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PLANNING THE COORDINATE MEASUREMENTS OF A FREEFORM SURFACE AFTER MILLING BASED ON A CAD MODEL SIMULATING THE SURFACE AFTER MACHINING

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Abstract: This paper proposes the planning of coordinate measurements of freeform surfaces based on a model simulating the surface after machining. This model is created by the determination of a theoretical tool deflection during machining. The determined components of the simulated machining deviations are used in the reconstruction of the nominal CAD model of the surface into a model simulating the geometry of the surface after machining. This model is subdivided into areas corresponding to the assumed machining deviation intervals. This makes it possible to control the number and distribution of measuring points in separate sections of the manufactured surface. Coordinate measurements of the machined surface are made in areas where maximum deviations are expected. Here, the number and distribution of measuring points are controlled over a wide range. Coordinate measurements in other areas are carried out with significantly fewer points or may be omitted altogether. This approach makes it possible to reduce the measurement time without losing important information affecting the evaluation result. The method proposed in this paper has been tested on samples containing freeform surface. The test object was manufactured using a 3-axis milling technique with a spherical end mill.

Key words: freeform surface, coordinate measurement, 3-axis milling, CAD surface model

1. INTRODUCTION

The manufacturing of objects with freeform surface (e.g. casting moulds, injection mould and dies, etc.) is currently carried out on multi-axis machining centres. Assessment of the accuracy of this class of products is based on the determination of the surface shape deviations after coordinate measurements. At each measuring point, the local deviation from the nominal CAD model is determined. In assessing compliance with the specifications, the shape deviation is determined from the maximum values of the local deviations. Traditionally, coordinate measurement is carried out at points distributed according to a regular grid. A disadvantage of this method is the possibility of missing critical points, which leads to an inaccurate estimate of the shape deviation. This can be eliminated by increasing the number of measuring points. As a result, coordinate measurements of parts of complex geometry can take numerous hours (in extreme cases, the measurement time can be longer than the machining time of the part). For this reason, it has been attempted to develop different methods to reduce measurement time while achieving the same required measurement uncertainty.

Menq et al. in their paper [1] carried out a statistical analysis to determine the number of points on the basis of the profile tolerance and the machining process capability. The proposal is to distribute the points uniformly over the entire surface, abstracting from its geometrical features. Pahk et al. in [2] proposed several sampling strategies for the freeform surface represented by the B-spline surface model: sampling according to a regular grid of points (determining the points at the centre of the grid elements), curvature-dependent sampling of the mean curvature, and combined sampling. In curvature-dependent sampling, the measurement points were concentrated in the areas with the greatest curvature and completely absent in the areas with less curvature. The authors therefore developed a hybrid method, which is a combination of the first two methods, thus eliminating omittance of areas of low curvature. Cho and Kim in [3] proposed to make the distribution of the measuring points dependent on the mean curvature. The measuring points should be concentrated in regions of higher surface curvature because, as it has been showed and illustrated, it is in these regions that the largest machining deviations occur. It has been proposed to divide the CAD surface into a number of regions, determine the average curvature in the regions, and then select the number of measurement points depending on the curvature. Edgeworth and Wilhelm in their paper [4] made the density of measurement points dependent on the values of local geometric deviations. They proposed an algorithm using data on the directions normal to the surface at the measurement points to guide a third-degree B-spline interpolating curve. This curve was then used to determine further measurement points using an iterative procedure. The method ensures the density of measurement points in regions with large deviations and significantly reduces the total number of points compared to the classic method, i.e. evenly distributed points.

The accuracy of the “point-by-point” coordinate measurement increases with the number of measurement points, but the number of points is limited by the measurement time. Therefore, for a limited number of points, it is necessary to precisely determine their location to still accurately describe the shape of the profile. In accordance with this idea, the authors of the paper [5] proposed algorithms based on the dominant points of the profiles of the nominal CAD model. B-spline curves can be approximated using a certain number of key points, reflecting selected features of the profile such as the curvature. In the works [6] of Rajamohan et al, the dominant points are the ones with the greatest local curvature and points of inflection. ElKott and co-workers proposed in [7] different methods for sampling a NURBS surface composed of multiple patches and an algorithm that automatically selects the most appropriate sampling method depending on the complexity of the surface, curvatures, and patch sizes. This algorithm optimises the distribution of points on the surface by minimising the maximum deviation between the original NURBS surface, which simulates the real surface, and the NURBS surface, matched to the measurement points (a surrogate surface). The same authors presented in [8] new proposals for sampling strategies. They proposed sampling along the isoparametric lines of the CAD model. The iterative sampling process is constrained by assuming a maximum number of lines and a minimum line spacing. The proposed methodology can be applied to a single patch of NURBS surfaces. The paper [9] extends the methodology to surfaces composed of multiple patches.

Obeidat and Raman [10] proposed three algorithms for determining the measurement points on curved surfaces divided into patches. They searched for a strategy which ensures the distribution of points on individual patches would depend on the complexity of their geometry and size in order to best represent the whole surface. Simulations were carried out on models of three surfaces of the same base size but with different degrees of complexity of the nominal geometry. A NURBS surface built on the measurement points and the maximum deviation of the surface resulting from the model simulating the real surface was determined to constitute an accurate representation.

Rajamohan et al. in paper [11] proposed, in addition to two new sampling strategies based on the nominal geometry of the profile, to include the influence of the tip size in the simulation studies. For ease of visualisation, they presented the proposed methods on a 2D profile. The first strategy is based on the lengths of the curve segments, and the second one is based on the dominant points. They compared the proposed new strategies with methods described in the literature and being in common use, and thus they distributed a certain number of points: uniformly in Cartesian space, uniformly in parametric space, and according to the size of the profile segment. In paper [12], the authors extended the method to freeform surface measurements.

A paper by Bowen Y. et al [13] proposes generating sampling points based on a triangular grid generated on a freeform surface to be measured. The length of the side of the triangular element responsible for the distribution of the measurement points depends in this case on the curvature of the surface.

An important aspect of coordinate measurements is proper stylus alignment and collision avoidance when measuring complex 3D objects. The paper [14] presents an algorithm for automatically planning an efficient five-axis inspection path of freeform surfaces. This strategy is based on transforming the inspection path planning problem into a set conversion problem, the solution of which then yields a near-minimum set of inspection paths for surfaces of freeform shape, subject to necessary constraints such as sampling resolution, no collisions, and others. In contrast, the paper [15] proposes a new method for optimising head alignment for contact 5-axis measuring machines. Given the paths of the stylus on a free-form surface, the optimal orientation of the stylus is calculated so that its tilt angle is within a specified range in relation to the surface normal.

An interesting aspect of measurement strategy planning is the use of both non-contact and contact measurements. The article [16] presents an approach in which the contact measurement strategy is determined based on the results of non-contact measurements (e.g. optical scanning). The critical areas, i.e. where the maximum machining deviations occur, are determined on the basis of the optical scanning. The contact measurements are selected on this basis to ensure higher measurement accuracy. Surface sampling is limited to the critical regions.

The sampling strategy proposals described in the literature require a lot of knowledge and skilled personnel, and most of them are not feasible in an industrial application due to the high density of measurement points and therefore long measurement time. In addition, these strategies require use of a non-standard, expensive software. Methods such as uniform point distribution in Cartesian and parametric space or distribution based on the size of surface patches/segments of the profile do not take into account the influence of machining whatsoever. Methods based on profile length or curvature take it into consideration, nevertheless not assigning it enough significance.

This article proposes planning of the coordinate measurements of freeform surfaces on the basis of a CAD model simulating the surface after machining. This model is determined from the theoretical deflection of the tool (cutter) during 3-axis milling. The proposed method can be implemented using standard CAD/CAM software and measuring equipment used in industrial applications.

2. PLANNING COORDINATE MEASUREMENT OF FREEFORM SURFACES

Planning of the coordinate measurements of the freeform surface after milling based on a model simulating the surface after machining contains the following steps:

– determination of deviation values simulated at points on a CAD model of the nominal surface (for the purpose of this article, cutting forces and the resulting deflection of the milling cutter were taken into account),
– creation of a CAD model simulating the surface after machining,
– determination of the location and number of the measurement points,
– carrying out coordinate measurements of surface according to the specified measuring point locations,
– analysis of the measurement results and comparison with the nominal CAD model of the surface in order to assess the accuracy of the machined surface and possible improvement of the milling process in the future.

The application of the steps above ensures effective coordinate measurements of freeform surfaces after three-axis milling.

2.1. Determination of the simulated deviation values

The creation of a CAD model simulating the surface after machining starts with determining the values of the simulated machining deviations. In this paper, it is assumed that the dominant influence on machining accuracy is the deflection of the cutter due to the cutting forces. Figure 1 shows the model used to determine the deflection of the milling cutter at a point on the machined surface [19].

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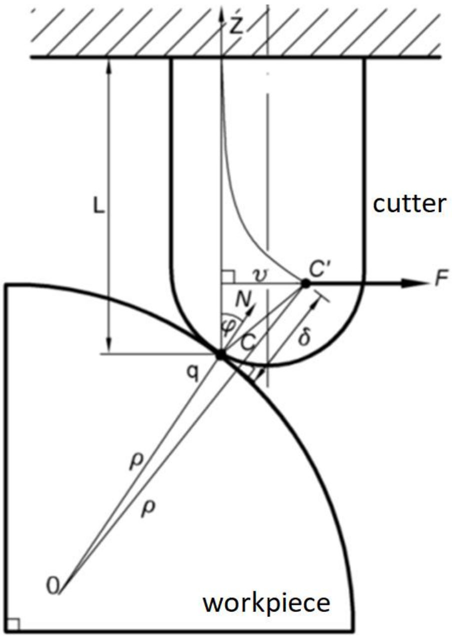

Fig. 1. Deflection of the cutter at a point on the machined surface: δ – the deviation resulting from the deflection of the cutter, *F* – the cutting force perpendicular to the tool spindle axis [N], φ – the angle between the cutter axis (Z) and the vector normal to the surface at the *q* point, *q* – a point on the nominal surface, *L* – the distance between the *q* point and the tool holder plane along the Z axis [mm], *N* – the vector normal to the surface at the *q* point, *C* – the point on the cutter blade that cuts the surface at the q point, *C'* – the position of the *C* point after applying the *F* force, υ – the horizontal deflection of the cutter at the surface machining point C [19]

The deviation resulting from the deflection of the cutter is determined from the following equation [17]:

$$\delta = \frac{S_u F}{K} = \frac{F sin\varphi}{K}\ [\mathrm{mm}] \tag{1}$$

where: S_u – sensitivity of the deviation to the deflection of the cutter in the horizontal direction, approximately equal to $sin\varphi$, K – stiffness of the cutter at the surface machining point [N/m].

To determine the values of the simulated deviations, a nominal CAD model of the machined surface is used. A grid of points is generated on this model, where the values of machining deviations are determined (Fig. 2). Using a typical CAD/CAM system (e.g. MasterCAM), in addition to the coordinates of the determined points, it is possible to obtain information about the direction cosines of the vectors normal to the surface at these points (Tab. 1).

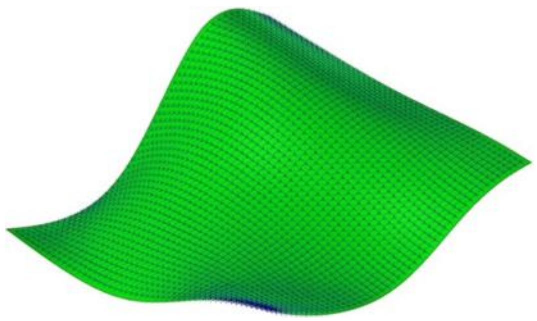

Fig. 2. Example grid of points on the nominal CAD model of the machined surface

Tab.1. Example coordinates of individual points and directional cosines of individual normal vectors

Xnom [mm]	Ynom [mm]	Znom [mm]	cosα	cosβ	cosγ
-20,7133	-22,9143	-7,3222	-0,035814	-0,309553	0,950208
-20,7064	-21,809	-6,9617	-0,028676	-0,309858	0,95035
-20,7006	-20,7737	-6,6242	-0,022714	-0,309431	0,950651
-20,6954	-19,7199	-6,2816	-0,01726	-0,308519	0,951062
-20,6909	-18,6699	-5,9418	-0,012529	-0,306945	0,951645

Then, using equation (1), the value of the theoretical deviations caused by the deflection of the cutter was determined for each nominal point. The generalized cutting force formulas found in tool manufacturer catalogues can be used to determine the cutting force values. Figure 3 shows a map illustrating an example of the distribution of the simulated deviations.

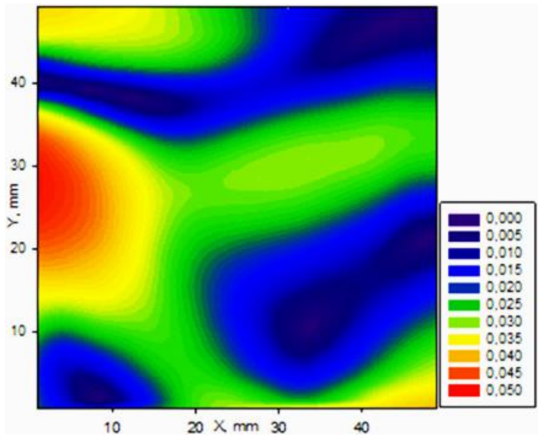

Fig. 3. An example map illustrating the distribution of the simulated deviations

2.2. Creation of a CAD model to simulate the surface after machining

Starting this step, two sets of data are available: the coordinates of points generated on the nominal CAD model of the machined surface, and the corresponding simulated deviations determined using equation (1). The first step is to carry out a correction of the coordinates of the nominal points by the value of the simulated deviation determined at the point. For this purpose, the equation (2) is used.

$$x_{ij}^{cor} = x_{ij}^{nom} + \delta x_{ij}$$
$$y_{ij}^{cor} = y_{ij}^{nom} + \delta \mathrm{y_{ij}} \tag{2}$$
$$z_{ij}^{cor} = z_{ij}^{nom} + \delta z_{ij}$$

where: $\mathrm{x_{ij}^{cor}, y_{ij}^{cor}, z_{ij}^{cor}}$ – the corrected coordinates [mm], $\mathrm{x_{ij}^{nom}, y_{ij}^{nom}, z_{ij}^{nom}}$ – the nominal coordinates [mm], $\mathrm{\delta x_{ij}, \delta y_{ij}, \delta z_{ij}}$ – the components of deviations simulated for each axis [mm].

The creation of a CAD model simulating the surface after machining (Figure 4) is performed by techniques used in reverse engineering. First, corrected points are transferred to the CAD system. Then, a series of curves are interpolated on these points, on which the surface patch is then unwrapped. The most suitable method for describing a surface in this case is the NURBS method.

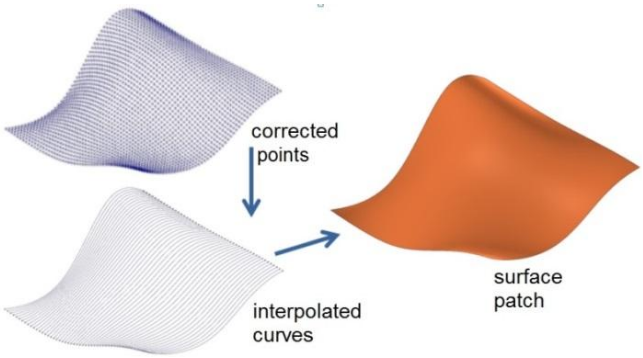

Fig. 4. Creation of a CAD model simulating the surface after machining

2.3. Distribution of the measurement points

With a CAD model simulating the surface after machining, it is possible to proceed to planning measurements on the coordinate measuring machine. The main goal is to minimize the measurement time while achieving the required measurement uncertainty. It was assumed that surface sampling would include the critical areas, i.e. the areas where maximum machining deviations are expected to be found.

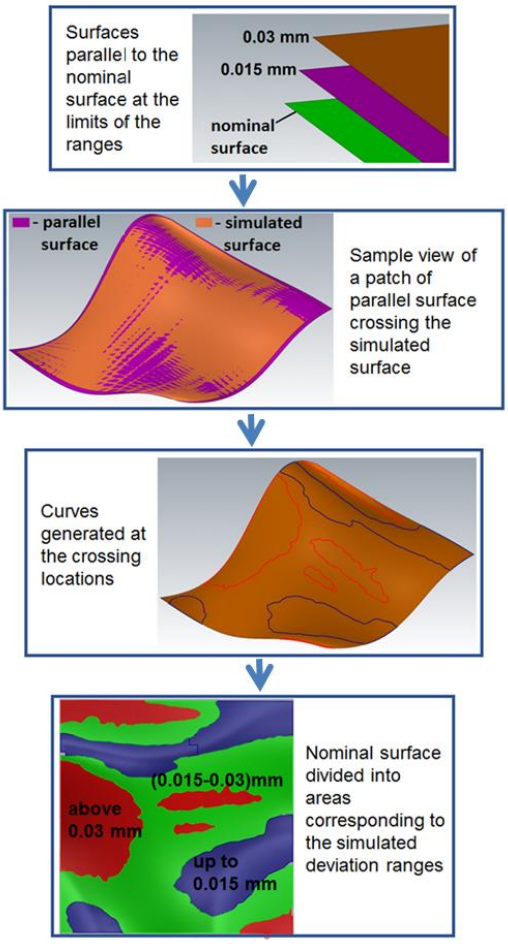

Fig. 5. Dividing the nominal CAD model of the milled surface into areas corresponding to the assumed ranges of the simulated deviations

In order to simplify the adopted measurement strategy, the data should be prepared in the following steps:
- step 1 – division of the nominal CAD surface into areas corresponding to the ranges of the simulated machining deviation values,
- step 2 – transfer of the isolated areas to the software of the coordinate measuring machine (CMM),
- step 3 – generating the measurement points in the selected areas in the CMM software.

The methodology of step 1 is shown in Figure 5.

First, according to the criterion adopted by the user depending on the construction requirements/surface accuracy, the division of the simulated deviation values into the ranges is carried out and the limits of the divisions are determined. Next, surfaces parallel to the nominal surface are created at the limits of the ranges. Each of these surfaces is crossed with a model simulating the surface after machining. Curves are generated at the crossing locations, which are used to divide the nominal surface into areas corresponding to the simulated deviation ranges. The nominal CAD model of the surface prepared this way is transferred to the CMM control software. Using the abilities of the software, the number and location of the measurement points in the measured areas can be managed. The measurements may be limited only to the critical areas, where maximum machining deviations are expected to occur.

3. EXPERIMENTAL VERIFICATION OF THE PROPOSED METHOD

Experimental verification of the proposed method has been carried out on the sample shown in Figure 6. It represents a fragment of the closing surface of an injection mould. The specimen was manufactured from steel 1.2344 (X40CrMoV5-1). Three-axis milling (parallel passes) was carried out using a ball-end mill with a diameter of 6 mm. The following machining parameters were used: feed rate 570 mm/min, step size at successive passes 0.05 mm, finishing allowance 0.25 mm.

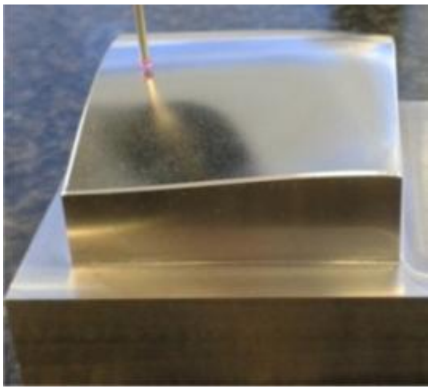

Fig. 6. The manufactured sample

After machining, coordinate measurements were carried out to determine the observed deviations. In this case, a Global Performance measuring machine from Hexagon Metrology was used (PC-DMIS software, $\mathrm{MPEE} = 1.5 + \mathrm{L}/333\ [\mu\mathrm{m}]$, Renishaw SP25M measuring head, 20 mm long stylus with a spherical 2 mm diameter tip). Measurements were taken according to a regular

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grid of 1 × 1 mm points across the surface (Figure 7). This resulted in 2,500 measuring points.

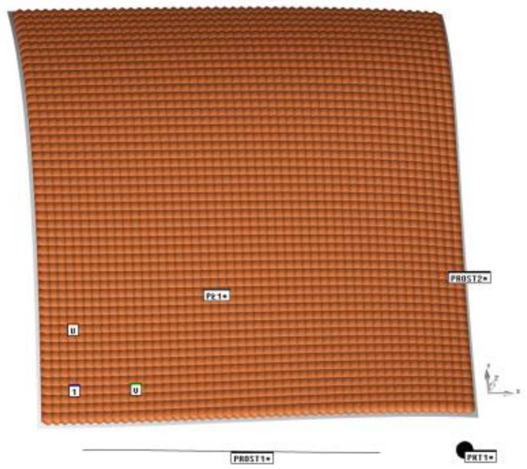

Fig. 7. The distribution of the measurement points over the surface, measurements according to the procedure implemented in the PC DMIS, regular grid, Scan u × v, (1 × 1) mm, 2,500 measurement points

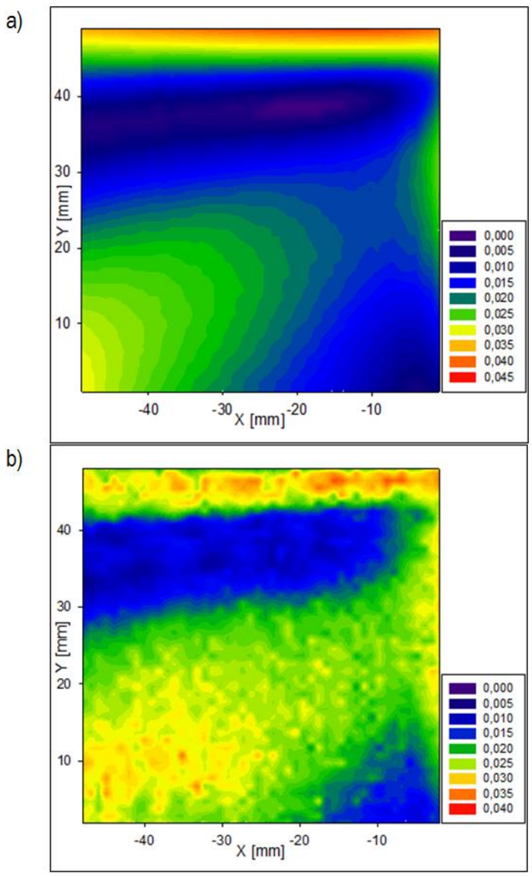

Fig. 8. Maps of the machining deviations: a) determined by a simulation, b) determined after machining based on coordinate measurements

After gathering information on the coordinates and the directional cosines from 2,500 measurement points, the corresponding local simulated deviations were determined using equation (1). Fig. 8a shows a map illustrating the distribution of the simulated deviations. The distribution of the deviations after machining (Fig. 8b) was determined from the coordinate measurements. A high degree of similarity between the numerical simulation and the experimental results can clearly be observed, therefore the experimental verification of the model simulating the machined surface has had a positive result. This allows this model to be adopted to determine the areas representing the ranges of the simulated machining deviations.

The next step was to isolate the areas on the CAD model of the nominal surface corresponding to the assumed ranges of the simulated machining deviation values (the procedure presented in point 1.3). Fig. 9 shows the division of the nominal surface. Different colours represent areas corresponding to four ranges of the simulated deviation values (red - maximum deviation values, green - minimum deviation values).

The nominal CAD model of the surface prepared this way was transferred to the software controlling the coordinate measuring machine (PC-DMIS system). This software allows a wide range of programming 3D surface measurements. The *UVscan* procedure was used in the measurements. Measurements of both the entire surface and selected areas were programmed. The size of the grid of points was also controlled. Figure 10 shows the measurement points generated on the selected areas of the surface.

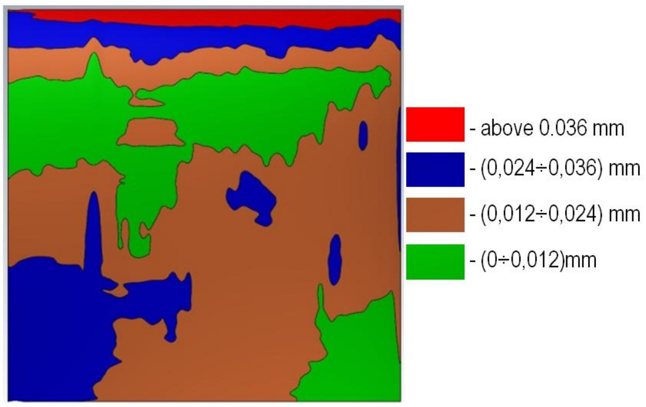

Fig. 9. The machined surface divided into 4 areas of the simulated deviation ranges

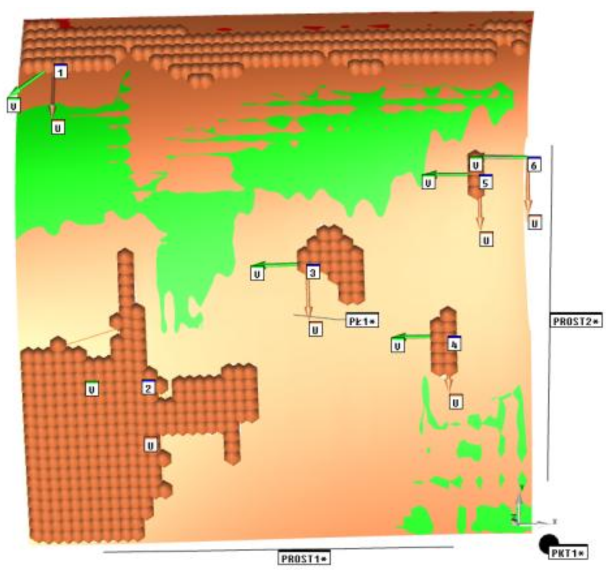

Fig. 10. PC DMIS point distribution (UV scan mode) in area corresponding to deviations of (0.024-0.036) mm

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Coordinate measurements were carried out for the entire CAD model of the surface by sampling according to a regular grid of points as shows Fig. 7 (2,500 measurement points) and according to the proposed procedure. Sampling by grid (1 × 1) mm was performed in areas (fig. 9):

– red and blue [red – a critical area for the largest simulated deviation values, blue – corresponding to the range of smaller deviation values (581 points)],
– red (166 points).

Table 2 presents the obtained results of coordinate measurements.

Tab. 2. Coordinate measurement results (d - diameter of spherical stylus tip, s - sampling step)

Measurement parameters		Number of points	Measurement uncertainty [μm]	Max. local deviation [mm]	Standard deviation [mm]
d [mm]	s [mm]				
2	1	2,500	2,6	+0,0479	0,0018
2	1	581	2,6	+0,0491	0,0012
2	1	166	2,6	+0,0501	0,0012

It can be observed (Tab. 2) that there is a high degree of correspondence between the obtained measurement results and different numbers of measurement points. While maintaining the same measurement uncertainty, the number of measurement points was reduced from 2,500 to 581 and 166. The measurement efficiency is numerous times higher in both cases, while the measurement time was significantly reduced from 1 h 40 min (2,500 points) to approx. 7 min (166 points).

4. SUMMARY

This paper presents a procedure in which the freeform surface measurement strategy is determined from a CAD model simulating the surface after machining. Based on the results obtained, it was shown that coordinate measurements do not have to be performed on the entire measured surface. They can be limited only to critical areas where maximum machining deviations are expected to occur, which significantly reduces the number of measuring points and thus the measurement time. The same measurement uncertainty is maintained. The proposed method makes it possible to improve the efficiency of free-form surface measurement - in the presented case, while maintaining optimal measurement uncertainty, the efficiency increased fourteen times. It should be noted that in order to ensure optimum measurement uncertainty, the measurement parameters should be adapted to the tolerances given in the geometrical specification. The measurement results of the new method and the method involving scanning the entire surface may be considered similar.

The advantage of the proposed method is that it does not require special investments. Standard equipment (machine tools, measuring machines) and CAD/CAM software used in engineering practice can be used in this method. The time to prepare the CAD model simulating the machined surface is short, and the time for coordinate measurement is significantly shorter compared to the traditional measurement method in which the whole surface is measured.

REFERENCES

1. Menq CH, Yau HT, Lai GY. Automated Precision Measurement of Surface Profile in CAD-direct Inspection. IEEE Transactions on Robotics and Automation. 1992;8(2):268-278. https://doi.org/10.1109/70.134279
2. Pahk HJ, Jung MY, Hwang SW, Kim YH, Hong YS, Kim S.G. Integrated precision inspection system for manufacturing of moulds having CAD defined features. International Journal of Advanced Manufacturing Technology. 1995;10:198-207. https://doi.org/10.1007/BF01179348
3. Cho MW, Kim K. New inspection planning strategy for sculptured surfaces using coordinate measuring machine. International Journal of Production Research. 1995;33:427-444. https://doi.org/10.1080/00207549508930158
4. Edgeworth R, Wilhelm RG. Adaptive sampling for coordinate metrology. Precision Engineering. 1999;23:144-154. https://doi.org/10.1016/S0141-6359(99)00004-5
5. Park H, Lee JH. B-spline curve fitting based on adaptive curve refinement using dominant points. Computer-Aided Design. 2007; 39(6):439-451. https://doi.org/10.1016/j.cad.2006.12.006
6. Rajamohan G, Shunmugam MS, Samuel G.L. Sampling strategies for verification of freeform profiles using coordinate measuring machines. Proceedings of 9th International Symposium on Measurement and Quality Control. Madras India. 2007;135-140.
7. ElKott DF, ElMaraghy HA, ElMaraghy WH. Automatic sampling for CMM inspection planning of free-form surfaces. International Journal of Production Research. 2002;40(11): 2653-2676. https://doi.org/10.1080/00207540210133435
8. ElKott DF, Veldhuis SC. Isoparametric line sampling for the inspection planning of sculptured surfaces. Computer-Aided Design. 2005;37:189-200. https://doi.org/10.1016/j.cad.2004.06.006
9. ElKott DF, Veldhuis SC. CAD-based sampling for CMM inspection of models with sculptured features. Engineering with Computers. 2007;23:187-206. https://doi.org/10.1007/s00366-007-0057-y
10. Obeidat SM, Raman S. An intelligent sampling method for inspecting free-form surfaces. International Journal Advanced Manufacturing Technology. 2009;40:1125-1136. https://doi.org/10.1007/s00170-008-1427-3
11. Rajamohan G, Shunmugam MS, Samuel GL. Effect of probe size and measurement strategies on assessment of freeform profile deviations using coordinate measuring machine. Measurement. 2011;44: 832-841. https://doi.org/10.1016/j.measurement.2011.01.020
12. Rajamohan G, Shunmugam MS, Samuel GL. Practical measurement strategies for verification of freeform surfaces using coordinate measuring machines. Metrology and Measurement Systems. 2011;18:209-222. http://dx.doi.org/10.2478/v10178-011-0004-y
13. Bowen Y, Fan Q, Nuodi H, Xiaosun W, Shijing W, Dirk B. Adaptive sampling point planning for free-form surface inspection under multi-geometric constraints. Precision Engineering. 2021;72:95–101. https://doi.org/10.1016/j.precisioneng.2021.04.009
14. Zhaoyu L, Dong H., Xiangyu L, Xiaoke D, Pengcheng H, Jiancheng H, Yue H, Hongyu Y, Kai T. Efficient five-axis scanning-inspection path planning for complex freeform surfaces. Robotics and Computer–Integrated Manufacturing. 2024;86:102687. https://doi.org/10.1016/j.rcim.2023.102687
15. Sliusarenko O, Escudero G, González H, Bartoň A, Ortega N, Lacalle LNL. Constant probe orientation for fast contact-based inspection of 3D free-form surfaces using (3+2)-axis inspection machines. Precision Engineering. 2023;84:37–44. https://doi.org/10.1016/j.precisioneng.2023.06.013
16. Magdziak M. Determining the strategy of contact measurements based on results of noncontact coordinate measurements. Procedia Manufacturing. 2020;51: 337–344. https://doi.org/10.1016/j.promfg.2020.10.048
17. Lim EM, Menq CH. The prediction of dimensional error for sculptured surface productions using the ball-end milling process – part 2: surface generation model and experimental verification. International Journal of Machine Tools and Manufacture. 1995;35:1171-1185. https://doi.org/10.1016/0890-6955(94)00045-L

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