MM Science Journal | www.mmscience.eu
ISSN 1803-1269 (Print) | ISSN 1805-0476 (On-line)
Special Issue | VRBA100
International Conference on Modern Manufacturing Technologies
4. 10. 2023, Ostrava, Czech Republic
DOI: 10.17973/MMSJ.2024_02_2023142

VRBA2024-00006

PROBLEMS OF MEASUREMENTS OF ROUNDNESS DEVIATIONS WITH THE USE OF COORDINATE MEASURING MACHINES

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Abstract

This work deals with the problem the measuring of form deviations of rotating parts with the use of coordinate measuring machines equipped with a scanning probehead. The authors investigated the influence of the measurement speed and the number of sampling points on the results of the roundness deviation assessment. The experiments were carried out on a Prismo Navigator coordinate measuring machine (Zeiss) equipped with a VAST GOLD XXL head for a scanning speed range of 10 to 60 mm/s and for three different values of sampling points on the roundness profile. The results were compared with reference values obtained from the Taylor Hobson Talyrond 365 instrument. The measurements results were compared both quantitatively (by means of roundness parameter compliance analysis) and qualitatively (by visual analysis of profiles obtained at different scanning speeds). The research showed that the scanning speed can significantly affect the result of the roundness deviation measurement with the use of CMMs.

Keywords

Form deviation, Measurement strategy, CMM, Scanning speed

1 INTRODUCTION

One of the basic challenges of the manufacturing sector is to constantly increase the quality of products while simultaneously reducing the production costs to a minimum. Quality control may involve inspecting, measuring, and/or testing products to ensure that they meet quality standards, for example, that they are within the desired dimensional tolerances [Adamczak 2015], [Jermak 2016]. Form deviations also need to be taken into account when assessing the accuracy of a product. The presence of form errors may lead to a variety of unfavourable conditions; they cause assembly problems or reducing the fatigue strength of other products. Thus, it is vital that state-of-the-art measuring instruments be applied and that they should be accurate, efficient, easy to operate, and versatile, i.e., applicable to various industrial conditions [Żórawski 2015], [Kundera 2014].

One of the most universal measuring techniques in the contemporary industry is a coordinate measuring technique. When measuring the deviations of the form with the use of a coordinate measuring machine (CMM), users can apply various measurement strategies. The measurement strategy is the term related to a scanning trajectory, that is, the path along which the probe moves on the surface of the workpiece. Another factor that is crucial for measuring form deviations is the number of probing points, which should be strictly defined by the user before the measurement [Poniatowska 2009]. Contemporary coordinate measuring machines also offer high scanning speed, which denotes the speed of the probe moving on the surface of the workpiece. The scanning speed can reach even a few hundred millimetres per second. Another parameter that is vital for a correct evaluation of form errors is the selection of a reference feature. The reference feature is a mathematically ideal feature calculated from the measurement data according to a preselected method (for example, minimum zone or least squares method).

Thus, it is vital to answer the question of how the selection of the measurement strategy and the measurement parameters affects the results of the measurement of form errors. This problem has been studied by several researchers. For example, the authors of work [Weckenmann 1998] deal with the problem of an influence of a number of probing points on the uncertainty of measurements of form errors with the use of CMMs.

Another problem investigated in the literature is the development of new measuring strategies that would allow obtaining reliable results of form deviations by applying as low a number of probing points as possible [Ascione 2013].

In industry, strategies are applied that assure the probing surface with a uniform distribution of the density of sampling points. However, research activities are conducted to develop concepts of nonuniform sampling strategies. In general, the concepts that are under study can be divided into two groups. To the first group belong strategies defined on the basis of the presumed model of irregularities of the surface, which was described, for example, in the works [Capello 2001] and [Summerhays 2001]. The second group comprises the so-called adaptive strategies that are usually based on Krige model [Pedone, 2009].

Another area of research activity focused on the problem of measurement of form deviations is the calculation of reference features. Most of the published papers in this field concern minimum zone reference features, as such features are usually more practical when taking into account technological aspects of manufacturing than the least-squares reference features. One of the methods that are applied to determine the minimum zone reference features are computational geometric techniques, which were described in the work [Samuel 2002]. Apart from that, the so-called particle swarm optimisation [Wen 2010] and genetic algorithms are applied to calculate the parameters of the features of the minimum zone.

Evaluation of surface irregularities can also be also conducted with the use of wavelet transform and wavelet pockets [Gowacz 2014, Głowacz 2016, Wang 2017]. In particular, methods based on wavelets are suiTab. to detect local surface defects, surface cracks, etc.

In industry, it is essential to minimise the roundness errors of cylindrical surfaces, especially in elements that will perform a rotary or linear motion. It is obvious that form errors may cause noise and vibration of machine parts. In industrial practice, two approaches are basically used to measure roundness: the radius change method and the V-block method [Adamczak 2010]. As the accuracy of coordinate measuring machines is increasingly higher, they are employed also to measure form deviations, including out-of-roundness and out-of-cylindricity [Stępień 2014]. Today's CMMs, designed for specialist measurement, are equipped with active or passive scanning probes. In the case of CMMs fitted with touch-trigger probes, the measurement time is too long, and the selection of an optimal number of data points is difficult because the number of data points affects the roundness profile results. The use of scanning probes improves the accuracy of measurement of form errors on CMMs. The authors of the work [Gąska 2017] present the method of enhancing the accuracy of the CMM measurement using a virtual model of the machine. When applying a contact sensor, it is noteworthy that the measuring tip may act as a mechanical filter [Lou 2019]. The analysis of factors that affect the measurement accuracy of CMMs should also include the effect of temperature variations, which is described in the work [Mussatayev 2020, Strbac 2020].

An analysis of the state-of-the-art on measurements of form deviations of rotary workpieces shows that the problem of an influence of the scanning speed on the measurement results has not been studied carefully so far. This is the reason the authors have conducted a series of experiments aiming at establishing how the value of the scanning speed affects the results of roundness measurements.

2 EXPERIMENTAL SETUP

The purpose of the study was to assess how the roundness measurement results were affected by two of the basic parameters preset on the coordinate measuring machine: the number of data points on the circle and the scanning speed. Measurements were carried out to assess the roundness of a bearing ring with a diameter of 111.76 mm by means of a Carl Zeiss PRISMO Navigator coordinate measuring machine with measurement ranges being X=900 mm, Y=1200 mm and Z=700 mm (see Fig. 1).

Fig. 1: Coordinate measuring machine Prismo Navigator by Zeiss.

The workpiece under analysis had an n-lobing type form deviation. Measurements were carried out at different scanning speeds (V = 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and 60 mm/s) and for a different number of data points, i.e., 512, 1024 and 2048. The least square circle was used as the reference feature to determine the roundness error. The experiments were conducted applying two ways of probing: by perpendicular probing and by tangential one. The basis of the results of the analysis of the experiment was the values of a roundness parameter, denoted as RONt, which is called the total roundness deviation.

The numbers of sampling points used in the experiment correspond to typical values requested by industrial customers of the laboratory where the experiment occurred.

The scanning speed given in Tab. 2 were selected on the basis of preliminary studies carried out by the authors. Although an application of scanning speeds at the level 100 mm/s is technically possible, in practice such a high value does not allow us to obtain reliable results of measurements of form deviations. The probable reason for this fact is the loss of contact of the tip and the surface when the scanning speed exceeds its critical value. The results of the preliminary study show that applying a scanning speed higher than 60 mm/s provides doubtful results of measurements of out-of-roundness.

The reference value of the RONt roundness deviation of the workpiece was determined with a radius change instrument (Taylor Hobson Talyrond 365). Roundness measurement with the Talyrond 365 was carried out at a speed of 6 rev/min in a measurement range of 0.41 mm using a Gaussian filter with a cutoff frequency of 1-50 undulations per revolution (upr). The sensor resolution for this measurement range was 6.3 nm. Clearly, the measurement was preceded by automatic centering of the workpiece. Tab. 1 shows the basic parameters of the instruments used in the experiment.

Tab. 1: Basic parameters of the experimental setup.

Machine type	Measurement range	Max. permissible error /Spindle error	Measuring head
PRISMO Navigator	X=900 mm; Y=1200 mm; Z=700 mm	Maximum permissible error: 0.9 + L/350 µm	Stylus length 100 mm, stylus tip diameter 8 mm
Talyrond 365	max. workpiece diameter: 400 mm, max. workpiece height: 300 mm	spindle error: +/-(0.02µm+ 0.0003µm/mm)	Stylus length 100mm, stylus tip diameter: 2 mm

3 RESULTS

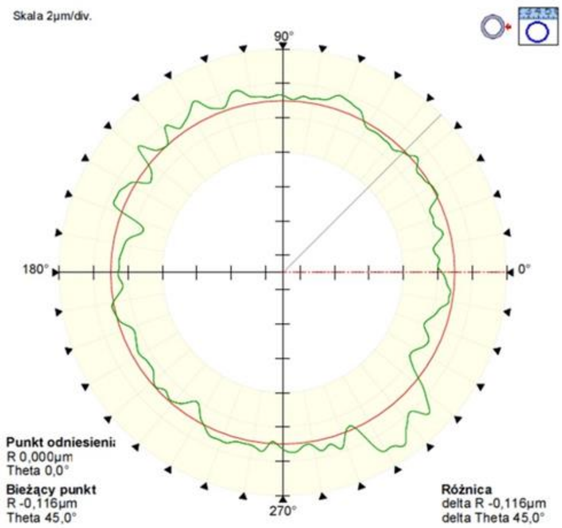
The first stage of the experiment was to measure the element with the use of Talyrond 365, which is a special-purpose instrument for highly accurate measurements of roundness and cylindricity. Fig. 2 shows the protocol for this measurement.

The value of the total roundness deviation RONt equal to 3,81 µm, measured by the Talyrond 365 was regarded as a reference value in further experiments.

The next stage of the research work was to perform a series of measurements of the element applying various values of scanning speeds and various values of probing points on the circle. Measurements were carried out with the use of so-called perpendicular probing.

Tab. 2 shows the roundness measurement results registered with a PRISMO navigator coordinate measuring machine for a different number of data points and at different scanning speeds.

a)



b)

Okrągłość		
ula11 - 1		
RON/Okrag LS/Gaussa/1-50 upr		
2014-09-20 15:44:37		
ula11		
360°/PS/TR365		
2014-09-20 15:43:50		
Specyfikacja		
Typ odsyłacza		Okrag LS
Typ filtra		Gaussa
Zakres filtra	1-50 upr	
Baza odniesienia		Wrzeciono
Parametry		
RONp	2.29	µm
Poz. RONp	304° 54' 0.0"	
RONv	1.52	µm
Poz. RONv	163° 18' 0.0"	
RONt	3.81	µm
Bicie	5.63	µm
Profile dolaczone	100.0	%
Nw	0.99	µm
Promień	55.8854	mm
Warunki		
Położenie Z	17.813	mm
Położenie R	55.887	mm
Ustawienie		Pionowy
Kierunek kontaktu		Ujemna oś R
Predkość kontaktowa	2.5	mm/s

Fig. 2: Protocol for the measurement of the part with the use of a reference instrument (Talyrond 365): a) profile, b) numerical values of selected roundness parameters.

Tab. 2: Roundness measurement results.

Roundness [µm]											
	Speed [mm/s]										
No. of data points	10	15	20	25	30	35	40	45	50	55	60
512	2,5	2,5	2,7	3	3,3	3,5	3,7	3,9	4	4,1	4,4
1024	2,5	2,5	2,7	3	3,3	3,5	3,7	3,9	4	4	4,4
2048	2,4	2,5	2,7	3	3,3	3,5	3,7	3,9	4	4	4,4

It is easy to notice that we have obtained practically the same results of the roundness deviation for all three values of probing points on the circle.

The diagram in Fig. 3 shows the relationship between the scanning speed and the measured value of roundness deviation for 2048 probing points on the circle. The diagrams for 512 and 1024 probing points are not presented in this paper, as they are practically the same as the diagram shown in Fig. 3.

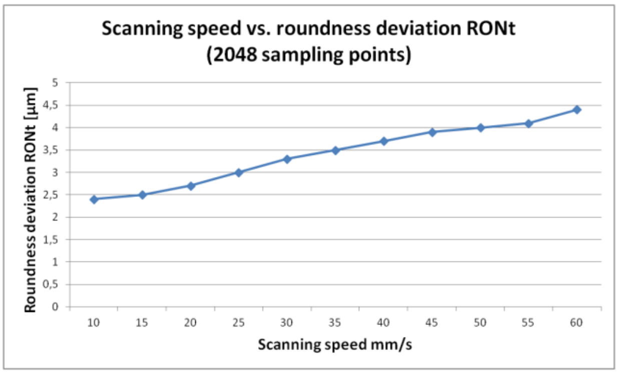


Fig. 3: Relationship between the scanning speed and obtained values of roundness deviation RONt for 2048 sampling points.

The diagrams in Fig. 4 show roundness profiles obtained from 1024 data points measured at 10 mm/s, b), 25 mm/s, c), 40 mm/s, d), and 60 mm/s with the use of perpendicular probing.

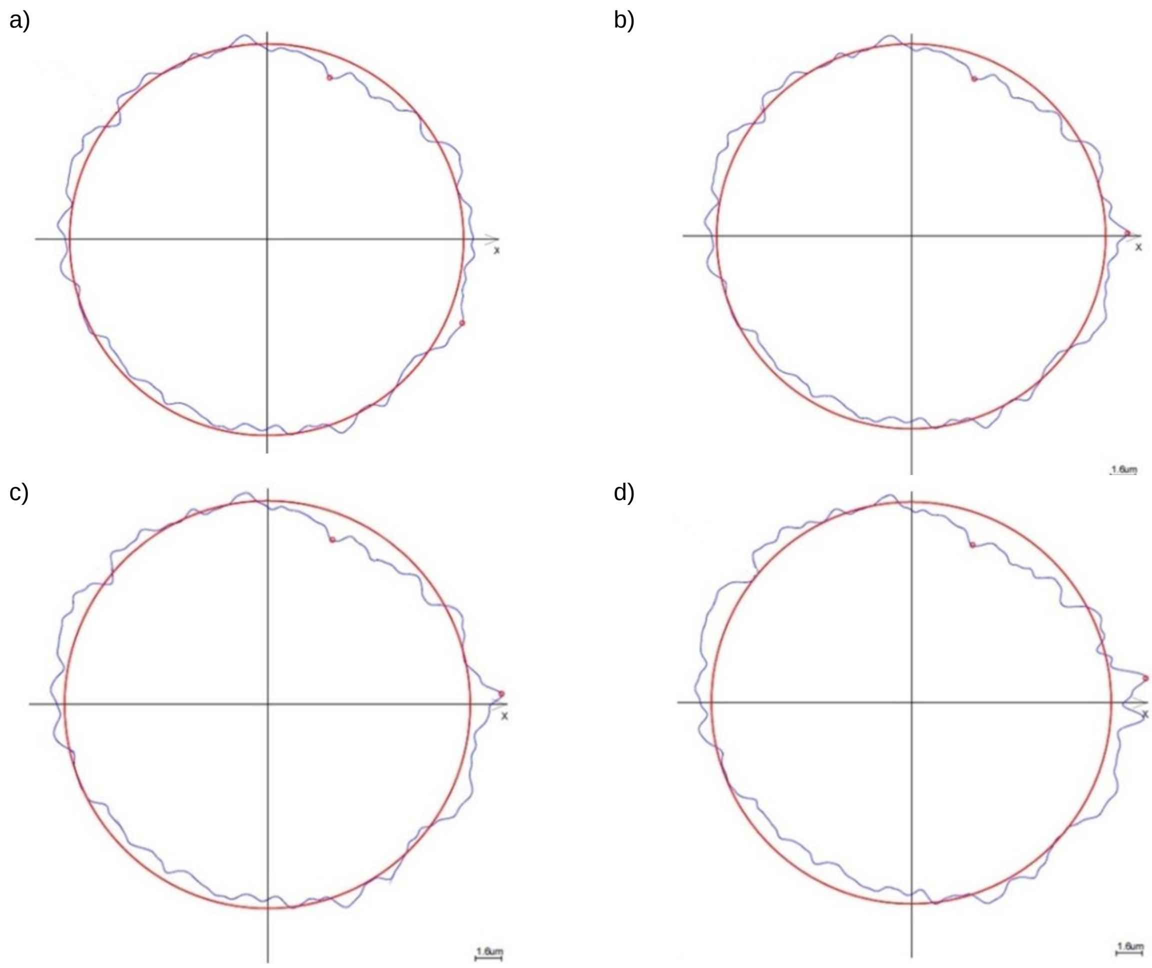


Fig. 4: Roundness profiles obtained from 1024 data points measured at 10 mm/s, b), 25 mm/s, c), 40 mm/s, d), and 60 mm/s with the use of perpendicular probing.

Another part of the experiment were measurements of the roundness profiles of the workpiece by application of so-called tangential probing. Diagrams in Fig. 5 show roundness profiles obtained from 1024 data points measured at 10 mm/s, b), 25 mm/s, c), 40 mm/s, d), 60 mm/s with the use of tangential probing.

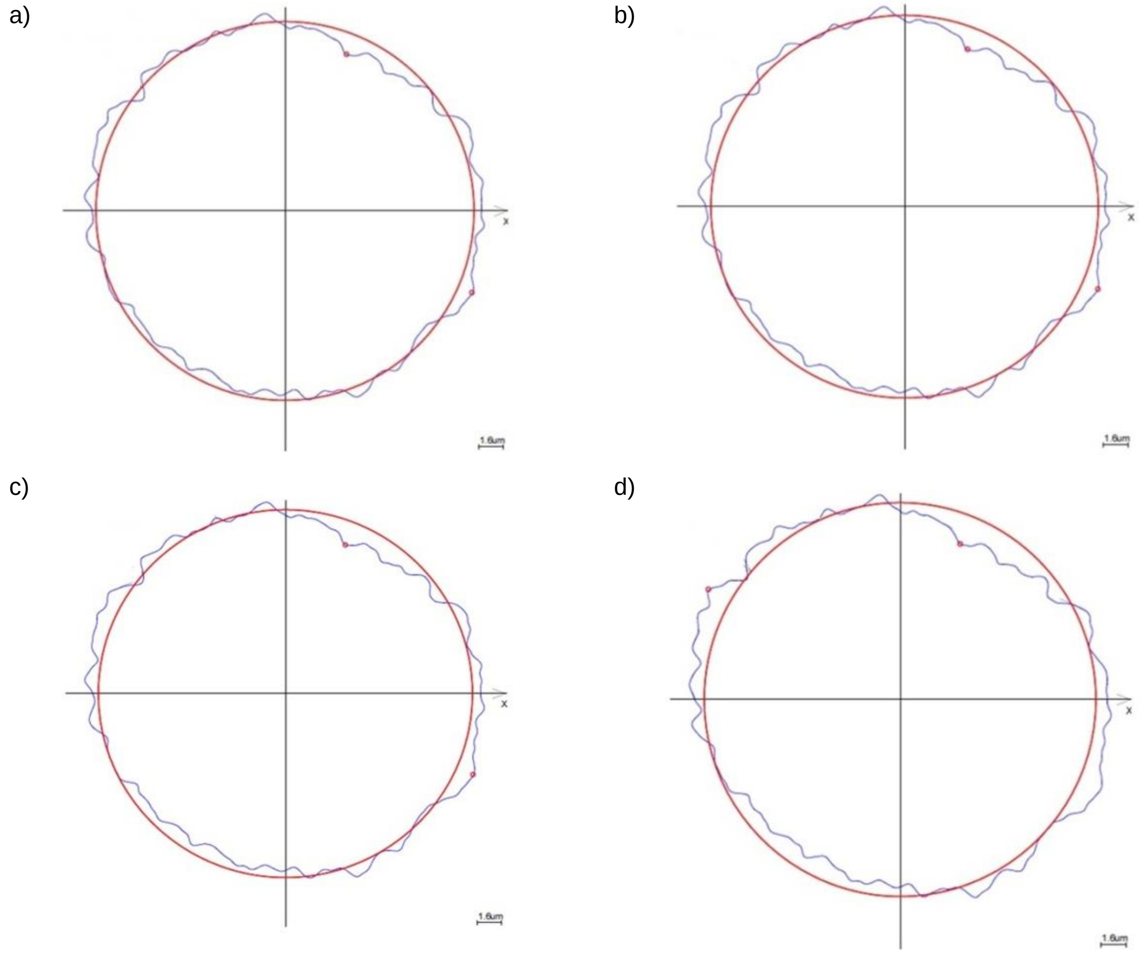


Fig. 5: Roundness profiles obtained from 1024 data points measured at 10 mm/s, b), 25 mm/s, c), 40 mm/s, d), and 60 mm/s with the use of tangential probing.

The diagram in Fig. 6 was presented to illustrate how the probe head movement and the scanning speed affect the roundness measurement results.

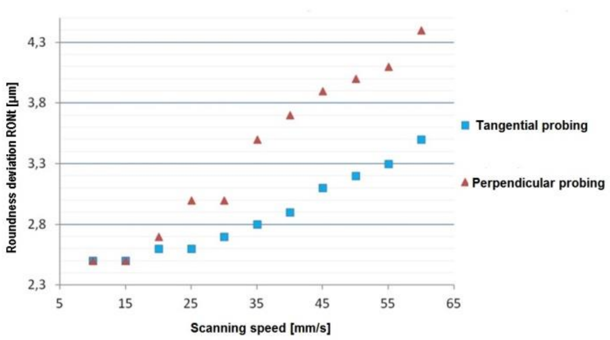


Fig. 6: Roundness deviation RONt versus scanning speed for tangential and perpendicular probing.

4 DISCUSSION

The experimental results given in Tab. 1 show that, for the case considered, the number of data points had no effect on the roundness measurement results obtained with a coordinate measuring machine. It should be noted that the number of data points analysed in this study was relatively large, with the lowest being 512. It can be concluded that, when the number of points were much smaller, the results could be different.

Analysing the diagram shown in Fig. 33, it is clear that the scanning speed can affect the measurement results of form deviations. The diagram in Fig. 3 shows that the lower the measuring speed, the lower the value of the roundness deviation, and the relationship between the scanning speed and the roundness deviation is approximately linear.

A careful analysis of the profiles presented in Fig. 4 shows that in some areas of the workpiece, the signal values differ significantly. Let us analyse the fragments of the profiles magnified, which are shown in Fig. 7.

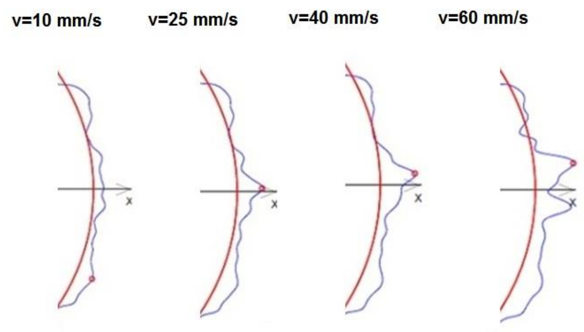


Fig. 7: Selected fragments of profiles obtained at different scanning speeds measured with the use of perpendicular probing.

It is easy to notice the difference between the profiles obtained at different scanning speeds for the case of perpendicular probing.

Similar analysis of the profiles obtained with the use of tangential probing shows that, for the case of tangential probing, the differences between profile values are much smaller. It is illustrated by the diagrams given in Fig. 8.

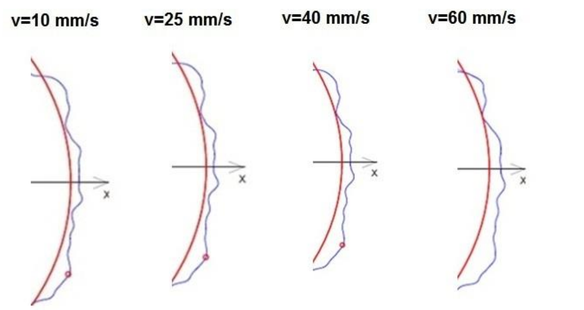


Fig. 8: Selected fragments of profiles obtained at different scanning speeds measured with the use of tangential probing.

Comparison of the diagrams shown in Figs. 7 and 8 shows that for tangential probing the profiles are generally smoother than the profiles obtained through perpendicular probing. This is the reason the values of the roundness deviation parameter RONt are generally smaller for the tangential probing, which is noticeable in Fig. 6.

The analysis of the diagram shown in Fig. 6 proves that for both tangential and perpendicular probing, the relationship between the scanning speed and the roundness deviation RONt shows an increasing tendency.

As the reference value of RONt determined by the Talyrond 365 was equal to 3,8 µm, it should be noted that an approximately similar value for CMM was obtained at scanning speed of 45 mm/s (perpendicular probing). For the case of tangential probing, the closest value to the reference was obtained at scanning speed of 60 mm/s. This is very interesting, as, according to popular opinion, the lowest values of measurement speeds ensure the most accurate results. The reason why the results obtained at low scanning speeds are not as close to the reference values as the ones obtained at higher scanning speeds is not quite clear for the authors. Perhaps such an effect comes from the difference between the diameters of the probes. The diameter of the reference instrument is 2 mm and the diameter of the probe used in the CMM was 8 mm.

5 CONCUSIONS

Coordinate measuring machines, due to their versatility and increasingly higher measurement accuracy, are commonly used to evaluate form deviations. The analysis of the state-of-the-art on this subject shows that the previously published papers do not deal thoroughly with the problem of the influence of scanning speed on the result of form deviation measurement. Therefore, the authors attempted to establish an estimate of this effect for the case of measurement of roundness deviations.

Based on the research results obtained by the authors, the following conclusions and recommendations can be formulated regarding the measurement of roundness deviations with the use of coordinate measuring machines :

- Measurement with tactile scanning heads should be used if possible. As a result, a large number of measuring points is maintained with a short measurement time at the same time.
- In the case of measurements with scanning heads, the use of tangential probing results in a smaller dispersion of results than in the case of perpendicular probing.
- The research indicated that in the analysed case, the values of the roundness deviation closest to the reference value were obtained for scanning speeds of 45 mm/s (perpendicular probing) and 60 mm/s (tangential probing).

Experiments conducted by the authors revealed that the results obtained at low scanning speeds are not as close to the reference values as the ones obtained at higher scanning speeds.

Therefore, the authors are going to conduct further research activity in the field of measurement of form deviations with the use of coordinate measuring machines. The further research will be focused on:

Therefore, the authors are going to conduct further research activity in the field of measurement of form deviations with the use of coordinate measuring machines. The further research will be focused on:

1. Measurements of roundness and cylindricity of a large number of workpieces (more than thirty). It would allow one to obtain statistical parameters describing the accuracy and uncertainty.

2. Measurements of workpieces of various diameters. We suppose that the influence of scanning speed on the measurement results of the deviations of larger and smaller elements will be different.

3. Measurements of workpieces whose surface structure is different. It would allow investigating if the dominant harmonic components of the profile can affect the measurement results.

All measurement results will be compared to the reference values. Thus, further experiments should be conducted by the probe whose diameter is equal to the diameter of the reference instrument to avoid the phenomenon of undesired mechanical filtering of the profile.

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