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Procedia CIRP 112 (2022) 122–127

www.elsevier.com/locate/procedia

14th CIRP Conference on Intelligent Computation in Manufacturing Engineering, Gulf of Naples, Italy

Close-to-process compensation of geometric deviations on implants based on optical measurement data

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Abstract

The production of implants is challenging due to their complex shapes, the filigree structures and the great regulatory effort. Therefore, a manufacturing cell with an integrated optical measurement was realized. The measurement system is used to determine the geometric deviations and to fulfill the documentation obligation. The measurement data are used to create a matrix containing the nominal coordinates and the error vector for compensation points at the relevant shapes. Based on this, the corresponding tool-path segments are isolated in the G-Code and compensated in order to reduce the geometric deviations. With this method, the deviation could be reduced by 85 %. However, it is pointed out, that the result of the compensation strongly depends on the quality of the optical measurement data.

Peer-review under responsibility of the scientific committee of the 15th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 14-16 July, Gulf of Naples, Italy

Keywords: Compensation; G-Code Adaption, Optical measurement, Implant production

1. Introduction

Manufacturers of implants are simultaneously facing an increase of the cost market pressures, individualization as well as variety. In addition, regulatory requirements of the certifying authorities are becoming more stringent with the result that more personnel resources are being tied up in non-productive activities [1]. Implants are often made of the biocompatible titanium alloy Ti6Al7Nb, which has similar mechanical properties to Ti6AlV4 and is considered difficult to machine due to its material properties [2]. The filigree shape and curved structure of the implants also result in complex cutting conditions and large deflections of the workpiece and cutting tools during machining, making it difficult to maintain the required tolerances [3].

In common practice, an iterative setup process is performed in which the process parameters and path planning are adjusted until the workpiece geometry achieves all tolerances [4]. In order to avoid the associated costs, especially for small series, approaches have been investigated to reduce the influence on manufacturing errors or to compensate for the occurring dimensional and form errors by suitable compensation methods. In predictive compensation, the manufacturing errors are determined and compensated for by models or simulation approaches before or in parallel with the manufacturing process [5]. However, these approaches reach their limits with complex cutting conditions and with the deflection of tool and workpiece. Reactive compensation provides a more accurate compensation because the real manufactured part geometry is measured after manufacturing. With this measurement data, a compensation can be performed for the next part [5].

Two methods have been established for the geometry measurement. First, the touch probe located in the machine is used to measure the geometry immediately after production [6]. One advantage of this procedure is the immediate measurement of the manufacturing errors while the workpiece is still in the clamping fixture. However, since the probe is guided by the

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10.1016/j.procir.2022.09.049

same machine, geometric errors for example due to thermoelastic displacements are not considered. In order to eliminate this disadvantage, a geometry measurement for subsequent error measurements often takes place with a coordinate measuring machine (CMM) [7-9].

The deviations regarding the target geometry is determined by comparing the measured workpiece geometry with the nominal geometry. For this purpose, various measuring points along a surface are evaluated to allow the consideration of a complex path of deviation. In order to compensate these complex errors, it is necessary to adapt the tool path. Different approaches along the process chain have been made, starting from CAD/CAM planning [10] and ending with the adaptation of the G-Code [11].

For close-to-process compensation, the direct adaptation of the G-Code is useful, since there is no post-processor necessary to generate the tool path after the adaptation. For this purpose, the mirror method is an established and easy method to derive the tool path for the compensation from the measured manufacturing errors. The measured points along a surface are mirrored against the ideal surface, resulting in one compensation point for each measured point (Fig. 1). These points are then used as points for the compensated tool path [12-15].

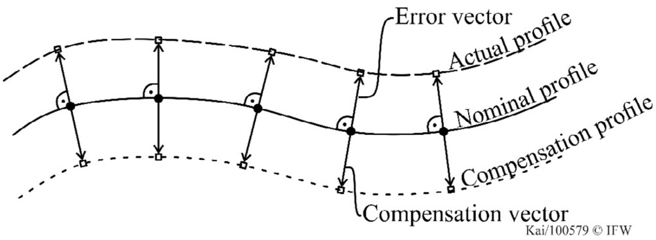

Fig. 1. Mirror method for the determination of the compensation profile

The compensation methods introduced refer without any exception to the measurement data obtained with tactile measuring systems. Compensation based on optical measurement data has rarely been investigated, since the optical measurement systems existing up to now do not achieve the required measurement accuracy. However, due to the continuous development of the optical measurement technology, it is increasingly reaching the application fields that were reserved for tactile measurement technology with regard to measurement accuracy and process reliability [16].

Therefore, first approaches to use optical measurement data for error compensation have been made. For machining with an industrial robot, a fringe light projection method was used to digitize the manufactured component. The generated 3D Model in a STL Format model can be compared with the nominal geometry, which is available as a Dexel model. By the intersection between the Dexel and the nominal profile from the STL model, measurement points are derived, which are thus used for compensation with the mirror method. This method leads to a reduction of the error from 0.6 mm to 0.1 mm [17].

The processing of the point cloud obtained with optical measurement technology is challenging since a large number of points are available, which must be processed in a way that the information necessary for the compensation is obtained and made usable [18]. One approach is to adapt the original 3D model based on optical measurement data of a manufactured component. Error vectors are derived between the initial STL model and the measured point cloud, which are used to create a new STL model in which the compensation values are already integrated. Path planning is then performed without modifications in the CAM software. This method is also able to significantly reduce the geometric errors [10].

This paper presents a new manufacturing cell for implants in which an automated optical measurement is integrated into a manufacturing cell to perform a measurement of each manufactured implant directly after production. On the one hand, this enables an automated documentation, which reduces the manual documentation effort. On the other hand, the measurement data from the optical measurement is used to perform an automated close-to-process G-code adaptation to compensate the manufacturing deviations. This paper describes a method for this close-to-process compensation based on the optical measurement data. This enables an immediate and fast reaction to occurring errors without the need of an additional CAD/CAM planning.

2. The manufacturing cell

An automated manufacturing cell was developed and operated for the production of implants (Fig. 2). It consists of an automation robot that loads the machine tool and a measuring robot (not shown) that guides the optical measuring system. This setup enables an automated documentation in accordance with regulatory requirements in addition to manufacturing. This includes automated quality inspection with the measuring system as well as documentation of all data relevant to the production.

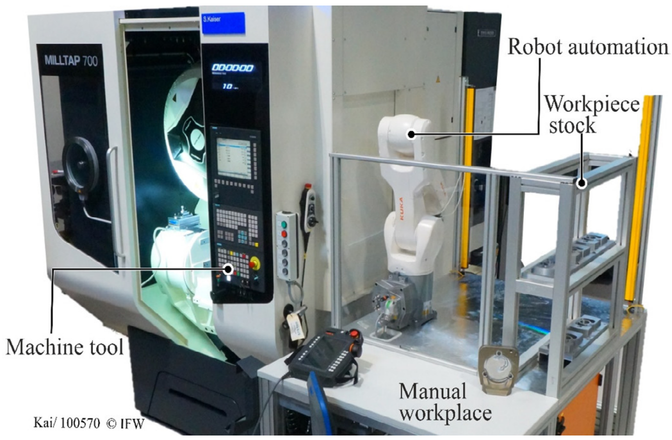

Fig. 2. The manufacturing cell

In addition, compensation can be performed, which is presented here. Implementing this compensation in the context of medical technology is an important step as the manufacturing process is certified. Automated adaptation of the tool paths is only possible if it can simultaneously be proven that the change is within a small permitted tolerance range and the manufactured geometry meets the certified criteria. This proof can only be provided by complete quality inspection of the manufactured implants. Therefore, a wrist implant is used as an example of application (Fig. 3). With seven tools the final contours are produced by face milling, peripheral milling and ball end milling. As common with implants, the manufactured implant not only remains on the raw part for the entire manufacturing process but also for quality inspection via thin retaining bars. For the following investigations, the shaft surface as well as the face surface were used.

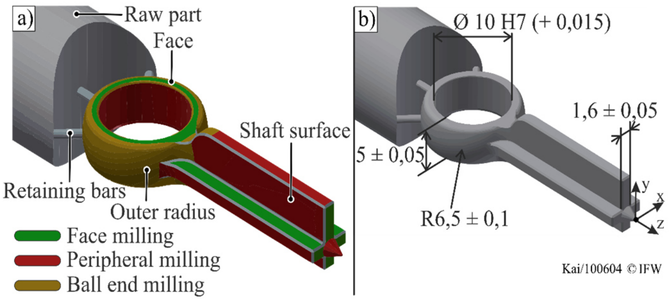

Fig. 3. Implant with the finish-operations a) and tolerances b)

3. Optical measurement of the implants

The optical measurement is currently carried out manually. The system consists of a hand-held laser line scanner (Fig. 4), which is spatially tracked by a tracking system via active infrared markers, enabling a three-dimensional reconstruction of the measurement data from the laser line.

The tolerances defined for the production process of the implant (Fig. 3b) require a measuring accuracy in the order of micrometers. To determine the suitability of the used measuring system, the optical measurement results were compared with measurement data from a coordinate measuring machine. Figure 5 shows the comparison of the measurement data on two surfaces on the shaft of the implant. The maximum measurement deviation of about 20 µm is sufficient for compensation.

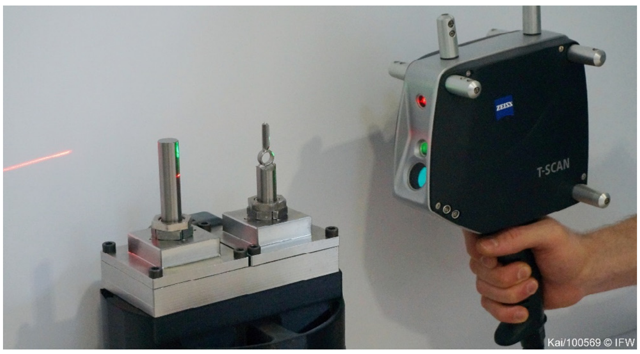

Fig. 4. Handheld laser scanner

Furthermore, the measurement data shows a significant increase in machining errors towards the tip of the implant, due to increasing deflection caused by the process forces Fig. 5 a). In addition, Fig. 5 b) shows an oscillating, stepped surface structure. The reason for this is a production of the surface with gradually increasing axial infeed depths. However, the measurement show that the measuring system is suitable for the measuring task. In addition, complex geometric deviations occur. For a compensation of these surfaces, an adjustment of the tool path is necessary.

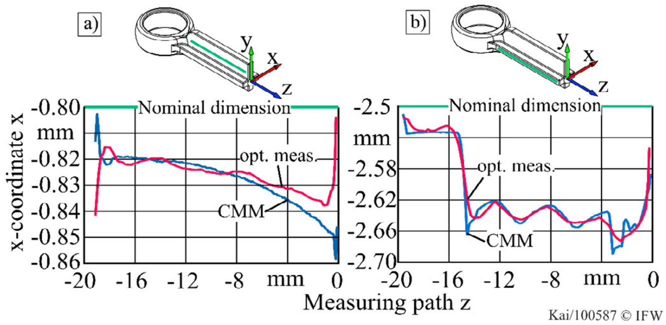

Fig. 5. Comparison of measurement results between optical measurement and CMM

4. Compensation approach based on optical measurement data

The measurement data of the current geometry are initially available in the form of a point cloud. According to the schematic sequence of the compensation shown in Fig. 6, data processing of the measurement data takes place first. The resulting compensation matrix is subsequently used in the G-code adaptation to modify the toolpath for the machining of the next implant in a way that compensates the errors that occur.

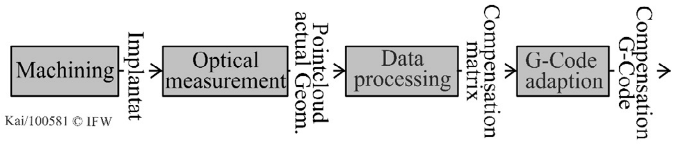

Fig. 6. Schematic procedure of error compensation

The steps of data processing and G-code adaptation are described more detailed below.

4.1. Data Processing

The measurement data processing is carried out using the Inspect Suite software from the company GOM. To allow for an automated processing, a Phython script was created that automatically processes the measurement data and calculates the compensation matrix.

The compensation methods described initially use the probed points on the workpiece surface to perform further data processing directly on them. In contrast, the optical measurement first makes a nominal-actual comparison of the entire implant without taking into account which surfaces will be compensated. For further evaluation, a matrix is specified that contains the points $P_{N,i}$ on the nominal geometry (blue points in Fig. 7). These points are located on the surface to be compensated and they represent the data points that assign which compensation is performed. A perpendicular vector is defined from each point on the surface that is long enough to intersect the face of the 3D model of the actual geometry. This results in the error vector $v_{F,i}$, which describes the error for each nominal point. In order to obtain an accurate result, the nominal points must be located on flat parts; corner points can lead to an incorrect evaluation and are not valid.

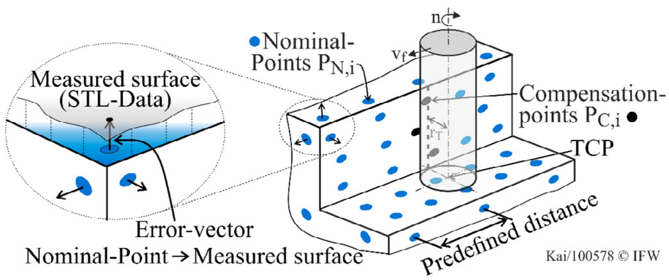

Fig. 7. Nominal points and determination of the error vectors

In the last step of the data processing, the error vectors are mathematically mirrored at the nominal point, resulting in the compensation vector $v_{comp,i}$. All nominal points are represented together with the corresponding compensation vector in columns in the compensation matrix M_{comp} which is exemplary shown in (1).

$$M_{comp} = \left[v_{comp,1}\; v_{comp,2}\; \dots\; v_{comp,n}\right] = \begin{bmatrix} x_1 & x_2 & & x_i \\ y_1 & y_2 & & y_i \\ z_1 & z_2 & & z_i \\ \Delta x_1 & \Delta x_2 & \cdots & \Delta x_i \\ \Delta y_1 & \Delta y_2 & & \Delta y_i \\ \Delta z_1 & \Delta z_2 & & \Delta z_i \end{bmatrix} \quad (1)$$

This matrix contains all geometric information in the workpiece coordinate system that is necessary for compensation.

4.2. G-Code adaption

For the adaptation of the G-code, the file available on the network drive of the machine is used and the adapted G-code is again copied directly to the machine. This procedure allows for an automated and close-to-process compensation. The compensation sequence is shown in Fig. 8. The following information are initially required as input parameters:

- G-code file for adaptation
- Compensation matrix from optical measurement
- Name of the machining operation for compensation
- Tool radius
- Machining type (peripheral/face/ball end milling)
- Point density of the tool path to be interpolated.

The processing of the G-code is taken over by the interpreter, whereby it handles the code line by line and in it again word by word. Its function is to identify the relevant machining operations in the code and to classify the machining operations (straight line, circle, TRAORI) in order to apply the correct compensation method. First, all lines of the original G-code are copied into the new G-code until the operation to be compensated is reached in the code. Usually, these final contouring operations result from the CAM planning. Subsequently, the compensation is activated and the G-code adaptation takes place. It begins with the acquisition of the start and end points of a machining operation, the rotary movements of the A and C axes as well as executed coordinate transformations.

This information is transferred to the geometry data processing. Here, a coordinate transformation of the tool paths into the workpiece coordinate system is performed. This ensures that the geometric information from the compensation matrix and the toolpaths are available in the same coordinate system.

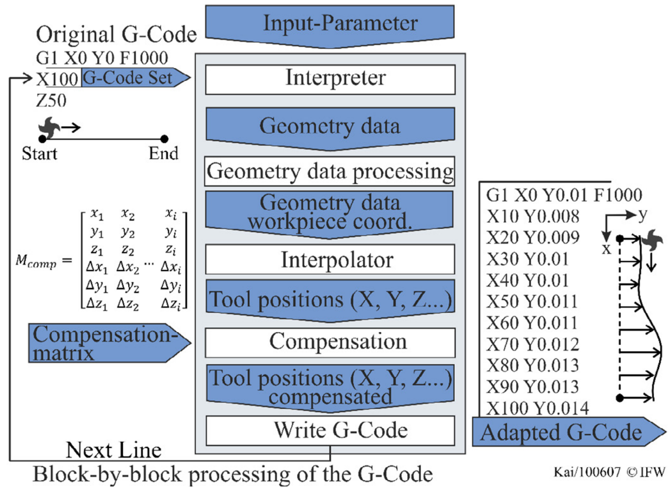

Fig. 8. Error compensation procedure

Until now, the tool paths in the G-code are only described by the start and end points between which the machine interpolates the path. However, only the start and end positions are not sufficient to compensate complex errors. For this reason, the density of the tool points in the G-code must be increased, which is realized by interpolating the tool paths between the start and end positions. The interpolator also considers movements during combined translational and rotational movements of the tool. As a result of the tool path interpolation, the tool paths are now available in small pieces with a high point density so that a detailed compensation of the errors along the tool paths is possible. The applied interpolation distance is an input parameter and should be defined based on the dimensions of the workpiece and the expected errors. In the present case the interpolation distance is 0.5 mm.

In the following step, the actual compensation of the toolpath is carried out. Three compensation-points $P_{C,1}, P_{C,2}, P_{C,3}$ (Fig. 7) are assigned to each tool path point P_T from the nominal points $P_{N,i}$ that are closest to the tool point P_T, considering the tool radius r_W. This assignment results in a spatial triangle in which the tool point is located on the plane spanned between the compensation points. Figure 9 schematically illustrates this triangle (highlighted in orange) in one planar plane. However, the compensation vectors C_i in the compensation matrix

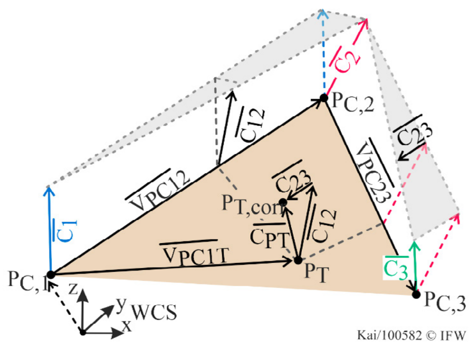

Fig. 9. Schematically compensation-interpolation

M_{comp} are related to the previously defined nominal compensation-points $P_{N,i}$ (Ch. 4.1.). These points do not correspond to the points of the toolpath P_T.

Therefore, the compensation-interpolation aims to set the tool path in relation with the compensation-vectors $\overline{C_i}$ of the compensation points $P_{C,i}$ in order to derive a compensation-vector $\overline{C_{PT}}$ for each toolpath point P_T. The result is the compensated point $P_{T,corr}$, which can be used directly as a new point of the toolpath. In case the tool point is located in the triangle between the compensation points, a spatial interpolation is performed as shown below. If only one associated compensation point is present, the compensation vector of this point is used directly. If two points are available or the tool point is located on a line between two points, a linear interpolation will be carried out.

First, the vectors between the compensation points and the vector between compensation point 1 to the tool point are determined.

$$\overline{V_{PC12}} = \overline{P_{C,2}} - \overline{P_{C,1}} \; ; \; \overline{V_{PC23}} = \overline{P_{C,3}} - \overline{P_{C,2}}$$
$$\overline{V_{PC1T}} = \overline{P_T} - \overline{P_{Pc,1}} \tag{2}$$

Defining the cross product of the vectors $\overline{V_{PC12}}$ and $\overline{V_{PC23}}$, an additional vector $\overline{V_\perp}$ is obtained which is perpendicular to the plane and indicates the first direction of the compensation vector.

$$\overline{V_\perp} = \overline{V_{PC12}} \times \overline{V_{PC23}} \tag{3}$$

An inverted matrix is established from the calculated vectors, which is multiplied by the vector $\overline{V_{PC1T}}$. This mathematical description allows a calculation of the weighting factors a, b and c. Starting from compensation point $\overline{P_{C,1}}$, these factors describe the fractions of each compensation vector $\overline{C_2}$ and $\overline{C_3}$, which are transferred to the tool point during the interpolation from all correction vectors.

$$\begin{pmatrix} a \\ b \\ c \end{pmatrix} = \left[\overline{V_{PC12}} \;\; \overline{V_{PC23}} \;\; \overline{V_\perp}\right]^{-1} \cdot \overline{V_{PC1T}} \tag{4}$$

In a last step, the compensated point $P_{T,corr}$ in the workpiece coordinate system is obtained by starting from the original tool point P_T and defining the linear combination of the three compensation vectors $\overline{C_{1-3}}$ at the measurement points with the factors a and b between the spanned surfaces.

$$P_{T,corr} = P_T + \{\overline{C_1} + \{a \cdot (\overline{C_2} - \overline{C_1}) + b \cdot (\overline{C_3} - \overline{C_2})\} \tag{5}$$

This new, interpolated tool point $P_{T,corr}$ is now used instead of the original point P_T. For each tool point in the operation, which is to be compensated, an interpolation is performed. Nevertheless, is it possible that no compensation point can be allocated to the current tool path. This occurs, for example, during infeed movements when the tool is not engaged. In this case, an interpolation of the tool path is performed in order to calculate additional interpolation points. However, a compensation cannot be realized and the original tool path is kept. This method can be used for the machining operations of face milling and peripheral milling with an end mill or three-axis machining with a ball end mill, even for free-form surfaces.

5. Results

The compensation methodology was evaluated on the implant presented in Fig. 3, but without the hole to obtain a larger face area, which can be used to better illustrate the results. Two series of tests were performed with a peripheral and a face milling process. The following Fig. 10 shows the measurement results of the peripheral milling process of the shaft surface. The optical measurement of the shaft is compared with measurement data from the coordinate measuring machine (CMM), which are used as a reference due to the significantly higher measurement accuracy. The line represents the averaged measurement results over three tests, the shadow behind shows the measurement span. The width of the shaft corresponding to 1.6 mm is considered and a tolerance of ± 0.05 mm is included.

The measurement data of the uncompensated implant in the left graph show that the deviation increase towards the end of the workpiece due to increased deflection during machining with a cantilever length of 17 mm. In addition to the bending line, a constant offset is present, which can be explained by incorrect tool geometry for example. The equal distance between the two lines show a constant measurement error of about 20 µm. The right graph sums up the measurement data of the compensated implant. The results show an increase in accuracy of about 65 % compared to the non-compensated implant. The deviation line was almost completely eliminated. This was also shown when the tests were repeated three times. The measurement results of the optical measurement are now close to the nominal dimension, what shows the effectiveness of the compensation, which only refers to the optical data. However, the reference measurement with the coordinate measuring machine shows that the true dimension is shifted due to the measurement inaccuracy of the optical measurement.

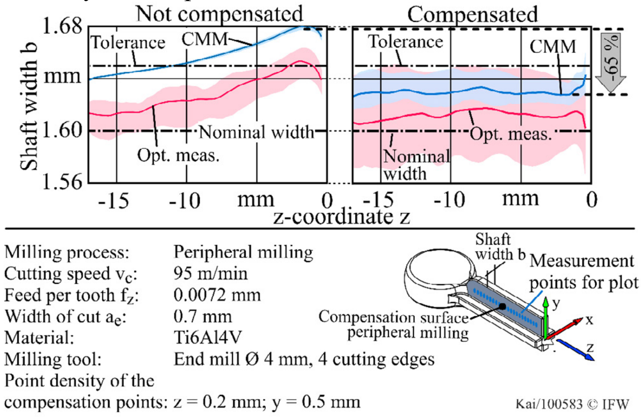

Fig. 10. Nominal points and determination of the error vectors

The compensation of the face milling process leads to similar results. An improvement of up to 85 % could be achieved. Figure 11 shows measuring points over the entire face area. It is noticeable that the variation of the measurement data of the uncompensated production presented in the left graph is (comparatively) low (~10 µm) for the coordinate measuring machine. However, the variation of the optical measurement data is about 50 µm much larger. By using this optical data for compensation, an improvement is achieved, although the variation of the measurement data obtained with the CMM for the compensated surface also increases.

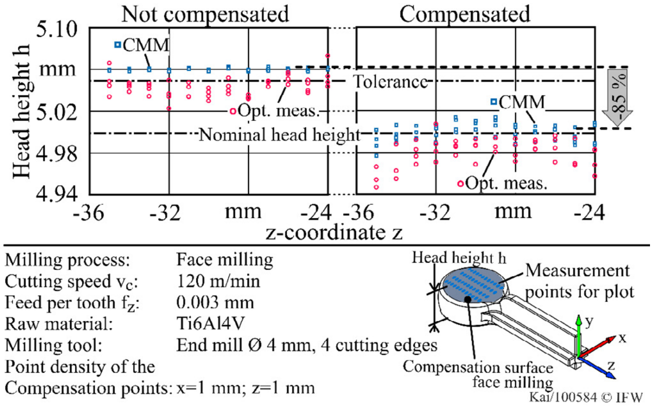

Fig. 11. Nominal points and determination of the error vectors

To further illustrate this, the relative frequency of the deviations is plotted against the measured deviation from the nominal surface. In Fig. 12, only the measurement data of the coordinate measuring machine are shown. This implies that the variation of the optical data due to the G-code adaptation is transferred to the actual compensated geometry.

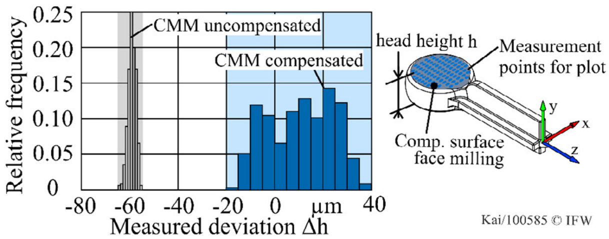

Fig. 12. Nominal points and determination of the error vectors

It can be concluded that the quality of the compensation strongly depends on the quality of the input data. An improvement can be achieved by smoothing the measurement data. However, to achieve an excellent quality of the compensation, the measurement-quality has to increase as well.

6. Conclusion

In this paper, a method for compensating geometric errors based on optical measurement data by adapting the G-code was presented. With a compensated (face milling) process the geometric deviation could be decreased up to 85 % compared to a non-compensated surface. However, it was shown that the quality of the optical measurement data is essential for the compensation quality. In the case of the presented face compensation, the variation in the measurement data of the optical measurement system was transferred to the new component surface by the compensation. The following development steps include another robot for automated optical measurement to achieve higher repeatability and a higher degree of automation. In addition, the optical measurement system should be further developed to be able to measure various form elements with increased precision. The introduced production cell is intended to be used specifically for medical technology. Subsequently, the work carried out will be harmonized with the medical technology requirements in order to derive the next development steps necessary to prepare the manufacturing cell for medical technology certification.

Acknowledgements

This project is funded by the German Federal Ministry of Education and Research (BMBF) within the Framework Concept “Production for medical technology - economical and in highest quality “(funding number 02P18C033) and managed by the Project Management Agency Karlsruhe (PTKA). The authors are responsible for the contents of this publication.

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