

## MEASUREMENT OF FREE-FORM SURFACES ON CNC MILLING MACHINE CONSIDERING TOOL WEAR AND SMALL CHANGES OF ITS WORKING LENGTH AND OFFSET RADIUS

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### Summary

This paper contains a survey of the selected strategies of measurements concerning free-form surfaces which may be used during in-process measurements of a workpiece on a CNC milling machine. Additionally, a supplement to conventional strategy of measurements of free-form surfaces directly on CNC machine tool is proposed, considering such variable factors as the real working length and real working radius of applied milling cutter as well as its wear. Results of experimental and numerical investigations are presented which show how tool wear and small changes of real working length and real working radius of applied milling cutter influence the shape and accuracy of machining a workpiece containing some free-form surfaces.

**Keywords:** coordinate measurement technique, on-machine measurement, CNC machine tool, free-form surfaces

### Pomiary powierzchni swobodnych na obrabiarce CNC uwzględniające zużycie narzędzia oraz małe zmiany jego roboczej długości i promienia

### Streszczenie

W artykule przedstawiono przegląd wybranych strategii pomiaru powierzchni swobodnych, które mogą mieć zastosowanie w trakcie pomiaru przedmiotu na obrabiarce sterowanej numerycznie. Dodatkowo zaproponowano uzupełnienie strategii pomiaru realizowanego bezpośrednio w warunkach produkcyjnych o czynniki wynikające ze zmiennej długości narzędzia skrawającego i rzeczywistej wartości jego promienia, a także zużycia narzędzia w trakcie procesu obróbki. Przedstawiono wyniki badań doświadczalnych, numerycznych wizualizujących wpływ zmiany długości i promienia narzędzia oraz jego zużycia na postać geometryczną wybranych powierzchni swobodnych.

**Słowa kluczowe:** współrzędnościowa technika pomiarowa, pomiar na obrabiarce, obrabiarka CNC, powierzchnie swobodne

## 1. Introduction

The requirements concerning manufacturing accuracy and economic efficiency led to application of computer numerical control (CNC) machine tools

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with measurement probes fixed with the toolholder in the spindle of CNC machine tool (Fig. 1). Therefore, measurements made directly on the same CNC machine tool on which the workpiece is machined, called on-machine measurements (OMM), are often used in the case of manufacturing of complex high-tech products, especially in automobile and aerospace industries. The well known manufacturers of measurement probes which can be used for such purposes are:

- Blum-Novotest GmbH,
- HEIDENHAIN,
- MARPOSS S.p.A.,
- M&H Inprocess Messtechnik GmbH,
- Renishaw plc.

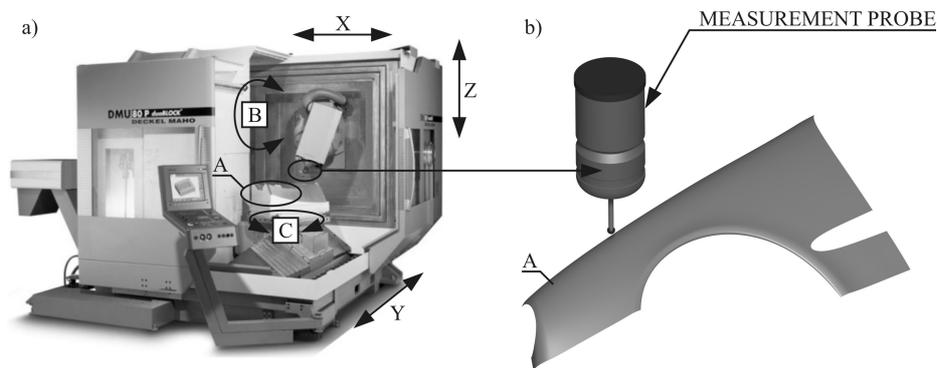


Fig. 1. The DMU 80P duoBLOCK machine tool equipped with the measurement probe MP700, operating in the Research and Development Laboratory for Aerospace Materials at the Rzeszow University of Technology: a) controlled axes, b) enlarged view of a measurement probe and a workpiece

Programming of measurement procedures on a suitable CNC machine tool is in general a similar process to programming of measurement procedures on coordinate measuring machines (CMM). It can be supported by using special programs or systems for computer aided measurements, called computer aided inspection (CAI) systems. Some of the well known CAI systems which make programming of measurement procedures more convenient compared to manual programming are:

- 3D Form Inspect (M&H Inprocess Messtechnik GmbH),
- FormControl V4 (Blum-Novotest GmbH),
- Inspection Plus (Renishaw plc),
- PC-DMIS NC Gage (M&H Inprocess Messtechnik GmbH),
- PowerINSPECT OMV (Delcam),
- Productivity+ (Renishaw plc),
- Renishaw OMV (Renishaw plc).

Application of the above named software makes also possible performing on-machine measurements of free-form surfaces which become an integral part of manufacturing process of a product machined on CNC machine tools.

The fundamental disadvantage of measurements made on CNC machine tools is lower accuracy compared to measurements on CMMs. Based on the recommendations of the Renishaw plc, the accuracy of measurement process performed in manufacturing conditions can be improved by the application of [1]:

- regular testing and certification of a measurement probe,
- measuring the errors of CNC machine tool using suitable laser interferometer, e.g. XL-80 or ML10 as well as ballbar systems QC20-W or AxiSet Check-Up,
- considering the influence of temperature fields on the geometry and accuracy in the analysis of measurements performed directly on CNC machine tool. According to recommendations of the Renishaw plc such types of errors can be compensated using some master sample (standard sample of master shape) for which the measurement process, called calibration, was formerly done using more accurate CMMs than applied CNC machine tools. After calibration, master samples are measured on applied CNC machine tools. The determined differences between results obtained on CNC machine tool and CMM are used for computing correction coefficients, which can be further utilized for the analysis of measurements made on the same CNC machine tools in manufacturing conditions. According to recommendations of the Renishaw plc:
  - master sample and manufactured workpiece made and measured on CNC machine tool in manufacturing conditions should have similar temperatures,
  - master sample should be made of the same type of material as manufactured workpiece made and measured on CNC machine tool,
  - master sample should be positioned for the process of calibration in similar location, within the working space of applied CNC machine tool, as the location of manufactured and measured workpiece,
  - both master sample and manufactured workpiece should be measured in short intervals of time.

Depending on the application and requirements concerning the accuracy of measurements the Renishaw plc recommends various types of master samples:

- master sample built of standard geometric features, used for the whole gamut of workpieces,
- master samples built of geometric features similar to the ones existing in workpieces manufactured and measured on applied CNC machine tool,
- master samples which exactly reflect the general geometry of workpieces manufactured and measured on applied CNC machine tool. Such master samples are used for measuring of workpieces which must be made with very good accuracy.

The Renishaw plc and the other firms focusing their activities on doing measurements, manufacturing equipment and processes did not publish recommendations concerning the strategy of measurements of workpieces on CNC machine tools. Such strategy, however, significantly influences the time and accuracy of OMMs made on CNC machine tool, equipped with measurement probe, in manufacturing conditions. Based on the literature survey focused on this subject it becomes possible to specify various methods for determining the location of measurement points on the boundary surface of measured workpiece. Several already developed methods used for determining the location of measurement points on boundary surfaces with various sizes and variable curvatures are briefly described in the following.

Some examples concerning the strategy of measurements of sculptured surfaces utilizing isoparametric line sampling are presented in paper [2]. The attention is focused on suitable choice of scanning curve on the surface of measured workpiece using:

- measurement probe working in scanning mode and
- separate coordinate measuring machine.

In the analyzed paper two methods for selecting the location of scanning curve are proposed:

- automatic sampling and
- sampling depending on the curvature of measured free-form surface.

Both methods are limited by the maximum number of scanning curves and the minimum distance between the curves. The above named methods are also compared with the method assuming the uniform distribution of scanning curves lying on measured surface. The last one, unfortunately, is little effective as far as the time of measurements is concerned. Assuming the location and shape of selected scanning curves computed according to proposed algorithms, the model consisting of substitute surface, i.e. a surface determined using collected measurement data, is created. In order to compute the deviations, this model is used for comparison with the nominal CAD model of a manufactured free-form surface. Information about these deviations is necessary for proper work, at each stage, of the above named algorithms. Both algorithms presented in paper [2] work in an iterative mode and their work is completed when either certain assumed levels of accuracy or limiting conditions are obtained.

The first algorithm, i.e. the automatic sampling algorithm consists in placing the successive scanning curve in location where the maximum deviation between measured and nominal CAD models of a manufactured free-form surface is achieved. The second algorithm presented in the referenced paper localizes scanning curve on the grounds of results of computations focused on average curvature of the measured free-form surface. This procedure is called curvature change-based sampling.

The paper [3] contains four sampling algorithms of free-form surfaces. The first consists in uniform distribution of measurement points in directions  $u$  and  $v$  of considered surface and may be used in the case of surfaces with moderate changes of curvature. The second one is based on division of the whole boundary surface on smaller surfaces – surface patches – in order to sort them in the sequence of increasing or decreasing size. The surface patch of the biggest size obtains in the second algorithm the biggest number of measurement points. The potential fault of using such algorithm consists in neglecting small surface patches which exhibit significant changes of curvature. In the third algorithm all considered surface patches are sorted in a sequence of increasing or decreasing average curvature computed separately for each of them. Similarly to the second algorithm the surface patch of the biggest average curvature obtains the biggest number of measurement points. The fourth algorithm is a certain combination of the second and the third one, which trace the sizes of surface patches and their average curvatures, respectively. This algorithm gives the user some possibility to define weighting coefficients for each criterion, associated with either the size of surface patch or its average curvature. These weighting coefficients enable influencing the importance of one criterion over the other, depending on the changes of the shape of the measured free-form surface.

In addition, the referenced paper [3] contains an algorithm for automatic selection of method of placing measurement points, from the four methods previously described, which verifies measured surface according to its complexity and decides in each particular case which one of the measurement methods is optimal. All of the presented four algorithms are compared with the algorithm assuming uniform distribution of measurement points and the method utilizing genetic algorithms, which are available within the Matlab package. In the case of application of genetic algorithms the objective of optimization computations done in Matlab is the minimization of the maximum deviation between measured and nominal CAD models of a manufactured free-form surface.

The algorithm concerning placing scanning curves on trimmed free-form surfaces, consisting of several surface patches or a set of joined surfaces is described in paper [4]. Numerical model consisting of substitute surfaces representing real workpiece boundaries is created from measurements made along selected scanning curves, similarly to approach utilized in algorithms presented in paper [2]. This model is compared with the nominal CAD model consisting of nominal free-form surfaces. In the process of the localization of scanning curves on the measurement surface the following factors are considered:

- the change of curvature along each scanning curve,
- information about how big is the portion of scanning curve included within the boundaries of considered surface or surface patch,

- the deviation between the model consisting of substitute surfaces, representing workpiece boundaries, and the nominal CAD model of manufactured free-form surfaces.

The algorithm works in an iterative mode. In the first step of the algorithm the first and the second factors listed above are considered. In the following, after each step, the third factor is considered for the location of scanning curve on measured surface. The work of this algorithm is completed when the determined deviation between the nominal CAD model and the model consisting of substitute surfaces becomes less or equal the magnitude of assumed tolerance. In the case of models consisting of several surfaces the algorithm is applied to each of them.

The method described above takes into consideration limiting conditions concerning the maximum allowable number of scanning curves and the maximum deviation computed for the model consisting of substitute surfaces. The measurement plan utilizing the idea of suitable localization of scanning curves is created for both  $u$  and  $v$  directions associated with measured surface and its evaluation is performed in respect of:

- the change of curvature along selected direction,
- the magnitude of deviation between the model consisting of substitute surfaces and the nominal CAD model consisting of corresponding surfaces,
- continuity between joined surfaces. In the case of models consisting of several surfaces so-called continuity coefficients are computed on boundary curves at which adjacent surfaces are joined. Those coefficients represent, to some extent, the continuity of superior complex surface and consider the directions of vectors normal to constituent surfaces as well as the curvatures of joined surfaces computed at points located on common boundary curves between adjacent surfaces. The coefficients are then compared with related coefficients determined for the nominal CAD model.

Creation of the model consisting of substitute trimmed surfaces contains the following steps:

- reading the model of trimmed surface and separating the mathematical description of trimming curves and untrimmed surface from the trimmed one,
- sorting of trimming curves – in the plan of measurements there are considered all those boundary curves which belong to considered surface, independently of their location in the sequence of sorted curves,
- creating the model of substitute untrimmed surface on the grounds of selected scanning curves,
- utilizing the trimming curves for trimming the substitute surface obtained in the preceding step.

The next three algorithms developed for the selection of measurement points on free-form surfaces consisting of surface patches are described in paper [5]. Those algorithms are compared with the following methods:

- the uniform distribution of measurement points in directions  $u$  and  $v$  of considered surface,
- distribution of measurement points depending on the location of particular patch in the sequence of patches with increasing or decreasing size.

In the first algorithm so-called critical points are determined for each surface patch depending on curvatures computed for that patch. In the following step the model of substitute surface is created for the initially selected measurement points and the deviation is computed between the created surface and the nominal one. If the deviation is outside the range of allowable tolerance then additional points are appended to the set of measurement points with consideration to the distribution of previously computed critical points. After each step of appending new measurement points the model of substitute surface is created and compared with the nominal one by computing the deviations between those surfaces. The procedure appends new measurement points to those surface patches at which the computed densities of measurement points are low. The densities of measurement points are computed with the consideration to the critical points previously located on such patches.

The second algorithm assumes the maximum number of measurement points located on particular measured surface. In this method the surface patches are sorted in a sequence of increasing or decreasing size. The number of measurement points is determined for each surface patch depending on its size and location within the ordered sequence. The initial measurement points, are the critical points, similarly to the previously described algorithm. Considering the points chosen for measurements the model of substitute surface is created and compared with the nominal one by computing the deviations between those two surfaces. In the case when the deviation is outside the range of allowable tolerance, new points are appended to the existing ones with consideration to the location of critical points and the maximum number of measurement points defined before the start of the algorithm.

At the beginning of the third algorithm the surface patches are sorted in a sequence of their increasing or decreasing average curvature. The number of points for the surface patch at the beginning of that sequence determines the number of measurement points for the other patches in the sequence. The location of measurement points is selected with consideration to the distribution of curvature at each surface patch. If better accuracy is required, then the algorithm considers additional step of computations. At that stage the analyzed sequence of surface patches is sorted according to increasing or decreasing size. Likewise in the first step of the described algorithm, the number of points computed for the surface patch located at the beginning of the above named sequence determines the number of points for the other patches. New measurement points are added with consideration to the number of already appended points according to the sorted, with increasing or decreasing curvature,

sequence of patches. The points are added to each surface patch taking into account the distribution of measurement points obtained after computations made at the first stage of the algorithm.

In the paper [6], among other things, an algorithm is presented concerning the selection of measurement points, according to which bigger number of points is appended at those areas of surfaces where bigger curvature occurs. At the first stage of algorithm action only two extreme points belonging to considered surface are taken into account. Those points are joined with the segment of straight line and using chord length criterion the distance between the segment and surface is computed. If that distance is outside assumed tolerance, then the next measurement point is considered. It is located in the midpoint between the current extreme points. In the following stage a line segment is created between the one of the extreme points and the recently defined midpoint. Next, the procedure is repeated.

The described above measurement strategies, concerning free-form surfaces, select the locations of measurement points on the grounds of the shape of measured workpiece by linking information about the curvatures of considered surfaces with the difficulty of their manufacturing. They, however, do not take into account the other factors existing in manufacturing processes and influencing the accuracy of manufactured product.

## 2. Experimental investigations

Several factors play important role in the machining processes performed on CNC machine tools. Those of them, which significantly influence the accuracy of manufactured products [7] are:

- kinematics of particular CNC machine tool,
- temperature distribution,
- cutting forces,
- control system of particular CNC machine tool.

Additional factors influencing the accuracy of machining workpieces are the wear of applied tool as well as its varying real working length and real working radius. The variation of them can be caused by:

- multiple fixing of applied tool with toolholder in machine tool spindle, which usually takes place in various machining processes concerning products with complex shapes,
- potential misalignments, which can occur in fixing of tool inserts to cutting arbor,
- various levels of repeatability of measurement system used for inspection of tools,
- rotational speed of applied CNC machine tool spindle, etc.

According to recommendations of the Renishaw plc [1], one of the methods for increasing manufacturing accuracy of particular product consists in regular measurement of applied tool during the machining process. It is not a common industrial practice. However, the results of measurements show (Tables 1 and 2) that when high accuracy is required the variation of real working parameters of applied tools and the factors influencing them should not be neglected.

Table 1. The influence of fixing tool inserts to cutting arbor, fixing tool with toolholder in machine tool spindle and tool inspection system on real working geometric parameters of applied tool

No	Fixing of tool insert	Fixing the tool in the spindle	Repeatability of laser	Result, real tool offset radius R, mm	Result, real working length of a tool L, mm
1	■	■		8.001	187.053
2				8.001	187.055
3				8.002	187.057
4		■		8.002	187.060
5				8.001	187.062
6				8.002	187.063
7		■		8.003	187.065
8				8.004	187.066
9				8.003	187.068
10	■	■		8.015	187.063
11				8.015	187.063
12				8.015	187.063
13		■		8.017	187.064
14				8.017	187.065
15				8.019	187.065
16		■		8.019	187.066
17				8.019	187.066
18				8.019	187.066
19	■	■		8.012	187.066
20				8.011	187.067
21				8.012	187.066
22		■		8.013	187.066
23				8.012	187.067
24				8.011	187.068
25		■		8.014	187.067
26				8.012	187.068
27				8.013	187.067
			<b>Dispersion</b>	<b>0.015</b>	<b>0.018</b>

Experimental investigations described in this paper are focused on determination of the influence of the above named factors on the accuracy of machining. They were made in the Research and Development Laboratory for Advanced Materials at the Rzeszow University of Technology using the CNC DMU 80P duoBLOCK machine tool (DMG) equipped with the SINUMERIK 840D control system (Siemens) and the system for the inspection of applied tools LaserControl NT (BlumNovotest GmbH). The experiments were done using the tool with inserts designated R300-016A20L-08L/R300-0828M-PM. Rotational speed of the CNC machine tool spindle was 1000 rpm. All measurements used for determining the influence of each of the above named factors on the real working geometric parameters of applied tool were repeated 3 times. The results are shown in Table 1.

Moreover, the real working length of tool was measured for various rotational speeds of the spindle of applied CNC machine tool. They were repeated 3 times for each rotational speed of the spindle. Obtained results are presented in Table 2.

Table 2. The influence of rotational speed of the spindle on real working length of applied tool

No	Rotational speed, rpm	Result 1, mm	Result 2, mm	Result 3, mm
1	1000	187.067	187.067	187.067
2	2000	187.068	187.067	187.068
3	4000	187.068	187.068	187.068
4	6000	187.068	187.069	187.069
5	8000	187.070	187.070	187.070
6	10000	187.071	187.072	187.072
7	12000	187.075	187.075	187.075
8	13000	187.077	187.078	187.077
9	14000	187.076	187.077	187.076
	<b>Dispersion</b>	<b>0.01</b>	<b>0.011</b>	<b>0.01</b>

Additional investigations were done for the determination of influence of wear index at tool flank  $VB_{Bmax}$  on the machined shape of free-form surface (Fig. 2). The considered surface contains convex and concave areas and can be approximated using polynomials of fourth order in both directions associated with variable parameters  $u$  and  $v$ , respectively. The sample was made of titanium alloy Ti6Al4V and was machined using cutting tool with inserts designated R300-016A20L-08L/R300-0828M-PM. The titanium alloy Ti6Al4V was chosen because it was important to determine tool wear after relatively short time of machining the workpiece. The following machining parameters were applied:

- $v_c = 100, 130, 200, 300$  m/min,
- $n = 2885, 3750, 5769, 8654$  rpm,

- $f = 0.1$  mm/tooth,
- $a_p = 0.3$  mm,
- $a_e = 8$  mm.

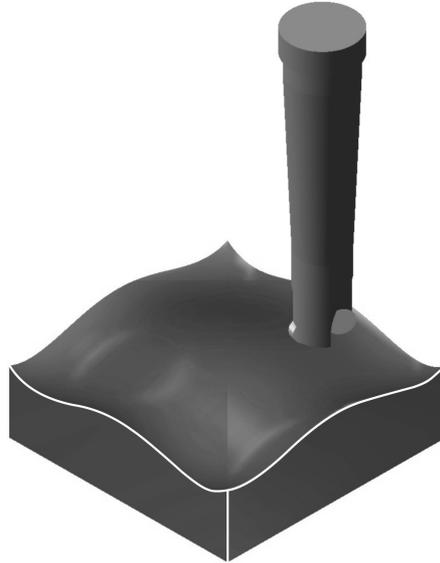


Fig. 2. Free-form surface machined for the determination of influence of tool wear on the shape of machined workpiece

Tool wear was measured using stereoscopic microscope equipped with camera Nikon SMZ 1000 and software NIS-Elements AR made by Nikon. Some representative results of performed investigations concerning tool wear obtained for the maximum selected cutting speed are shown in Figs. 3 and 4.

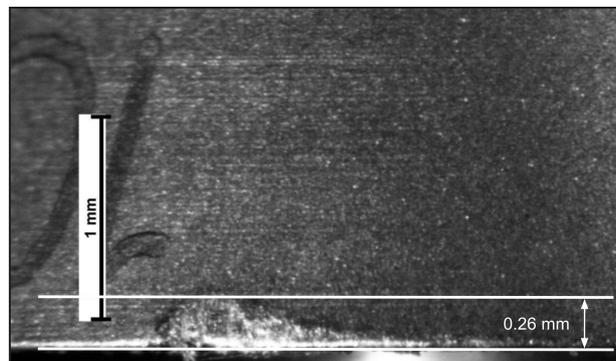


Fig. 3. Tool wear on tool flank of the first tool insert after machining Ti6Al4V with speed  $v_c = 300$  m/min

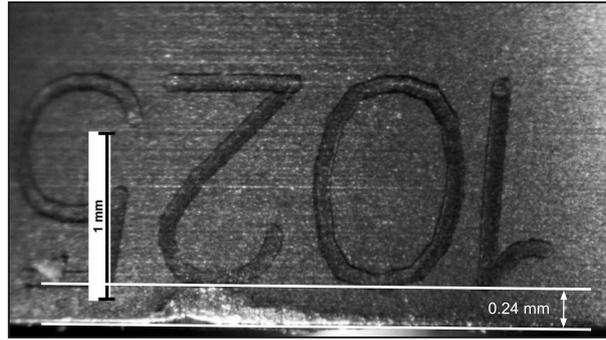


Fig. 4. Tool wear with visible loss of material observed on tool flank of the second tool insert after machining Ti6Al4V with speed  $v_c = 300$  m/min

During the next stage of investigations machining processes were made using new and worn out tool inserts and two samples made of aluminum alloy (grade EN AW-2007), respectively. In this case the aluminum alloy was chosen in order to minimize those distortions of results which may be caused by other factors influencing machining accuracy than tool wear.

Both manufactured surfaces were measured using the coordinate measuring machine LH87 ( $MPE_E = 2.0 + (L/300) \mu\text{m}$ ,  $MPE_p = 2.0 \mu\text{m}$ ) equipped with the measurement probe SP25M ( $MPE_{Tij} = 2.6 \mu\text{m}$ ,  $MPE_\tau = 72.0$  s) and suitable software for performing measurements Metrosoft. The measurements were done along 10 scanning curves. The results of comparing machined surfaces using two tool inserts along the free-form scanning curves are shown in Fig. 5.

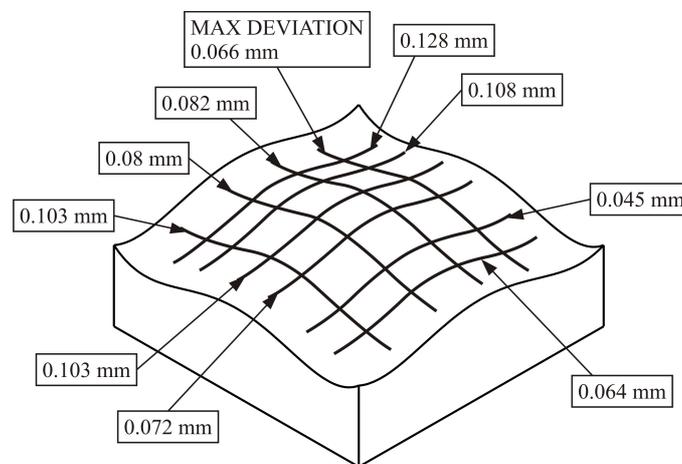


Fig. 5. Results of comparing free-form surfaces along the free-form scanning curves (maximum deviation) obtained for two tool inserts

### 3. Numerical investigations

The results presented in Table 1 yield that, in the case of applied tool and CNC machine tool, the range of tool length is 0.015 mm and the range of tool radius is 0.018 mm. The objective of performed research was determination and visualization of the influence of real working length and radius of applied tool on the accuracy of manufacturing free-form surfaces with various levels of complexity (Fig. 6). Numerical investigations were made using the CATIA V5R19 system and in particular its two modules Surface Machining and Digitized Shape Editor. The investigations covered both simulation of machining and making a comparison of obtained results in the form of models representing machined surfaces. Those surfaces were received for the extreme magnitudes of real working length and radius of applied tool. At the stage of simulations the tolerance of machining was 0.01 mm and the distance between the adjacent tool paths was 0.1 mm. Numerical investigations were performed for milling cutters with diameters 5 and 10 mm. Some of the results are shown in Figs. 7-10.

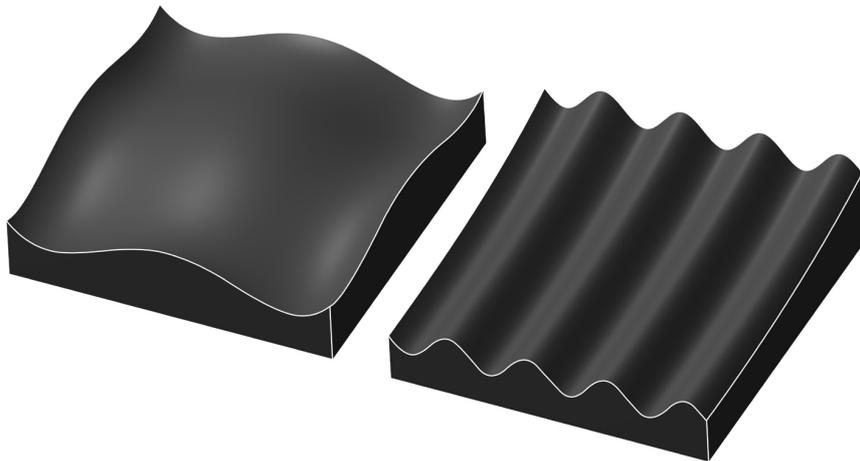


Fig. 6. Free-form surfaces used in simulations

From the results of investigations obtained for the samples with various free-form boundary surfaces and different curvatures in both parametric directions  $u$  and  $v$  it follows, that the influence of tool offset radius associated with the real working radius of tool on the accuracy of machining was not substantial. On the other hand, as far as the geometric accuracy of machined free-form surface is concerned more significant factor was the real working length of a tool. Therefore, only the influence of the real working length of applied tool on the accuracy of machining was illustrated on the graphs.



Fig. 7. The influence of the real working length of applied tool on the accuracy of machining free-form surface considered in investigations; surface 1, tool diameter 5 mm



Fig. 8. The influence of the real working length of applied tool on the accuracy of machining free-form surface considered in investigations; surface 1, tool diameter 10 mm

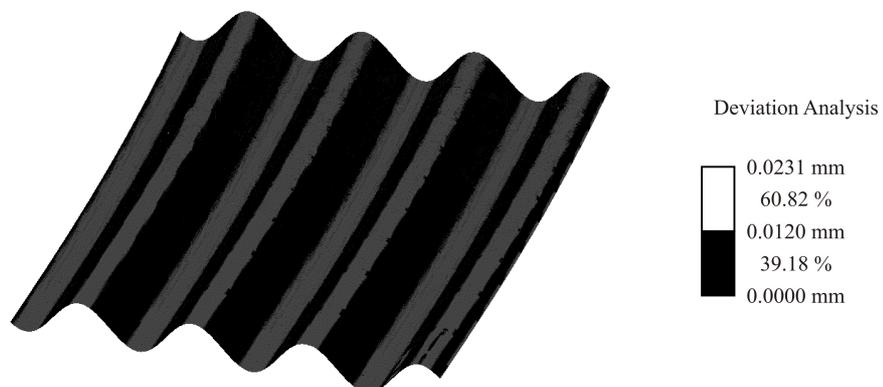


Fig. 9. The influence of the real working length of applied tool on the accuracy of machining free-form surface considered in investigations; surface 2, tool diameter 5 mm

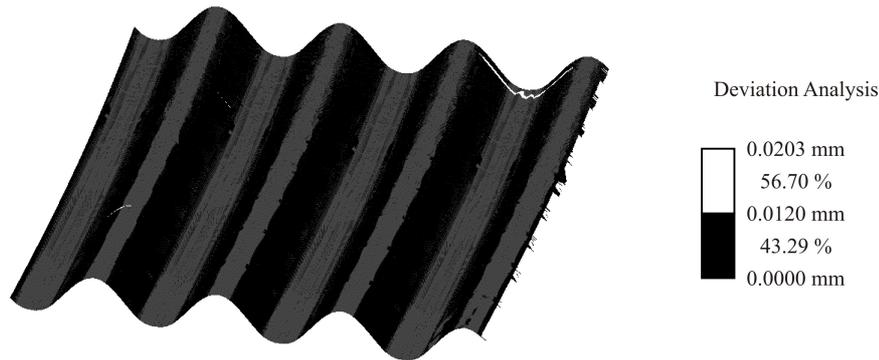


Fig. 10. The influence of the real working length of applied tool on the accuracy of machining free-form surface considered in investigations; surface 2, tool diameter 10 mm

#### 4. Conclusions

On the grounds of performed experimental and numerical investigations it can be concluded, that in order to obtain high machining accuracy of a product it becomes important to make systematic measurements of applied tools applied in manufacturing process. Those measurements should be included in the general strategy of the process as its integral part. Such approach is compatible with the general recommendations of manufactures of measurement equipment used for monitoring machining processes.

The strategy of on-machine measurements requires the determination of suitable location of measurement points on machined surface. It should take into account such geometric loci at which there exists big probability that the maximum machining errors can appear.

From published results of numerical investigations described in the literature and briefly presented in the first section of this work it follows, that in the case of free-form surfaces a combination of several factors should be taken into account. The most important are:

- the magnitude of average curvature at each considered patch,
- the size of each patch,
- the change of curvature along selected direction,
- the magnitude of deviation between the model consisting of substitute surfaces and the nominal CAD model consisting of corresponding surfaces, etc.

The investigations made in this work concerned the determination of the changes of real working length of applied tool and its real offset radius as well as tool wear in the process of machining of free-form surfaces. The obtained results of performed investigations show, that collected information from both numerical simulations and experimental investigations is helpful for establishing the measurement strategy of free-form surfaces. In particular, it can be used for

the determination of such zones of measured surface where the measurement points should occur with greater density than at the rest areas of that surface. Therefore, further research should be focused on developing efficient algorithms for establishing suitable positions of measurement points on the investigated surfaces of a workpiece. They should take into consideration, among the others, not only the shape of free-form surface to be machined on CNC machine tool, but also the magnitudes of real working length of applied tool and its real offset radius as well as tool wear, because their influence on the accuracy of machining free-form surfaces, especially in the aerospace industry must not be neglected.

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