

## PARAMETERS FOR CMM CONTACT MEASUREMENTS OF FREE-FORM SURFACES

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### Abstract

Obtaining discrete data is inseparably connected with losing information on surface properties. In contact measurements, the ball tip functions as a mechanical-geometrical filter. In coordinate measurements the coordinates of the measurement points of a discrete distribution on the measured surface are obtained. Surface geometric deviations are represented by a set of local deviations, i.e. deviations of measurement points from the nominal surface (the CAD model), determined in a direction normal to this surface. The results of measurements depend both on the ball tip diameter and the grid size of measurement points. This article presents findings on the influence of the ball tip diameter and the grid size on coordinate measurement results along with the experimental results of measurement of a free-form milled surface, in order to determine its local geometric deviations. One section of the surface under research was measured using different measurement parameters. The whole surface was also scanned with different parameters, observing the rule of selecting the tip diameter  $d$  and the sampling interval  $T$  in the ratio of 2:1.

Keywords: coordinate measurements, free-form surface, geometric deviations, measurement parameters

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### 1. Introduction

Due to their complex geometry, free-form surfaces can only be designed, processed, and measured using CAD/CAM techniques and numerically controlled equipment. There has been observed an unceasing increase in requirements pertaining to accuracy of producing free surfaces, which forces improvement of measurement techniques.

For workpiece validation in manufacturing, numerically controlled coordinate measurement machines (CMMs) equipped with a ball-end touch trigger or scanning probes are mainly used. As a result of the measurement, a set of discrete data is obtained in the form of coordinates of the measurement points. The form accuracy inspection of free-form surfaces consists of digitalizing the workpiece under research, followed by comparing the obtained coordinates of the measurement points with the CAD design (model). Software of CMMs automatically performs calculation of the values of local geometric deviations (or normal deviations of measurement points from the nominal surface) in the  $UV$  scanning option designed for scanning on the basis of the CAD model ( $UV$  – directions of the B-spline surface parameterization). The local geometric deviation with the greatest absolute value needs to be determined and then the doubled value of the deviation has to be compared with the specification [1].

Measurements of real surfaces produce only their approximate views. The approximation degree depends on the accuracy of the applied measuring method. Among numerous factors which have an influence on accuracy, connected with the tool instrument and the measurement environment, there are factors which can be rationally adjusted – such measurement parameters as the sampling (discretization) interval and the diameter of the

measuring tip. Both these factors have a strictly specific impact on the measurement results [2]. Different sampling strategies (number and location of measurement points) provide different measurement results for the same surface. This is connected with the fact that measurement of a finite number of discrete points on the measured surface is actually described by an infinite number of points. Since geometric deviations are different at each point, the measurement results depend on the number and location of these points [3, 4, 5]. Planning an effective strategy for a coordinate measurement requires making decisions on selecting the sampling area as well as the number and location of measurement points. These factors are decisive for the measurement results. In order to verify whether the observed surface profile lies within the tolerance zone, it is important to choose a sampling strategy which would ensure the greatest probability of locating the maximum deviation at the smallest number of points. If the purpose of measurement is exact diagnostics of surfaces, and thus of the course of processing, then the lengths of irregularities which are to represent measurement data, need to be taken into consideration while planning the measurement. If this is the case, then measurements should be taken along a regular grid of points. In the majority of cases measurements of free-form surfaces are carried out along a regular  $u \times v$  grid with the use of the *UV* scanning option, which is inbuilt in the CMM software. Obtaining data of a discrete character is inseparably connected with losing information on the surface properties. In contact measurements, the ball tip functions as a mechanical-geometrical filter [2, 6]. The scope of information included in measurement data depends on the ball tip diameter. Therefore, results of coordinate measurements of geometric deviations of free-form surfaces depend on three factors – the active area, the grid size and the diameter of the ball tip end.

Surface geometric deviations connected with irregularities can be decomposed into three components: form deviations, waviness and roughness, and they differ from each other with respect to the lengths of their respective basic irregularities [2, 6, 7, 8]. In measuring geometric surface textures of primitive shapes, for the particular types of deviations, guidelines for selecting measurement parameters including the tip radius, sampling lengths and assessment lengths, the sampling interval (the number of measurement points), as well as rules of digital roughness filtration have been developed and incorporated in standards. In standards pertaining to measuring straightness and roundness, the recommended maximum tip radii were worked out according to the principle stating that the tip radius is comparable to the boundary wavelength (the filter passing limit), while the distance between measurement points was established according to the principle holding that the number of measurement points in a segment whose length is equal to that of the boundary wavelength, amounts to 7 [2]. However, there are no strict standards which would unambiguously determine what boundary length of the elementary (harmonic) wave should be adopted for waviness/form deviations, what the sampling interval should amount to, or which tip radius should be used in a specific measurement. No unambiguous criteria exist as to categorizing deviations as waviness or form deviations.

In selecting sampling parameters for coordinate measurement of form deviations of free-form surfaces, results of many years of research pertaining to measuring roughness of regular surfaces which include analyses of the influence of tip geometry and radius on measurement results can be applied. The authors of articles [9, 10] showed that increasing the tip size leads to profile deformation, and in effect to decreasing values of the height parameters. Many problems are also connected with selecting the sampling interval. If it is too small, excess data are available, data are strongly correlated, and the surface is represented by a vast number of measurement points. If, on the other hand, the sampling interval is too big, information on the surface properties is lost (the phenomenon of aliasing occurs). It is suggested that selecting the sampling interval should be made according to the tip radius size [11, 12]. The boundary

length of the measured roughness depends on which parameter, the tip size or the sampling interval, is greater [6, 12]. In measuring form deviations, measurement parameters are not as significant as in measuring surface roughness, although their influence on the measurement results cannot be neglected, as shown by experimental results in Section 3.

## 2. Sampling parameters selection

In contact measurements, significant information on irregularities is lost when the ball tip touches the measured surface. The scope of information on the surface under consideration in the obtained data depends on measurement parameters such as the ball tip diameter and sampling interval, as they cause mechanical-geometric filtration of irregularities. The sampling parameters listed above determine the least boundary length of elementary irregularities represented in measurement data. The parameter which has a decisive influence is the one which causes a longer wave to be passed. Literature sources suggest different principles of selecting the appropriate tip radius in relation to the sampling interval, most often in the ratios of 1/2:1, 1:1 and 2:1 [2, 6, 11].

In coordinate measurements, ball-tip styluses are mainly used, styluses with ball tips of diameters ranging from 0.3 to 8 mm are available. When planning a measurement, the ball tip diameter  $d$  should be chosen in the first place for practical reasons, considering the purpose of the measurement and thus the scope of information which the measurement data are to represent. The nature of a ball tip functioning in the character of a mechanical-geometrical filter is illustrated in Fig. 1.

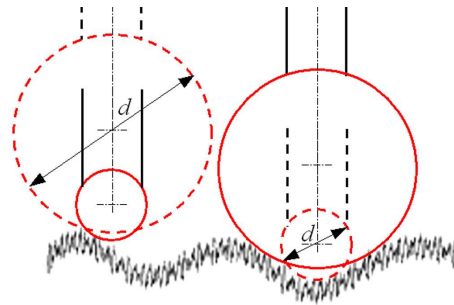


Fig. 1. The nature of a ball tip functioning in the character of a mechanical-geometrical filter

Defining the influence of the ball tip diameter/radius as a mechanical filter, i.e. unambiguously determining the filtration boundary, is difficult, especially in the case of changing-curvature surfaces. Adopting to measurement the principle suggested in the literature sources pertaining to measuring roundness deviations [2], which states that the boundary wave length is comparable to the tip radius value, means that in the case of using a stylus tip of  $d = 1$  mm in diameter, irregularities of the length values greater than 0,5 mm are passed; in the case of the stylus tip of  $d = 2$  mm in diameter, irregularities of the length values greater than 1 mm are passed, etc.

Coordinate measurements of free-form surfaces are usually carried out along a regular grid of points. The size of this grid should be adjusted to the selected ball tip according to the rules used in tests on measurement signals derived from the Nyquist theory. The theorem connected with this theory states that in order to obtain an accurate representation of a continuous signal, the  $f_p$  sampling frequency which is defined as the reciprocal of the  $T$  sampling interval  $f_p = \frac{1}{T}$ , needs to be at least twice as high as the spectrum limit frequency [13]. Knowledge of the mentioned principle makes it easier to make decisions on the length of the sampling interval while planning coordinate measurement strategies. According to the theorem quoted

above, adopting the interval value of 1 mm means that the obtained measurement data contain information of elementary surface irregularities of more than 2 mm in length.

Adopting the principles cited in the literature [6, 12] regarding selecting parameters of contact measurement at the same time,  $d:T$  equal to 2:1, choosing a ball of e.g. 2 mm in diameter, and the 1 mm sampling interval, the boundary length of elementary irregularities represented in measurement data amounts to 2 mm.

Since there is no unambiguous criterion for categorizing irregularities such as waviness or form deviations, while presenting measurement results, it is difficult to specify what these results represent. In deciding on the ball tip diameter and the size of the measurement grid, it is advisable to focus on the purpose of measurement and to include detailed information concerning the measurement parameters in measurement reports. In measuring free-form surfaces characterized by different curvatures at each of the points, the cut-off value of irregularities filtration cannot be determined nor can the results be generalized. The research was performed in order to obtain quantitative information concerning the influence of measurement parameters on passing information about geometry of the surfaces on which tests on the method of decomposing the components of geometric deviations, which was described in [14], were carried out.

### 3. Experimental investigations

The experiments were performed on a free-form surface of a workpiece made of aluminium alloy with the base measuring  $100 \times 100$  mm, obtained in a three-stage milling process using in the last stage a ball-end mill of 6 mm in diameter, rotational speed equal to 7500 rev/min, working feed 300 mm/min and zig-zag cutting path in the  $XY$  plane. The measurements were carried out under laboratory conditions, on a Global Performance Brown&Sharpe CMM (PC-DMIS software,  $MPE_E = 1,5 + L/333 \mu\text{m}$ ), equipped with a Renishaw SM25 scanning probe, a 20 mm stylus with ball tips of 1, 2, 3 and 4 mm in diameter. At the beginning, the surface was scanned in one cross-section with the use of three different sampling intervals for one tip end size (without applying radius compensation). Subsequently, two measurement tip ends were used at the same sampling interval. In the last stage, scanning of the whole surface was performed for two different combinations of the measurement parameters, the tip end diameter, and the sampling interval (the number of measurement points), observing the rule of selecting  $d:T$  equal to 2:1. All the measurements were repeated five times; the tables and plots present mean values of the obtained results.

#### 3.1. Researching into the influence of the sampling interval

The surface was scanned in one cross-section with the use of the  $UV$  option; the section determined by  $v = 0.20$  (Fig. 2) and the tip end diameter of  $d = 2$  mm were chosen. Different numbers of measurement points for the  $u$  direction were adopted – 100, 50, and 20 points. The sampling intervals amounted therefore to  $T = 0.01u$ ,  $0.02u$ , and  $0.05u$  respectively. Curves illustrating the observed profiles (Fig. 3) were then built on the obtained local geometric deviations. To show the significance of result differences for various measurement parameters, on one curve ( $P = 0.95$ ) confidence intervals are marked. For the other curves, confidence intervals are similar to those presented, which can be concluded from Tab. 1.

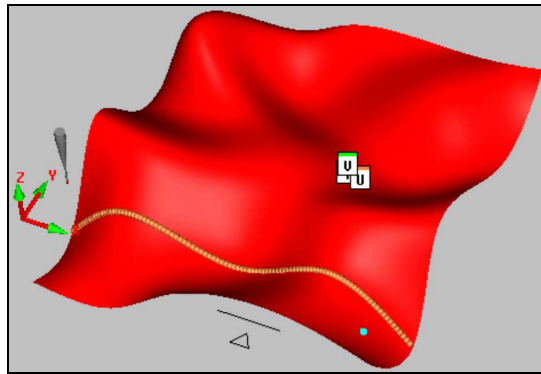


Fig. 2. The location of the scanned section on the CAD model ( $U, V$  – directions of the surface parameterization, PC DMIS software)

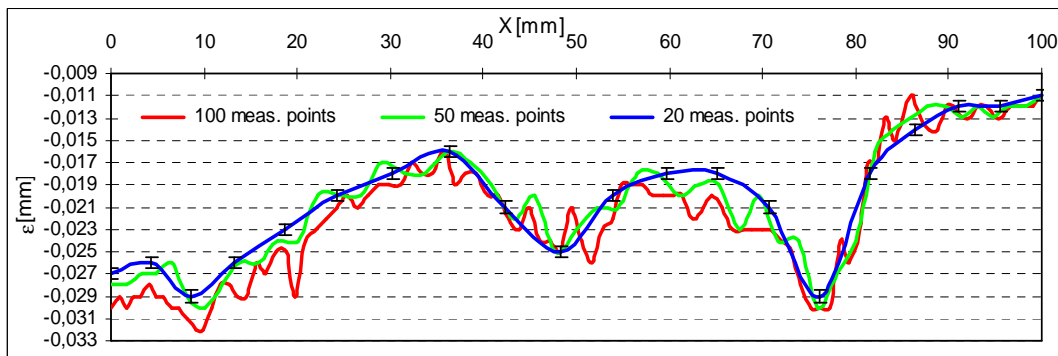


Fig. 3. Surface profiles for different numbers of measurement points

Analyzing the shapes of the obtained profiles (Fig. 3) makes it possible to observe a distinct effect of filtering short wavelengths in the measurement with the longest sampling interval. In the case of 100 measurement points, the sampling interval was similar to the tip end dimension. According to the principles described in Section 2, it can be assumed that in this case the observed data include information on elementary irregularities of the lengths exceeding 2 mm. In the two remaining cases (50 and 20 points), the  $T$  sampling intervals (approx. 2 and 5 mm) were greater than the tip end dimension and where the parameters which determined filtering out deviations whose lengths were less than approx. 4 and 10 mm respectively. The measurement results are summed up in Tab. 1. As can be seen, the mean value and the minimum value of the observed local deviations take smaller values for greater numbers of measurement points (smaller sampling intervals).

Table 1. Statistical parameters of  $\varepsilon$  local deviation sets, scanning in one section with different intervals,  $d = 2$  mm

Number of meas. points	100	50	20
Sampling interval $T$	$0.01u$ ~ 1 mm	$0.02u$ ~ 2 mm	$0.05u$ ~ 5 mm
Std. deviation [mm]	0.006	0.006	0.005
Mean [mm]	-0.022	-0.021	-0.019
Minimum [mm]	-0.032	-0.031	-0.029
Maximum [mm]	-0.011	-0.011	-0.011
Max. height of the profile [mm]	0.043	0.042	0.040
Averaged standard error of measurement results [mm]	0.00023	0.00026	0.00020

### 3.2. Researching into the influence of the tip end size

The measurements described in Section 3.1 were repeated for a tip end of 4 mm in diameter and the number of measurement points amounting to 100. Figure 4 presents the surface profiles for tip ends of  $d = 2$  mm and  $d = 4$  mm in diameter and 100 measurement points. The measurement results are compiled in Tab. 2.

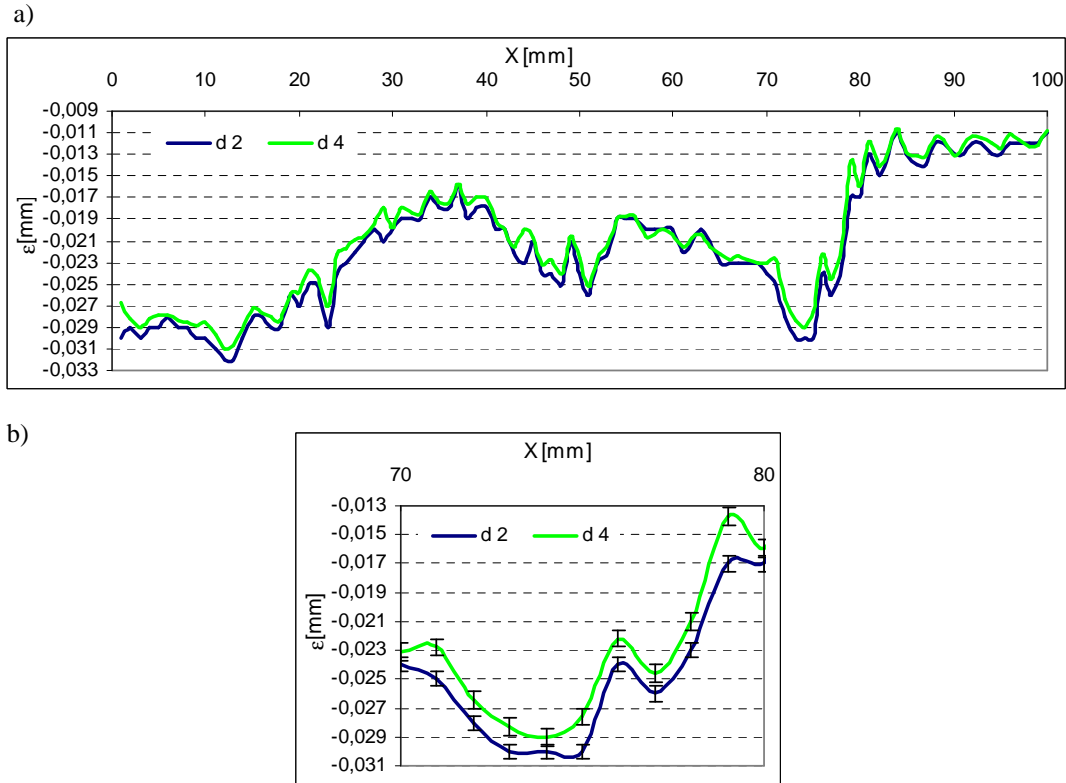


Fig. 4. Surface profiles for different tip end sizes: a) the entire profiles, b) an increased sector of the profiles, confidence intervals for measurement results are marked.

Table 2. Statistical parameters of  $\varepsilon$  local deviation sets, scanning in one section with different tip end sizes

Tip diameter $d$ [mm]	2	4
Number of meas. pts.	100	100
Sampling interval $T$	$0.01u$ $\sim 1$ mm	$0.01u$ $\sim 1$ mm
Std. deviation [mm]	0.007	0.006
Mean [mm]	-0.022	-0.021
Minimum [mm]	-0.032	-0.031
Maximum [mm]	-0.011	-0.010
Max. height of the profile [mm]	0.043	0.041
Averaged standard error of measurement results [mm]	0.00023	0.00030

For the tip end of  $d = 2$  mm in diameter, the mean and minimum values of the observed local geometric deviations were smaller. This tip went deep into the surface irregularities and reached surface points which were located lower than the points established with the use of the tip end of  $d = 4$  mm. Moreover, the scatter of the values of the observed deviations was

greater. The height of the profile determined in measurements with the use of the tip end of  $d = 2$  mm was greater by approx. 0.003 mm. Similarly to the situation observed in surface texture measurements with the use of profilers [11], applying a tip end of a greater diameter (radius) results in a decrease in the height parameters which describe surface roughness.

**3.3. Measuring local geometric deviations of the free-form surface**

In the first stage, the surface area  $(0.1 \div 0.9)u \times (0.1 \div 0.9)v$  was scanned (without applying probe radius compensation), with the use of a ball end tip of 1 mm in diameter with the *UV* scanning option (the option built in the PC-DMIS software), 22500 uniformly distributed measurement points were scanned from the surface (150 rows and 150 columns, sampling grid  $0.005u \times 0.005v$ ), and the process of fitting the data to the nominal surface was then carried out in which the least square method was applied and all the measurement points were used [13]. The location and orientation deviations were minimized in this way. The obtained local geometric deviations are presented in a graphical form. Figure 5 shows a spatial plot of the  $\varepsilon$  local deviations with reference to the  $x$  and  $y$  nominal coordinates.

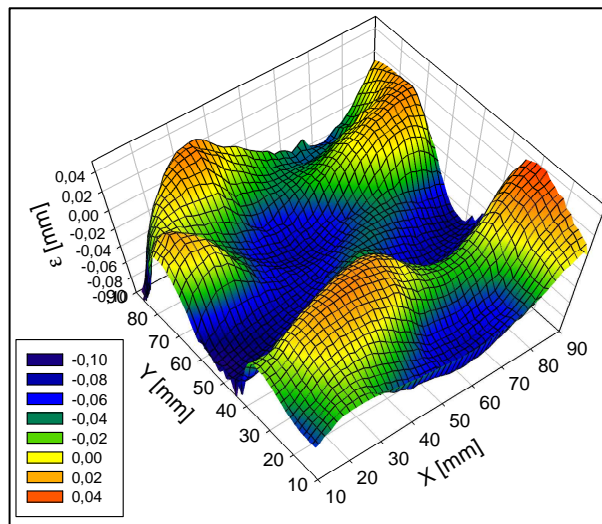


Fig. 5. Spatial plot of geometric deviations versus the *XY* plane

In the subsequent stage, the measurements were carried out with the use of a ball end tip of  $d = 4$  mm in diameter, and 1600 uniformly distributed measurement points (40 rows and 40 columns, sampling grid  $0.02u \times 0.02v$ ) were scanned. The experiment results are compiled in Tab. 3 as well as in Fig. 6.

Table 3. Statistical parameters of  $\varepsilon$  local deviation sets, with the whole surface scanned

Number of meas. points	22500	1600
Sampling grid	$0.005u \times 0.005v$	$0.02u \times 0.02v$
Sampling interval $T$ [mm]	$\sim 0.5$ mm	$\sim 2$ mm
Tip diameter $d$ [mm]	1	4
Std. deviation [mm]	0.025	0.016
Mean [mm]	-0.007	0.002
Minimum $\varepsilon$ [mm]	-0.089	-0.044
Maximum $\varepsilon$ [mm]	+0.042	+0.035
Max. height of irregularities [mm]	0.131	0.079



In both cases, the principle of selecting  $d:T - 2:1$  was applied. According to the principles described in Section 2, measurement data obtained in measurements performed with the tip end of  $d = 1$  mm in diameter and the sampling interval of  $T = \sim 0.5$  mm, include information on surface irregularities whose lengths exceed 1 mm. In the second case, for the tip end of  $d = 4$  mm in diameter and the sampling interval  $T = \sim 2$  mm, data include information on cases of wavelength longer than 4 mm. As had been expected, the maximum height of irregularities value for the tip end of  $d = 4$  mm and  $T = \sim 2$  mm was smaller than that for  $d = 1$  mm and  $T = \sim 0.5$  mm (Table 3). The tip end of the bigger diameter did not reach points located in the irregularities indentations less than 4 mm in length; additionally, some cases of irregularities on prominences were omitted because of a bigger sampling interval. Consequently, the mean plane is located higher and the minimum value is bigger than in the case of a smaller diameter and a smaller sampling interval (Fig. 6, Table 3). In order to facilitate comparison of the deviation maps, the plots in Fig. 6 were made using the same scale for the  $\varepsilon$  deviations axis.

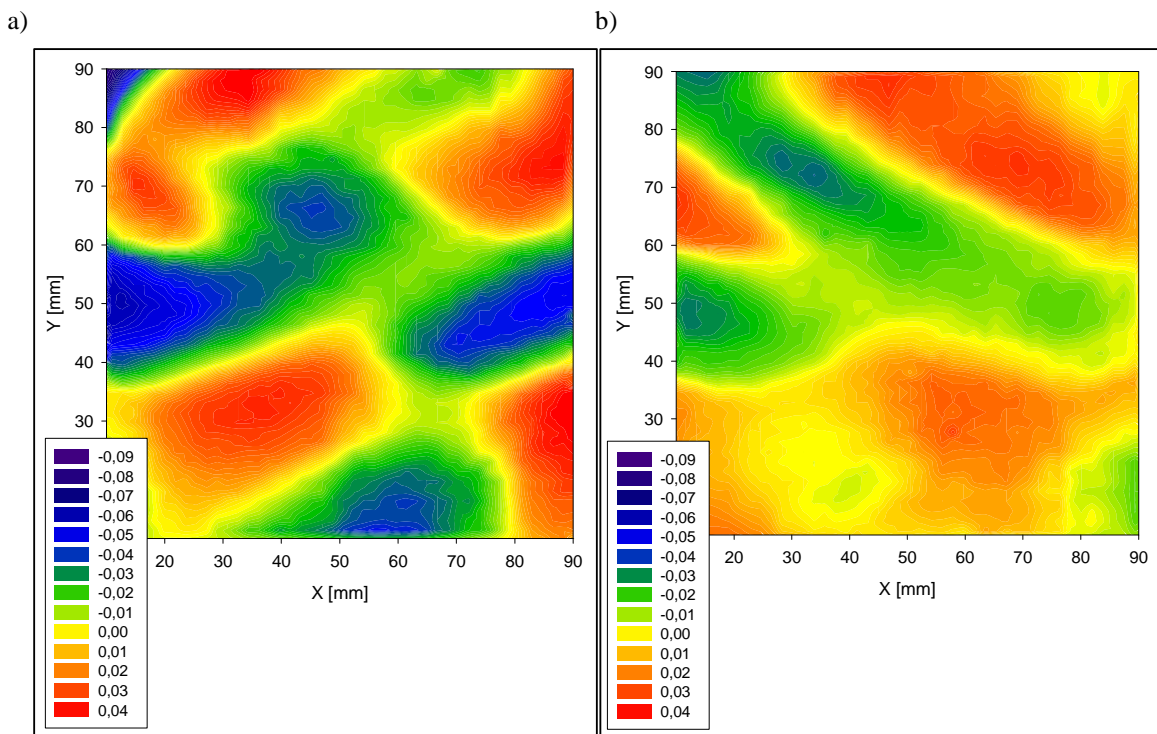


Fig. 6. Maps of geometric deviations versus the XY plane, a)  $d = 1$  mm and 22500 points, b)  $d = 4$  mm and 1600 points

Comparing the maps, a bigger area of negative deviations can be observed in the case of measurements with the tip end of  $d = 1$  mm (Fig. 6a). As a result of applying different measurement strategies, significantly different results were obtained. The observed maximum height of irregularities differed by approx. 0.05 mm, which constitutes approx. 2/5 of their values.

#### 4. Conclusions

Each contact measurement is accompanied by the inherent loss of information about the geometry of the surface caused by mechanical-geometric filtration by the ball tip and sampling interval. The parameter which determines passing longer waves exerts a decisive influence. In the article the principles of selecting parameters, suggested in literature sources, were summarized and the results of research on the influence of these principles on the results



of coordinate measurements of geometric deviations of a free-form milled surface were presented. In the first step investigations on the influence of different sampling parameters on the measurement results in one cross-section of the surface were conducted. Three different sampling intervals for one tip size and two tip sizes at one sampling interval were used. Differences of the observed maximum height of the profiles were a few micrometers. For the whole surface measurement two different parameter combinations were applied, observing the rule of the ratio of the ball end diameter to the sampling interval equal to 2:1. In the first measurement, the tip end amounted to  $d = 1$  mm, and the sampling interval to  $T = \sim 0.5$  mm; in the second, the values were 4 mm and 2 mm respectively. The obtained measurement results differed to a great extent. In the case of the bigger diameter and the greater sampling interval, cases of elementary irregularities of the lengths less than 4 mm were filtered mechanically, and the observed maximum height of irregularities was smaller by  $2/5$  than when the parameters had smaller values.

## Acknowledgments

The work is supported by the Polish Ministry of Science and Higher Education under research project No. N N503 326235.

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