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OPTIMIZING SAMPLING PARAMETERS OF CMM DATA ACQUISITION FOR MACHINING ERROR CORRECTION OF FREEFORM SURFACES

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Abstract: An optimization study using the design of experiment technique is described, in which the surface profile height of a freeform surface, determined in coordinate measurements, is the response variable. The control factors are coordinate sampling parameters, i.e. the sampling grid size and the measuring tip diameter. As a result of the research, an optimal combination of these parameters was found for surface mapping with acceptable measurement uncertainty. The presented study is the first stage of optimization of machining error correction for the freeform surface and was intended to take into account mechanical-geometric filtration of surface irregularities caused by these geometrical parameters. The tests were carried out on a freeform workpiece milled with specific machining parameters, Ra of the surface roughness was 1.62 µm. The search for the optimal combination of parameters was conducted using Statistica software.

Key words: Freeform Surface, Machining Error Correction, Coordinate Measurement, Measurement Parameters, Design of Experiment Technique

1. INTRODUCTION

Objects with freeform surfaces are more and more often designed for functional and aesthetic reasons. The complex geometries of such surfaces are challenging both at the manufacturing stage and at the accuracy assessment stage.

The first step in accuracy assessment of freeform surfaces is to map the actual geometry with the use of a cloud of points. For that purpose, coordinate measuring machines (CMMs) with ball-tip touch probes are usually used (Savio et al., 2007; Sładek, 2016).

Numerically controlled CMMs make it possible to generate the path of automatic movement of the touch probe, i.e. to generate nominal points on the CAD model, according to the adopted criterion. The distribution and number of these points are called the sampling strategy. The complete measurement plan involves also configuration of the measuring probe set, i.e. the orientation and length of the stylus, and also the ball tip diameter.

In coordinate measurements of freeform surfaces, local deviations at the measurement points, i.e. normal deviations of the measurement points from the nominal surface represented by the CAD model, are determined. These deviations may be the basis for determining geometric deviations or corrections compensating machining errors. Both of these applications require a complete knowledge of the surface. However, information on surface irregularities depending on the adopted measurement parameters – the sampling step and probe tip diameter – are separated as early as at the sampling stage, because both these factors cause mechanical-geometric filtration of irregularities (Adamczak et al., 2010; Rajamohan et al., 2011a, 2011b). Rajamohan et al. (2011b) in their calculations included the contact error resulting from the surface curvature for the specified probe tip size in the performed computer simulations of various sampling strategies. Moreover, they observed the effect of mechanical-geometric filtration bringing about minimising of the observed surface deviation in measurements with the use of a ball with a bigger diameter.

It is assumed that measurement points faithfully represent measured surfaces. However, measurement results are always burdened with uncertainty. One of the reasons for measurement uncertainty, in addition to the contributions of measuring equipment, workpiece geometry and measurement conditions, is the sampling strategy (Mehrad et al. 2013; Moroni and Petro, 2014; Weckenmann et. al., 2004) whose influence is entirely dependent on the metrologist. An unreasonable strategy planning can be the largest uncertainty contributor. Considering the measurement time, the number of points should be as low as possible, while larger numbers of points characterise surfaces more accurately. Therefore, a strategy is intensely searched for in which the number of points would be as low as possible, and their distribution would enable an efficient surface mapping with an acceptable measurement uncertainty. In the area of accuracy assessment, different sophisticated methods for distributing points, both on geometric primitives and freeform surfaces, are used. Some of the researchers pay more attention to the number of points, whereas others focus on the distribution of measurement points (Moroni and Petro, 2014; Poniatowska, 2012; Obeidat and Raman, 2009). In the application to the correction of machining errors, the only solution is to measure according to the regular grid of points, as in reverse engineering, but in this case measurements are based on the CAD model.

In this paper, in search of the optimal combination of sampling parameters research was conducted using the DOE (Design of Experiments) technique. This technique may be applied to solving problems related to the manufacturing and measurement processes, in order to change these processes and to understand the influence of different factors on the final process or product quality

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(Karaszewski and Skrzypczyńska, 2013; Kowalczyk, 1995). DOE is an experimental technique that helps to investigate (design) the best combinations of process parameters, changing quantities, levels, and combinations, in order to obtain statistically reliable results. It is a way that may be followed so as to find solutions to process problems with greater objectivity by means of experimental and statistical techniques. In the work, the loss of measurement process quality, caused by applying various combinations of sampling parameters, was investigated.

In the literature of the art, many researchers sought for optimal measurement parameters and uncertainties, both in touch measurements (Feng et al., 2007; Moroni and Petro, 2014) and non-touch measurements (Al-Ahmari and Aalam, 2015), including applying DOE techniques (Al-Ahmari and Aalam, 2015; Barini et al., 2010, Feng et al. 2007)). The influence of many parameters was taken into account, such as: measuring speed, stylus length, number of points and measuring distances.

The tests described in the present paper were carried out on a milled freeform surface classified by Savio et al. (2007) as a surface of medium shape complexity characterised by moderate to large curvature changes. The problem of selecting surface sampling parameters – the tip diameter and the point grid size – for surface irregularities mapping with acceptable measurement uncertainty, has been solved. The presented study is the first stage of optimization of the machining error correction for the surface of an injection mold and was intended to take into account mechanical-geometric filtration of surface irregularities caused by these geometrical parameters. The effect of parameters causing geometric-mechanical filtration depends on surface topography. The tests were carried out on the workpiece milled with specific machining parameters, Ra of the freeform surface roughness was 1.62 µm. The solution should be treated as a task specific with the possibility of applying to milled surfaces with a similar curvature and roughness.

2. APPROACH DESCRIPTION

In designing the coordinate sampling parameters, the Taguchi method was applied. It is one of the methods that can be used successfully in DOE. The basic notion in the described method is the quality loss function applied in quality loss assessment and dependent on the adopted quality characteristics (Karaszewski and Skrzypczyńska, 2013).

According to Taguchi, the parameters which exert great influence on the measurement and manufacturing process can be adjusted to varying levels so that some settings can result in the robustness of the process (Karaszewski and Skrzypczyńska, 2013; Kowalczyk, 1995).

Control factors are the selected independent variables of the experiment, which have different effects on the response variables when adjusted to different levels, in this case – the sampling grid size and probe diameter.

Factor levels are the intensity to which the control factors are adjusted in a particular experiment. They can be identified as low level, intermediate level, and high level.

Response variables are the dependent variables which change when they go through different process parameters. In the experiments, there may be one or more response variables, in this case – the surface profile height of a freeform surface, determined from local deviations at the measurement points.

Noise factors are the variables which influence the response variables. They may or may not be known. Special care should be taken to prevent noise factors from interfering in the experimental results.

Treatments: each experimental run is a treatment, that is, a combination of factor levels, in this case – the combination of sampling parameters.

Experimental matrix is the matrix composed of control factors with different levels for each treatment given.

Repetition is the reproduction of the selected combination under the same experimental conditions. Repetition makes it possible to estimate the experimental error that is used to define whether the differences in the control variables are significant.

According to the approach used in the Taguchi method, to measure the process quality, minimisation of the changeability of this process in response to the *N* noise factors should be adopted, with simultaneous maximization of the changeability in response to the S signal factors. Combining the two criteria, the ratio of the signal to the noise η = *S/N* is obtained. It should be noted that *S/N* is reversely proportional to the quality loss function. This means that as *S/N* increases, the quality improves and loss is minimised. The way in which η is expressed differs depending on the optimization problem concerned. In practice, three types of the η coefficient are applied:

– the 'nominal is the best' characteristics

$$\eta = \frac{S}{N} = 10 \log \frac{\bar{y}}{S^2}, \tag{1}$$

– the 'smaller is the better' characteristics

$$\eta = \frac{S}{N} = -10 \log \frac{1}{n} \sum y^2, \tag{2}$$

– the 'larger is the better' characteristics

$$\eta = \frac{S}{N} = -10 \log \frac{1}{n} \sum \frac{1}{y^2}, \tag{3}$$

where: *y* – observed data or each type of characteristics, $\bar{y}$ – the average of observed data, *S* – signal factors, *N* – noise factors, η – signal to noise ratio, *n* – the number of repetitions.

In touch measurements, the probe tip acts like a mechanical-geometric filter. It means that the range of information included in the measurement data is related to the probe tip size. In the presented experiments, an attempt to assess the influence of the sampling parameters on the height of the determined irregularities was made. It was assumed that the *H* height of the surface profile (a response variable), i.e. the sum of the absolute value of the biggest *min.* and *max* local deviations is the value that best represents the level of mapping of the actual surface in the measurement process. The reason for that is the different operation of the probe tip on peaks and in valleys of irregularities, in particular, the valley detection error of the probe tip due to its size (Fig. 1).

In the performed optimization tests, the *H* of the surface profile with various combinations of control factors was determined. The influence of the following control factors on the measurement results: (1) the *d* diameter of the ball tip, and (2) the $s \times s$ grid size was investigated. Four ball tips of the diameters of 1, 2, 3, and 4 mm, typically applied in coordinate measurements, were used. The freeform surface measurements were taken under the same conditions and along a regular grid of points, using different combinations of the *d* and $s \times s$ parameters. The $s \times s$ sampling grid sizes, with the *s* values of 0.25; 0.5; 1, and 2 mm were selected.

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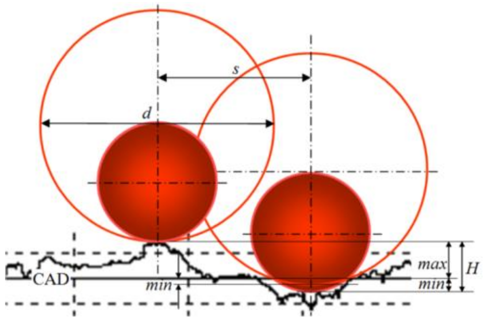

Fig. 1. The nature of a ball tip functioning in the character of a mechanical-geometric filter

The freeform surface of the workpiece on which the tests were performed was previously calibrated in an accredited calibration laboratory using the tip d = 2 mm and grid size (1 × 1) mm. This knowledge on the surface was used in the experiment. However, to determine only the effect of the parameters causing the mechanical-geometric filtration, and to take into account the smaller parameters d and $s \times s$, as the 100% process quality, the arithmetic mean of the profile height from 5 repetitions for the ball tip of the smallest diameter d = 1 mm, and the sampling grid (0.25 × 0.25) mm was adopted. All tests were carried out under the same experimental conditions. According to literature data, in general, larger sampling parameters are used in data acquisition for machining error correction (e.g. Chena et al., 2013, Chen et al., 2018)). Chena et al. (2013) used data obtained from measurements on a machine tool applying the ball tip of 6 mm and (3.5 × 3.5) mm, while Chen et al. (2018) carried out their measurements on CMM with the tip of d = 5 mm and $s \times s$ = (4 × 4) mm. The question is: what values of these parameters should be used to ensure effective freeform surface mapping? According to the Taguchi method approach, the loss of the measurement process quality, caused by applying higher measurement parameters (the d and $s \times s$ control factors), was investigated. The process quality loss (the Δ loss of the information on the surface irregularities) was represented by the difference between the profile H for a given combination of the control factors and the H representing 100% of the process quality.

The experiment included 16 treatments with 5 repetitions. The control factors combinations used in the experiment are presented in Fig. 2.

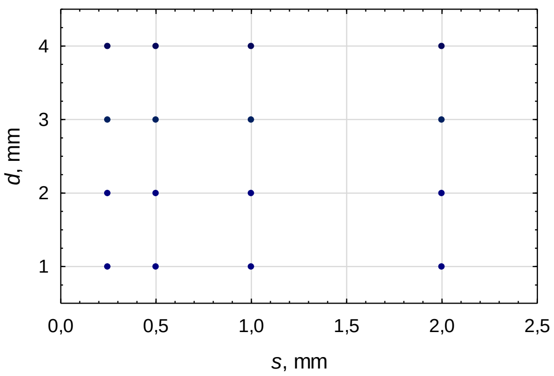

Fig. 2. Experimental matrix

The experiment plan was developed with STATISTICA software, using the option 'planning experiments according to the Taguchi method' (orthogonal tables). The 'smaller the better' characteristics was selected. This characteristics is applied when minimising undesirable characteristics is needed.

3. EXPERIMENTAL RESEARCH

3.1. Data acquisition

The measurements described in this paper were carried out on a Global Performance CMM (with PC DMIS software), (Maximumm Perissible Error) MPE_E = 1.5 + L/333 [μm], equipped with a Renishaw SP25M probe and a 10 mm stylus with a ball tip. The measurement uncertainty for the form deviation with reference to datum features, estimated using EMU software developed at University of Bielsko-Biala (the author – W. Jakubiec) (Jakubiec et al. 2012), was equal to U = 0.9 μm. The experiment was performed on a freeform surface of a workpiece made of WCLV steel with the base measuring (50 × 50) mm, obtained in the milling process using a ball-end mill of 6 mm in diameter, with the rotational speed equal to 8000 rev/min, the working feed of 800 mm/min, and a zig-zag cutting path in the XY plane (Fig. 3, Ra = 1.62 μm). Fig. 3 shows an example of the point distribution on the measured surface.

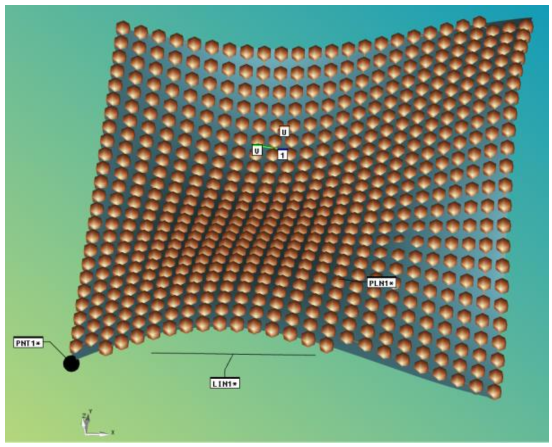

Fig. 3. Distribution of measurement points on CAD model in PC DMIS software, measurement parameters d = 2 mm, $s \times s$ = (2 × 2) mm

3.2. Results and discussion

Pursuant to the Taguchi theory, the quality of the investigated process increases with the increase of the η coefficient. In order to illustrate the trend of the signal-to-noise ratio, graphs of the main effects, showing the effect of each control factor on the response variable, are created. In the described experiment, the H determined for the measurement parameters of $s \times s$ = (0.25 × 0.25) mm and d = 1 mm was adopted as 100% of the process quality. The mean values of the main effects can be seen in Fig. 4.

While analysing the graphs (Fig. 4), it can be observed that the η value decreases more rapidly for the ball tip diameter than for the sampling step. It means that increasing the d parameter has a greater impact on the process quality loss, in this case – on the loss of the information on the surface profile height.

While analysing the η values for the particular combinations of the $s \times s$ and d parameters (Fig. 5) we can see that we obtain a similar process quality loss for some combinations of these

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parameters. For example, for d = 3 mm and $s \times s$ = (0.5 × 0.5) mm, the η value is 49.1, while for d = 1 mm and $s \times s$ = (1 × 1) mm the η value equals 49.7. This means a similar loss of information about surface irregularities for a smaller number of measurement points for d = 1 mm and $s \times s$ = (1 × 1) mm. In this case, the numbers of the measurement points are 10,000 and 2,500, respectively. Similarly, for d = 1 mm and $s \times s$ = (2 × 2) mm, the value of η = 45.8 is similar to the value of η = 45.1 for the combination of d = 3 mm and $s \times s$ = (1 × 1) mm, and to the value η = 45.0 for the combination of d = 4 mm and $s \times s$ = (0.25 × 0.25) mm. In this case, the numbers of the measurement points are 625, 2 500 and 40 000, respectively.

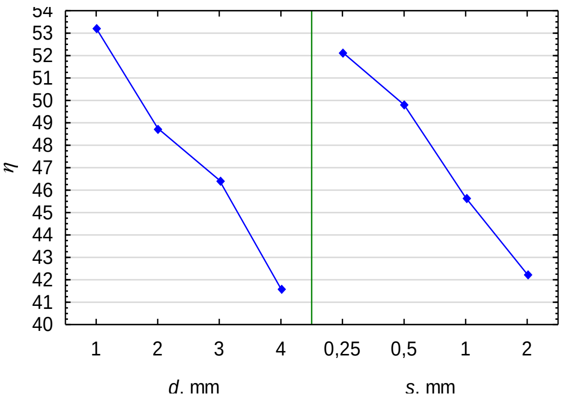

Fig. 4. Mean values of η of main effects

In the graphs (Fig. 5) it can be observed that changing the sampling grid for the constant diameter value of the ball tip for d = 3 mm and d = 4 mm affects the process quality to a lesser extent (with a small increase in η) than in the case of ball tips with d = 1 mm and d = 2 mm. At the same time, it can be seen that the use of the ball with d = 4 mm for all the applied $s \times s$ values results in an exceptionally low quality of the measurement process. It is caused by strong mechanical-geometric filtration of the surface irregularities, which indicates that in the measurement practice, in geometric accuracy assessment, ball tips of this size shall not be used. Using ball tips with d = 2 mm and d = 3 mm yields similar process quality for the same $s \times s$ values. A significantly better measurement process quality is obtained in measurements for which the ball tip with d = 1 mm is applied. In connection with the above findings, Fig. 6 presents charts illustrating the absolute value of the Δ loss of information on the H of surface profile for the ball tips with d = 1 mm and d = 2 mm. The estimates of the experimental errors are included to show that the differences in the control variables are significant (Chapter 2).

In evaluating the acceptable measurement uncertainty, the principle as in the accuracy assessment was adopted. Accuracy assessment and machining process are performed according to a given geometric specification. Acting in accordance with the rules for proving conformity or nonconformity with the specifications defined in the relevant standards (ISO 14253-1:2014; ISO 14253-2:2011), and using the charts in Fig. 5 and Fig. 6, it is possible to select the optimal combination of sampling parameters so that – after including the influence of these parameters in the uncertainty budget (Sładek, 2016; ISO/IEC Guide 98-3:2008, Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement) – the measurement is efficient. In industrial applications, the ISO 9000 series of standards for quality management systems are used for determining the acceptable measurement uncertainty. In some industry sectors, internal directives on quality management consisting of an examination of the measurement process capability are applied (Sładek, 2016; Dietrich and Schulze, 2000). To confirm the capability of the measurement process, the measurement uncertainty must be known and it must remain within an acceptable relation to the corresponding tolerance of a controlled feature of the part under question.

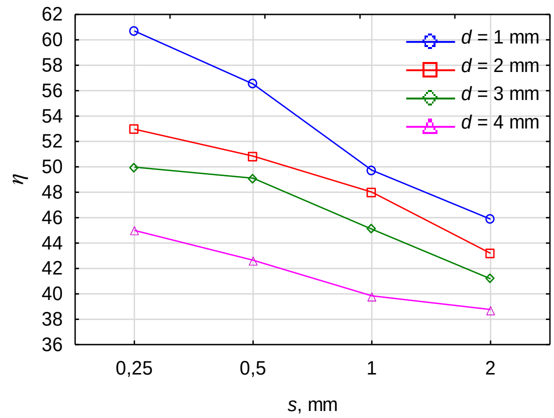

Fig. 5. Values of η ratio for all combinations of s and d parameters

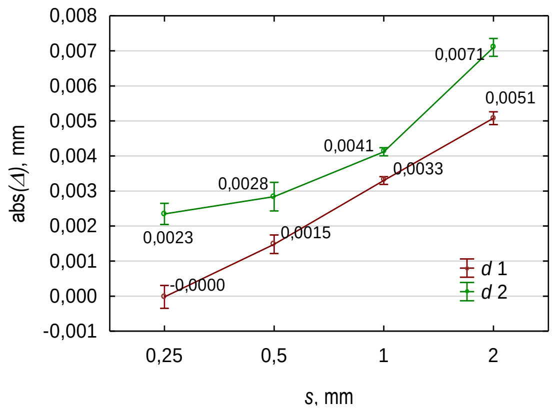

Fig. 6. Loss of information on surface profile height for ball tips with diameters d = 1 mm and d = 2 mm

Tab. 1. The examples of selected measurement uncertainties for various combinations of measurement parameters

Form tolerance [μm]	**Uncertainty limit [μm]**	**abs(Δ) [μm]**	**Measurement uncertainty [μm]**	**Measurement parameter combination (*optimal)**	
				d [mm]	***s*** [mm]
20	2.0	1.40± 0.41	1.3	1	0.5
		2.22 ± 0.34	1.6	2	0.25
		2.83 ± 0.40	1.9	2	0.5
		3.31 ± 0.02	**2.0**	**1**	**1**
		4.19 ± 0.15	2.6	2	1

In this study, parameters were sought for efficient mapping of the freeform surface of the injection mold with a form tolerance of 0.02 mm. In accordance with the documents mentioned above the measurement process may be considered as capable if the measurement uncertainty does not exceed 2.0 µm. This means that under laboratory conditions, for the form deviation measurement uncertainty of 0.9 µm (Section 3.1), taking into consideration the Δ loss resulting from the applied measurement parameters and their statistical error (Fig. 6, Tab. 1), as well as statistical error of the reference value, the optimal combination of measurement parameters to this task is the combination of d = 1 mm and $s \times s$ = (1×1) mm (the measurement uncertainty in this case amounts to 2.0 µm for coverage factor equal 2).

4. CONCLUSIONS

While taking measurements on CMMs for freeform surfaces mapping, the sampling parameters should be rationally selected so that the measurement process is efficient – that is, so that it makes it possible to map the surface irregularities for the smallest possible number of measurement points. In search of the optimal combination of the sampling parameters to data acquisition for machining error correction, the DOE experimental and statistical techniques were applied. The performed optimization experiments described in the present paper provided information on the influence of the coordinate sampling parameters – the d ball tip diameter and the $s \times s$ grid size – on the loss of the measurement process quality. The loss of information on the height of the surface profile, included in the measurement data, was investigated. The experiments showed that the ball tip diameter is the parameter that affects the results most. Styluses with ball tips of d = 4 mm cause such great loss of the process quality that they should not be used in surface irregularities mapping. Using the presented test results, and with the specified, acceptable contribution of the influence of the parameters in the measurement uncertainty budget, it is possible to select their optimal combination with respect to the geometric specification. In the presented experiment, for the freeform surface of an injection mold with a form tolerance of 0,020 mm, the optimal combination of measurement parameters, to keep the measurement uncertainty at the acceptable level, is d = 1 and $s \times s = (1 \times 1)$ mm.

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