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Balázs Mikó, Gabriella Farkas, István Bodonyi, Budapest, Hungary

INVESTIGATION OF POINTS SAMPLING STRATEGIES IN CASE OF FLATNESS

Abstract:*The use of geometric tolerances has increasing importance in the industry, but the correct application of it needs deeper understanding. Several aspects should be considered like the work of the product, material properties, manufacturing and measuring circumstances, and the regulations of concerning standards. The article presents the measuring and evaluation problems through the example of flatness. The effect of different point sampling strategies is investigated: twelve methods are compared in case of eight test surfaces, and a modification method is suggested.*
Keywords: *Geometric tolerances, Flatness; Point sampling strategy; Coordinate measuring; Minimum zone method;*

INTRODUCTION

In case of machine design one of the most important aspects is the accuracy of the parts and the assembly. The accuracy has different aspects, from micro level to macro level. The required accuracy comes from the working requirements of the product, but the manufacturing and measuring circumstances have to be considered too.

The different types of tolerances show the allowed errors. Considering the errors, the most often used tolerances are the dimensional tolerance, the surface roughness, the shape, position and orientation tolerances (geometric tolerances). The standards define the marking of tolerances on the drawings, the general tolerance values and other definitions (1, 2). The determination of specific values is a serious and important phase of the design process.

The geometric tolerances have increasing importance in machine design, manufacturing and measuring. As Plowucha (3) says, the designer and metrology engineers need deep knowledge on geometric product specification (GPS). The GPS system of a design documentation should consider the functional and manufacturing requirements (4). The manufacturing specifications must be derived from functional specifications for each machining phase (5). The vectorial analyses of degree of freedom of the geometric tolerance zone supports the interpretation of the requirements. The geometric error of a geometric feature can describe the real state of it with higher accuracy, so Moroni and Petro (6) think as a key element of Industry 4.0 concept. The origin of an error, based 5M model (7), can be the man, the machine, the material, the method and the measurement. In the current article, the focus is on the measurement.

In case of geometric tolerances, the error can generally be measured by coordinate measuring machines (CMM). During the coordinate measurement, coordinate values of points on the surfaces are recorded and based on them mathematical algorithms calculate the errors. Therefor the accuracy of the CMM, the mathematical algorithms, and the point sampling method has effect on the accuracy of the result.

Based on measured points the form and position tolerances can be evaluated, but several mathematical methods and their implementations can be used. Beside the white-box methods, black-box methods can be used too, like genetic algorithm or different search algorithms (8, 9). The most often used white-box methods are the following:

- Least square (LS) method, when the regression geometry is defined based on points by minimizing the distance of the points from the regression geometry.
- Minimum zone (MZ) method, when the position and orientation of the two parallel investigation elements is optimized by minimizing the distance between the two objects.
- Envelope method (EM), when a cover geometric feature is located to 3 points, and every other points there are under (or inside) the feature. The distance of the farthest point is the geometric error. During the evaluation, a cover geometric element has to be found where this distance is the smallest.

In the current article the effect of the measurement is analysed through the example of flatness deviation. The flatness is defined as the distance between two parallel planes (Figure 1), which cover the real surface (1). Beside the mathematical evaluation methods, there are several parameters, which have effect on the calculated flatness error. Jalid et al (10) investigates the size of the sample surface and the number of measured points. The number of measured points increases the calculated flatness error. Lakota and Görög (11) presents the effect of number of points in case of multi-point methods, which match with the results of Jalid et al. Furthermore, in case of continuous scanning method, the scanning path has effect on the calculated flatness error.

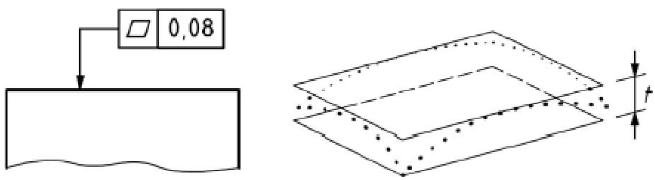


Figure 1 – Marking end definition of the flatness

The effect of the point sampling strategies was investigated through machined surfaces. The aim of the research is (a) investigating the effect of the point sampling methods on the calculated value of the flatness error, (b) identifying a correction coefficient, which can compensate this effect, and (c) selecting the most effective point sampling strategy.

Method and equipment

The flatness error, based on the standard (1) can be calculated several ways. In this research the minimum zone method was used. During the minimum zone (MZ) method, the orientation of two parallel planes has to be defined, which cover the measured point cloud with the minimum distance. This distance must be compared with the tolerance.

If one point of the investigation plane is $\underline{P}_o = [0; 0; 0]$ and the normal vector is $\underline{N} = [N_x; N_y; N_z]$ the distance of any point, which is described by $\underline{P}_i = [P_{ix}; P_{iy}; P_{iz}]$, is

$$D_i = \frac{N_x \cdot (P_{0x} - P_{ix}) + N_y \cdot (P_{0y} - P_{iy}) + N_z \cdot (P_{0z} - P_{iz})}{\sqrt{N_x^2 + N_y^2 + N_z^2}} \tag{1}$$

The flatness error of a point cloud is:

$$FL = D_{i\,max} - D_{i\,min} \tag{2}$$

The orientation of the investigation plane can be determined by iteration algorithm by changing of the normal vector and minimizing the calculated flatness error. In the current research the MS Excel Solver was used.

The investigated test parts were made of 42CrMo4 (1.7225) pre-hardened steel; the size is 175x155 mm. 8 test surfaces were analysed (*Sf#1 - Sf#8*), which were machined by different machining methods and cutting parameters. The Table 1 shows some details of the machining processes. Milling, turning and grinding technology were applied.

Four surfaces were machined by face milling. *Sf#1* was machined by face milling on a conventional milling machine, but *Sf#2*, *Sf#5* and *Sf#6* were machined on CNC machining centre. Two planes (*Sf#3*, *Sf#4*) were machined by face turning with a conventional turning machine, so the cutting speed was changed continuously. The *Sf#7* and *Sf#8* were grinded by a conventional surface grinding machine without spark-out and with spark-out.

The surface roughness was measured by Mahr-Perten GD120 contact measuring instrument. The *Ra* and *Rz* parameters were measured in 16 (4x4) region, 3 times, in two perpendicular directions in order to investigate the importance of the machining and measuring directions. The surface roughness is characterized by the average value and the standard deviation.

Table 1 – Manufacturing data of test surfaces

	Sf#1	**Sf#2**	**Sf#3**	**Sf#4**	**Sf#5**	**Sf#6**	**Sf#7**	**Sf#8**
Method	Face milling		Face turning		Face milling		Grinding	
Strategy	Zig-Zag		Radial feed outside-in		Zig-Zag	Spiral	Surface grinding without spark out	with spark out
Machine	UF-231	MAZAK A410-II	E400-1000		MAZAK A410-II		Jotes SPD-30B	
Type	Conv.	CNC	Conv.		CNC		Conv.	
D_c [mm]	80	50	-		63		350	
z	7	4	1		6		-	
v_c [m/min]	60		(100)		180		26 m/s	
n [1/min]	240	382	190		910		1440	
f; f_z [mm]	0.046		0.6	0.2	0.09		-	
v_f [mm/min]	78	70	115	40	490		-	
a_p [mm]	1		0.5		1		0.02	
a_e [mm]	40	25	-		31.5		40	

The measured point cloud was measured by Mitutoyo Crysta-Plus 544 coordinate measuring machine. 1020 points were recorded with 5x5 mm grid. The reference values of the flatness error were determined by same, previous mentioned iteration process based on 1020 points.

During the investigation, a limited set of points were selected based on 12 different point sampling strategies (PSS) (Figure 2). The red dots show the positions of the selected points. During the creation of point sampling strategies, one of the constrain was the maximum number of points, because of the limited time of CMM work. The first 10 strategies show regularity, the last two are random selection of points.

1. 13 points in the corners, mid points and diagonals,
2. 17 points in the corners, mid points and diagonals,
3. 17 points on the diagonals,
4. 15 points in the corner of defined regions,
5. 15 points in the corner of defined regions,
6. 20 points in the centre of regions,
7. 20 points in the centre of regions,
8. 16 points around a circle,

9. 20 points around 4 circles and centre points,
10. 16 points around 2 circles,
11. 16 random points,
12. 20 random points.

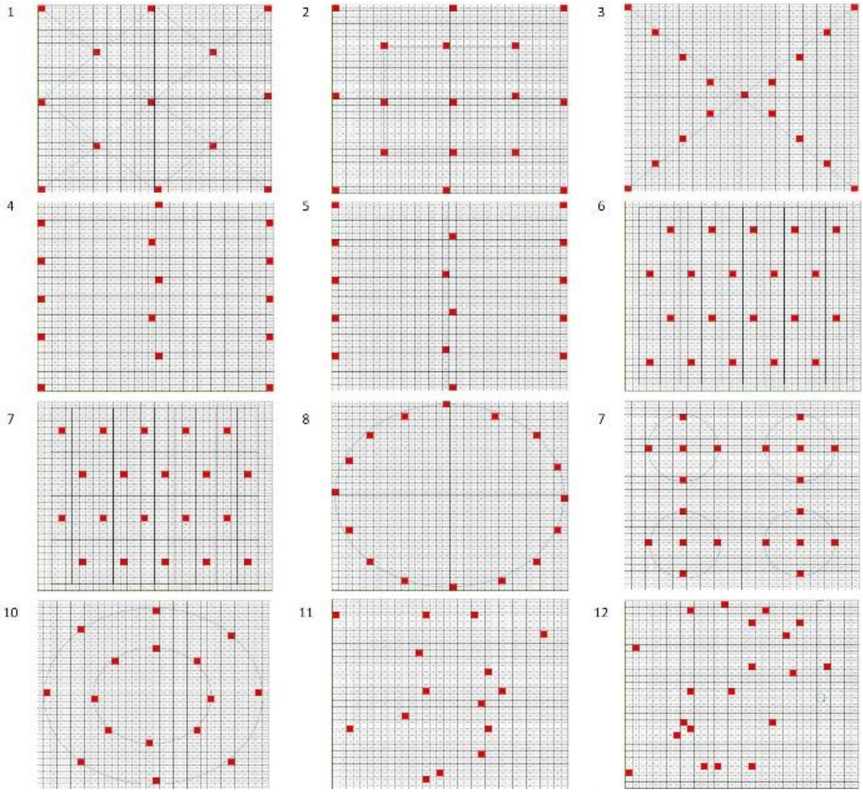


Figure 2 – Investigated point sampling strategies

Results

The look of the surfaces is very different because of the cutting technologies. This inhomogeneity appears in the values of surface roughness parameters, the standard deviation can be very large (Table 2), because the measured value of the surface roughness can be very different in perpendicular directions.

Table 2 – Surface roughness and reference flatness values

Surface	Ra [µm]	σ_{Ra}	Rz [µm]	σ_{Rz}	ΔZ_{max} [mm]	FL_{ref} [mm]
#1	2,97	0,89	14,75	4,50	0,043	0,034
#2	1,18	0,28	6,58	1,36	0,018	0,013
#3	3,16	0,76	14,42	3,12	0,045	0,045
#4	2,33	0,95	12,33	5,21	0,057	0,057
#5	0,54	0,19	2,68	0,91	0,016	0,013
#6	0,54	0,17	2,52	0,76	0,021	0,021
#7	0,60	0,36	4,19	2,57	0,011	0,010
#8	0,13	0,06	1,00	0,48	0,006	0,005

The Figure 3 shows the average values of *Ra* and the relative values of the standard normal deviation. Based on the chart, three groups can be identified. In the first group the surface roughness is high, but the relative deviation is moderated. They are the conventional milling and turning methods. In the second group there are CNC milled parts, where the surface roughness is better, but the relative deviation there is in a similar range as in first group. The third group (grinding) shows smaller *Ra*, but the relative standard deviation is the highest.

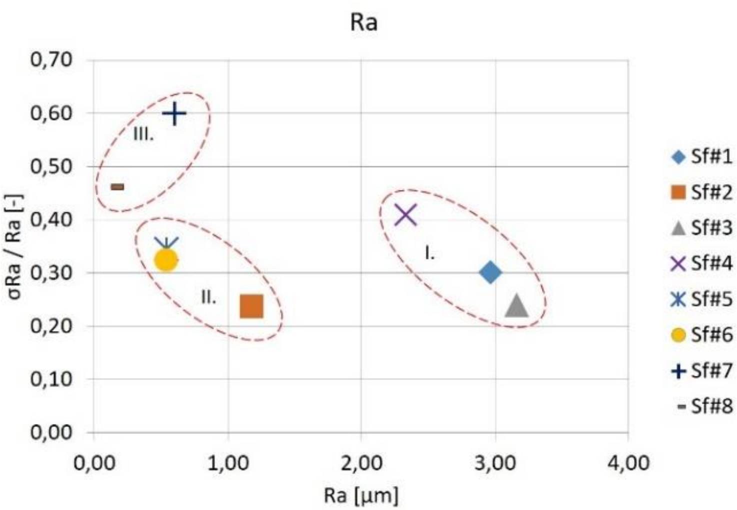


Figure 3 – Ra surface roughness and the relative standard deviation

The surface roughness and the flatness error have just a general relationship (Figure 4), the three previous group can’t be recognised, only the first, the second and the third are mixed. The surface roughness and the flatness move parallel: the better surface roughness means smaller flatness error.

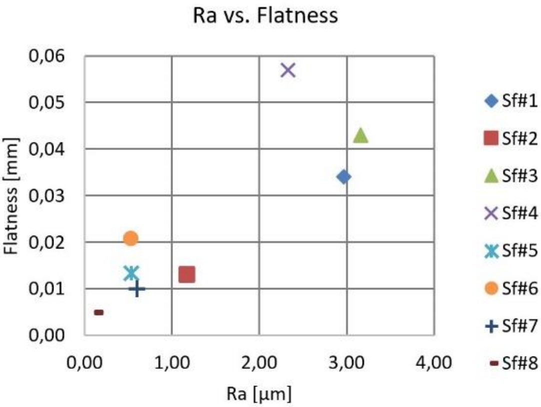
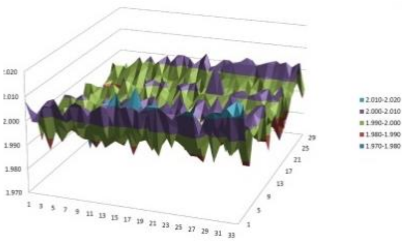
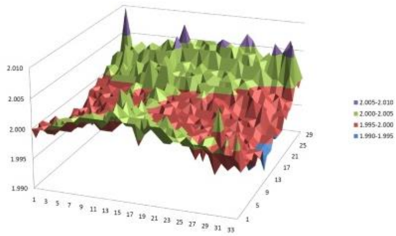


Figure 4 – Surface roughness and the flatness



#1



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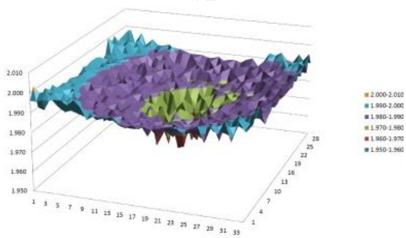

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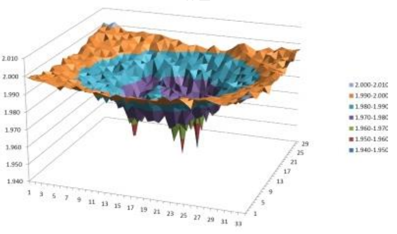

#4

Figure 5 – Macro topography of the test surfaces #1-#4

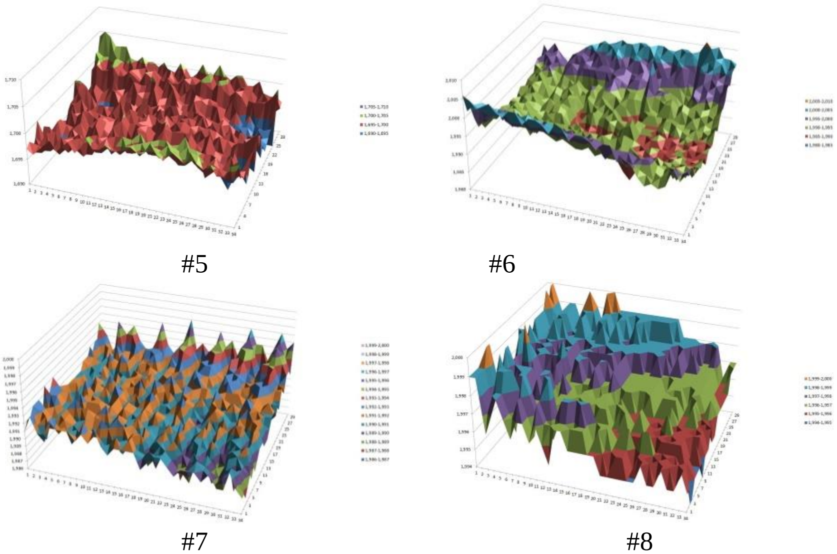

Figure 6 – Macro topography of the test surfaces #5-#8

The reference values of the flatness error based on 1020 points are shown in Table 2. The point clouds over the measuring grid show special macro topography, which characterise the machining method (Figure 5, Figure 6). In case of milling (*Sf#1; Sf#2; Sf#5; Sf#6*) the stripes of tool path can be recognised, and the side regions are higher. The face turning shows concentric pattern (*Sf#3; Sf#4*) with deeper centre. At grinding (*Sf#7; Sf#8*) a clear pattern is not visible.

The ΔZ_{max} means the maximum difference in *Z* coordinates value, so the distance between the deepest valley and the highest peak in *Z* direction. Generally, it is larger, than the flatness error, because of the degree of freedom of the investigation plane. It can be equal with the flatness error, if the best orientation of the investigation plan is equal with the theoretical surface. The ΔZ_{max} can never be larger than flatness. At face turning (*Sf#3; Sf#4*) the two values are equal, because of the concentric pattern. The difference is larger if the orientation error increases and the topography is not symmetric, like in case of milling.

The differences in macro topography can be characterised by flatness error. In case of different point sampling strategies, a limited set of points substitute the whole surface. The limited set of points decrease information about the surface, but ensures shorter measuring time. The measuring time of 1020 points was 45 minutes.

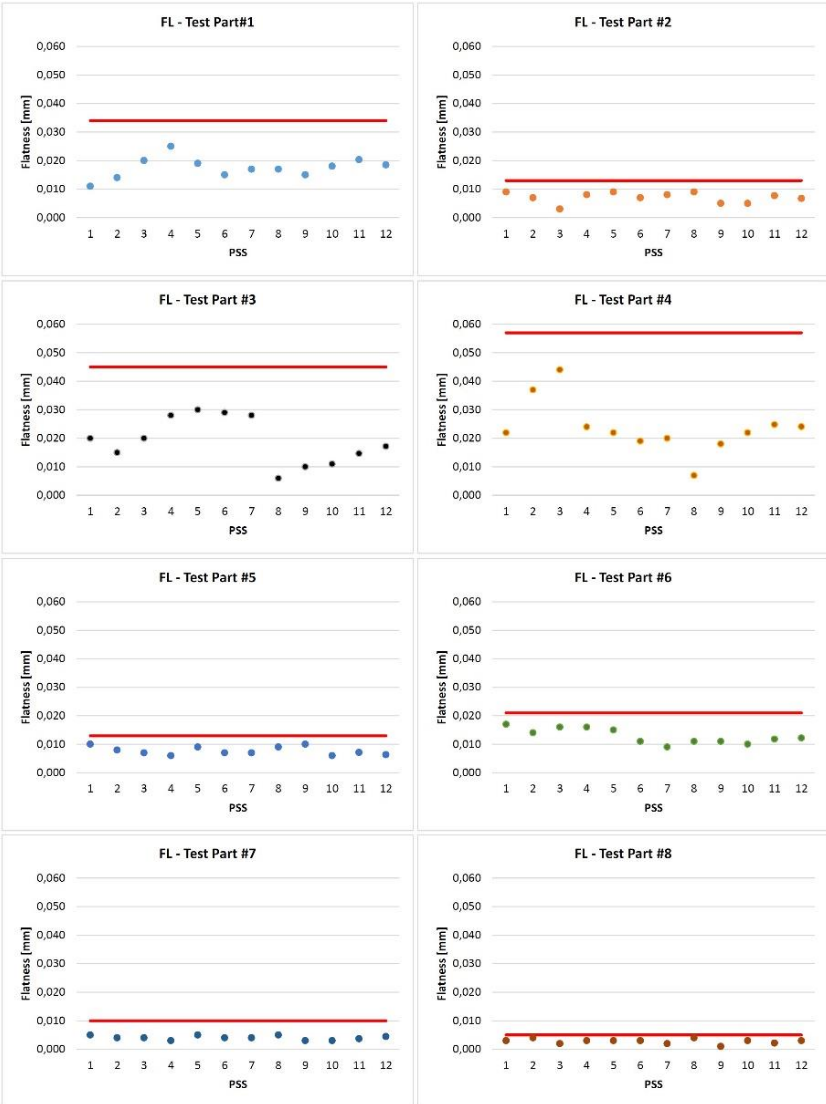

Figure 7 – Flatness errors in case of 8 surfaces and 12 points sampling strategies

The Figure 7 shows the flatness error in case of 8 surfaces and 12 points sampling strategies. The horizontal lines indicate the reference values of the flatness. In case of different PSS, the flatness can be very different, but the difference depends on the machining strategy and the surface nature. For example, in case of turning, the *PSS#8* shows very low values, because there are no points at the deepest central region. But when the topography looks more equable, the results show smaller deviations. The calculated flatness error is always smaller than the reference values.

Discussion

In order to adjust the measured flatness value (FL_c) to the reference value (FL_{ref}), a modification coefficient (C_{FL}) can be introduced:

$$FL = C_{FL} \cdot FL_c \tag{3}$$

The correction coefficients (C_{FL}) were defined as the quotient of reference value (FL_{ref}) and the calculated value (FL_c) of the flatness error.

$$C_{FL} = \frac{FL_{ref}}{FL_c} \tag{4}$$

If the coefficients are calculated, 12 different PSS related values are given (Figure 8), and considering the 8 test surfaces, standard deviation can be calculated. The coefficient shows the scale of the modification, and the standard deviation shows, how general this modification is in case of PSS. The result is better, if the standard deviation is smaller. The smallest standard deviation (Table 3) there are at *PSS#12* (20 random points) and *PSS#5* (15 points in the corner of defined regions).

Table 3 – Values of modification coefficients and standard deviations

PSS	1	2	3	4	5	6	7	8	9	10	11	12
C_{FL}	1,95	1,96	2,22	1,93	1,73	2,08	2,16	3,21	3,01	2,55	2,16	2,05
σ_{CFL}	0,66	0,61	0,98	0,68	0,40	0,48	0,45	2,86	1,26	0,81	0,51	0,33

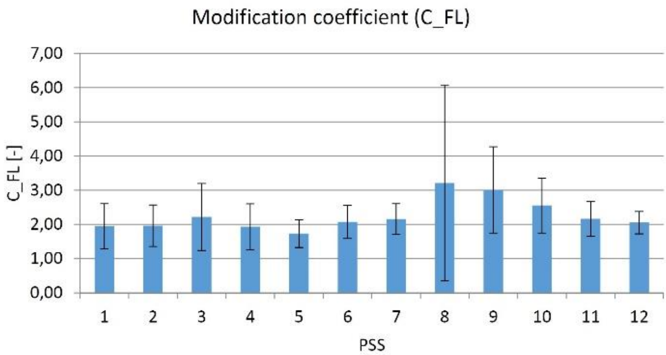

Figure 8 – Values and standard deviation of modification coefficients

The Figure 9 shows the result of the estimations at 8 test parts, the dashed line shows the ideal state. The *PSS#5* and the *PSS#12* show a good result; the estimated values are close to the reference values. But the points of *PSS#8*, which has the largest standard deviation, are far from the dashed line, they have large error.

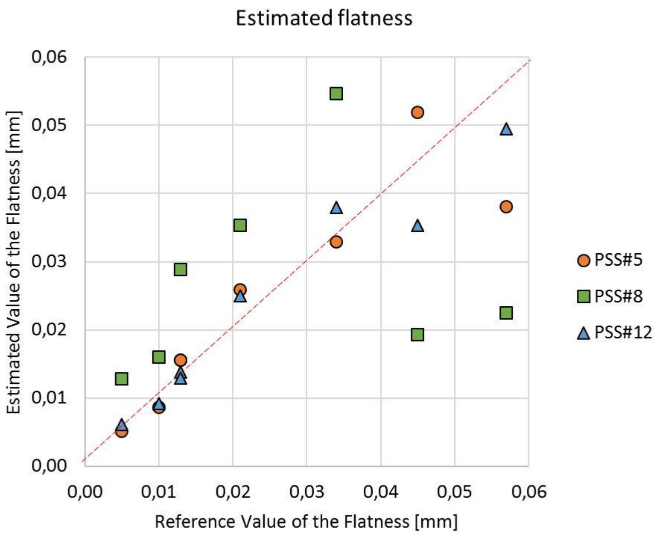

Figure 9 – Estimated values of flatness

Let’s compare the accuracy of the estimation by modification coefficients. The accuracy can be described by standard deviation of differences between the reference value and the estimated value of flatness. Based on these values (Figure 10), the result is same like at the preliminary conjecture: the *PSS#5* and the *PSS#12* is the best strategy.

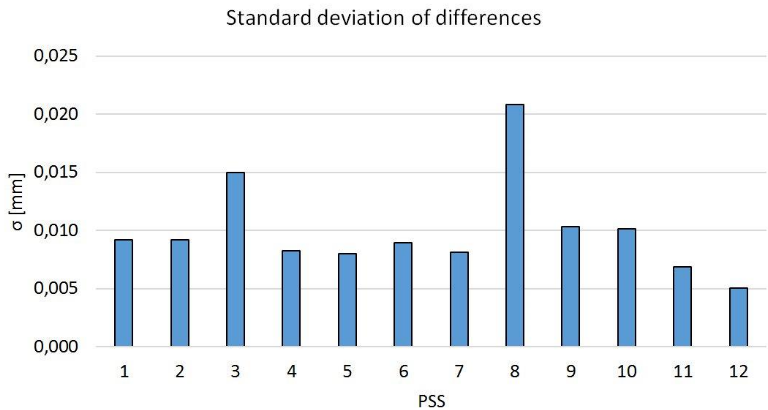

Figure 10 – Standard deviation of differences of estimated data

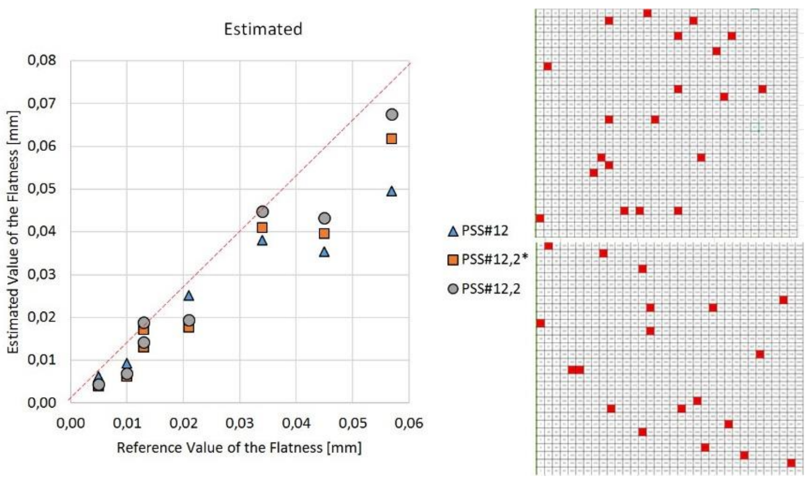

Figure 11 – Results of *PSS#12* random points method

The investigated point sampling strategies are regular; expect of *PSS#11* and *PSS#12*, which works with randomly selected points. Therefore, no matter how good results the *PSS#12* shows, if another 20 points are selected randomly, the values are changed, so the randomly selected points methods are not reliable. As the Figure 11 shows, the original coefficient based estimation is not so good (*PSS#12.2**), like estimation with recalculated value (*PSS#12.2*). A new set of points gives new coefficient (2,25) and standard deviation (0,57). Both values are higher, than the original, and the accuracy of the estimation looks better. So if the selected points are changed the previous coefficient is not appropriate. Therefore in case of random point methods, more parameters should be considered in order to define the modification coefficient.

Summary

The tolerance design is an important and complex problem, because of the diverse set of requirements and circumstances. Lot of factors have effect on the type and value of the tolerances. In the current article the effect of point sampling was investigated in case of coordinate measuring of flatness error. 12 different point sampling strategies were study on 8 different machined surfaces.

On the basis of the results above, it was found that the surface roughness and the flatness move parallel. The surface roughness in different measuring directions can be very different; the relative standard deviation is specified by machining technology. The point sampling strategy influences the result of evaluation of flatness. The standard deviation of the ratio of calculated and the reference values shows the most appropriate strategy. This ratio can be used to modify the measured flatness in order to estimate the real flatness error. 20 random points and the 15 points in the corners of regions ensured the best result, but the random method has poor repeatability.

The presented method can be extended to more machining technologies, and the modification coefficient can be specified. The size of the plane surface can be another important factor for the evaluation of flatness, so it should be considered during the further research.

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Балаш Міко, Габрієлла Фаркаш, Іштван Бодоньї, Будапешт, Угорщина

ДОСЛІДЖЕННЯ СТРАТЕГІЙ ТОЧКОВОЇ ВИБІРКИ ПРИ ОЦІНЦІ ПЛОЩИННОСТІ

Анотація. *Використання геометричних допусків в промисловості набуває все більшого значення, але для правильного їх застосування потрібно більш глибоке розуміння. Слід враховувати кілька аспектів, таких як робота продукту, властивості матеріалу, умови виробництва і вимірювання, а також правила, що стосуються стандартів. У статті представлені проблеми вимірювання та оцінки на прикладі площинності. Досліджується вплив різних стратегій точкової вибірки: порівнюються дванадцять методів в разі восьми випробувальних поверхонь, і пропонується метод модифікації. Помилка площинності, заснована на стандарті, може бути розрахована декількома способами. У цьому дослідженні був використаний метод мінімальної зони. При використанні методу мінімальної зони (MZ) необхідно визначити орієнтацію двох паралельних площин, які охоплюють хмару виміряних точок з мінімальною відстанню. Ця відстань повинна бути зіставлена з допуском. Досліджувані випробувальні деталі були виготовлені з попередньо загартованої сталі. Були проаналізовані 8 випробувальних поверхонь, які були оброблені різними методами обробки і параметрами різання. Були застосовані технології фрезерування, точіння і шліфування. Виміряна хмара точок була здобута за допомогою координатно-вимірювальної машини Mitutoyo Crysta-Plus 544. 1020 точок були записані з сіткою 5x5 мм. Контрольні значення помилки площинності були визначені ітераційним методом. На підставі результатів, наведених у статті, було виявлено, що шорсткість поверхні і площинність рухаються паралельно. Шорсткість поверхні в різних напрямках вимірювання може бути дуже різною. Відносне стандартне відхилення визначається технологією обробки. Стратегія точкової вибірки впливає на результат оцінки площинності. Представлений метод може бути поширений на більшу кількість технологій обробки, а також може бути вказаний коефіцієнт модифікації. Розмір плоскої поверхні може бути ще одним важливим фактором для оцінки площинності, тому його слід враховувати при подальших дослідженнях.*

Ключові слова: *геометричні допуски; площинність; стратегія точкової вибірки; координатне вимірювання; метод мінімальної зони.*