary of measurement results at a length of 500 mm.

Machine tool as a gauge	Measured standard KM 500-D
	length 500.00256 [mm]
x_{bar}	500.00119
s_x	0.000207149
$u_A = s_x/n$	3.78E-05
u_B = MPE/✔	0.005773503
u_C	0.005773627
$U = u_C*2$	0.011547253
result according to GUM	500.00119 ± 0.01155
Specification	500.00256 ± 0.0177
(USL-LSL)/u_c	6.13132831
$g_A = g_{UA} = g_{LA}$	1.65
$g_A * u_C$	0.009526484

5. Discussion over the machine tool setup

5.1. Influence of geometric accuracy of the machine

It is evident from the experiments that setting of the geometric accuracy of the CNC machine tool has a significant effect on the capability of the measuring process. The performed experiment took place under temperature stable conditions and clean environment. It can be assumed that as the temperature changes, the geometric accuracy of the machine changes and thus the TOL_{min} size also changes. If a method for assessing the suitability of the measuring process is used, it is necessary to check the capability of the measuring process of the machine, ideally before the workpiece inspection.

Accuracy and repeatability of positioning on CNC machine tools have an important role to consider in production. It will have the same role in assessing the capability of the touch probe measurement. The machine must be properly operated and maintained to ensure the competence of the measuring system. It is possible to assess this negative influence by checking the inspection cycle on a specific Johansson gauge. Another negative effect on the resulting size of TOL_{min} is the non-constant compliance of the machine. For example, a high variability of results can be observed in machine designs where the workpiece moves in at least one axis. Due to its weight, it influences the change of geometric accuracy under static load (e.g., cantilever milling machine). The optimal machine type for further research activities are machines with all axes in the tool.

5.2. Suitability of the inspection process with consideration of linearity according to VDA 5

Further research can be focused towards the assessment of the entire workspace, considering all Johansson gauges placed in several positions of the Z axis.

When considering the linearity of MS, we calculate the combined measurement uncertainty according to Eq. (13).

$$u_{MS} = \sqrt{u_{cal}^2 + max\{u_{EVR}^2, u_{RE}^2\} + u_{BI}^2 + u_{LIN}^2 + u_{MS\_REST}^2} \tag{13}$$

We can calculate the values of the uncertainty components u_{cal}, u_{RE} and u_{BI} in the way already explained – see Eqs. (4), (6) and (7). The measurements uncertainty components u_{LIN} and u_{EVR} are calculated using the ANOVA method according to Eqs. (14) and (15).

$$u_{LIN} = \sqrt{\frac{\sum_n \sum_k (\bar{y}_{n\cdot} - \hat{y}_n)^2}{N-2}} \tag{14}$$

$$u_{EVR} = \sqrt{\frac{\sum_n \sum_k (y_{nk} - \bar{y}_{n\cdot})^2}{N(M-1)}} \tag{15}$$

In Eqs. (14) and (15), N denotes the number of standards used and M the number of repetitions. The meaning of the other symbols is shown in Fig. 13.

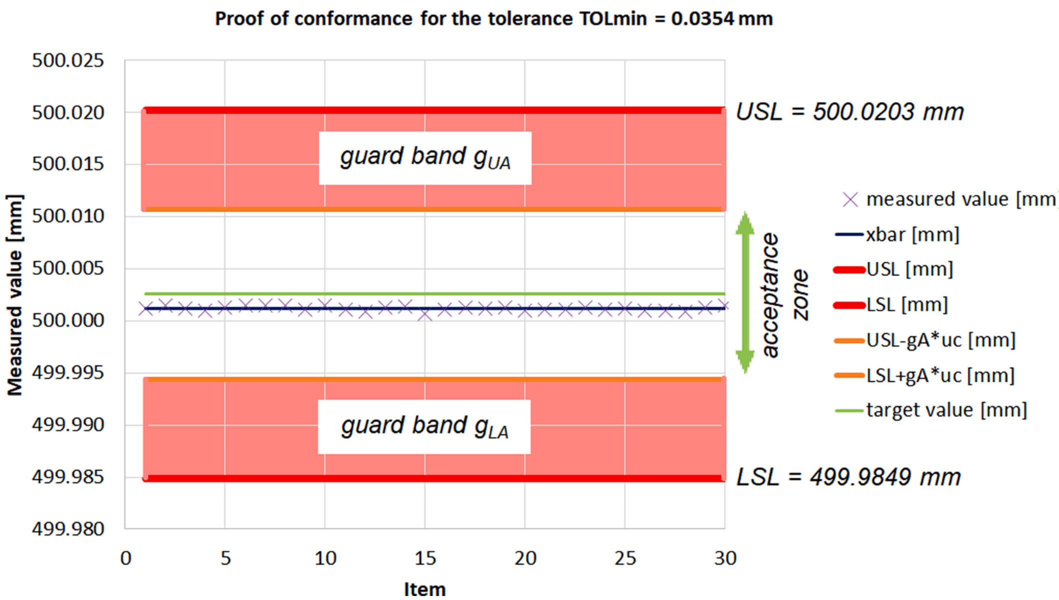

Fig. 12. Proof of conformance for the tolerance TOL_{min} = 0.0354 mm according to ISO 14253-1:2017.

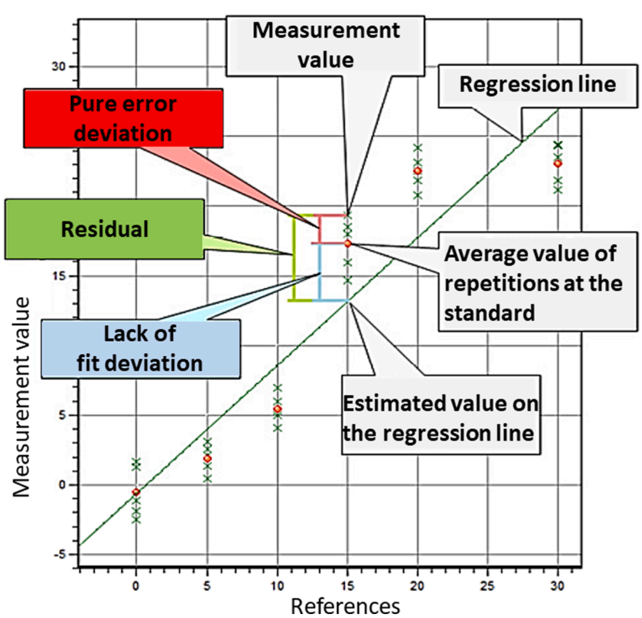

Fig. 13. Use of ANOVA for calculation of u_{LIN} a u_{EVR} measurement uncertainties, taken from [VDA 5].

6. Conclusion

This article presents the possibilities of assessing the capability of the measurement process on CNC machine tools using a touch probe based on VDA 5 and 14253-1:2017, which could enable and expand the use of CNC machine tools to inspect dimensional tolerances on workpieces. The output of the tests is the determination of the permissible minimum tolerance of the assessed workpiece, which can be measured on a CNC machine tool; the machine tool being classified as a gauge.

An experiment was presented, which pointed out the effect of setting the geometric accuracy of the machine and the resulting minimum controlled length tolerance TOL_{min} according to VDA 5. Four configurations of geometric accuracy settings were set for the assessed machine.

When setting the machine using ENC and CEC compensations, the change of the assessed value TOL_{min} with respect to the initial state of the machine in the length range of 100–500 mm is almost constant. This is due to the nature of the activated compensation.

When setting up the machine using the volumetric compensation, the following was achieved:

- improvement of the final TOL_{min} value by ca. 120 µm at a length of 500 mm,
- with increasing length, the TOL_{min} value decreases to 0.0354 mm,
- has the character of a linear dependence of the ratio of the initial state to the volumetric compensation and with increasing distance the TOL_{min} decreases.

The findings gained above can significantly expand the application possibilities of on – CNC machine tool touch probes in the inspection process directly in the production.

Future research will further focus on medium-sized machine tools with all controlled axes in the tool designated for series production and on the reduction of the time required to set TOL_{min}.

CRediT authorship contribution statement

Petr Blecha: Project administration, Supervision, Writing – review & editing. **Michal Holub:** Conceptualization, Methodology, Resources, Writing – original draft, Validation, Investigation. **Tomas Marek:** Resources, Investigation, Validation. **Robert Jankovych:** Methodology, Writing – original draft. **Filip Misun:** Resources, Investigation, Validation. **Jan Smolik:** Funding acquisition, Project administration. **Martin Machalka:** Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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