Measurement and evaluation of the flatness error of a milled plain surface

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Abstract – The accuracy requirement of a machine part means not only the dimensional accuracy, but the surface quality, the accuracy of shape and the position of a geometric feature. Because of the increasing industrial requirements, the meaning, measuring and manufacturing of shape and position tolerances come into the limelight. In this article the effect of the different measuring strategy on the coordinate measuring machine is investigated in case of a milled plain surface. The question is, how can be minimized the number of measured points beside the right measured value. From the viewpoint of the measuring process the aim is to create an appropriate strategy, which can ensure the real value of the errors and short measuring time.

1. Introduction

During the machine part manufacturing, there are differences between the designed and the realized properties. The reasons of these deviations are the uncertainty of the different parameters, like material, machine tool, cutting tool, process parameters, measuring devices and process, environment and human factors. The level of the deviation can be reduced by the process planning and quality control. The deviation cannot be eliminated, so the acceptable level of it can be defined as tolerance. Based on standards, dimensional tolerances [1], shape, orientation and form tolerances [2], and surface roughness [3] can be defined.

During the identification of the type and value of the tolerances, the designer must consider the nature, the use, the size, the material of the part and the manufacturing and assembly technologies [4]. The final design requirements must satisfy contradictory conditions and constrains. Dimensional tolerances don't ensure right definition of requirements, so the shape, orientation and position tolerances came into view in the last decade. This tendency increases the importance of the defining, measuring, interpretation and producing of this type of tolerances. Płowucha et al. [5] summarizes the geometric product specification (GPS) related standards and points out the importance of the GPS in the engineering work and the education. The development of implementation algorithms is an important and actual field in the GPS [6][7][8][8].

Runje et al. [10] defines the flatness by the least square method in case of a granite table. Different measurement routes were applied, and the measuring instrument was an electronic level. Wang et al. [11] describes the mathematical model of the flatness error evaluation and suggests a genetic algorithm to calculate the error based on minimum zone solution. Wen et al. [12] proposes an improved genetic algorithm (GA) for flatness error evaluation and the GUM and Monte Carlo (MCM) methods for evaluate the uncertainty.

Hadžistević et al. [13] investigates the flatness of surfaces created by turning, milling and grinding. The flatness was determined based on different number of points (10 to 2000) by least square (LS) and minimum zone (MZ) methods. Based on the LS method largest values of flatness are determined. In case of turning (3 test parts) the number of points has the largest effect, but the increasing surface roughness means increasing flatness. In case of grinding (1 test part) the number of investigated points has no effect to the flatness value. In case of same surface roughness the face milling (1 test part) ensures better flatness than turning and the number of points has smaller effect to the flatness.

Mikó and Drégelyi-Kiss [14] investigates the flatness, perpendicularity and parallelism in case of shoulder milling. Besides the cutting parameters and the machine tool, the milling direction and the position of the surface have effect to the geometric error. The quality of the milled plain surface can be described or evaluated by geometric parameters of the tool and the cutting parameters (e.g. [15]), but the question is the effect of these parameters to the geometric deviation of the surface.

The different types of form, orientation and position standards are defined by ISO 1101-2017 standard [2]. The current article focuses on the flatness. The standard defines the flatness as the distance of two parallel plains which bound the produced geometric feature (Figure 1). The position and the orientation of the two plains which create the flatness tolerance zone are independent within the dimensional tolerance zone.

During the measuring by a coordinate measuring device (coordinate measuring machine (CMM), measuring arm, 3D scanner etc.) points of the surfaces are recorded, and this point cloud substitutes the surface. The size of the point cloud and the methods of mathematical modelling aren't determined in the standards.

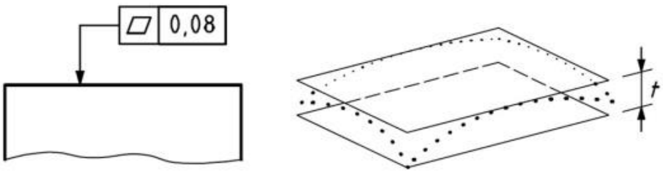

Figure 1 The standard mark of the flatness tolerace and the interpretation of the tolerance zone [2]

In this article the influence of the measuring strategy in case of coordinate measuring machine is presented in connection with the flatness of a milled plain surface. The question is how the number of measured points can be minimized, beside the right measured value. From the viewpoint of the measuring process, the aim is to create an appropriate strategy, which can ensure the real value of the errors and short measuring time.

2. The methods and devices of the test

The applied test part was made of 42CrMo4 (1.7225) pre-hardened steel; the size is 175x155 mm. The plain surface was machined by milled with a UF-231 conventional milling machine. The diameter of the milling cutter was 80 mm, the number of teeth is 7 (ISCAR HeliDo SOF 45 8/16-D080-07-27 R). The cutting parameters are: v_c = 60 m/min, f_z = 0.046 mm, n = 240 1/min, v_f = 78 mm/min, a_p = 1 mm, a_e = 40 mm. The surface roughness was measured by Mahr-Perten Concept instrument, in two perpendicular direction, at 2x(4x4) position. The measured surface roughness was Ra = 2,97 μm (σ = 0,9 μm), Rz = 14,75 μm (σ = 4,5 μm).

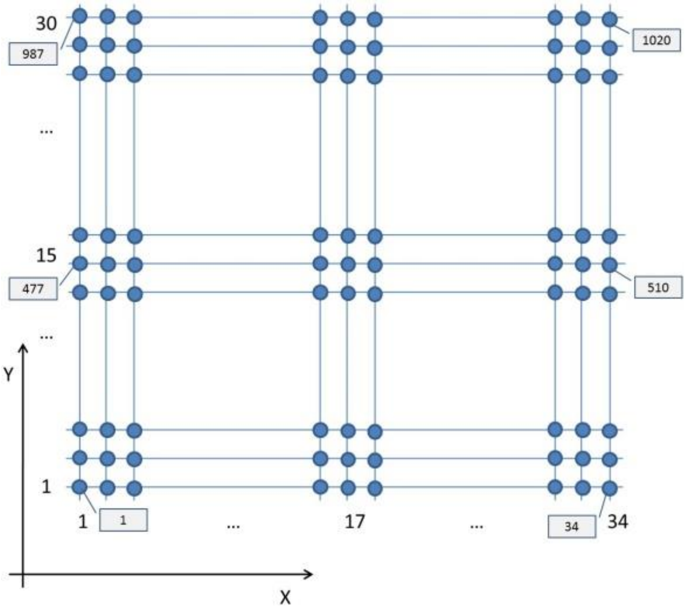

Figure 2 The pattern of the test points

The surface was measured by Mitutoyo Crysta-Apex S 776 CMM, 1020 points were recorded in 34x30 pattern with 5 mm distance (Figure 2). During the evaluation of the flatness (*FL*), the minimum zone method was used: seek the best fitted boundary plains, which have the smallest distance. The applied algorithm is showed in Figure 3.

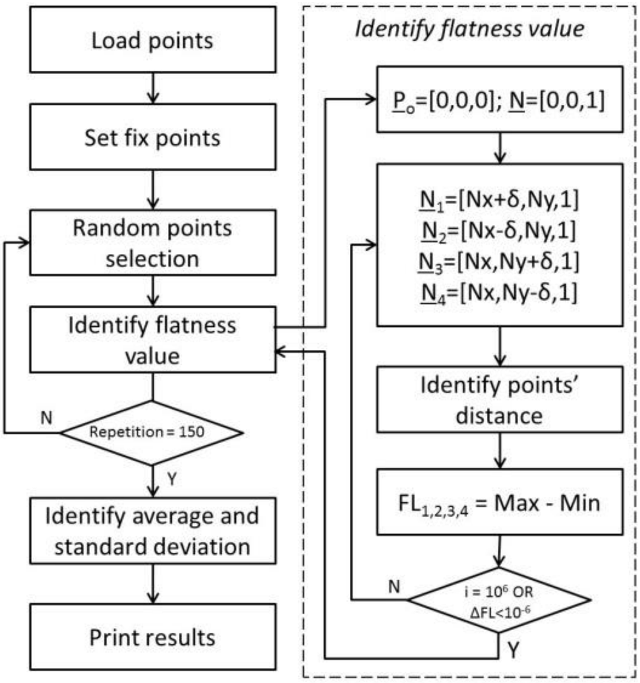

Figure 3 Evaluation algorithm

The equation of a plain is (where the $\underline{P}_0$ is a point of the plain, $\underline{N}$ is the normal vector):

$$N_x \cdot x + N_y \cdot y + N_z \cdot z - (N_x \cdot P_{0x} + N_y \cdot P_{0y} + N_z \cdot P_{0z}) = 0 \qquad (1)$$

The distance between a $\underline{P}_i$ point and the plain is:

$$D_i = \frac{N_x \cdot (P_{0x} - P_{ix}) + N_y \cdot (P_{0y} - P_{iy}) + N_z \cdot (P_{0z} - P_{iz})}{\sqrt{N_x^2 + N_y^2 + N_z^2}} \quad (2)$$

The orientation and position of the two boundary plains were determined by iteration algorithm. The initial position of the reference plain is horizontal, the normal vector is N = [0,0,1], and contains the P_0 = [0,0,0] point. During the iteration the X and Y components of the normal vector were changed with δ, and in case of the four possible new positions the distance of the elements of the point cloud were determined. The flatness is the difference between the minimum and maximum distance (Figure 4). The best value can be selected, and in the next iteration step this position was modified. The iteration stops, if the difference between two iterations (*ΔFL*) is less than 10^{-6} mm or the iteration step number (i) is 10^6. The δ is randomly defined in every iteration step, the value is $\delta = 10^{-6}\, r$ (where r = 0…1 random value).

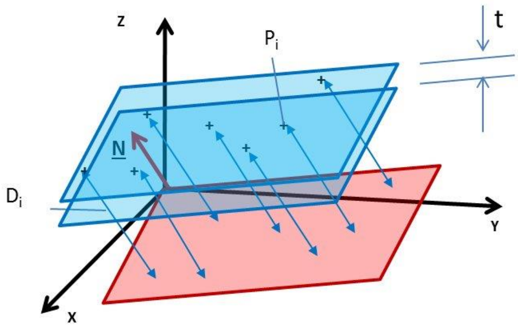

Figure 4 Interpretation of the flatness

The reference value of the flatness deviation was determined based on 1020 points by Kotem SmartProfile 4.0 evaluation software based on ISO 1101 by least square method. The reference value is FL_{1020} = 0.075 mm (Figure 5).

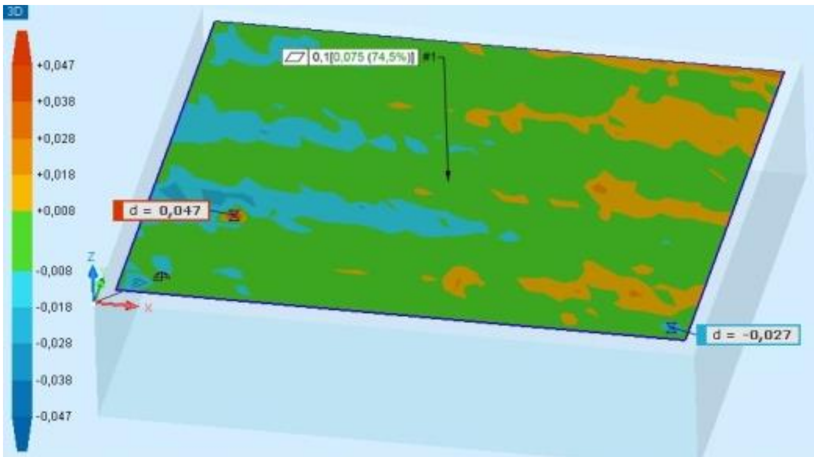

Figure 5 The reference flatness value in SmartProfile

3. The Random Points Method

In case of the Random Points Method (RPM) the points, which represent the whole plain and define the flatness are selected randomly. The random selection was repeated 150 times, and the average value of the different selection gave the result. During the research constant points were defined beside the random points, in order to increase the accuracy of the evaluation.

In case of RMP-0 there isn't a constant point, only random. In case of RPM-4, the four corners are the constant elements; at RPM-5 the centre point is added. The RPM-9, RPM-16 and RPM-25 mean 3x3, 4x4 and 5x5 fixed points (Figure 6).

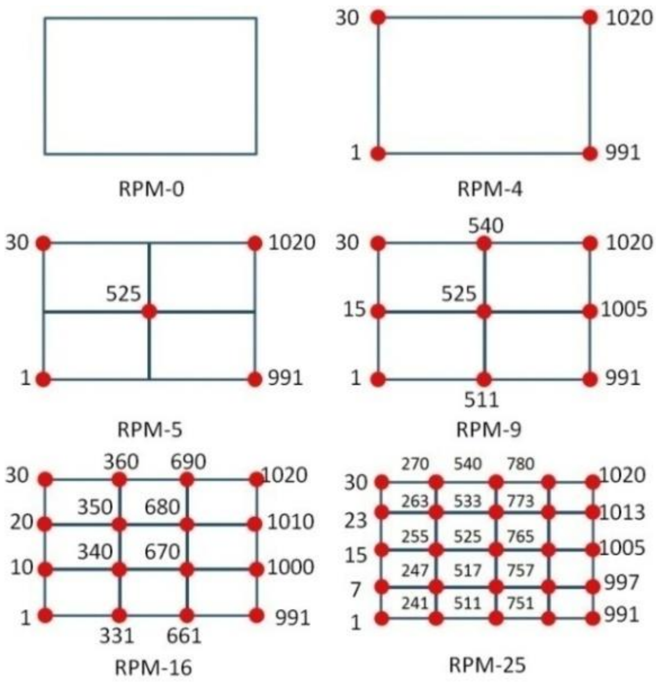

Figure 6 The location of the constant points

The number of investigated points (*NoP*) was: 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 20, 25, 30, 35, 40, 45, 50, 75, 100, 150, 200, 250, 500, and 999, and 0, 4, 5, 9, 16 or 25 points were defined in fix position and the rest were selected randomly. The random point selection causes uneven distribution of the points, the 4, 5, 9, 16 and 25 fixed points compensate this effect (Figure 7). Not every test were started from 6 points, the RPM-9 test series starts from 15 points, the RPM-16 starts from 20 and RPM-25 starts from 30 points. In the abbreviation the first number shows the number of fix points (*NoCoP*), and the second value shows the number of investigated points (*NoP*), for example the RPM-9/20 means the flatness is calculated based on 20 points and 9 points were in fix position.

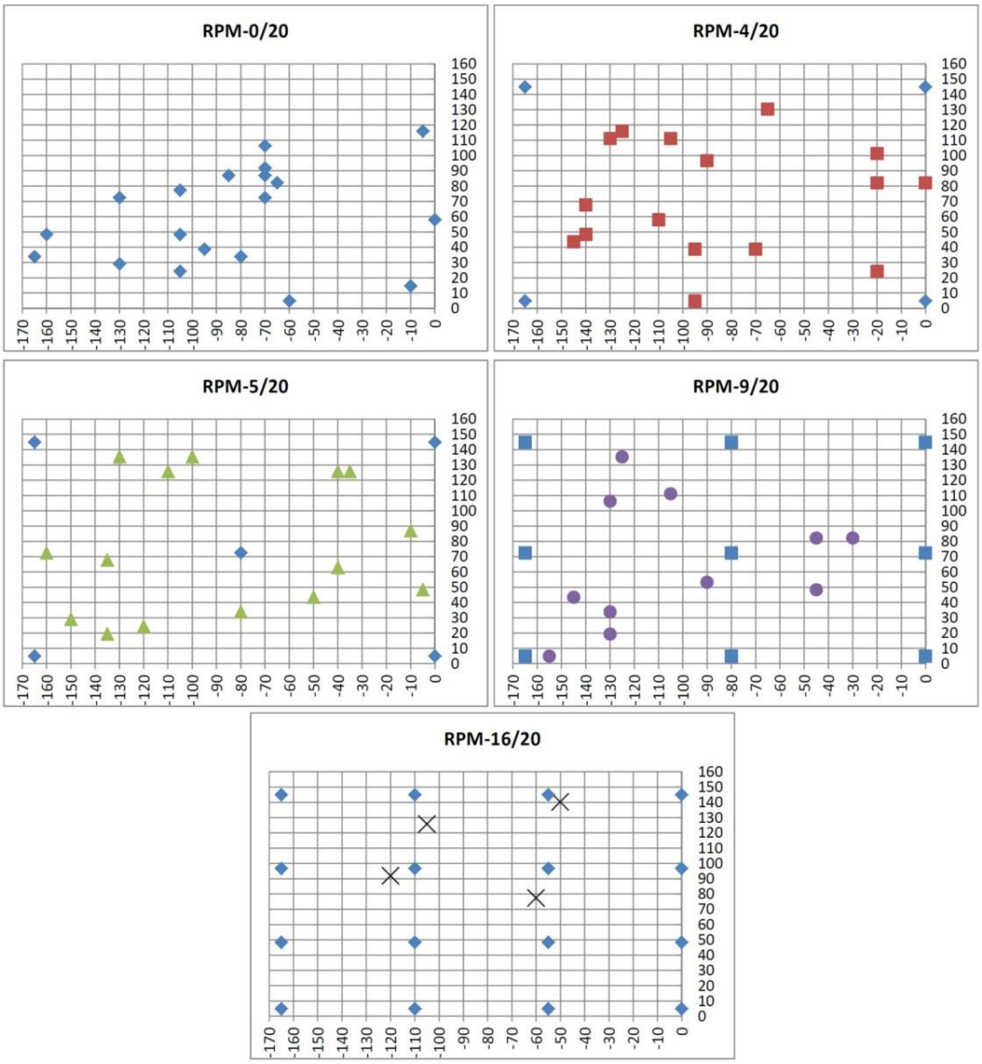

Figure 7 An example of distribution of the selected points (20 points example)

4. The results of the Random Points method

The flatness deviation is calculated by the average of 150 selection cycle in case of every number of points (*NoP*). Beside the average value, the standard deviation was determined too. In case of increasing number of points, the flatness deviation is increasing as well (Figure 8), but it never reaches the reference value (FL_{1020}). So in case of limited number of points the determined flatness is underestimated.

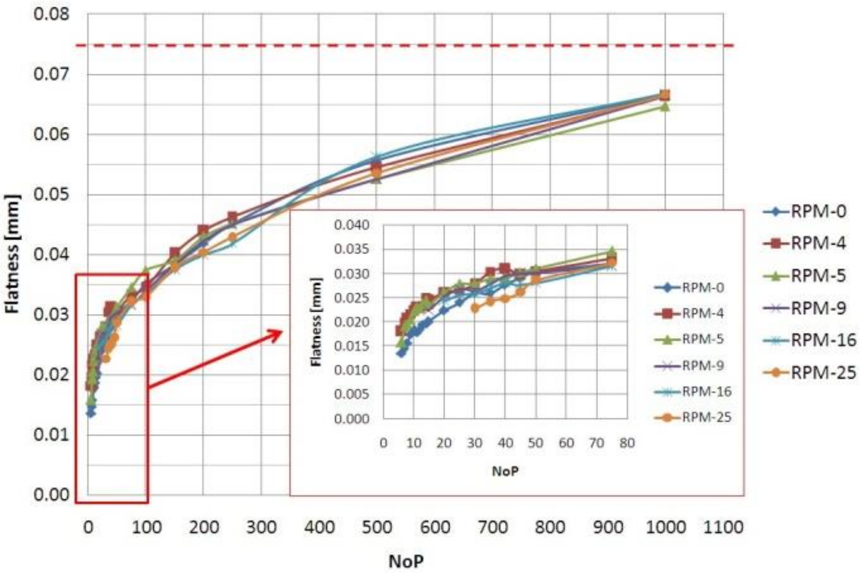

Figure 8 The value of the flatness

The standard deviation is smaller in case of less measured points, but fluctuates. Parallel with increasing number of points the standard deviation is increasing also, but at large number of points it is decreasing a little (Figure 9).

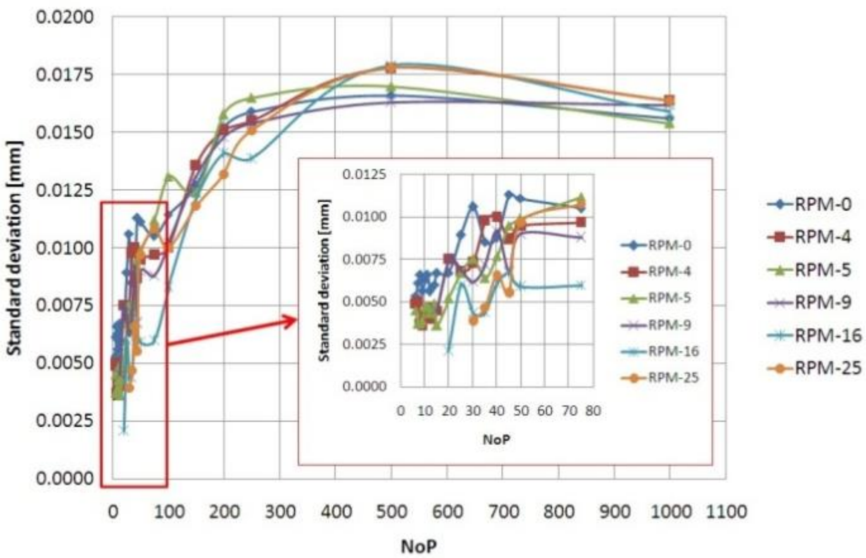

Figure 9 The values of the standard deviation of the flatness

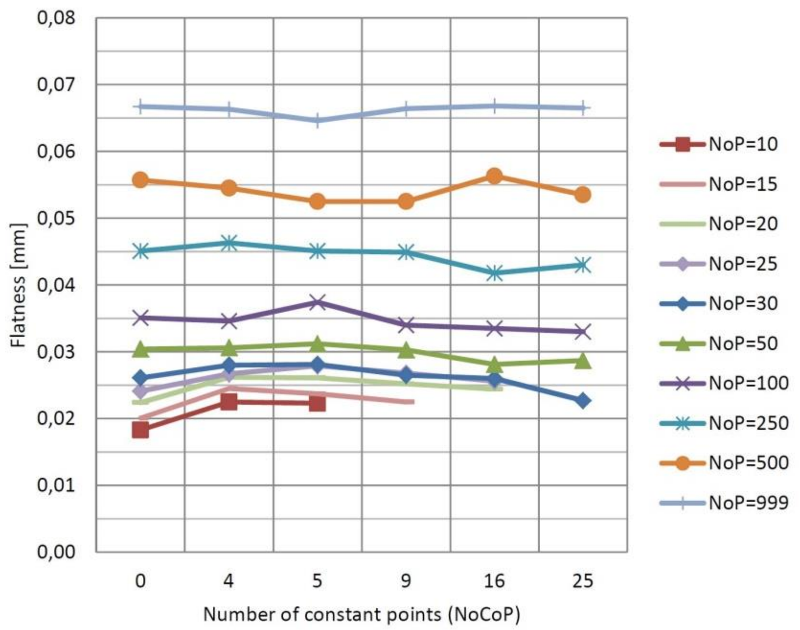

Figure 10 The values of the flatness

Based on the diagrams (Figure 10), the effect of the parameters of the sets (number of points, number of fixed points) are hard to identify, but based on the main effect plots (Figure 11) the importance of number of points (*NoP*) is clear. The number of constant points (*NoCoP*) has a smaller, but important effect.

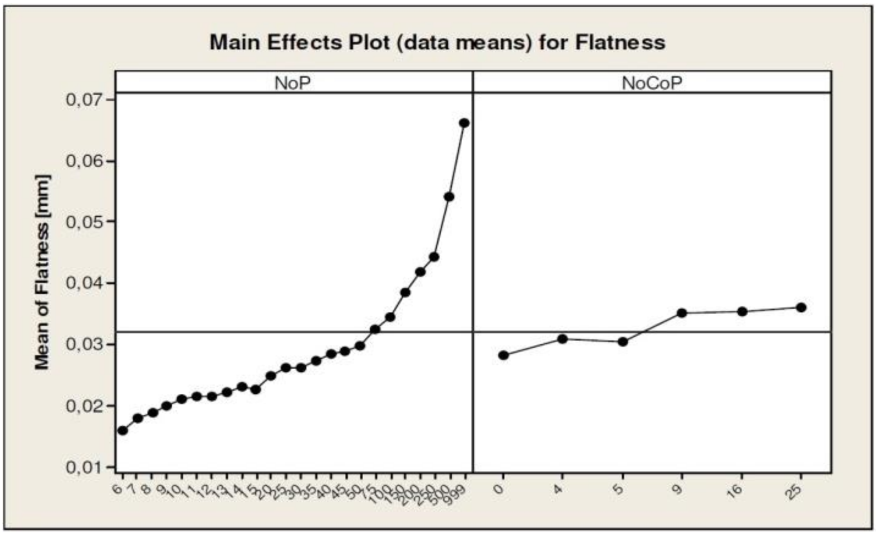

Figure 11 Main effects plot for flatness

The evaluated flatness value approximates continuously to the real (FL_{1020}) value, so the real value can be estimated by the correction of the measured value, where the FL_E is the estimated flatness, the FL_M is the measured flatness, and the C_{FL} is the correlation coefficient.

$$FL_E = C_{FL} \cdot FL_M \,. \qquad (3)$$

The correlation coefficient depends on the number of points (*NoP*) and the number of constant points (*NoCoP*):

$$C_{FL} = f(NoP, NoCoP) \tag{4}$$

This coefficient is optimized by MS Excel Solver, by minimizing the R^2adj (#1; R^2adj = 0.862):

$$C_{FL} = 5.4311 - 0.6968 \cdot \ln(NoP) - 0.0035 \cdot NoCoP \tag{5}$$

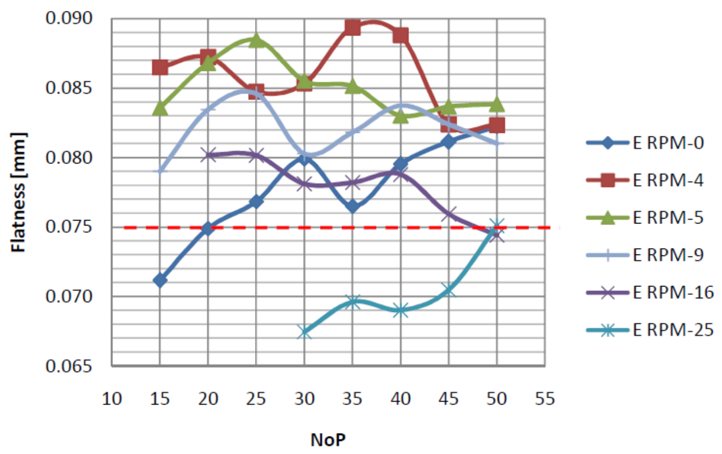

Figure 12 Estimated flatness #1

Based on this result the method underestimates the flatness at the two ends of the value range, and overestimates at the middle of the range. Less than 15 points is not enough to cover the surface, in case of more than 50 points, the measuring time is quite long. From the viewpoint of the measuring process, the 15-50 measuring points are the relevant. In this zone, there is a large difference in the estimated flatness; the error range is 0.025 mm (Figure12).

Based on this middle (15-50 points) zone the coefficient is recalculated (#2; R^2adj = 0.700):

$$C_{FL} = 5.8901 - 0.9360 \cdot \ln(NoP) - 0.0165 \cdot NoCoP \tag{6}$$

The estimated flatness values by the modified coefficient shows better results (Figure 13), the values there are in a±0.009 mm zone.

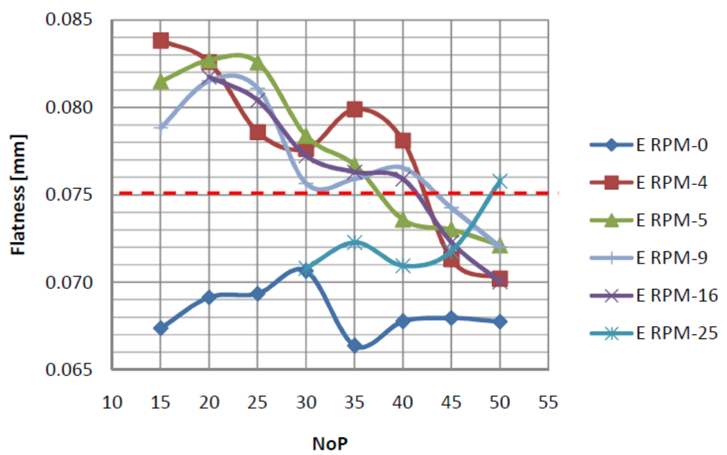

Figure 13 Estimated flatness #2

The application of RPM-0 is not realistic, because the cover of the surface is very uncertain. If the RPM-0 is excluded, the coefficient factor modifies next (#3; R^2adj = 0.902):

$$C_{FL} = 4.7991 - 0.6607 \cdot \ln(NoP) - 0.0238 \cdot NoCoP \tag{7}$$

As the Figure 14 shows, the error range deceased, the zone is only ±0.005 mm

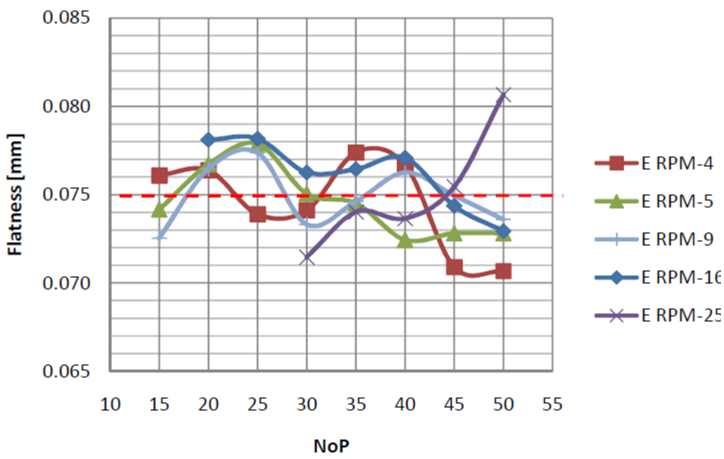

Figure 14 Estimated flatness #3

5. Results and discussion

With the definitions of standard in mind, the flatness deviation can be evaluated by different methods. In case of measuring by coordinate measuring devices, the key question is the number of measured points and the strategy of points recording. In case of the presented random points method (RPM), the evaluated flatness is increased parallel with the increasing number of points, but the real value of the flatness cannot be reached.

The constant points have important role in better cover of surface, but based on statistical analysis the influence to the flatness is small. More constant points are correct the flatness value, but in case of 4/5 points strategies and 9/16/25 points strategies there are no significant differences. Therefore 9 (3x3) constant points strategy is more productive, than 16 (4x4) or 25 (5x5) strategies, because of the faster measuring process can be ensured.

Based on the presented theory, the real flatness value can be evaluated with help of a correction coefficient, which depends on the number of measured points and the number of constant points. The presented numerical solution is valid in case of the investigated conditions, but the idea can be extended to other test parts, where the effect of the manufacturing methods, the size of the surface can be investigated.

Summarizing the results the following statements are made:

- The measurement of the flatness by coordinate measuring machine is influenced by the number of recorded points.
- Based on the randomly selected points, the value of flatness is determined by the position of the points, which can be specified by the fixed points with providing better coverage of the surface.
- Since the number of measuring points and fixed points correlates with flatness value, the result can be corrected by measuring strategy depending correction factors in order to estimate the real flatness.

Based on the results, there are several further possibilities and aims:

- The correction coefficient can be specified by further machined surfaces, this way other influence factors can be considered, like the machining technology and the surface roughness.
- The size of the surface is an important factor, so other surface sizes must be investigated.
- The evaluated points were selected randomly. A method should be developed, which ensures equable cover of the surface.

References

[1] ISO 14405-1:2010, Geometrical product specifications (GPS) — Dimensional tolerancing — Part 1: Linear sizes
[2] ISO 1101-2017 Geometrical product specifications (GPS) — Geometrical tolerancing — Tolerances of form, orientation, location and run-out
[3] ISO 4287-2002, Geometrical Product Specifications (GPS) — Surface texture: Profile method — Terms, definitions and surface texture parameters
[4] Henzold G 2006 *Geometrical Dimensioning and Tolerancing for Design, Manufacturing and Inspection* (Elsevier)
[5] Płowucha W; Jakubiec W; Humienny Z; Hausotte T; Savio E; Dragomir M; Bills P; Marxer M; Wisła M; Mathieu L 2014 Geometrical product specification and verification as toolbox to meet up-to-date technical requirements; *The 11th International Scientific Conference "Coordinate Measuring Technique" CMT2014* pp.131-139.
[6] H.S. Halkacı; Ö. Mavi; O. Yigit 2007 Evaluation of form error at semi-spherical tools by use of image processing; *Measurement* Vol.40 pp.860-867
[7] Rossi A, Antonetti M, Barloscio M, Lanzetta M 2011 Fast genetic algorithm for roundness evaluation by the minimum zone tolerance (MZT) method; *Measurement* Vol.44 pp.1243-1252
[8] Rossi A and Lanzetta M 2013 Roundness: A closed form upper bound for the centroid to minimum zone center distance by worst-case analysis; *Measurement vol.46* pp.2251-2258
[9] Mao J; Cao Y; Yang J 2009 Implementation uncertainty evaluation of cylindricity errors based on geometrical product specification (GPS); *Measurement* Vol.42 pp.742-747
[10] Runje B; Marković M; Lisjak D; Medić S; Kondić Z 2013 Integrated procedure for flatness measurements of technical surfaces; *Technical Gazette* Vol.20 No.1 pp.113-116.
[11] Wang D; Wen X; Wang F 2012 A Differential Evolutionary Algorithm for Flatness Error Evaluation; *AASRI Conference on Computational Intelligence and Bioinformatics AASRI Procedia 1* pp.238-243
[12] Wen X; Zhu X; Zhao Y; Wang D; Wang F 2012 Flatness error evaluation and verification based on new generation geometrical product specification (GPS); *Precision Engineering* Vol.36 pp.70-76
[13] Hadžistević M; Štrbac B; Spasić Jokić V; Delić M; Sekulić M; Hodolič J 2015 Factors of estimating flatness error as a surface requirement of exploitation; *Metalurgija* Vol.54 no.1 pp.239-242
[14] Mikó B and Drégelyi-Kiss Á 2015 Study on tolerance of shape and orientation in case of shoulder milling; *Development in machining technology* Vol.5. pp.136-150.
[15] Kundrák J; Felhő Cs 2018 Investigation of the topography of face milled surfaces; *Material Science Forum* Vol.919, pp.78-83