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# Analysis of Results of Non-Contact Coordinate Measurement of a Cutting Tool Applied for Mould Machining

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## Abstract

One of the main problems of machining of moulds is the need for an effective monitoring system of wear of cutting tools. This paper presents the results of coordinate measurements of a cutting tool which were obtained by using the non-contact measuring system based on the ACCURA II coordinate measuring machine equipped with the LineScan laser measuring probe and the Calypso metrology software. Investigations were carried out for several measurement strategies including different measurement resolutions and scanning speeds. The results of the coordinate measurements obtained by using the above-mentioned coordinate measuring system were compared to the reference data measured by means of the InfiniteFocus microscope. The measurement results were analysed by means of two software packages: Focus Inspection and Zeiss Reverse Engineering. The point clouds measured by using the LineScan probe were characterized by the selected deviation statistics equal to 4-6 μm when a good match between measurement points and the reference data was obtained. Moreover, these statistics mainly depend on the measurement resolution. The results of the performed experimental research allowed for drawing conclusions concerning the significance of the effect of the adopted measurement strategies on the results of the non-contact coordinate measurements of the selected cutting tool. The application of the non-contact coordinate measurements to the above-mentioned measurement task may contribute to the development of regeneration methods for cutting tools applied for mould manufacturing.

**Keywords:** Tool wear monitoring, Coordinate measuring technique, Non-contact coordinate measurements, Accuracy of measurements

## 1. Introduction

Machining of metal parts characterized by complex geometric shapes, such as moulds, plays an important role in the modern manufacturing process [1-4]. Achieving a high quality of such parts requires, among others, innovative technological solutions and accurate, reliable machining. Wear of cutting tools has been found to have a direct impact on the accuracy of machining and consequently reduces the quality of final products [5-8]. Therefore, the analysis of cutting tool wear plays a very important role in the industry for proper planning, control and optimization of machining [8]. Wear is the primary and most important form of damage of a cutting tool. Reghorn et al. [9] noted that machine downtime caused by damage of cutting tools can be even up to 20% of this time.

Methods applied for measurements of tool wear often use image processing [10-11]. However, they are usually applied for coarse monitoring of the condition of a tool and they do not allow for obtaining more detailed information about the geometry of a tool as well as its worn parts, as presented, among others, in works [12-15]. Nowadays, coordinate measuring machines (CMMs) are very often used in many manufacturing industries and research laboratories due to e.g., the accuracy of the inspection process of components characterized by different shapes and dimensions [16-19]. Industry requires minimising the time of coordinate measurements when using CMMs and maintain their high accuracy. The selection of the optimal measurement strategy, including the best combination of measurement parameters, plays a key role when performing measurements conducted by means of CMMs due to both the accuracy and execution time of individual measurement tasks.

In the case of the study presented in [20], the time of measurements performed by using a CMM was reduced four times thanks to applying the appropriate measurement strategy, which includes the application of both contact and non-contact measuring probes cooperating with a CMM. Measurement tasks conducted by using a CMM in the contact mode are performed in order to achieve the lowest possible measurement uncertainty. However, the use of non-contact probes, also applied for coordinate measurements, makes it possible to obtain more points, compared to contact probes, in a short period of time. The application of non-contact coordinate measurements to the inspection process of cutting tools requires the in-depth knowledge of the factors determining the uncertainty of such measurements. Geometrical and dynamic errors of coordinate measuring machines are only examples of elements affecting the final accuracy of coordinate measurements. The appropriate measurement strategy, as mentioned before, also becomes very important [20-23]. For example, it may include different distributions of measurement points on the surface of a cutting tool.

The experimental research, the results of which are presented in this paper, is a preliminary study aimed at selecting the best strategy of the non-contact coordinate measurements applied for investigating wear of cutting tools used in mould machining. This article focuses on the analysis of the impact of the adopted strategy of the non-contact measurements conducted by using the LineScan probe produced by the Carl Zeiss company on the measurement results of the selected cutting insert. The main aspect addressed in this paper is the measurement resolution. For the selected resolution, the effect of a scanning speed was also analysed. Moreover, the article presents the results of the investigations regarding the application of the Alicona's InfiniteFocus focus variation (FV) microscope as the reference measuring system for measurements conducted by using the LineScan probe. The comparison of the measurement data obtained by means of the laser probe to the reference model created based on the data gained by using the FV microscope was carried out by means of two software packages Zeiss Reverse Engineering and Focus Inspection dedicated to, among others, point clouds processing and their analysis.

The following parts of the article concern the explanation of the methods applied for research, presentation of the obtained results of investigations and conclusions drawn on their basis.

## 2. Methods

The experimental investigations were carried out as a preliminary study, so the new part of the circular cutting insert (Figure 1) was chosen as an example of an investigated object. The fragment (covering the area of approximately 7.5 mm x 3.5 mm) of the surface was measured from the rake face of the insert (Figure 1).

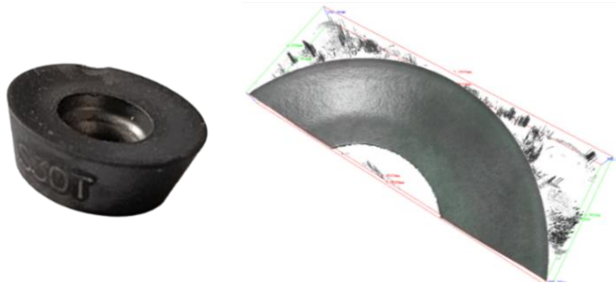

Fig. 1. The view of the considered insert (left) and the fragment of the insert measured by using the InfiniteFocus microscope (right)

Fig. 2. The LineScan probe (left) and measurements of the insert conducted by using the InfiniteFocus microscope (right)

One of the objectives of the study was to determine the significance of the influence of the selected scanning parameters, while measuring the insert geometry by using the LineScan scanning probe (Figure 2), on the measurement results. In the case of the conducted experimental research, the selected orientation of the LineScan measuring probe in relation to the axes of the CMM ACCURA II was applied. The qualification process of the LineScan probe was carried out for the chosen orientation. The measurements of the selected part of the cutting insert were carried out by scanning in the selected plane located at a suitable distance from the measured object. The scanning process was performed in the direction perpendicular to the light beam of the non-contact probe falling on the surface of the measured insert of the cutting tool. The coordinate measurements were carried out without a nominal model of the cutting insert. Therefore, the position of the above-mentioned plane, within which the measurements were conducted, was selected experimentally with respect to the analysed object. The Calypso software of the Carl Zeiss company cooperating with the CMM ACCURA II was applied for programming the coordinate measurements conducted by using the LineScan probe. In addition, filtration of measurement data and removing outliers were not applied when using the Calypso inspection software.

The measurement parameters of the measuring system based on the LineScan probe are shown in Table 1. The maximum scanning speed of the selected probe depends on the applied exposure time, which, in the case of the performed investigations, was selected experimentally for the considered measured object by using the appropriate functions of the Point Cloud measurement element, which is the part of the Calypso metrology software. The exposure time is the key element of the strategy of non-contact coordinate measurements carried out by using the LineScan probe determining the final measurement results. In turn, the density of measurement points, when using the LineScan probe, is dependent on the measuring speed. The measurement densities applied for coordinate measurements conducted with the use of the LineScan probe were chosen arbitrarily, because, as mentioned before, the investigations were treated as a preliminary study.

The geometry of the selected cutting insert measured by using the Alicona's InfiniteFocus G4 focus variation microscope (Figure 2) was used as the reference geometry to which the measurement results obtained by means of the LineScan probe were compared. The InfiniteFocus microscope is dedicated to measurement tasks requiring high accuracy. The time of measurements on the microscope is much longer than the time of measurements conducted by using the LineScan probe. In the case of the considered measurement task, the time of measurements conducted by using the microscope was equal to 2.5 minutes for the x5 objective and 8.5 minutes for the x10 objective. The measurements performed by means of the LineScan probe took less than 1.0 minute.

In order to select both (i) the appropriate parameters of the measurements of the insert geometry conducted by using the InfiniteFocus microscope and (ii) parameters of saving the results of the measurements (the nominal model) as the STL file the preliminary study had to be carried out. In the first step of this study, the single imaging field was measured by using the objectives with the following magnifications x5 and x10 and the parameters presented in Table 2.

Table 1.
The measurement parameters when using the LineScan probe of the CMM ACCURA II

| **Scanning speed *v*, mm/s** | **Resolution *res*, mm** |
|---|---|
| 1 | 0.2 |
| | 0.1 |
| | 0.05 |
| | 0.03 |
| 5 | 0.2 |

Table 2.
The parameters of measurements performed with the use of the InfiniteFocus microscope

| **Objective** | **Lateral resolution *LR*, μm** | **Vertical resolution *VR*, μm** |
|---|---|---|
| x5 | 7.82 and 15 | 1 and 5 |
| x10 | 3.91 and 8 | 0.5 and 2 |

In the next step the repeatability of the results obtained during measurements conducted with the same parameters was investigated. For this purpose, from three to four measurements were carried out with the same settings. Each pair of surfaces measured with the same parameters was then compared. The comparison of the data of two surfaces was carried out by using the Difference measurement module of the IFM 3.5.1.5 software (responsible for microscope control and analysis of obtained measurement results). As a result of the comparison of two surfaces, the histogram of the local deviations for the given surfaces and their descriptive statistics were obtained. In each analysed case, the distribution of the deviations was close to the normal distribution with the mean close to 0. The standard deviation (*std.*) of the deviations was taken as a measure of repeatability. In the case of the x5 objective, the values of *std.* of 1-2 μm were observed. For the x10 objective the range of the *std.* values equal to 0.12-0.35 μm was obtained.

Further analysis was only carried out for the x10 objective. The lateral resolution significantly affected the repeatability. The s*td.* value was almost twice as small for *LR*=8 μm and it was equal to 0.14 μm on average. Changing the vertical resolution has not significantly affected the repeatability (*std.* varied in the range of 0.12-0.16 μm). It is worth noting at this point that the surface roughness parameters determined based on the measurements conducted with the use of the x50 objective were as follows: *Ra*=0.14 μm and *Rz*=0.68 μm. Therefore, the order of the magnitude of the local deviations during the repeatability tests and the deviations calculated based on the mean line of a roughness profile are comparable.

In the next step the effect of the compression when exporting the measurement data obtained by means of the InfiniteFocus microscope to the STL file was investigated. For this purpose, the fragment of the insert (Fig. 1) was measured twice by using the x10 objective and the following parameters: *LR*=8 μm and *VR*=2 μm. The measured data was then exported to the STL files without compression (1x1: 4374 x 1649 points) and with the 2x2 (2187 x 825 points), 4x4 (1094 x 413 points) and 8x8 compressions (547 x 207 points).

Comparing the original measurement data saved in the al3D format to the data represented by the STL file without compression, the standard deviation of the obtained local deviations was equal to 0.004 nm. Differences between the same data saved in the STL format with different levels of the compression resulted in the *std.* of the deviations equal to 2-7 nm.

Finally, the measurement data of the fragment of the cutting insert measured with the use of the x10 objective, *LR*=8 μm, *VR*=2 μm and exported to the STL file by using the 8x8 compression was used as the nominal for testing the influence of the measurement parameters during conducting measurements by means of the LineScan probe. The original STL file was modified by removing facets that were not connected to the main part of the model as well as those that significantly stood out on the edges of the insert model. The modification process was performed by using the Focus Inspection 9.3.

Differences between the results of the measurements obtained by using the LineScan probe (the point clouds saved in the text files) and the nominal geometry (STL) were determined by using two software packages: Focus Inspection 9.3 (FI) and Zeiss Reverse Engineering 2.6 (ZRE). The best-fit of the point clouds to the nominal geometry was performed by means of both software packages. The images of the fitted points and the values of the 3D deviation were then analysed.

In the case of the Zeiss Reverse Engineering software, the comparison of two data sets resulted in the deviation map and the following deviation statistics: number of analysed points (*n*), maximum negative deviation (*min*), maximum positive deviation (*max*), mean deviation value (*mean*), mean of the deviations' absolute values (*abs. mean*) and standard deviation (*std.*). The Focus Inspection software also provides the deviation map and fundamental descriptive statistics. Moreover, the deviation values can be saved in the text file for a more detailed analysis.

# 3. Results

## 3.1. Analysis of the measurement resolution during measurements with the use of the LineScan probe

Figure 3 presents the distribution of the points in the XY plane of the fragment of the point cloud measured by using the scanning speed (*v*) of 1 mm/s. The 3D deviation values were obtained by fitting the point clouds, measured by using the LineScan probe and different resolutions, to the reference model. The fitting processes were conducted by means of the Focus Inspection and Zeiss Reverse Engineering software. The minimum and maximum deviations occurred at the edges of the insert. It is natural, due to the measurement methodology, that these areas were exposed to occurrence of outliers. The relatively uniform distribution of the deviations on the surface of the insert was observed after conducting the fitting process by using the FI software (Figure 4) regardless of the applied measurement resolution.

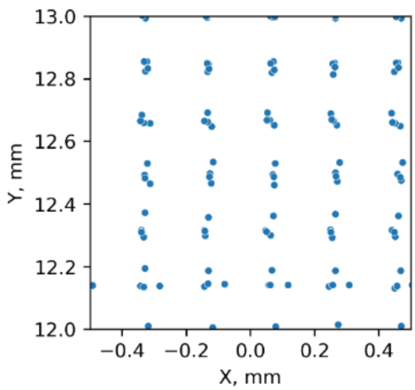


Fig. 3. Fragment of the measured point cloud obtained by using: *v*=1 mm/s, *res*=0.2 mm

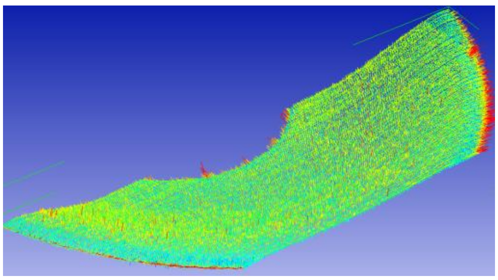

Fig. 4. View of the deviations in the FI software for the data measured by using the following parameters: *v*=1 mm/s, *res*=0.03 mm

In the case of the fitting process conducted with the use of the ZRE software such uniform distribution was only visible for the data measured by using the highest resolution (Figure 5). In other cases, the distributions of the deviations were non-uniform (Figure 6). In the cases where the uniform distribution of the deviations was obtained, some points had positive deviations and others were characterized by negative values of the deviations. This was observed when analysing the groups of the measurement points that were very close to each other (Figure 7), which means that the reference model was between these points.

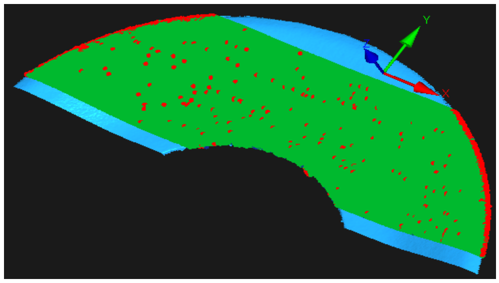

Fig. 5. View of the deviations in the ZRE software for the data measured by using the following parameters: *v*=1 mm/s, *res*=0.03 mm

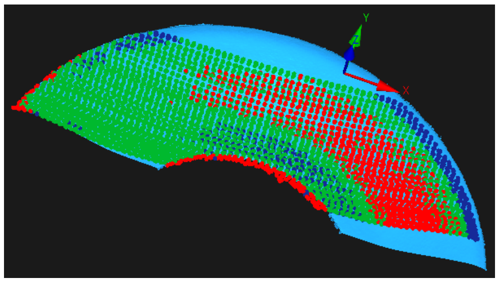

Fig. 6. View of the deviations in the ZRE software for the data measured by using the following parameters: *v* = 1 mm/s, *res* = 0.2 mm

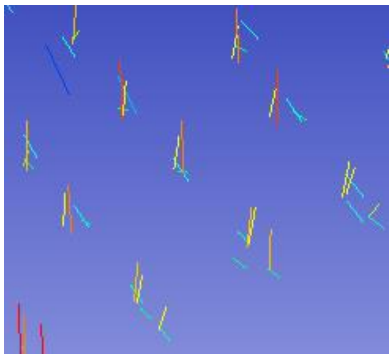

Fig. 7. Deviations represented in the FI software by lines: points next to each other characterized by positive (warm colours) and negative (cool colours) deviations

The values of descriptive statistics of the deviations determined by using the Zeiss Reverse Engineering and Focus Inspection software are summarised in Tables 3 and 4. The mean deviation is close to 0 because best-fitting of surfaces is mainly conducted by using the least squares method in the CAD/CAI software. The mean of the absolute values of the deviations and the standard deviation of the deviations are the best indication of the quality of the best-fitting process (Figures 8 and 9). In the case of the fitting process carried out by using the FI software, *abs. mean* and *std.* were in the range 4-6 µm and increased with increasing the resolution (increasing the number of points). *Abs. mean* and *std.* were equal to respectively 5-10 µm and 6-14 µm in the case of using the ZRE software for the fitting process. The smallest values of *abs. mean* and *std.* were associated with the data obtained when measuring at the highest resolution i.e., 0.03 mm. This means that a better fit of the measurement data to the reference model is associated with the uniform distribution of the deviations. The distributions of the deviations were bimodal and symmetrical with respect to 0 regardless of the measurement resolution. Figure 10 shows the example of the histogram of the 3D deviation values after conducting the fitting process by using the Focus Inspection software.

Table 3.
Descriptive statistics of the deviations determined by using the Zeiss Reverse Engineering software

| ***res*, mm** | ***n*** | ***min*, mm** | ***max*, mm** | ***mean*, mm** | ***abs. mean*, mm** | ***std.*, mm** |
|---|---|---|---|---|---|---|
| 0.2 | 1427 | -0.030 | 0.054 | 0.00040 | 0.0062 | 0.0081 |
| 0.1 | 5858 | -0.072 | 0.122 | 0.00247 | 0.0099 | 0.0144 |
| 0.05 | 22629 | -0.132 | 0.219 | -0.00015 | 0.0066 | 0.0121 |
| 0.03 | 63138 | -0.024 | 0.050 | -0.00155 | 0.0045 | 0.0056 |

Table 4.
Descriptive statistics of the deviations determined by using the Focus Inspection software

| ***res*, mm** | ***n*** | ***min*, mm** | ***max*, mm** | ***mean*, mm** | ***abs. mean*, mm** | ***std.*, mm** |
|---|---|---|---|---|---|---|
| 0.2 | 1418 | -0.01 | 0.010 | 0.000372 | 0.0042 | 0.0046 |
| 0.1 | 5561 | -0.011 | 0.011 | 0.000367 | 0.0047 | 0.0050 |
| 0.05 | 22086 | -0.012 | 0.012 | -0.00014 | 0.0053 | 0.0056 |
| 0.03 | 60713 | -0.014 | 0.014 | -5.03E-05 | 0.0058 | 0.0062 |

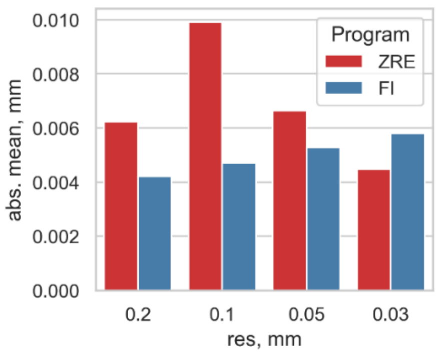


Fig. 8. Comparison of the values of the abs. mean of the 3D deviations determined by using the Zeiss Reverse Engineering and Focus Inspection software packages

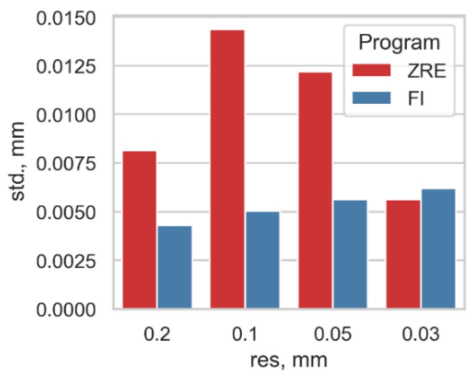


Fig. 9. Comparison of standard deviations of the 3D deviations determined by using the Zeiss Reverse Engineering and Focus Inspection software packages

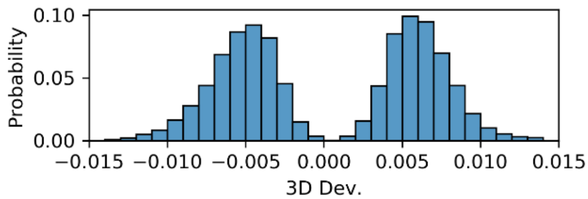


Fig. 10. Example of the distribution of the deviations ($v$ = 1 mm/s, *res* = 0.03 mm)

## 3.2. Analysis of the measurement speed during measurements conducted by using the LinEscan probe

Figure 11 shows the distribution of the points in the XY plane in the case of the fragment of the point cloud measured with $v$=5 mm/s. It can be observed that the change of the scanning speed did not affect the values of the deviations determined by using the FI software (Table 5, Figure 12). The values of the *abs. mean* higher by about 26% and almost twofold increase in the *std.* of the deviations were achieved for the higher scanning speed when conducting the fitting process by using the ZRE software.

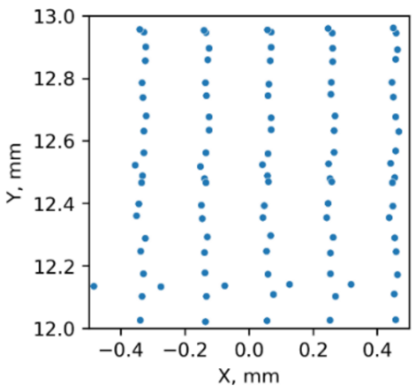


Fig. 11. Fragment of the measured point cloud obtained with the following parameters: $v$=5 mm/s, *res*=0.2 mm

Table 5.
Descriptive statistics of the 3D deviations determined by using the ZRE and FI software for the data measured with *res*=0.2 mm and different scanning speeds

| ***software*** | ***v, mm/s*** | ***min, mm*** | ***max, mm*** | ***mean, mm*** | ***abs. mean, mm*** | ***std., mm*** |
|---|---|---|---|---|---|---|
| ZRE | 1 | -0.030 | 0.054 | 0.00040 | 0.0062 | 0.0081 |
| ZRE | 5 | -0.185 | 0.208 | -0.00098 | 0.0078 | 0.0158 |
| FI | 1 | -0.01 | 0.010 | 0.000372 | 0.0042 | 0.0046 |
| FI | 5 | -0.01 | 0.009 | 5.42E-06 | 0.0039 | 0.0043 |

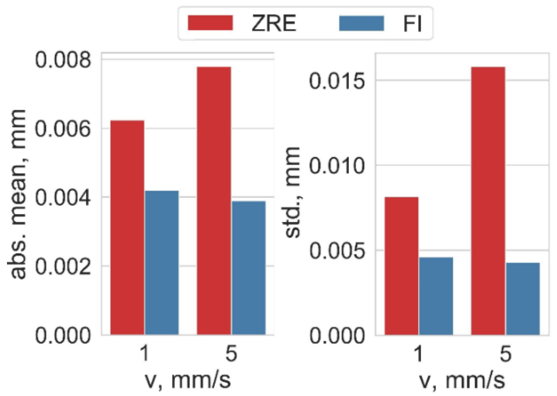


Fig. 12. Comparison of the *abs. mean* and standard deviation of the 3D deviations of the data measured with the use of different scanning speeds (*res*=0.2 mm) and determined by using the Zeiss Reverse Engineering and Focus Inspection software

# 4. Conclusions

The experimental research, the results of which are presented in this article, was aimed at analysing the strategy for non-contact coordinate measurements of wear of cutting tools (applied for machining dies and moulds) when using the LineScan probe cooperating with the ACCURA II coordinate measuring machine. During the performed research the main attention was focused on two elements of the measurement strategy i.e., a resolution and a scanning speed. The point clouds measured by using the LineScan probe were compared to the reference geometry calculated based on the results of the measurements conducted with the use of the InfiniteFocus G4 focus variation microscope. The investigated object was a new cutting insert because, as mentioned, the experimental investigations were treated as a preliminary study. However, the results of the research may be applied for measurements of worn inserts. Thus, they may contribute to the development of the methodology of carrying out processes related to the regeneration of tools applied for machining of moulds.

The results of the study, the purpose of which was to select the appropriate parameters for measuring the geometry of the cutting insert by using the InfiniteFocus microscope and processing the data indicate that the good quality of the measurement data can be obtained by means of the objective with the magnification of x10. The level of the measurement noise is significantly influenced by the lateral resolution. Increasing the *LR* from 3.91 μm to 8 μm reduced the noise and resulted in improving the repeatability expressed by the standard deviation of the local deviations equal to 0.14 μm. The vertical resolution had little effect on the repeatability of the measurements. Exporting data from the al3d format to the STL file did not affect the data quality. The change of the compression ratio when exporting the data to the STL file was also insignificant.

The results of the study regarding the analysis of the selected aspects of the measurement strategy when using the LineScan laser probe allow the following conclusions to be drawn:

1. A good match between the measurement points and the reference geometry can be recognized from a deviation map, which should be characterized by a uniform distribution of positive and negative deviations on the analysed surface. The distribution of the deviations is then bimodal and symmetrical with respect to 0.
2. Good results of the fitting processes were obtained by using the FI software for all measurement resolutions and for the highest resolution i.e., 0.03 mm when using the ZRE software. *Abs. mean* and the standard deviation were within 4-6 μm regardless of the applied software when a good fit was obtained.
3. It can be concluded that the scanning speed did not influence the deviation values when there was a good fit of the point cloud to the reference geometry.

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