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Evaluation of Measurement Uncertainty Obtained With a Tool Probe on a CNC Machine Tool

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The paper presents the results of measurement uncertainty obtained with a tool probe for 4 cutting tools with different values of the nominal radius r_f = {3,4,5,7} mm. The tool probe was used to collect experimental data enabling the evaluation of the uncertainty budget of the measuring system. The evaluation was made based on a statistical analysis of measured tool radius values. Each radius value was determined by 30 repetitions of tool probe measurement. The mean value and the standard uncertainty of obtained results were determined. Assuming that the expansion factor was k=2, the expanded uncertainty U was determined, its value ranging between 0.00142 mm and 0.00462 mm for the tested tool radius values. The standard uncertainty ranged from 0.00081 to 0.00231 mm. According to the manufacturer's specifications, the standard uncertainty of the probe is 0.0015 mm.

Keywords: tool probe, measurement uncertainty, contour tolerance, dimensional and shape accuracy, CNC machine tool

1 Introduction

A key aspect in the evaluation of part dimensions is the uncertainty budget determination of in-machine tool measurement. The use of a tool probe as an internal machine measuring system ensures the assessment of tool dimension at a time t (at the time of measurement) during tool radius compensation in CNC machining. The literature review [10] shows that the objective assessment of tool measurement during machining affects the dimensional and shape accuracy of a product. By knowing the measurement uncertainty of a machining tool itself, one can determine exactly how the tool probe should be measured. This uncertainty will, to a large extent, affect the uncertainty of the shaped dimension. An incorrect determination of the measurement uncertainty value causes the machining tool to move away from the shaped profile by an incorrect uncertainty value in the tool correction table of a CNC machine tool.

Machining quality is inextricably linked with cutting tool compensation. Tool compensation is an essential function of the CNC machine tool system and can be carried out automatically by calculating and adjusting the cutter's position in the tool trajectory according to the machining program. The understanding of the principle of tool nominal radius compensation is an important factor in ensuring accurate and efficient machining [16].

Measurement uncertainty is closely related to measurement results. It applies to all types of measurements, including those made with machine tools [20,21]. A standard measurement with a tool probe on a CNC machine is performed under changing ambient conditions. Studies [1, 23] have shown that the measured quantity value depends on the measurement conditions. Therefore, it is worth asking whether the measurement result obtained with a tool probe on a CNC machine can be reliable and useful in further analysis. To answer this question, it is necessary to define the range of values in which the actual value of the measured quantity falls. When determining this range, it should be remembered that the range depends on the confidence level (usually it is 95% or 99%). Measurement results obtained at the assumed high confidence level can be used to correctly estimate the nominal radius of a machining tool.

The problem of reliability and effectiveness of measurement results was investigated in [9]. The study compared three methods of determining uncertainty types A and B and undertook to explain when a given estimator was the most effective. The effectiveness of estimators is based on two concepts: compatibility and reliability. Compliance means that the estimator conforms to a specific standard or correctness. In mathematical terms, compliance means impartiality. Reliability, on the other hand, stands for precision and ensures that the estimator allows for reproducible results under the same ambient conditions. In statistical interpretations of the results, it is obvious that the impartiality of estimators may not be more reliable than their bias. On the other hand, a reliable estimator may not comply with a given standard.

Therefore, the effectiveness of the estimator should take into account both compliance and reliability.

According to [18,25] and many other studies, two types of measurement uncertainty evaluation can be distinguished: *A* and *B*. The type *A* uncertainty evaluation is a method involving the statistical analysis of a specific series of measurements. On the other hand, the type *B* evaluation of uncertainty is a method for assessing the uncertainty by means other than statistical analysis. Both methods focus on evaluating all components of measurement uncertainty and are based on probability distributions, and the individual components of uncertainty are determined by the standard deviations or variances of these distributions. The difference between the two methods is how these deviations are achieved.

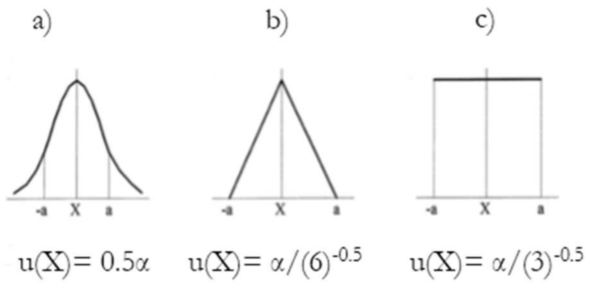

Fig. 1 *Probability distributions in type B uncertainty evaluation: a) normal distribution, b) triangular distribution, c) rectangular distribution [24]*

In the type *A* evaluation of uncertainties, deviations are determined based on a series of repeated measurements. In the type *B* uncertainty evaluation, the deviation shall be assessed by:

- previously developed measurement data,
- technical specifications of the measuring system,
- general state of knowledge,
- uncertainties attributed to references data from the literature.

The type *B* evaluation of uncertainty is a more subjective method than the type *A* uncertainty evaluation and can be as reliable as the type *A* method when the type *A* assessment is based on a small number of measurements [18,19].

The concept of measurement uncertainty is applied not only in machine tool measurements, but also in studies on the accuracy of manufacturing processes, for instance in the sorting of machined parts. A study [15] evaluated the impact of the expanded uncertainty of measuring instruments on the measurement of linear dimensions of manufactured parts. The study investigated the effect of probability distribution laws of uncertainty on the accuracy of sorting workpieces and on the ways of minimizing the risk of erroneous workpieces. In order to minimize the risk of erroneous workpieces, the manufacturer would have to use such manufacturing processes in which the position of the probability distribution was symmetrical in the centre of the tolerance zone.

As reported by the literature [20], when estimating the nominal radius of the cutter with a tool probe, the most useful and reliable result is the one with the lowest possible uncertainty. According to relevant ISO standards [25,26], the measurement uncertainty should make it possible to obtain the most accurate measurement results. When assessing the uncertainty of measurement with a tool probe, it is important to accurately determine the uncertainty budget [14]. An incorrect uncertainty budget analysis can result in accepting the wrong result or rejecting the correct one. A study [11] provided an illustration of the zones of agreement and disagreement of measurement results based on uncertainty values (Fig. 2).

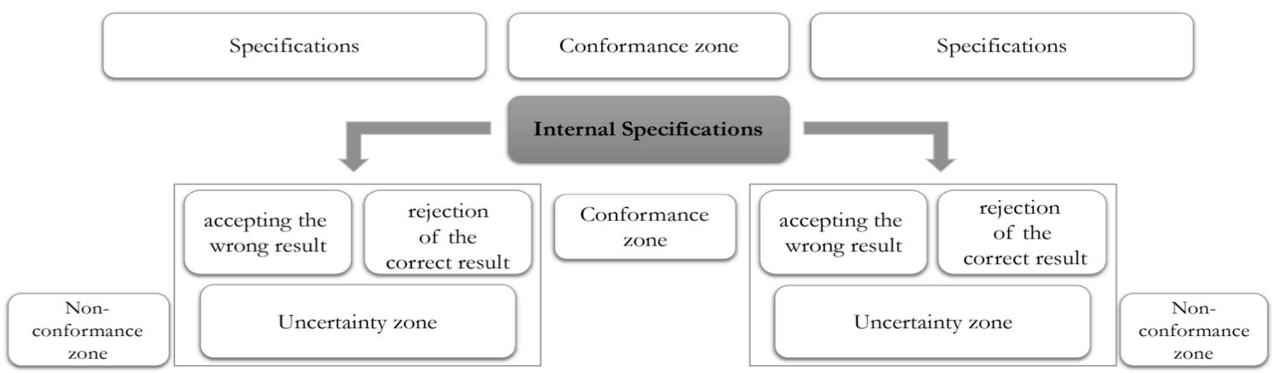

Fig. 2 *Influence of measurement uncertainty on the zone of results agreement [11]*

Fig. 2 shows that the acceptance of an incorrect measurement result may occur when the uncertainty is outside the tolerance range, but the measurement remains within the tolerance. Still, a false rejection can occur when the measured value is within the tolerance zone, but the uncertainty is greater. If the measurement uncertainty is reduced, the agreement zone will be increased, which will thus reduce the false acceptance and rejection of the result [11,22]. Performing measurements with the use of a tool probe with large measurement uncertainties may cause errors during contour cutting. As has been previously reported in the literature, there are many factors that contribute to these uncertainties.

According to a study [2], the key factors influencing the measurement uncertainty were stem length, measurement strategy and probe accuracy. A study [13] presented the results of systematic error compensation of a faulty tool probe that were obtained based on its trigger radius characteristics. The measurement results were used to adjust the measurement speed accordingly and to minimize probe errors. Those individual sources of error were found to contribute to the resulting measurement uncertainty at a 95% confidence level.

A study [8] described the frequency of the contact probe hysteresis phenomenon that could affect the measurement uncertainty. It was emphasized that during measurements performed on CNC machine tools the phenomenon was omitted; also, its effect as a source of arising errors was not taken into consideration by users of CNC machine tools contact probe hysteresis at the stage of planning the measurement strategy for a given component.

The selection of correct machining tools is of vital importance when planning the machining process for parts with a specific dimensional tolerance. The use of tools with relatively large diameters or lengths may increase uncertainty. A study [6] proposed a method for optimizing tool diameter in the machining of complex-shaped details. The causes of theoretical and deformation-related errors were analysed, and the trend of error changes with changes in the tool diameter was explained. Obtained measurement results were used after applying several tool diameter selection methods which, according to the authors, yielded the expected results and thus helped improve product accuracy.

As stressed in studies [7,17], probe repeatability was one component of the uncertainty budget. In addition to that, factors such as measurement method selection, operator errors [12], increase in the dispersion of results, probe calibration [2], elastic deformation, cutting tool condition, vibration, temperature, pressure, together with high uncertainty of cutter nominal radius estimation could also cause the dimensional tolerance of the shaped contours to be exceeded.

The authors [5] presented the share of probe errors on the accuracy of machine tool measurements. In the article, they paid attention to one of the main factors affecting the probe measurement is the accuracy of the probe. In addition to that, factors such as change in the diameter of the probe ball, the length of the stylus, the probe arm and the direction of probe movement can also affect the accuracy of measurements.

The authors [4] indicated that in order to obtain uncertainty at the level of several micrometres, the uncertainty budget should be determined in detail. According to the authors, some of the main factors affecting the measurement are: probe resolution, linearity, mechanical noise, thermal drift and misalignment of the probes.

Work [3] presented the results of calibration of beam vector deviation for four-axis precision on-machine measurement using chromatic confocal probe intended for measuring the surface of objects. The authors emphasized that in order to obtain a real profile with a large surface area using chromatic confocal technology, it is necessary to add degrees of freedom to increase the detectable angle of the probe. It was underlined that this is problematic because the rotation of the probe during the measurement process increases the measurement uncertainty. Minimization of uncertainty can be achieved by compensation the measuring movements of the linear axis of the machine tool. Surface scan control provides an efficient machine calibration procedure and improves the accuracy of multi-axis measurement of complex surfaces.

Therefore, the purpose of this study is to evaluate the uncertainty of measuring cutter nominal radius with a tool probe. The influence of the measurement uncertainty on the tolerance behaviour of the shaped contour is investigated. The fact that there are few publications on the problem of measurement uncertainty evaluation using tool probes justifies the undertaking of this research work, while the focus on the assessment of tool dimension during tool radius compensation and the accuracy of shape and dimension in manufactured details can be considered a novelty of this study.

2 Materials and Methods

2.1 Methodology

The object of the study was an OTS tool probe, the use of which made it possible to measure the nominal radius r_f= {3,4,5,7} mm of the machining tools. Each radius value was determined by 30 repetitions of the measurement conducted with a constant tool feed speed of v_f =1000 [mm/min]. The estimation was based on a statistical analysis of obtained tool radius values. The following uncertainty parameters were analysed: standard uncertainties u_A, u_B, $u_w(\Delta t)$, $u_w(\Delta p)$, submitted uncertainty u_C, and expanded uncertainty U, assuming that the value of the coverage factor was k=2. Four cutters were used in the study:

- one carbide end mill for finishing, r_f = 3 mm, 6-blade,
- two carbide end mills with chip dividers, r_f = {4,5} mm, 4-blade,

- one high-speed steel end mill for keyway processing, r_f = 7 mm, 2-blade.

The selection of the tools was determined by checking the effect of their nominal radius on the measurement uncertainty. A research plan (Fig. 3) was devised so that the experiment could be carried out in an orderly and systematized manner.

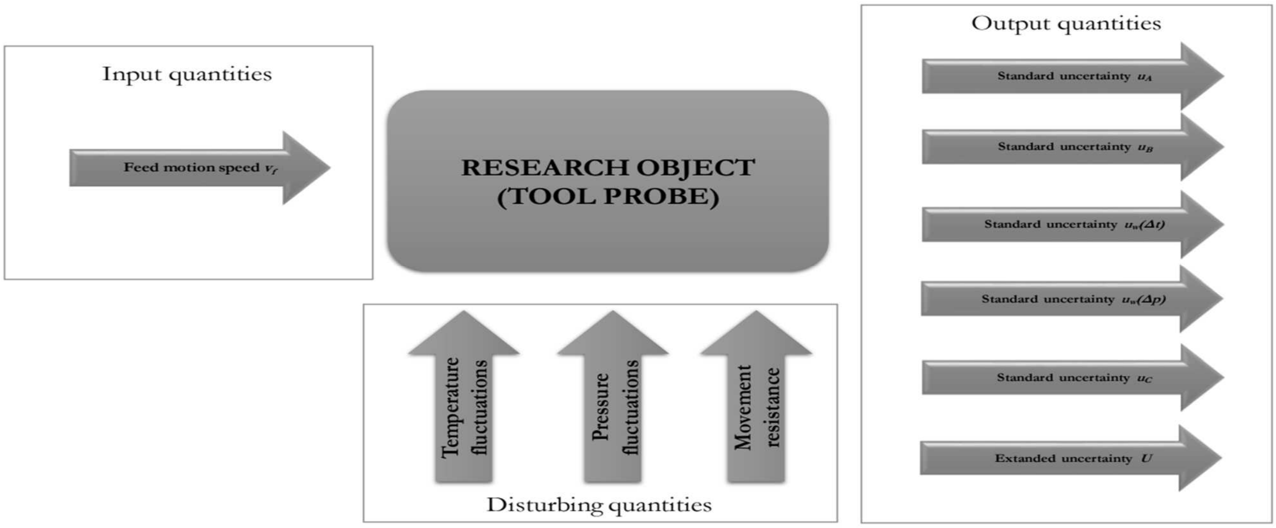

Fig. 3 *Research plan for assessing the uncertainty of measurement made with a tool probe on a CNC machine tool*

Nominal radius measurements were performed on the Highlights MILLTAP 700 four-axis CNC machining centre equipped with a Siemens 840D control system and having the maximum spindle speed of 24000 rpm. The maximum travel of the table and spindle of the machine tool is 700 mm for the *X* axis, 420 mm for the *Y* axis and 380 mm for the *Z* axis. The test stand is shown in Fig. 4. Fig. 4a shows the CNC machine tool used in the study. Fig. 4b shows the test object, while Fig. 4c shows the machining tools used in the experiments.

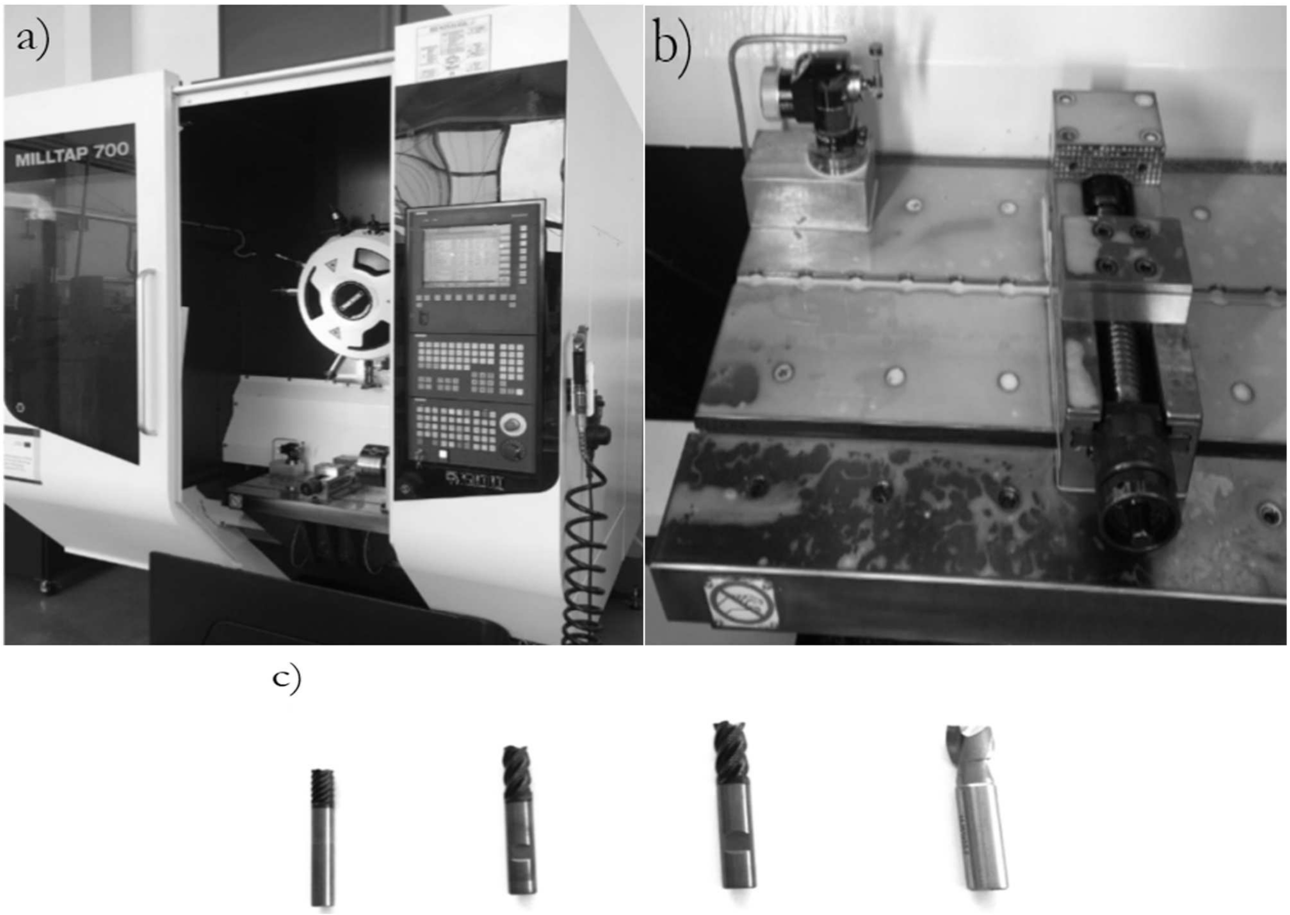

Fig. 4 *Highlights MILLTAP 700 four-axis machining centre: a) general view, b) tool probe arrangement in the working space of the machine tool, c) machining tools*

Nominal radius measurements were made with an OTS tool probe. Technical parameters of the probe are listed in Tab. 1. Each measurement was repeated 30 times for each nominal radius value to determine the mean values and standard deviation.

Fig. 5 shows how the nominal radii of the machining tools were measured with the OTS tool probe using the feed speed v_f=1000 [mm/min] Fig. 5a shows the measurement of the nominal radius of the carbide end mill for finishing. Fig. 5b and 5c show two carbide end mills with chip dividers. Fig. 5d shows the high-speed steel end mill for keyway processing.

Tab. 1 *Technical specifications of the OTS probe*

Direction of action	±X, ±Y, ±Z
Transmission type	optical, infrared
Transmission scope	5 m
One - way repeatability (2σ)	±1 μm
Trigger force of the measuring tip	1.3 N – 2.4 N

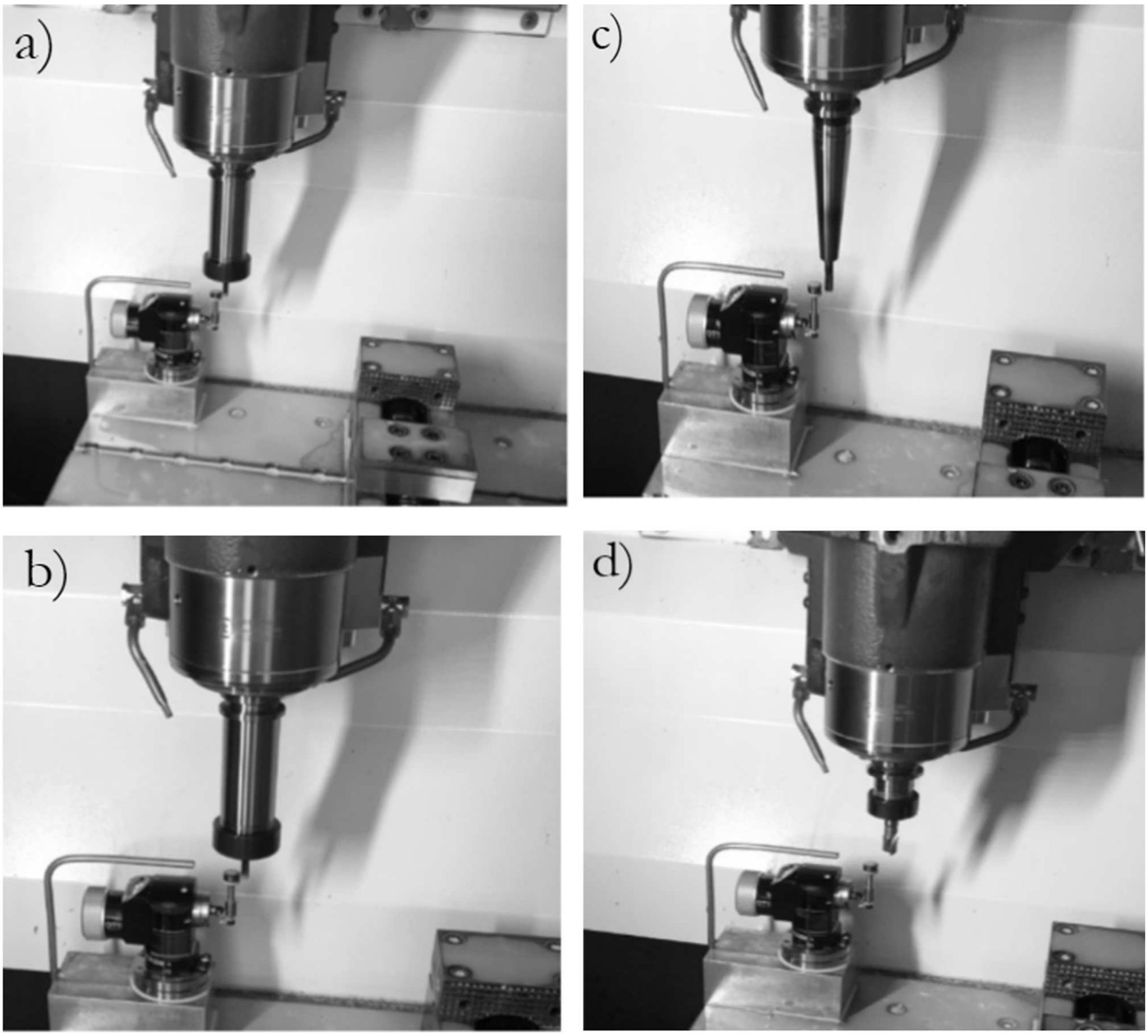

Fig. 5 *Measurement of the machining tool nominal radius made with the OTS probe: a) milling cutter with r_f = 3 mm, b) milling cutter with r_f = 4 mm, c) milling cutter with r_f = 5 mm, d) milling cutter with r_f = 7 mm*

The tools used in the experiments were selected not only based on their different nominal radius, but also based on their general condition.

2.2 Objective of the Study and Its Novelty

This paper presents an analysis of the measurement uncertainty of tool nominal radius measured with the use of a tool probe. The literature review has shown that a vast majority of previous studies focused on the problem of measurement uncertainty determined using workpiece probes. Therefore, this study is a novelty in terms of the originality of its research objective. The uncertainties analysed in this study, i.e. standard uncertainties u_A, u_B, $u_w(\Delta t)$, $u_w(\Delta p)$, submitted uncertainty u_C and expanded uncertainty U, are important when calculating the measuring system uncertainty budget, both for statistical reasons and owing to the possibility of assessing the dimensional and shape accuracy of manufactured parts.

Moreover, the literature review has demonstrated that many researchers predominantly dealt with the analysis of workpiece measurement with measuring probes and the basic sources of errors when creating the uncertainty budget. This state of knowledge is insufficient; hence the present study undertakes to evaluate tool dimension during tool radius compensation in CNC machining. The main goal of this study is to objectively evaluate the measurement of the tool during machining, as this will make it possible to determine the dimensional and shape accuracy of finished details.

The evaluation of machining tool measurement can serve as a basis for specifying all components of the uncertainty budget which are the sources of inaccuracy in the execution of shaped contours. The use of statistical analysis can help specify as many factors as possible that affect the measurements made with the tool probe. In addition, the analysis may be interesting in terms of the availability of both tools and the measuring systems of the CNC machine tool.

3 Results and discussion

3.1 Scheme of the Measurement Uncertainty Budget

The measurement uncertainty budget is a summary of all measurement uncertainty components and shows how they are calculated and combined. The uncertainty budget makes it possible to take into account all components of measurement uncertainty and sensitivity factors that were used for calculations. It also allows one to determine which components are dominant and to analyse whether an error was made during the measurement procedure. It contains data on the probability distribution of individual components and the method of calculating their uncertainty.

This section provides information about the sources of uncertainty that affected the measurement of the nominal radius of the tools made with the tool probe. A detailed diagram of the uncertainty budget is presented in Fig. 6.

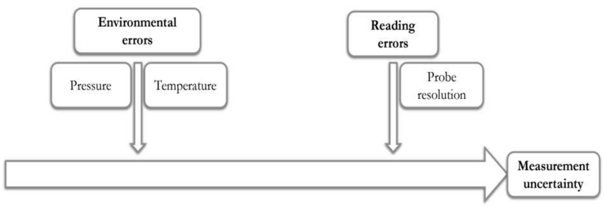

Fig. 6 *Sources of errors affecting the measurement uncertainty of the machining tool nominal radius measured with the OTS tool probe*

Factors from two groups of measurement errors were taken into account when calculating the measurement uncertainty budget. These errors included:

- environmental errors which pertained to the conditions of measurements. The factors considered in this study were ambient temperature and pressure,
- reading errors which were related to the unreliability of human senses and the resolution of the tool probe.

3.2 Statistical Analysis

A measurement uncertainty analysis of the cutters was performed depending on the nominal radius of the tools. The values of the measured nominal radius of the cutters were obtained from the measurements. The results of the standard uncertainty u_A and the expanded uncertainty U were averaged from each test series for each tool. The standard uncertainty of type A was determined from relation (1):

$$u_A = \sqrt{\frac{1}{n \cdot (n-1)} \sum_{i=1}^{n} (r_i - \bar{r})^2} \tag{1}$$

Where r_i is the next measurement result, $\bar{r}$ is the arithmetic mean value of the cutter radius, n is the number of measurements.

The expanded uncertainty of the mean value U was determined from dependence (2):

$$U = u_A \cdot k \tag{2}$$

Where k is the expansion factor. For the purpose of the experiment, it was assumed that k=2.

For a detailed calculation of the uncertainty budget in tool probe measurements, equations for individual components of the budget were determined. The uncertainty resulting from the tool probe resolution was estimated using the B-type method and determined using relation (3):

$$u_B = u_R = \frac{\alpha}{\sqrt{6}} \tag{3}$$

Where α is the variability of the measured value, α= 0.001mm.

During the measurement, the average ambient temperature was t = 291.15 K, with its fluctuations ranging Δt =2 K. For this case, a rectangular probability distribution was assumed. Therefore, the standard uncertainty of temperature deviation was determined from formulae (4) and (5):

$$u(\Delta t) = \frac{\alpha}{\sqrt{3}} \tag{4}$$

Where α is the is the half width, α=1K.

$$u_w(\Delta t) = \frac{u(\Delta t)}{t} \tag{5}$$

During the measurement, the average ambient pressure was p = 100 kPa, with its fluctuations in the range Δp =2 kPa. For this case, a rectangular probability distribution was assumed. Therefore, the standard uncertainty of pressure deviation was determined from formula (6) and (7):

$$u(\Delta p) = \frac{\alpha}{\sqrt{3}} \tag{6}$$

Where α is the is the half width, α=1 kPa.

$$u_w(\Delta p) = \frac{u(\Delta p)}{p} \tag{7}$$

The submitted measurement uncertainty u_c was determined from formula (8):

$$u_c = \sqrt{u_A^2 + u_B^2 + \left(u_w(\Delta t)\right)^2 + \left(u_w(\Delta p)\right)^2} \tag{8}$$

Table 2 presents the uncertainty budget for measuring the nominal radius of the machining tools with the OTS tool probe.

Table 3 presents the results of the standard uncertainty u_A and the expanded uncertainty U of the cutter nominal radius.

***Tab. 2** Uncertainty budget for measuring the nominal radius of the machining tools with the OTS tool probe*

Symbol	Size estimate	Measurement uncertainty	Probability distribution	Sensitivity factor	Relative uncertainty
u_R	1	0.00041	triangular	1	0.00041
$u_w(\Delta t)$	1	0.00196	rectangular	1	0.00196
$u_w(\Delta p)$	1	0.00577	rectangular	1	0.00577
u_c	0.00611				

***Tab. 3** Measurement results and calculations of the standard uncertainty u_A and the expanded uncertainty U of the cutter nominal radius*

No.	Nominal radius of the cutter r [mm]	Average observed cutter radius r_i [mm]	Standard uncertainty $u_A(r)$ [mm]	Expanded uncertainty U(r) [mm]
1	3	2.954	0.00195	0.00390
2	4	3.959	0.00081	0.00161
3	5	4.929	0.00231	0.00462
4	7	6.958	0.00071	0.00142

Subsequently, a Grubb's test was performed to determine whether the values of the minimum and maximum radius of the cutters were subject to gross error and whether they should be rejected. The null hypothesis and the alternative hypothesis were as follows:

- H_0: all results in the sample are derived from an established population,
- H_1: at least one unit was drawn from a different population.

A statistical test was carried out for each tool radius. Before the hypothesis verification, the set of experimental results was ranked according to increasing values. The gross error could be the highest (r_{max}) ora the smallest (r_{min}) value of the result in the sample. For these results, the parameters G_1 and G_n were calculated. Then, the parameter with the higher value was compared with the critical parameter, corresponding to the number of measurement series and the selected confidence level. The critical value of the test statistics was obtained from the tables of the Grubbs test. If the experimental value was greater than the critical value, then the suspicious result had a gross error and could be dismissed. All value of G_1 and G_n were determined on the basic formulas (9)-(12). The results of the Grubb's test are shown in Tab. 4.

All values of variance are determined from formula (9), which at the same time represents the variance for the cutter's nominal radius with r_1=3 mm. The other values were determined in the same way. The variance was determined from the formula (9):

$$S^2 = \frac{\sum_{i=1}^{n}(r_i - \bar{r})^2}{n} = \frac{0.001332933mm}{30} = 4.443 \cdot 10^{-5} mm \tag{9}$$

The formula (10) presents the standard deviation for the nominal radius of the cutter with r_1=3 mm. The other values were determined in the same way.

$$S = \sqrt{S^2} = \sqrt{4.443 \cdot 10^{-5}} = 0.006mm \tag{10}$$

The values of G_1 and G_n needed for the Grubb's test were determined form formulas (11) - (12):

$$G_1 = \frac{\bar{r} - r_{min}}{S} \tag{11}$$

$$G_n = \frac{r_{max} - \bar{r}}{S} \tag{12}$$

Where r_{min} is minimum measured radius value, r_{max} is maximum measured radius value.

***Tab. 4** Summary of Grubb's test results*

No.	Nominal radius of the cutter r [mm]	Wariance [mm]	Standard deviation [mm]	Critical value [mm]	Test significance level	Sample size	Hipothesis	
							G_1	G_n
1	3	$4.443 \cdot 10^{-5}$	$6 \cdot 10^{-3}$	2.74	0.05	30	7.071	1.930
2	4	$1.83 \cdot 10^{-5}$	$4 \cdot 10^{-3}$				1.955	2.953
3	5	$2.89 \cdot 10^{-5}$	$1.7 \cdot 10^{-2}$				0.472	3.760
4	7	$1.46 \cdot 10^{-5}$	$4 \cdot 10^{-3}$				0.009	0.253

As the next part of the statistical analysis, the Durbin-Watson test was also carried out, which aimed to detect autocorrelations between the determined uncertainties. The null hypothesis and the alternative hypothesis were as follows:

- H_0: absence of autocorrelation of measurement uncertainties,
- H_1: there is a first-order autocorrelation.

The statistical test was performed for type *A* uncertainty and expanded uncertainty *U*. The statistic is given by the formula (13):

$$DW = \frac{\sum_{i=2}^{T}(e_i - e_{i-1})^2}{\sum_{i=2}^{T}(e_i)^2} \tag{13}$$

Taking into account the uncertainty values of u_A and *U* for each tool radius, the value of the *DW* statistic was presented in formula (14):

$$DW = \frac{7.46 \cdot 10^{-8}}{5.62 \cdot 10^{-8}} = 1.33 \tag{14}$$

The resulting *DW* statistic was compared to the two critical values d_L and d_U, determined from Durbin-Watson tables. These values were $d_L = 1.35$, $d_U = 1.49$, respectively. $DW < 2$, $DW < d_L$ and $DW < d_U$, so the null hypothesis of no autocorrelation was rejected and it was assumed that there is positive autocorrelation in the model under study.

A summary of the variables describing the set of values of the measured radius for each tool was performed. The results are shown in Tab. 6.

***Tab. 5** Summary of Durbin-Watson test results*

No.	Nominal radius of the cutter r [mm]	Standard uncertainty $u_A(r)$ [mm]	Expanded uncertainty U(r) [mm]	e_i	$e_i - e_{i-1}$	e_i^2	$(e_i - e_{i-1})^2$
1	3	1.95·10-3	$3.9 \cdot 10^{-3}$	$-1.78 \cdot 10^{-4}$		$3.17 \cdot 10^{-8}$	
2	4	8.1·10-4	$1.61 \cdot 10^{-3}$	$3.61 \cdot 10^{-6}$	$1.82 \cdot 10^{-4}$	$1.31 \cdot 10^{-10}$	$3.3 \cdot 10^{-8}$
3	5	2.31·10-3	$4.62 \cdot 10^{-3}$	$1.55 \cdot 10^{-4}$	$1.52 \cdot 10^{-4}$	$2.41 \cdot 10^{-8}$	$2.3 \cdot 10^{-8}$
4	7	7.1·10-4	$1.42 \cdot 10^{-3}$	$1.92 \cdot 10^{-5}$	$-1.36 \cdot 10^{-4}$	$3.68 \cdot 10^{-8}$	$1.85 \cdot 10^{-8}$
Total						$5.62 \cdot 10^{-8}$	$7.46 \cdot 10^{-8}$

***Tab. 6** A summary of the variables describing the set of values of the measured radius for each tool*

No.	Nominal radius of the cutter r [mm]	Mean	Median	r_{max} value [mm]	r_{min} value [mm]
1	3	2.955	2.954	2.968	2.908
2	4	3.959	3.960	3.97	3.951
3	5	4.929	4.926	4.993	4.921
4	7	6.958	6.958	6.966	6.951

Fig. 7 presents histograms showing the frequency of occurrence of measured tool radius values in the statistical sample. For this purpose, their ranges were defined.

The presence of asymmetry in the distribution of radius values for each tool was then confirmed using the box graphs shown in Fig. 8.

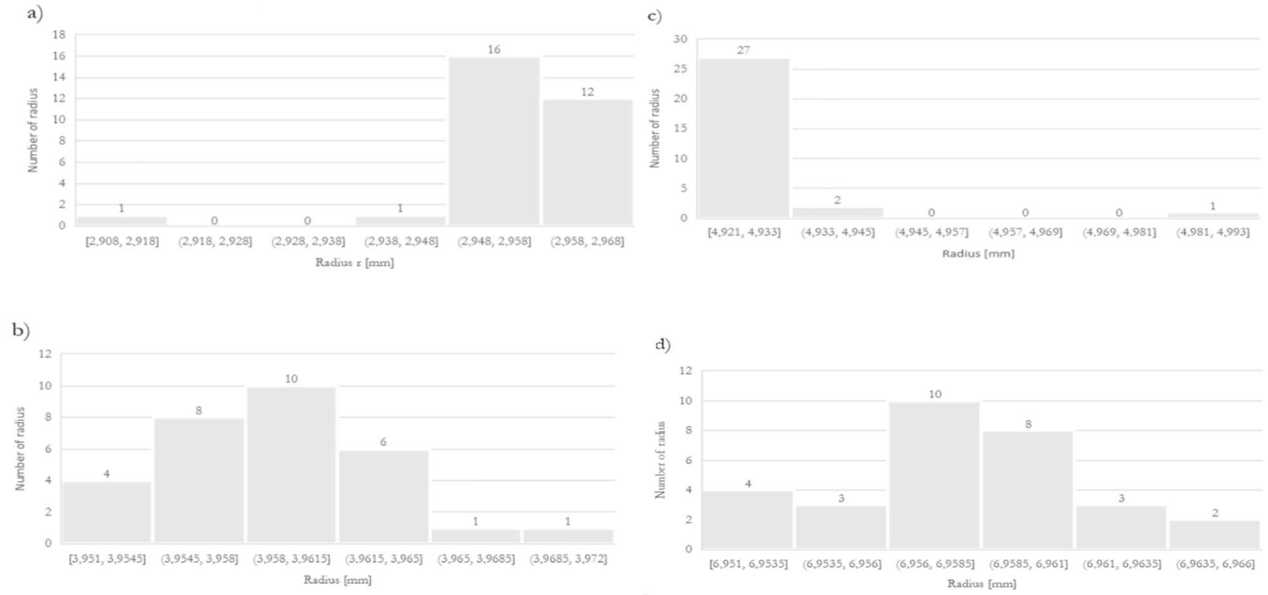

Fig. 7 *The frequency of occurrence of measured tool radius values in the statistical sample: a) r_f = 3 mm, b) r_f = 4 mm, c) r_f = 5 mm, d) r_f = 7 mm*

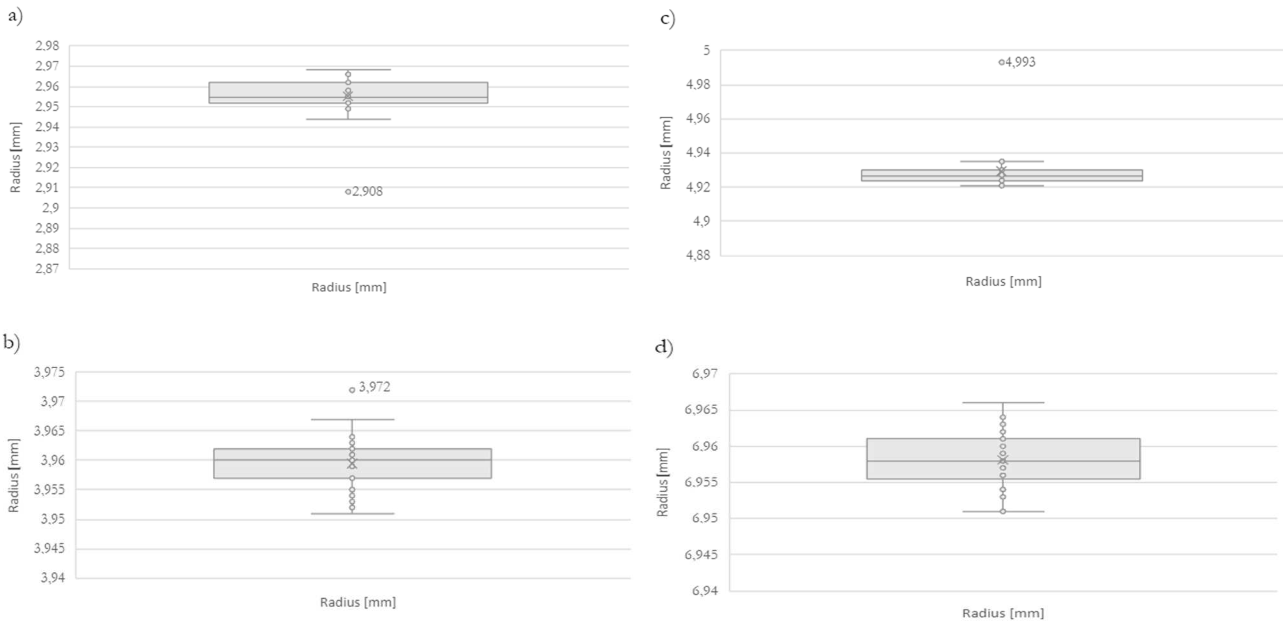

Fig. 8 *Asymmetry of distribution of nominal values of radius for cutters: a) r_1= 3mm, b) r_2= 4mm, c) r_3= 5mm, d) r_4=7mm*

Tab. 2 shows the results of the measurement uncertainty budget for the tools with a variable nominal radius. It can be observed that the component associated with pressure has the largest share with a rectangular distribution. On the other hand, the component related to tool probe resolution has the smallest share in the uncertainty budget.

Tab. 3 shows the results of $u_A(r)$ and $U(r)$ for the tools with a variable nominal radius. It can be observed that for the cutters with a nominal radius of r_f = 4 mm and r_f = 7 mm, the standard uncertainty does not exceed the standard uncertainty assumed by the probe manufacturer. The standard uncertainties for the cutters with r_f = 3 mm and r_f = 5 mm are above 1.5 μm, thus exceeding the standard uncertainty of the probe assumed by the manufacturer. When taking the expanded uncertainties into account, the range of the nominal radius values of the cutter becomes larger (more extensive).

Tab. 4 shows the results of the Grubbs test for tools with variable nominal radius. It is noted that for a cutter with r_f = 3 mm G_1 (outliner) is an observation whose value differed significantly from the other values. For the cutters with r_f = 4, 5 mm, the G_n values are outliners. On the other hand, for a cutter with r_f =7 mm, the values of G_1 and G_n were within the specified range. For the cutters with r_f = 3 - 5 mm, the null hypothesis H_0 was rejected, while for the cutter with r_f =7 mm there were no grounds to reject the null hypothesis. Exceeding the critical value means that the outliners were burdened with a gross error and therefore, they were rejected in the statistical analysis.

Verification the symmetry of the measured radius values distributions for each tool showed that the distribution of the results for the cutter with r_f = 3 mm is left-sided asymmetry. The distributions of the results for the cutters with r_f = 4, 5 mm are right-sided asymmetry. Whereas the distribution of the results for the cutter with r_f = 7 mm most resembles a normal distribution, which means that a significant part of the observations was concentrated around the mean.

Tab. 5 shows the results of the Durbin-Watson test for tools with variable nominal radius. It is noted that the measurement uncertainty values correlate positively. This means that each uncertainty value is correlated with the value preceding it. A positive measurement uncertainty correlation means that one value could be predicted from another based on the data.

To sum up, the difference between the uncertainty assumed by the manufacturer of the probe and the highest standard uncertainty is 0.81 μm. This means that the uncertainty range exceeds the probe uncertainty assumed by the manufacturer and that this difference may affect the tolerance of the shaped contour. The measurement results also demonstrate that the standard uncertainty of type A for the cutters with r_f = 3 mm and r_f = 5 mm is 2-3 times greater than the measurement uncertainty for the cutters with r_f = 4 mm and r_f = 7 mm. The combined measurement uncertainty for the tools with r_f = 3 mm and r_f = 5 mm is more than 2 times greater than the combined uncertainty for the cutters with r_f = 4 mm and r_f = 7 mm. Thus, the main causes of the results scatter may be pressure, ambient temperature and probe resolution.

4 Conclusions

The results of this study lead to the following conclusions:

- an increase in the tool nominal radius affected the measurement uncertainty. For the tools with r_f = 3 mm and r_f = 5 mm, an increase in the standard uncertainty value was observed;
- for the tools with r_f = 4 mm and r_f =7 mm, the standard uncertainties did not exceed the uncertainty assumed by the probe manufacturer;
- the statistical analysis showed that for all cases, a change in the radius value affected the uncertainties $u_A(r)$ and $U(r)$. The differences in the uncertainty values depended on the tool used and were clearly observed after tool change;
- the statistical analysis results confirmed that the significant differences in the measurement uncertainty were related to the changes in the nominal radius of the tool. For the milling cutter with r_f = 3 mm and r_f = 5 mm, the measurement uncertainty increase had a negative effect on the tolerance field for the shaped contour. The exceeding of the dimension and shape tolerance limit caused a deterioration in the dimensional and shape accuracy of the workpiece;
- the study concerned a wider area of measurement uncertainty evaluation. Six components of the uncertainty budget were taken into account in this study, which made it possible to provide a detailed description of the inaccuracies that might occur when shaping a given contour.

In laboratory practice, it might be most useful to determine the measurement uncertainty by analysing all possible factors that may be the sources of manufacturing errors. It should be emphasized that the more accurate the analysis of the uncertainty budget of measurements conducted on CNC machine tools is, the more precisely the error occurring during contour shaping is detected. Thus, the dimensional and shape accuracy of a given detail depends on the correct evaluation of tool dimension measurement during machining. The results of this study can be valuable owing to the numerous applications for the tool probe in an industrial environment. As far as machining tool radius compensation is concerned, it is important to use a measuring system that will enable an accurate assessment of tool dimensions. Therefore, the results of this study may be applied in both industrial and production practice.

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