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# EXPERIMENTAL METHODS FOR DETERMINING UNCERTAINTY OF MEASUREMENT USING INSPECTION PROBES

# DOŚWIADCZALNE METODY WYZNACZANIA NIEPEWNOŚCI POMIARU SONDAMI PRZEDMIOTOWYMI*

*The paper presents the results of determining uncertainty of measurement using an inspection probe on numerically controlled vertical milling machines. To do the measurements, methods developed for coordinate measuring machines were employed. For the measurement system consisting of a vertical machining center FV-580A and OMP60 touch probe, the uncertainty of measurement was determined for the coordinates of the point, one-dimensional length measurement, two-dimensional length measurement, as well as for length measurement using multiple measurement strategies.*

***Keywords**: uncertainty of measurement, CNC machines, inspection probe.*

*W pracy przedstawiono wyniki wyznaczania niepewności pomiaru sondą przedmiotową na frezarkach pionowych sterowanych numerycznie. Do pomiarów zaadaptowano metody opracowane dla współrzędnościowych maszyn pomiarowych. Dla systemu pomiarowego składającego się z centrum obróbkowego FV580A i sondy OMP 60 wyznaczono niepewność pomiaru: współrzędnych punktu, jednowymiarowego pomiaru długości, dwuwymiarowego pomiaru długości oraz pomiaru długości z zastosowaniem przedmiotu niekalibrowanego.*

***Słowa kluczowe**: niepewność pomiaru, obrabiarki CNC, sonda przedmiotowa.*

## 1. Introduction

Inspection probes have become a standard feature of CNC machine tools. These probes are mainly used to determine workpiece position in the mill area and for inter operational dimensional control. Given the present developments in computer software and special equipment for machine tools, technological capabilities of on-machine measurement systems are greatly enhanced. Owing to the integration of measurement systems with CNC machine tool controls, special software interfaces such as PC-DMIS NC GAGE or STEP-NC could be created. These systems allow for performing measurement cycles directly on the machine tool, without using postprocessors. They also allow for creating reports on the conducted measurements. The development in modern software (OMV) allows for controlling dimensional conformity of a workpiece with the CAD model. Reverse engineering can also be applied.

Irrespective of its purpose, the use of a machine tool equipped with an inspection probe requires that measurement inaccuracy of such system be defined. Using the inspection probe to locate the zero point when machining in several positions can lead to the accumulation of measurement errors, which – in turn – can lead to the unconformity of workpiece shape and dimensions.

## 2. Inaccuracy of measurement by inspection probes

Determining uncertainty of measurement using an inspection probe is a complex problem. Manufacturers of inspection probes usually provide unidirectional repeatability (2σ) as the parameter that characterizes measurement inaccuracy. Yet, it is only one of many components of uncertainty budget. Other components characterizing the probe pertain to its calibration, direction of the stylus tip access to the workpiece being measured [2], or repeatability of fix [9].

The accuracy of measurements made by inspection probes depends on the machine-holder-workpiece-tool (MHWT) arrangement. For this reason, both geometric and kinematic accuracy of the machine tool, the accuracy of standards as well as of positioning have a considerable effect on measurement accuracy [2, 13, 14]. To date, no uniform methods for determining measurement uncertainty of a measurement system by an inspection probe have been developed. In the works [13] and [14], measurement inaccuracy is evaluated based on the difference between the measurement result of a hole diameter obtained using a probe and a coordinate measuring machine. The observed differences are considerable, as the values vary even by 1 mm. Based on the results of measuring geometric accuracy of a machine tool by a laser interferometer and of measuring a certified gauge ball, the authors of the work [2] created a map of errors with pre-travel variation depending on the access direction. The authors of [5] take advantage of the difference between the probe-measured dimensions before and after the first and second pass of the machine tool. The obtained measurement results and evaluation of inaccuracy of the measurement system equipped with an inspection probe presented in [2, 5, 13, 14] were employed to correct the tool path, which – according to the authors—led to the expected improvement in workpiece quality. The presented methods for determining inaccuracy cannot, however, be applied to evaluate inaccuracy of dimensional control effected in-between the operations and after the machining process. To this end, the method described in [11] can be employed; it is based on measuring the material standard of size in accordance with the procedures used to verify coordinate measuring machines.

Apart from instrumental errors generated by measurement systems, the workpiece being measured can also become a source of

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** measurement errors [1]. Systematic uncertainty resulting from the temperature of the workpiece being measured is of vital importance in the case of on-machine measurement systems. Considerable amounts of heat generated during the machining process (even up to 20% [6]) are accumulated inside the workpiece, thus causing an increase in its temperature. The temperature distribution over the workpiece volume is uneven, which results in uneven strains [6]. The problem of thermal strains generated in the course of machining a thin-walled profile has also been analyzed in [3]. The work analyzes the time change in temperature and thermal strain distributions. In both cases, the distributions were uneven, and the regions of maximum strains only slightly corresponded with the regions in which the maximum temperature was observed. After the machining process, a further increase in strain was observed. It is vital if one takes the use of inspection probes into consideration. Unfortunately, the experiment was stopped 5 seconds after the end of the machining process. The time needed to substitute the tool with the inspection probe as well as the duration of a measurement cycle itself are usually much longer. Therefore, another crucial problem of measurement uncertainty is to investigate changes in workpiece dimensions after the machining process, in the course of workpiece cooling.

## 3. Methodology and measurement results

The measurement system consisted of a machining center FV-580A with the Fanuc 0iMC control, equipped with a direct measurement system, and of the Renishaw OMP 60 touch trigger probe. The maximum travel of the table and machine tool spindle are as follows: for the X axis – 580 mm, for the Y axis – 420 mm, and for the Z axis – 520 mm. The machine is available in the Department of Production Engineering and it is used by both the Department staff and students to conduct scientific research. The probe technical specifications are given in Table 1.

*Table. 1. Technical specifications of OMP 60.*

| | |
|---|---|
| Sense directions | ±X, ±Y, ±Z |
| Signal transimssion | optical-infrared 360° |
| Transmission range | 6m |
| Unidirectional repeatability<br>(2 σ using standard stylus) | ± 1µm |
| Stylus trigger force<br>XY minimum<br>XY maximum<br>Z | <br>0.75 N<br>1.4 N<br>5.3 N |
| Stylus overtravel<br>XY<br>Z | <br>±18°<br>11mm |

Inspection probes are based on the coordinate measurement technique. To date, no standards for determining the uncertainty of measurement for inspection probes have been established. In the tests, the methods developed for coordinate measuring machines were employed. For the measurement system consisting of a machining center FV-580 A and OMP 60 touch trigger probe, the uncertainty of measurement was determined for:

- the coordinates of the point,
- a one-dimensional length measurement
- a two-dimensional length measurement
- a length measurement using multiple measurement strategies.

In order to determine the measurement uncertainty of the coordinates of the point and one- and two-dimensional length measurements, computational algorithms used in the calibration of instruments and measurement systems described in [4] were employed. The measurement uncertainty of length using an uncalibrated workpiece was determined by means of the instructions given in [8].

### 3.1. Measurement uncertainty of the coordinates of the point

The repeatability of measuring the coordinates of the point is affected by the repeatability of position and stability of pre-travel length. The measurements of the coordinates of the point were made for the point located on the measurement plane of the gauge block of class 1. The block was placed in a specially designed handle, thanks to which the block could be placed in such way that its measurement planes were not parallel to any of the base planes of the machine. Fig. 1 shows the designed handle.

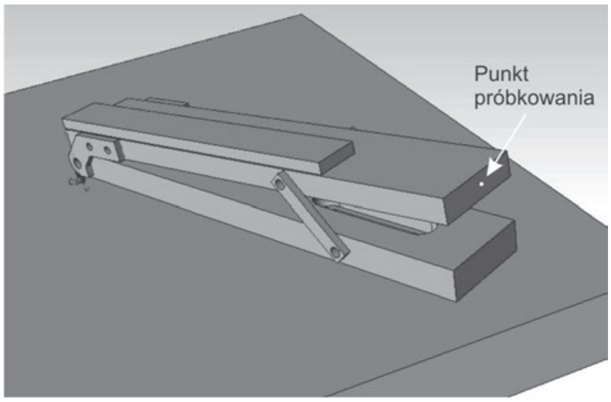


*Fig. 1. Designed model of the handle used to measure the coordinates of the point*

The coordinates of the vector components normal to the measurement plane were [−0.8924; −0.4462; −0.0667]. The measuring of the coordinates was repeated 10 times, each time changing the travel path. The probe traveled with the velocity $v_f$ of 1000 mm/min, while the measuring motion velocity $v_f$ was of 50 mm/min.

The standard uncertainty of measuring the coordinates consists of the uncertainty resulting from the dispersion of the measurement values $u_A$ evaluated by the Type A method and the uncertainty which results from the resolution of the measurement system $u_R$. The standard uncertainty $u_a$ is taken as the standard deviation of the arithmetic mean [4], calculated in accordance with the formula (1):

$$u_a = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}{n\left(n-1\right)}} \tag{1}$$

where $u_a$ is the standard uncertainty, $\bar{x}$ is the arithmetic mean, $n$ is the number of measurements, $x_i$ is the $x$ coordinate obtained in the i-measurement.

The measurement system resolution $r$ was of 0.001, which resulted from the linear encoders the machine tool was equipped with. The effect of the resolution was estimated using the Type B method, adopting the rectangular probability distribution:

$$u = \sqrt{u_a^2 + u_R^2} = \sqrt{u_a^2 + \frac{r^2}{3}} \tag{2}$$

where: $u$ is the combined standard uncertainty, $u_a$ is the standard uncertainty, $u_R$ is the resolution uncertainty, $r$ is the variation of indications.

*Table. 2. Measurement results of the coordinates of the point.*

| Travel path | 100 mm | | | 200 mm | | | 300 mm | | |
|---|---|---|---|---|---|---|---|---|---|
| Coordinate | X | Y | Z | X | Y | Z | X | Y | Z |
| Standard uncertainty $u_a$ [mm] | 0.0003 | 0.0001 | 0.0000 | 0.0003 | 0.0003 | 0.0000 | 0.0011 | 0.0004 | 0.0001 |
| Combined standard uncertainty $u$ [mm] | 0.0007 | 0.0006 | 0.0006 | 0.0007 | 0.0007 | 0.0006 | 0.0012 | 0.0007 | 0.0006 |
| Expanded uncertainty $U$ [mm] | 0.0014 | 0.0012 | 0.0012 | 0.0014 | 0.0014 | 0.0012 | 0.0024 | 0.0014 | 0.0012 |

In order to evaluate the properties of instruments and measurement systems, the expanded uncertainty was employed, calculated by the formula:

$$U = k \cdot u \tag{3}$$

where $U$ is the expanded uncertainty, $k$ is the coverage factor, $u$ is the combined standard uncertainty.

The coverage factor $k$ is selected depending on the assumed trust level. In technical measurements, the trust level is set to 0.95, while the coverage factor $k$ is set to 2 [4], on the assumption that the uncertainty budget components are subject to the normal distribution. In the case of measuring the uncertainty of the coordinates of the point using the inspection probe, at least one of the components does not meet this condition. Based on the analyses presented in [7], when evaluating the Type B uncertainty it can be assumed that $k$ is equal to 2 also for the uniform distribution. Table 2 presents the measurement and calculation results.

It can be observed that the travel path affects the value of uncertainty, yet this effect is insignificant. The length of the travel path was measured along the direction determined by the vector normal to the plane, therefore the probe motion along the particular axes has different values, which results in different values of the uncertainty $u_a$.

### 3.2. Uncertainty of one-dimensional length measurement

Even though the coordinate measuring technique is based on, first, measuring the coordinates of the points and then, with the application of measurement algorithms, relevant values are determined, it is not possible to determine the uncertainty of measurement of length based on the measurement uncertainty of the coordinates. Determining the one-dimensional measurement inaccuracy by means of an inspection probe for particular axes was conducted using the material standard of size, i.e. gauge blocks of class 1. A detailed description of the conducted research is given in [11]. The equation of the measurement has the following form:

$$L = \overline{L} + P_{Ex} + P_t + P_r \tag{4}$$

where $L$ is the length of the gauge block, $\overline{L}$ is the arithmetic mean, $P_{Ex}$ is the correction resulting from the systematic indication error, $P_t$ is correction of the temperature difference between the gauge block and measurement system model, $P_r$ is the correction of changing the gauge block length that results from the unparallelity of the gauge block position relative to the machine axis.

The systematic indication error is calculated from the dependence (5), while the correction $P_{Ex}$ is calculated using the dependence (6)

$$E_x = \overline{L} - L_N \tag{5}$$

where $E_x$ is the systematic indication error, $L_N$ is the nominal length of the gauge block.

$$P_{Ex} = -E_x \tag{6}$$

It was assumed that the corrections $P_t = 0$ and $P_r = 0$ [11]. The combined standard uncertainty was determined using the following dependence:

$$u = \sqrt{u_a^2 + u_L^2 + u_R^2} = \sqrt{u_a^2 + \frac{te^2}{6} + \frac{r^2}{3}} \tag{7}$$

where $u$ is the combined standard uncertainty, $u_a$ is the standard uncertainty resulting from dispersion, $u_L$ is the uncertainty of the gauge block length, $u_R$ is the resolution uncertainty, $te$ is the limit deviation of the gauge block length, $r$ is the variation of indications.

The nominal length was taken as the real length of the gauge blocks, with a dimensional tolerance limit defined as the upper and lower limits of the length variation range [16]. The limit deviations

*Table.3. Measurement results of gauge block lengths.*

| | X Axis | | | | Y Axis | | | | Z Axis | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Gauge block dimensions,[ mm] | 100 | 150 | 200 | 300 | 100 | 150 | 200 | 300 | 50 | 100 | 150 |
| Mean, mm | 100.002 | 150.004 | 200.003 | 300.010 | 100.007 | 150.009 | 200.001 | 300.001 | 50.006 | 100.010 | 150.017 |
| Standard uncertainty $u_a$, [mm] | 0.0005 | 0.0005 | 0.0005 | 0.0005 | 0.0004 | 0.0003 | 0.0003 | 0.0003 | 0.0001 | 0.0003 | 0.0001 |
| Combined standard uncertainty $u$, [mm] | 0.0006 | 0.0006 | 0.0007 | 0.0008 | 0.0005 | 0.0005 | 0.0006 | 0.0007 | 0.0004 | 0.0005 | 0.0005 |
| Expanded uncertainty $U$, [ mm] | 0.0012 | 0.0012 | 0.0014 | 0.0016 | 0.0010 | 0.0010 | 0.0012 | 0.0014 | 0.0008 | 0.0010 | 0.0010 |
| Systematic indication error, [mm] | 0.002 | 0.005 | 0.003 | 0.010 | 0.007 | 0.009 | 0.001 | 0.001 | 0.006 | 0.010 | 0.017 |
| Correction $P_{Ex}$, [mm] | –0.002 | –0.005 | –0.003 | –0.010 | –0.007 | –0.009 | –0.001 | –0.001 | –0.006 | –0.010 | –0.017 |

of the length $te$ had the following values: gauge block $L = 50$ mm – $te$ =±0.4 µm, $L = 100$ mm – $te$ = ±0.6 µm, $L = 150$mm – $te$ =±0.8µm, $L = 200$mm – $te$ =±1µm, $L = 300$mm – $te$ = ±1.4 µm and $L = 400$ mm – $te$ = ±1.8 µm [16]. The triangular probability distribution was assumed, with the center in the nominal dimension of the gauge block. The measurement system resolution was 0.001 mm. The variability of indications $r$ was estimated to be of ±0.0005 mm, assuming the triangular probability distribution. The combined standard uncertainty was calculated from the dependence (7), while the expanded uncertainty was calculated using the dependence (3), on the assumption that the coverage factor $k$ had a value of 2. Table 3 presents the measurement results of the gauge block lengths as well as inaccuracy calculation results.

Analyzing the results presented in Table 3, it can be observed that in all cases the systematic indication error has considerably greater values than the measurement inaccuracy. This is caused by the stylus head motion parallelity to the linear encoders and the rectilinearity of this motion.

*Table. 4. Two-dimensional measurement uncertainty of the gauge block length [10]*

| Gauge block length [mm] | 50 | 100 | 150 | 200 | 300 |
|---|---|---|---|---|---|
| Mean [mm] | 50.0091 | 100.0014 | 150.0116 | 200.0236 | 299.9990 |
| Standard uncertainty $u_a$ [mm] | 0.0004 | 0.0004 | 0.0003 | 0.0005 | 0.0004 |
| Gauge length uncertainty $u_L$ [mm] | 0.0002 | 0.0002 | 0.0003 | 0.0004 | 0.0006 |
| System resolution uncertainty $u_R$ [mm] | 0.0006 | 0.0006 | 0.0006 | 0.0006 | 0.0006 |
| Cosine error uncertainty $u_{cos}$ [mm] | 0.0002 | 0.0004 | 0.0006 | 0.0008 | 0.0013 |
| Combined uncertainty $u$ [mm] | 0.0007 | 0.0007 | 0.0006 | 0.0008 | 0.0009 |
| Expanded uncertainty $U$ [mm] | 0.0014 | 0.0014 | 0.0012 | 0.0016 | 0.0018 |
| Correction $P_{EX}$ [mm] | –0.0091 | –0.0014 | –0.0116 | –0.0236 | 0.0010 |

*Table. 5. Two-dimensional measurement uncertainty of the ring diameter [10]*

| | |
|---|---|
| Mean[mm] | 49.9480 |
| Standard uncertainty $u_a$[mm] | 0.0010 |
| Uncertainty of gauge length $u_L$ [mm] | 0.0002 |
| Syatem resolution uncertainty $u_R$ [mm] | 0.0006 |
| Combined uncertainty $u$ [mm] | 0.001 |
| Expanded uncertainty $U$[mm] | 0.002 |
| Correction $P_{EX}$ [mm] | +0.0552 |

### 3.3. Uncertainty of two-dimensional length measurement

As shown in numerous publications on the coordinate measurement technique, e.g. in [12], determining the uncertainty of one-dimensional length measurement cannot be used to evaluate the accuracy of measurements which are not parallel to the machine tool axis or to the measurement of diameters. The two-dimensional uncertainty of length measurement was determined based on the measurements of the gauge ring and gauge blocks of class 1 positioned at an angle of 28° to the X axis of the machine tool. A detailed description of this is given in [1]. The equation for measuring the gauge blocks takes the following form:

$$L = \overline{L} + P_{Ex} + P_t + P_r \qquad (8)$$

where $L$ is the gauge block length, $P_{Ex}$ is the correction resulting from the systematic indication error, $P_t$ is the correction of the temperature difference between the gauge block and the gauge measurement system, $P_r$ is the correction of the gauge block length resulting from the unparallelity of the gauge block position relative to the indicated measurement direction.

The temperature correction can be omitted given the long time needed for leveling the temperatures of the gauge blocks and machine tool units. The correction of the gauge length resulting from the position relative to the measurement direction $P_r$ had a value of 0, while its uncertainty was estimated according to the scheme given in [10]. The correction $P_{EX}$ was calculated according to the dependences (5) and (6). The assumed standard uncertainty was calculated according to the dependence (9):

$$u = \sqrt{u_a^2 + u_L^2 + u_R^2 + u_{\cos a}^2} \qquad (9)$$

where $u$ is the combined standard uncertainty, $u_a$ is the standard uncertainty, $u_L$ is the uncertainty of the gauge length, $u_R$ is the resolution uncertainty, and $u_{cos\alpha}$ is the uncertainty of the gauge position.

The gauge length uncertainty and resolution uncertainty were calculated in the same way as when calculating the one-dimensional uncertainty. Table 4 presents the results of determining the two-dimensional uncertainty of length measurement, using the gauge blocks, whereas in Table 5 the results of determining it using the gauge ring with $50^{+0.0005}$diameter. To measure the ring, there was no need to take the positioning accuracy into account.

In the case of parts produced using the machine tool, the uncertainty component resulting from the positioning accuracy cannot be taken into consideration, as the positioning conformity between the measured planes and the assumed model depends on the production accuracy. The repeatability of the investigated measurement system for both cases was satisfactory, while the systematic indication error had high values.

### 3.4. Uncertainty of length measurement using multiple measurement strategies

The standards for determining the uncertainty of measurement using the coordinate measuring machine based on the measurement of an uncalibrated workpiece are still being developed. Some instructions can be found in ISO/CD TS 15530-2 Geometrical Product Specification (GPS). Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement. Part 2: Use multiple measurement strategies [8]. According to this project, any part from the batch is measured at different positions, with different measuring strategies for every position. Such measurement is then used to determine the following parameters of uncertainty: $u_{rep}$ which denotes the uncertainty of the obtained measurement repeatability connected with the measuring of the same element at different orientations, as well as $u_{geo}$ which denotes the uncertainty component connected with the product geometric accuracy. Likewise, the measuring of the gauge length is conducted. The gauges should be measured in the same measuring volume in which the product was measured. The measuring should be made three times, in three different directions, each time with a different arrangement of the measuring points. The standard uncertainty is calculated in accordance with the dependence (10):

$$u = \sqrt{s_{wz}^2 + s_p^2} \qquad (10)$$

where: $u$ is the uncertainty of measurement, $s_p$ is the standard deviation of the workpiece , $s_w$ is the standard deviation of the model.

In order to determine the uncertainty of measurement using the method described above, the workpiece shown in Fig. 2 was designed.

The workpiece was produced on a vertical machining center FV580A equipped with the numerical control Fanuc 0iMC. The programme controlling the work of the vertical machining center was generated from the NX6 system. To this end, a 3D model was designed and machining scheme was developed, whose particular stages are shown in Fig. 3. In the machining process, a carbide end-mill (two blades) with 16 mm diameter was used. The machining parameters of rough milling were as follows: the milling cutter speed *n* was of 4500 rpm, the feed $v_f$ was of 1200 mm/min; in finish milling the parameters were: $n$ = 6000 rpm and $v_f$ = 800 mm/min, respectively. In the course of milling, the workpiece was cooled using an oil emulsion.

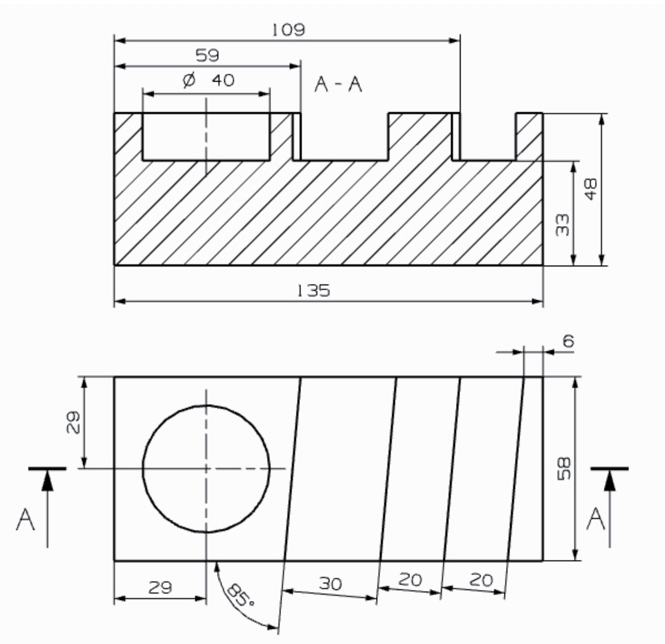


*Fig. 2. Dimensions of the uncalibrated workpiece*

a) b) c)

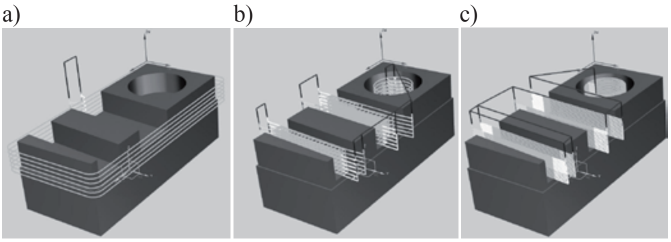

*Fig. 3. Tool paths in consecutive stages of milling: a) outer surface roll forming, b) rough milling of ribs and circular pocket, c) roll forming of ribs and circular pocket*

The measuring of the workpiece was conducted in two stages in order to better visualize and observe differences between the dimensions of its particular elements as well as to eliminate expansion errors. The first stage was conducted immediately following the end of the milling process when the workpiece temperature was still high – this stage is later referred to as "hot measurement." The second stage of the tests was conducted 24 hours later, when the temperature of the workpiece and moving knots of the machine tool was leveled to the ambient temperature of 20°C.

The hot measurement consisted of three measuring series, in each series the following workpiece elements were inspected (Fig. 4):

- Hole diameter (nominal dimension – 40 mm),
- Length (nominal dimension – 135 mm),
- Rib A (nominal dimension – 58 mm),
- Rib B (nominal dimension – 58 mm),
- Pocket 1 (nominal dimension – 30 mm),
- Pocket 2 (nominal dimension – 20 mm).

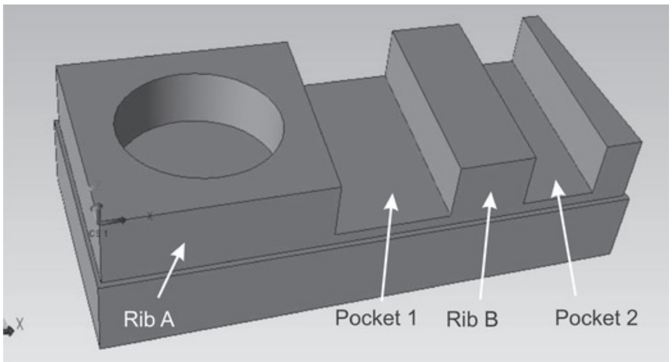


*Fig. 4. Geometric features of the measured workpiece*

In order to enhance the measurement process, Productivity+ was used on the machine. To measure the characteristic features of the workpiece (hole, pocket, rib), a relevant measuring cycle was used. The change in the measurement strategy consisted in using three and four sampling points when measuring the hole (Fig. 5) and in using the measurements on three different levels, determined starting from the taken zero point (the upper, left, front corner of the workpiece). The employment of these variables allowed for considering the effect of shape deviations of the element being examined (e.g. ovality), as well as considering the effect of the tool and its possible strains. The pockets and ribs were measured using a varying number of the sampling points (3, 5 and 7) on the level distanced by 5 mm from the upper plane of the workpiece (Fig. 6).

a) b)

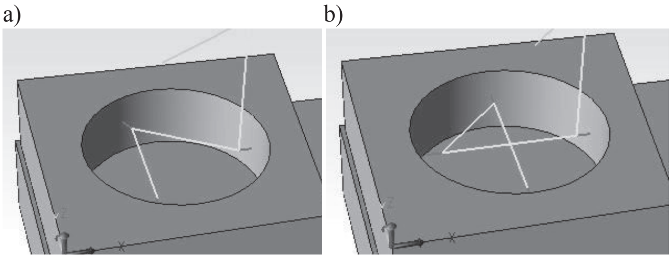

*Fig. 5. Strategy for measuring the hole: a) measurement with 3 sampling points, b) measurement with 4 sampling points*

a) b) c)

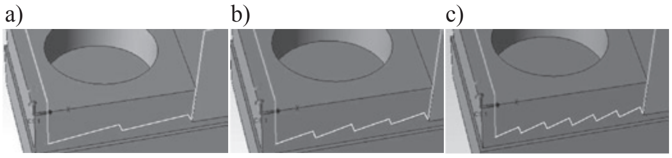

*Fig. 6. Strategy for measuring the ribs and pockets: a) measurement with 3 sampling points, b) measurement with 5 sampling points, c) measurement with 7 sampling points*

Such selection of points is in a way a compromise, as the optimum solution to achieve measurement accuracy would have been to select as many sampling points as possible (due to the fact that with an increase in the number of points, the uncertainty of profile evaluation decreases). Yet, an excessive increase in the number of sampling points can have a negative effect on the uncertainty of measurement, because every sampling point will be burdened with the measurement system error, which affects the coordinate measurement result. Such solution is especially vital in the case of measurements performed on machine tools and – to a lesser degree – in the case of measurements performed under laboratory conditions. Besides affecting the measurement accu-

*Table 6. Measurement results of the uncalibrated workpiece*

| Start time | after 1min | | | | | | after 24 h | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dimension | Hole | Length | Rib A | Rib B | Pocket 1 | Pocket 2 | Hole | Length | Rib A | Rib B | Pocket 1 | Pocket 2 |
| Mean, [mm] | 39.908 | 135.035 | 58.030 | 58.023 | 29.952 | 19.952 | 39.909 | 135.034 | 58.034 | 58.030 | 29.944 | 19.946 |
| Standard deviation of dimension $s_p$ [mm] | 0.0016 | 0.0035 | 0.0007 | 0.0027 | 0.0009 | 0.0031 | 0.0027 | 0.0005 | 0.0025 | 0.0012 | 0.0009 | 0.0022 |
| Standard deviation of gauge $s_{wz}$, [mm] | 0.0004 | 0.0015 | 0.0009 | 0.0009 | 0.0009 | 0.0009 | 0.0004 | 0.0015 | 0.0009 | 0.0009 | 0.0009 | 0.0009 |
| Standard uncertainty $u$, [mm] | 0.0017 | 0.0039 | 0.0012 | 0.0029 | 0.0013 | 0.0032 | 0.0028 | 0.0016 | 0.0026 | 0.0015 | 0.0013 | 0.0024 |
| Expanded uncertainty $U$, [mm] | 0.0034 | 0.0078 | 0.0024 | 0.0058 | 0.0026 | 0.0064 | 0.0056 | 0.0032 | 0.0056 | 0.0030 | 0.0026 | 0.0048 |

racy of the workpiece shape, the number of measuring points has also a considerable effect on the duration of a measuring cycle.

Productivity+ registered the measurement results in a declared memory cell of the Fanuc system. The results were then transferred to a spreadsheet in which the necessary calculations were made. The following gauge lengths were used: for the dimensions of 58 mm, 30 mm and 20 mm a 50mm length gauge block of class 1 was used, for a dimension of 135 mm a 150 mm length gauge clock of class 1 was used, for the 40 mm diameter hole a 50 mm diameter gauge ring was used. Table 5 presents the results of the measurements and calculations of measurement uncertainty.

For the comparison reasons, the sample workpiece was measured using the coordinate measuring machine whose measurement uncertainty $u_1$ given by the manufacturer is of ±( 2.5 +$L$/250) μm, where $L$ was the length measured in mm. The following results were obtained:

- Hole diameter – 39.911 mm,
- Length -135.042 mm,
- Rib A – 58.017 mm,
- Rib B – 58.019 mm,
- Pocket 1- 29.951mm,
- Pocket 2 – 19.945 mm.

## 4. Result analysis and conclusions

The measurement results described in the present paper are unequivocal. The results of the uncertainty measurement of the coordinates of the point given in Table 2 demonstrate that in most cases the standard uncertainty $u_a$ is lesser than the one-dimensional repeatability given by the manufacturer. It is only in the case of the uncertainty of measurement of the X coordinate that it slightly exceeds this value for the 300 mm travel path. Therefore, the main reason for the scatter of results is caused by the resolution of the measurement system. It is worth noticing that the results of measurement of the Z coordinate are stable. This is due to the probe design. This can also be observed analyzing the results of determining the one-dimensional uncertainty of measurement of length that are given in Table 3. In the case of the gauge blocks parallel to the Z axis, the standard uncertainty $u_a$ has lower values than in other cases. Analyzing the results presented in Table 3, it can be observed that the standard uncertainty $u_a$ of the on-machine measurement system using the OMP60 is much lower than the systematic indication error. The high values of the systematic indication error are caused by lack of parallelity of the head motion to the linear encoders, while the considerable differences in the values of this error results from the misalignment of this motion. This is due to the geometric accuracy of the machine tool and the condition of its power units.

Analyzing the results presented in Table 4, it can be observed that the standard uncertainty of Type A (which results from the repeatability of measurements) has low values and does not exceed 0.5 μm in the whole investigated measurement range. The combined standard uncertainty depends on the length of the gauge block being measured. This results from two components – the uncertainty of the gauge length $u_L$ and the uncertainty resulting from the precision of setting $u_{cos\alpha}$. In the case of the workpieces produced on the machine tool, the uncertainty component resulting from the accuracy of positioning can be omitted, because the compatibility between the position of the planes being measured and the assumed model depends on the precision of production. The repeatability of the investigated measurement system is satisfactory, while the systematic error has high values. Comparing the results given in Table 4 with the results of determining the unidirectional uncertainty given in Table 3, it can be claimed that in the case of 50, 100, 150 and 300 mm length gauge blocks, such correction values result from the geometric accuracy of the machine tool, while the high value of the systematic error of the 200mm length gauge block results from is probably caused by its relatively inaccurate positioning.

Given in Table 5, the measurement results of the gauge ring demonstrate that the standard uncertainty of Type A is almost by two times higher than in the case of the 20mm length gauge block (the worst case). Also, the corrections for the gauge ring have considerably higher values than the corrections for the gauge blocks. This is due to a different way of ball radius compensation when measuring the planes and circles.

Comparing the measurement results of the uncalibrated workpiece presented in Table 6, it can be observed that the dimensions of the sample workpiece measured immediately after the end of the machining process and after a 24-hour time lapse can be considered identical (except for the dimensions of pocket 1 and pocket 2). The measuring cycle lasted for about 30 minutes. The workpiece underwent cooling during this period of time. Pockets 1 and 2 were measured at the beginning of the measuring cycle, i.e. when the effect of the thermal expansion caused by the milling process was the most significant. These factors led to the differences in the results of the measurements taken immediately after the process and after the 24-hour time lapse. The difference in the dimensions caused by the occurrence of thermal strains was also observed in the values of the standard deviations of the workpiece. Comparing the standard deviation of 'length' (nominal dimension of 135) whose value was of 0.0035 after the machining process and of 0.0005 mm after the 24-hour time lapse, it can be claimed that the temperature decrease in the course of the measuring cycle led to the change in the dimensions and, consequently, to the dispersion of their measured values. When measuring the hole, a reverse situation could be observed: a higher scatter of results of the diameter measurement was obtained after 24 hours. According to the measurement of the hole using the coordinate machine, the cylindricity deviation was of 0.006 mm – conicity (diameter decreases together with depth). The measurements of the hole using the probe were made at three depths, starting from the highest one. It partially compensated the diameter decrease caused by the temperature decrease. The on-machine measurement system using the OMP 60 and the coordinate measuring machine had different control and measurement software. In effect, different measuring strategies had to be employed, which – combined with the geometric deviations of the workpiece (deviations of the plane parallelity and flatness, cylindrical deviations) can cause differences in measurement results that exceed the acceptable differences resulting from metrological properties of measurement systems.

The present paper described various methods for determining the uncertainty of measurement of the on-machine measurement system using the OMP 60 probe. The discussed methods differ in terms of their labor-consumption. The most labor-consuming methods are based on the measurement of the material standard of size. Additionally, they require interpolating corrections for the systematic error of the dimensions different from the ones used for the gauge blocks or gauge rings. The advantage of these methods is that the calibration once made can then be used when measuring other workpieces. The method with the uncalibrated workpiece is less labor-consuming, but the determined uncertainty of measurement has higher values than the uncertainty of calibration. A clear disadvantage of this method is the fact that it can only be applied to a specific workpiece.

Based on the measurement results and their analysis, the following observations were made:

- selecting the method for determining the uncertainty of measurement should depend on its purpose;
- if the purpose of the measurement is to locate the zero point, the uncertainty of measurement of the coordinates of the point should be determined;
- if the purpose of the measurement is to perform an inter operational control, after-machining control or reverse engineering, then the method based on the uncalibrated workpiece can be employed proved that the machining technology allows for minimizing thermal strains;
- if the machining process generates considerable amounts of heat, the following need to be determined: unidirectional uncertainty of measurement for the dimensions parallel to the axis, bidirectional uncertainty of measurement using gauge blocks for the dimensions in the XY plane, for holes – bidirectional uncertainty of measurement using a gauge ring.

## References


1. Arendarski J. Niepewność pomiarów. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2006.
2. Cho MW, Kim H, Seo I, Hong YC, Cheng HH. Integrated machining error compensation method using OMM data and modified PNN algorithm. International Journal of Machine Tools and Manufacture 2006; 46: 1417–1427.
3. Deneka B, Schmidt C, Krüger M. Experimental investigation and modeling of thermal and mechanical influence on shape deviation in machining structural parts. International Journal of Machine Tools and Manufacture 2010; 50: 1015–1021.
4. Dokument EA-4/02. Wyrażanie niepewności przy wzorcowaniu. GUM. Warszawa 1999.
5. Guissa R, Mayer JRR. Predictive compliance based model for compensation in multi-pass milling by on-machine probing. CIRP Annals – Manufacturing Technology 2011; 60(1): 391–394.
6. Hang Y, Hoshi T. Optimizaton of fixture design consideration of thermal deformation in face milling. Journal of Manufacturing System in face milling 2000; 19.
7. Horálek V. Analysis of basic probability distributions, their properties and use in determining type B evaluation of measurement uncertainties. Measurement 2012; 46: 16–23.
8. ISO/CD TS 15530-2 Geometrical Product Specification (GPS). Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement. Part 2: Use multiple measurement strategies.
9. Jacniacka E, Semotiuk L. Powtarzalność mocowania jako składnik budżetu niepewności pomiaru sondą przedmiotową na obrabiarkach CNC. Mechanik 2012; 5–6: 456–459.
10. Jacniacka E, Semotiuk L, Babkiewicz M. Wyznaczenie dwuwymiarowej niepewności pomiaru wewnątrzobrabiarkowego systemu pomiarowego z zastosowaniem sondy OMP60. Pomiary, Automatyka, Robotyka 2012; 10: 68–73.
11. Jacniacka E, Semotiuk L, Pieśko P. Niepewność pomiaru wewnątrzobrabiarkowego systemu pomiarowego z zastosowaniem sondy OMP 60. Przegląd Mechaniczny 2010; 69(6): 36–42.
12. Jakubiec W. Analityczne wyznaczanie niepewności pomiaru we współrzędnościowej technice pomiarowej. Akademia Techniczno-Humanistyczna w Bielsku-Białej. Bielsko-Biała 2008.
13. Kwon Y, Jeonng MK, Omitaomu OA. Adaptive support vector regresion analysis of closed-loop inspection accuracy. International Journal of Machine Tools and Manufacture 2006; 46(6): 603–610.
14. Kwon Y, Tseng T-Z, Ertekin Y. Characterization of closed-loop measurement accuracy in precision CNC milling. Robotics and Computer-Integrated Manufacturing 2006; 22: 288–296.
15. Pakiet oprogramowania Inspection Plus. Podręcznik programowania. Renishaw 2003.
16. PN EN ISO 3650:2000. Specyfikacje geometrii wyrobów (GPS) – Wzorce długości – Płytki wzorcowe.



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