Practical Aspects of Roundness Measurements with the use of Coordinate Measuring Machines Equipped with Scanning Probe Heads

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Abstract

One of the most universal measuring techniques in contemporary industry is a coordinate measuring technique. This paper focuses on a problem of measurements of form deviations with the use of coordinate measuring machines (CMMs). Nowadays, such measurements are usually carried out using a scanning probe-heads. The paper discusses the problem of measurements of roundness deviations by a scanning probe-head. Authors conducted an experiment aiming at the study of the influence of the number of probing points and the scanning speed on parameters of roundness error. The results were compared to the reference values obtained from the radius change instrument for highly accurate roundness and cylindricity measurements. The paper presents the introduction to the problem, the methodology of the study, the results of the experiment, discussion and final conclusions including the plan of further research.

1. Introduction

One of the basic challenges of the manufacturing sector is to constantly increase the quality of products while simultaneously reducing 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 keep within the desired dimensional tolerances. [1, 2]. Form deviations also need to be taken into account while assessing the accuracy of a product. The presence of form errors may lead to a variety of unfavorable conditions; they cause assembly problems or reduce the fatigue strength of other products. It is thus vital that state-of-the-art measuring instruments should be applied and that they should be accurate, efficient, easy to operate and versatile, i.e. applicable to various industrial conditions [3, 4].

One of the most universal measuring techniques in contemporary industry is a coordinate measuring technique. When measuring form deviations with the use of a coordinate measuring machines (CMM) users can apply various measurement strategies. The measurement strategy is the term relating to a scanning trajectory, i.e. the path along which the probe moves on the surface of the workpiece. Another factor that is crucial for measurements of form deviations is the number of probing points, which should be strictly defined by a user before the measurement. Contemporary coordinate measuring machines offer also 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 millimeters per second. Another parameter that is vital for a correct evaluation of form errors is 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 the least squares method).

Thus, it is vital to answer the question how selection of the measurement strategy and measurement parameters affects measurement results of the form errors. This problem has been studied by a number of researchers. For example, authors of work [6] 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 development of new measuring strategies that would allow obtaining reliable results of form deviations by applying as low number of probing points as possible [7]. In industry the strategies are applied that assure probing the surface with uniform distribution of density of sampling points. However, research activities are conducted aiming at development of concepts of non-uniform 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 presumed model of irregularities of the surface, which was described, for example, in works [8] and [9]. The second group constitute so-called adaptive strategies that are usually based on Krige model [10].

Another area of research activities focused on the problem of measurements of form deviations are methods of calculation of reference features. Most of published papers in this field concern minimum zone reference features, as such features are usually more practical 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 was described in work [11]. Apart from that, so-called particle swarm optimization [12] and genetic algorithms are applied to calculate parameters of minimum zone features.

The evaluation of surface irregularities can be also conducted with the use of wavelet transform and wavelet pockets [14-16]. In particular, methods based on wavelets are suitable to detect local surface defects, surface cracks, etc.

In industry, it is extremely important to minimize 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 radial datum method and the V-block method [17]. 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 [18]. 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 roundness profile results. The use of scanning probes improves the accuracy of measurement of form errors on CMMs.

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 measurement results has not been studied carefully so far. This is the reason why authors have conducted series of experiments aiming at establishing how the value of the scanning speed affects results of roundness measurements.

2. Experimental Setup

The aim of the study was to assess how roundness measurement results were affected by two of the basic parameters preset at the coordinate measuring machine: the number of data points on the circle and the scanning speed. The measurements were conducted 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 the measurement ranges being X=900 mm, Y=1200 mm and Z=700 mm. The workpiece under analysis had an n-lobing type form deviation. The measurements were conducted 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 the tangential one. The basis of the analysis of the experiment results were values of a roundness parameter denoted as RONt, which is called a total roundness deviation.

The reference value of the roundness deviation RONt of the workpiece was determined with a radius change instrument (a Taylor Hobson Talyrond 365). The roundness measurement with the Talyrond 365 was carried out with 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. Obviously, the measurement was preceded by automatic centering of the workpiece. Table 1 shows the basic parameters of the instruments used in the experiment.

Table 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. 1 shows the protocol from this measurement.

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

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

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

Table 2. Roundness measurements 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	4,1	4,4
2048	2,4	2,5	2,7	3	3,3	3,5	3,7	3,9	4	4,1	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.

Diagram in Fig. 2 shows the relationship between the scanning speed and 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. 2.

Diagrams in Fig. 3 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 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. 4 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

The diagram in Fig. 5 was generated to illustrate how the probe-head movement and the scanning speed affect the roundness measurement results.

4. Discussion

The experimental results given in Table 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 analyzed in this study was relatively large, with the lowest being 512. It can be concluded that, when the number of points would be much smaller, the results could be different.

Analyzing the diagram shown in Fig. 2 it is clear that the scanning speed can affect the measurement results of form deviations. The diagram in Fig. 2 proves 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 profiles presented in Fig. 3 shows that in some areas of the workpiece obtained signal values differ significantly. Let us analyze the fragments of the profiles magnified, which is shown

in Fig. 6

It is easy to notice difference between 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 profiles values are much smaller. It is illustrated by diagrams given in Fig. 7.

Comparison of diagrams shown in Fig. 6 and 7 shows that for tangential probing the profiles are generally smoother than profiles obtained through perpendicular probing. This is the reason why values of roundness deviation parameter RONt is generally smaller for the tangential probing, which is noticeable in Fig. 5.

The analysis of the diagram shown in Fig. 5 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 instrument Talyrond 365 was equal to 3,8 μm, it is noteworthy that approximately similar value for CMM was obtained at scanning speed 45 mm/s (perpendicular probing). And for the case of tangential probing the closest value to the reference one was obtained at scanning speed 60 mm/s. This is very interesting, as according to popular opinion, the lowest values of measurement speeds assure most accurate results. The reason why results obtained at low scanning speeds are not as close to reference value as ones obtained at higher scanning speeds is not quite clear for authors. Perhaps, such effect comes from the difference between diameters of probes. The diameter of the probe of the reference instrument is 2 mm and the diameter of the probe used in CMM was 8 mm.

5. Conclusions

The results of the study presented in this paper show that the number of probing points did not affected measurement results. The reason is obvious – if we use a scanning probe-head then the number of probing points is usually very high. However, the experiment proved that the scanning speed can influence roundness measurements results very significantly. The relationship between the scanning speed and roundness parameter RONt shows an increasing trend and it is approximately linear. Moreover, the difference was observed for the results obtained with the use of tangential and perpendicular probing. Apart from it, it turned out that results obtained at low scanning speeds are not as close to reference value as ones obtained at higher scanning speeds.

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

1. Measurements of roundness and cylindricity of large number of workpieces (more than thirty). It would allow obtaining statistical parameters describing measurement accuracy and uncertainty**.**
2. Measurements of workpieces of various diameters. We suppose that the influence of scanning speed on measurement results of form deviations of larger and smaller elements will be different.
3. Measurements of workpieces whose surface structure is different. It would allow investigating if dominant harmonic components of the profile can affect measurement results.

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

Declarations

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Conflicts of interest/Competing interests

not applicable

Availability of data and material

All data are stored at the Laboratory of Computer-Aided Measurements of Geometrical Quantities (Kielce University of Metrology). Date can be provided to the reader on their request.

Code availability (software application or custom code) Measurement data are stored as a part of Calypso software (IGES/DXF files).

Authors' contributions

Krzysztof Stepien’s contribution: General concept of the manuscript, supervising the experiments, FInal conclusions,

Urszula Kmiecik-Sołtysiak’s contribution: conducting the experiments.

Anna Zawada-Tomkiewicz’s contribution: Analysis of the results of experiments

Uros Zuperl’s contribution: discussion of the results

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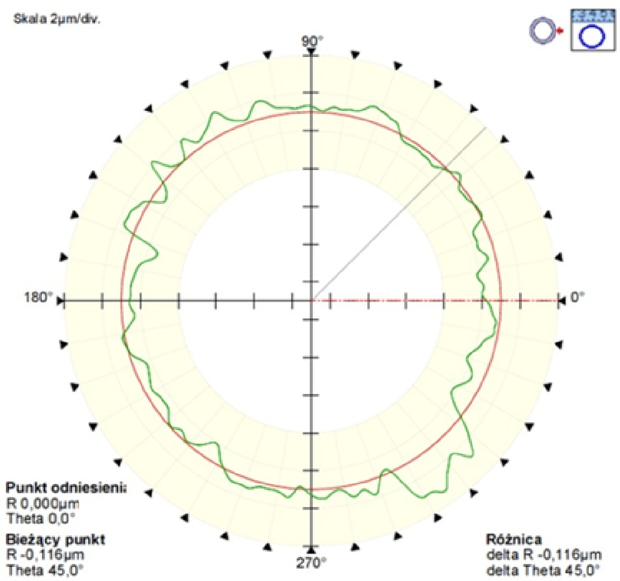
Figures

a)



b)

Okrągłość		
ula11 - 1		
RON/Okrąg LS/Gaussa/1-50 upr		
2014-09-20 15:44:37		
ula11		
360°/PS/TR365		
2014-09-20 15:43:50		
Specyfikacja		
Typ odsyłacza		Okrąg 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 dołączone	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
Prędkość kontaktowa	2.5	mm/s

Figure 1

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

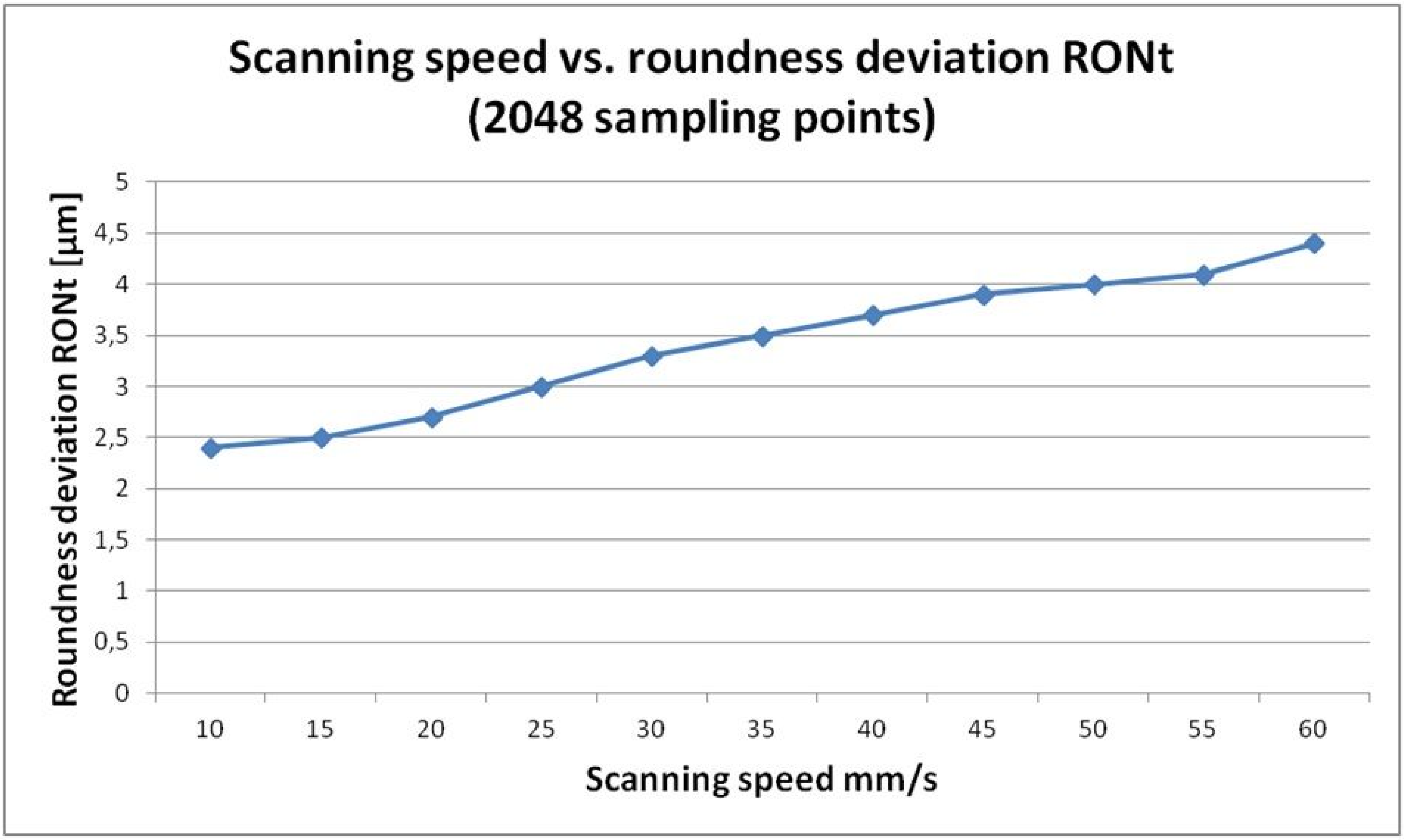


Figure 2

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

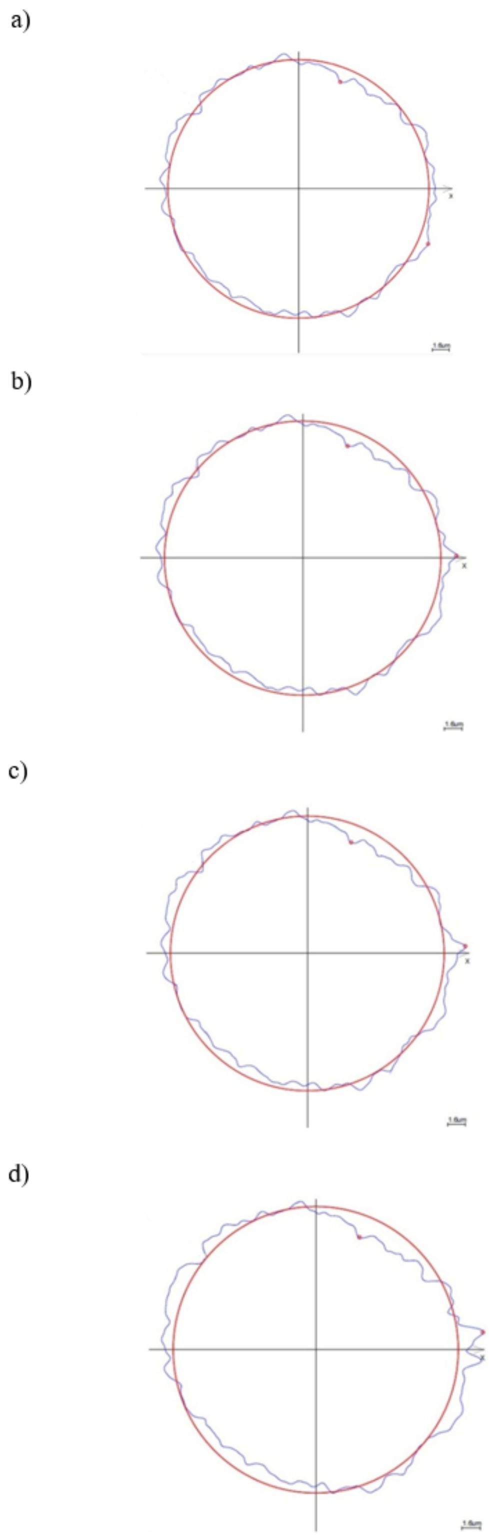


Figure 3

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 perpendicular probing.

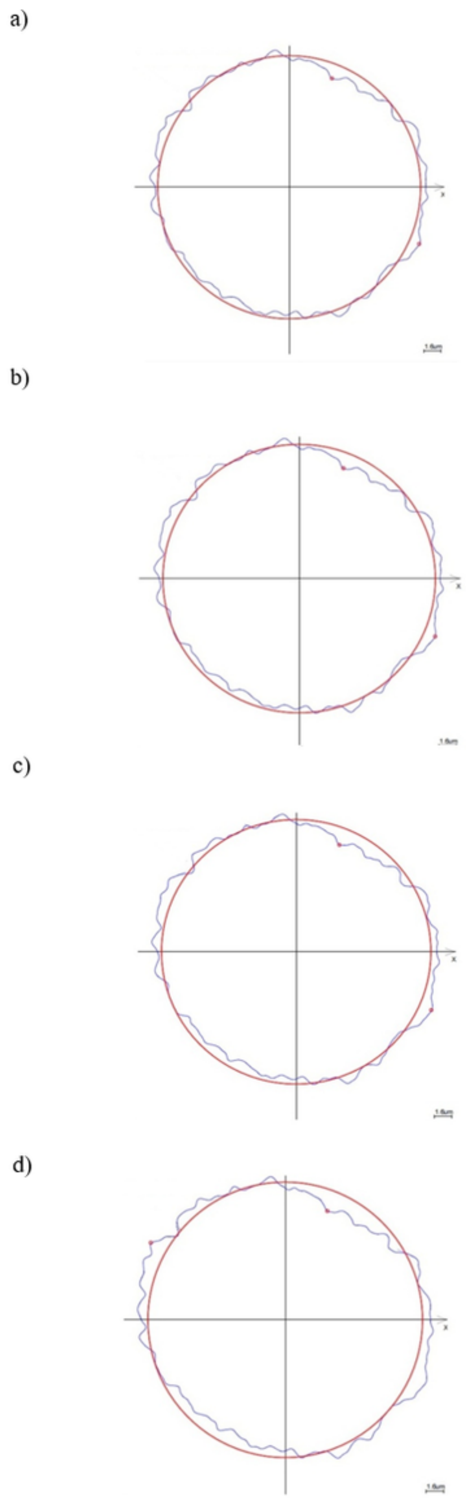


Figure 4

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.

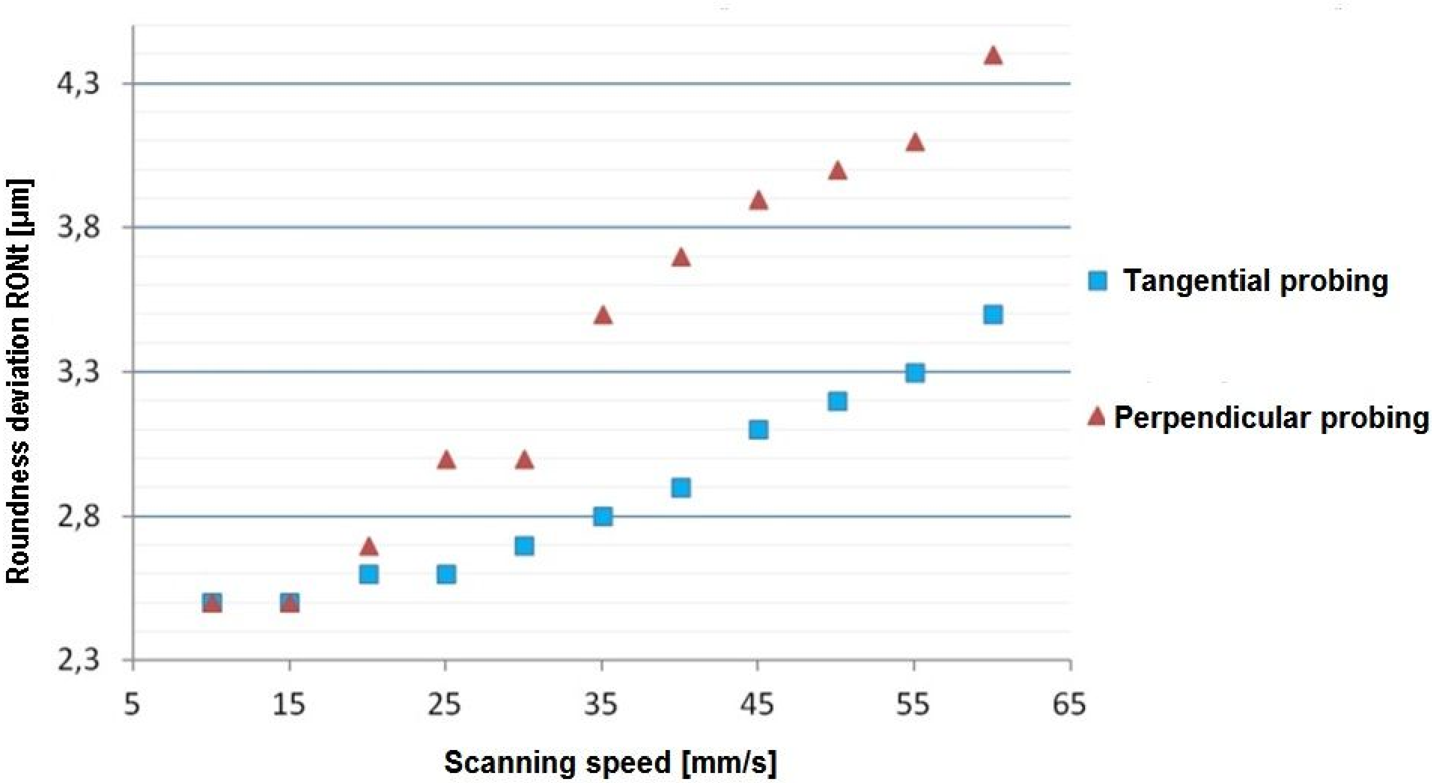


Figure 5

Roundness deviations RONt versus scanning speed for tangential and perpendicular probing.

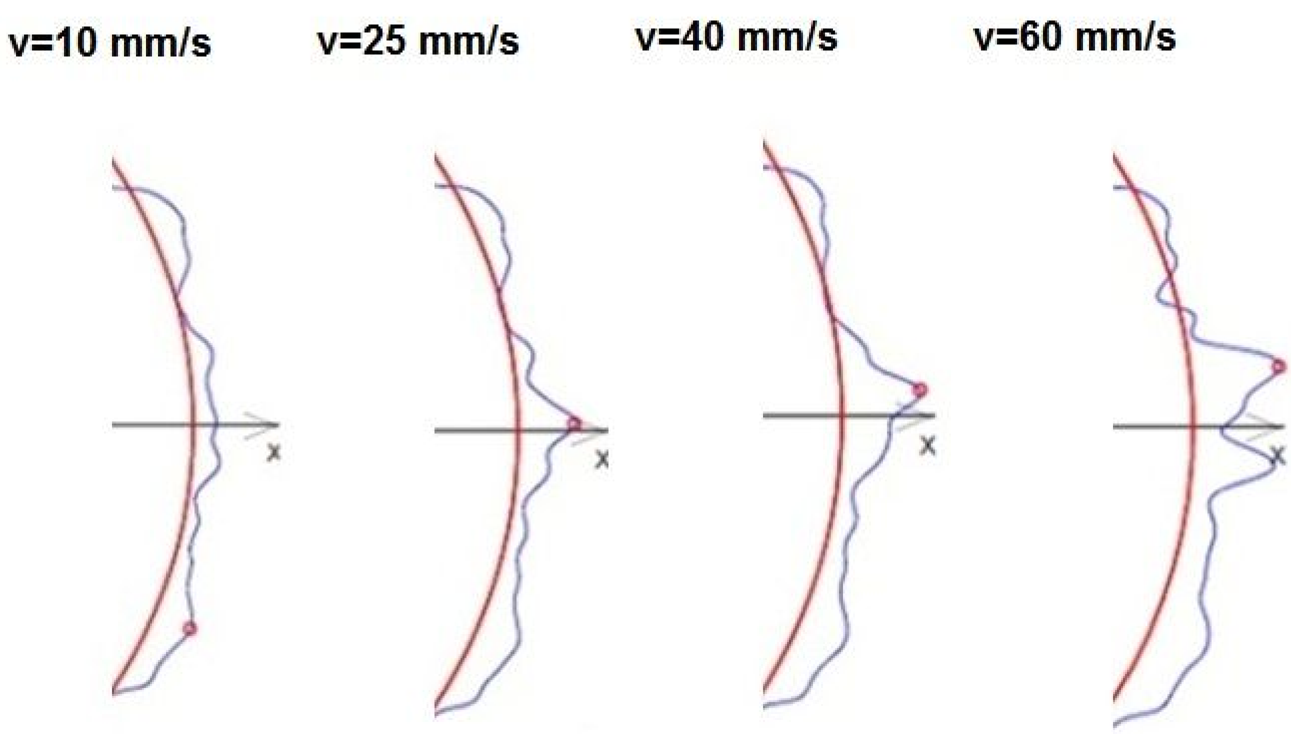


Figure 6

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

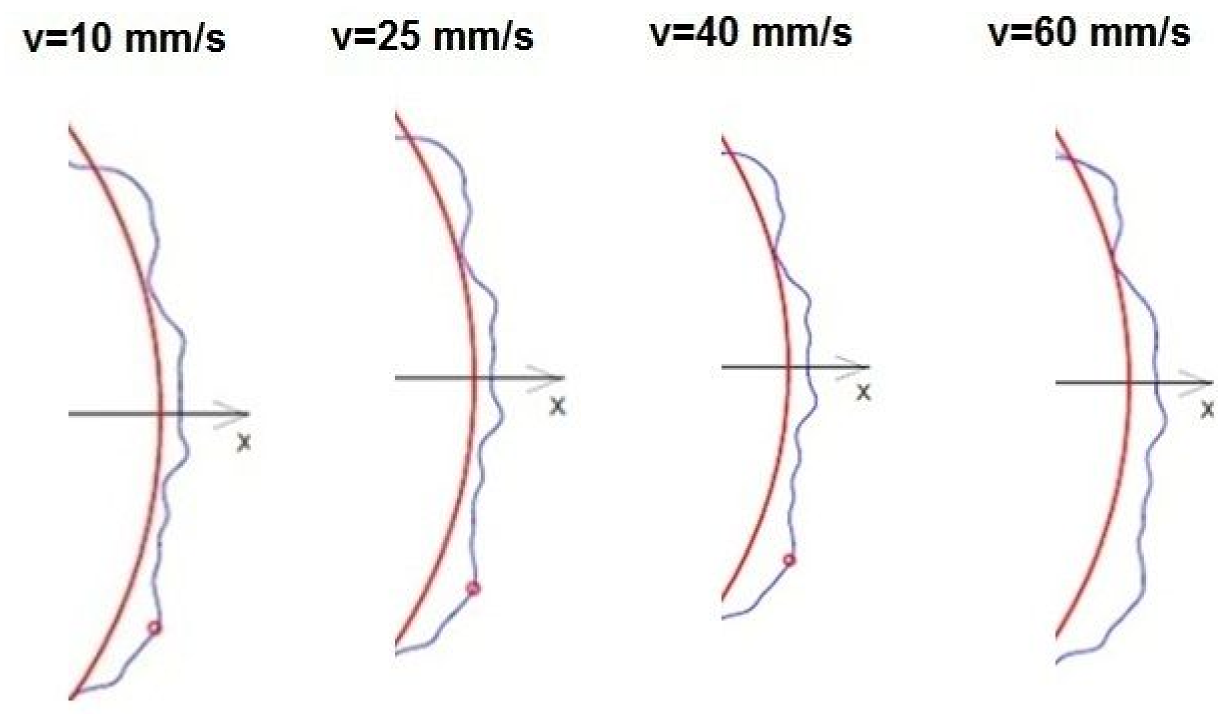


Figure 7

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