3D-DATA AQUISITION, PROCESSING AND ANALYSIS OF GEAR SHAFT MEASUREMENTS USING OPTICAL SENSORS

Rüdiger GILLHAUS, Markus KÄSTNER, Jörg SEEWIG, Eduard REITHMEIER
Institute of Measurement and Automatic Control at the Leibniz Universität Hannover, Hanover, Germany

In the collaborative research centre 489 (CRC 489) ”Process chain for production of precision forged high performance components” an inline measurement process is necessary. Due to the forging and the heat treatment process, the manufactured components show form deviations, which have negative effects on the subsequent processes because of positioning errors. Fast optical sensors, which measure line shaped profiles of the manufactured components, are used for the geometry acquisition. With the results of the data analysis, the manufactured part can be positioned optimally for subsequent process steps like pitch grinding. The data acquisition, the data processing and the analysis of the gear shaft measurements are part of the fine positioning process step.

1. INTRODUCTION

The globalisation increases the cost pressure for high wage countries like many members of the EU. To stay competitive the mechanical engineering must research on more efficient production processes to decrease the impact of the wage-factor. At the same time, the produced components must be of superior quality to justify high investments in the research of production processes. To reach this goal the German Research Centre supports the Leibniz Universität Hannover with the collaborative research centre 489 (CRC 489) called „Process chain of precision forged high performance components“ [1]. Currently, the research centre deals with precision forged integral helical gear shafts, which are categorized as “rotation-symmetric long components”. Compared to the conventional process chain for gear shafts, which basically operates with metal cutting manufacturing methods that implement high cost and long elapsed time, the researched newly process chain substitutes these expensive process steps with novel and integrated process steps. Therefore, an innovative process chain is implemented at the Leibniz Universität Hannover. The difference between the conventional and the new innovative process chain is shown in figure 1.

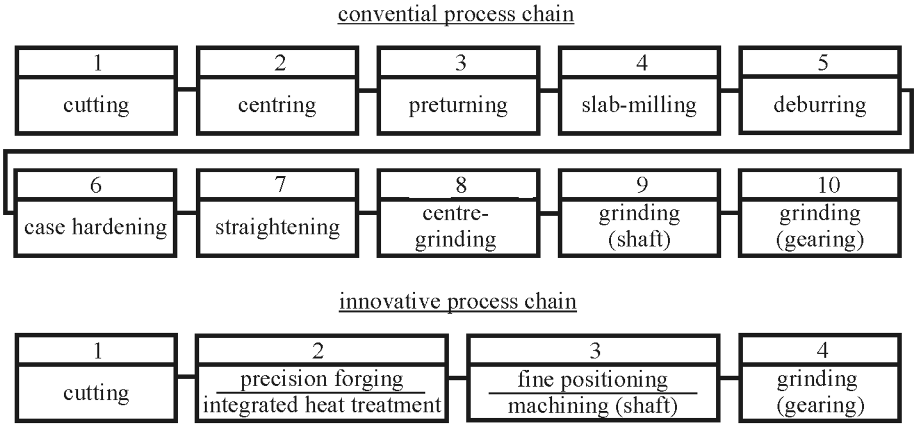

Fig. 1. Comparison of the process chains

The conventional process chain contains ten process steps, which are dominated by metal cutting manufacturing. In contrast, the innovative process chain uses new process steps like precision forging with integrated heat treatment or the material allowance based fine positioning. As a result the amount of process steps can be reduced to four. Therefore, the processing time can be decreased enormously and the economic efficiency of the whole production can be raised.

However, the innovative production using precision forging evokes a novel problem, which has to be solved. Whereas in the conventional manufacture both function elements of a gear shaft, i.e. the gearing and the upper shaft, stand to each other optimally, the innovative production results in position failures in form of displacements (excentricity) and tilts (run out radially) on and between the function elements. These failures, which have to be minimized, generally have two main reasons [1]:

- The precision forging produces the whole gear shaft near-net-shaped in one production step. That means that the gearing and the upper and lower shaft are forged simultaneously. Because of the play of the guidance and the displacements of different tool parts of the forging die the gearing and the shaft can have position deviations. Therefore, it is not guaranteed, that the shaft and the gearing are exactly concentric.
- The integrated heat treatment effects hardness distortions, which cause form deviations on the two functional elements. That provokes position failures between the gearing and the shaft.

These position failures in form of position and form deviations influence the quality of the produced components. In the worst case, the deviations are so high that the subsequent process of tooth grinding cannot be executed and parts have to be rejected by quality control. To assure a high component quality the innovative process chain includes the process step “material allowance based fine positioning” which minimizes the existing deviations and ensures final machining of the produced component.

2. Material allowance based fine positioning

To make sure that the precision forged near-net-shaped gear shafts can be finished, the whole component holds a minimal, but adequate material allowance. Therefore, the position failures can be detected and minimized with the aid of the fine positioning before the machining of the function elements starts.

The main problem for the subsequent machining of the shaft and of the gearing is that the shaft is the reference element for the grinding of the gearing. In the conventional process chain, the shaft has the optimal position and form to process the grinding of the gearing. In the “innovative” process chain, the shaft and the gearing have position and form deviations, which enormously influence the machining processes. The minimal material allowance on both function elements fluctuates also due to the forging and heat treatment process. To obtain the real geometries of all produced gear shafts, every gear shaft is fitted into a reference geometry. For this purpose the functional elements of the gear shaft, the upper shaft and the gearing, are measured. For the fitting process, several optimization algorithms with different parameters can be used. The result of the fitting process is a 3D-adjustment vector, which includes the necessary correction of the position of the component. This 3D-adjustment vector is transmitted to actuators in a machine tool, where an innovative rotating clamping mechanism executes the position correction until the component is aligned [2]. Now, the upper shaft can be processed and afterwards be used as reference element for the grinding of the gearing. Figure 2 shows the method of the material allowance based fine positioning [3].

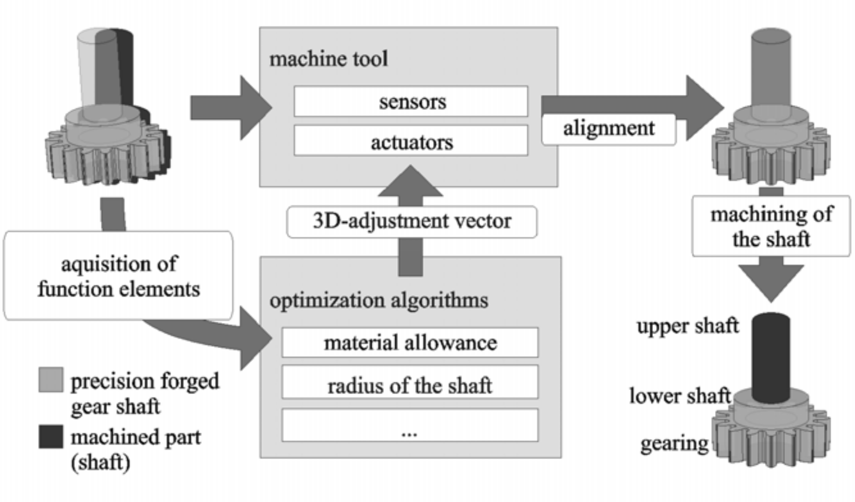

Fig. 2. Procedure of the material allowance based fine positioning

3. Data acquisition

For the detection of position and form deviations on the function elements, the upper shaft and the gearing of the gear shaft, two or more line shaped profiles are acquired.

In the experimental rig two optical sensors of the company OPTIMET Ltd. and a formtester MFU 7 (form measuring station) of the company Mahr GmbH are used. Figure 3 shows the measuring setup.

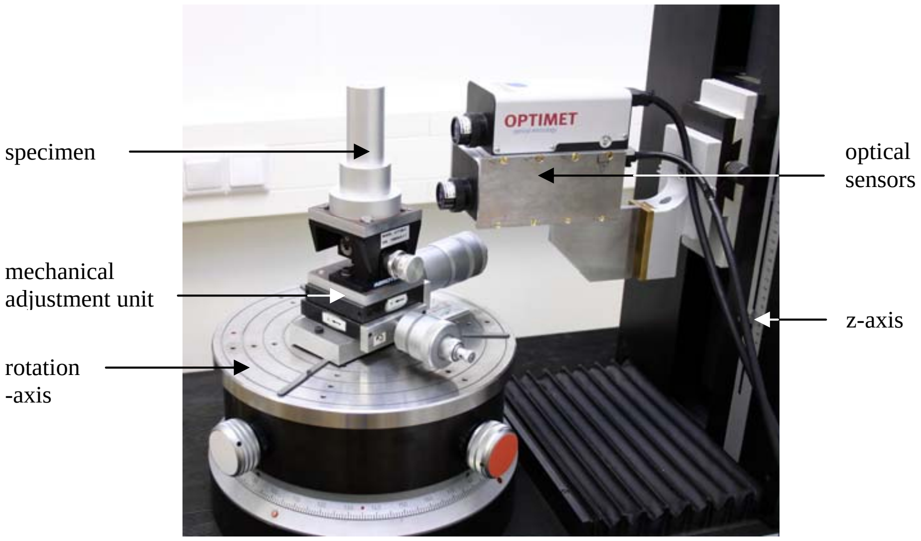

Fig. 3. Experimental rig

Figure 3 shows two optical sensors, which are fixed on the z-axis of the formtester, so line shaped measurements can be taken in the longitudinal direction of the gear shaft. During a measurement, the component rotates around the rotation axis (r-axis) of the formtester. With help of a mechanical adjustment unit the calculated correction can be performed manually. To ensure, that every produced gear shaft will be fine positioned, measurements must be taken in the process chain. Therefore, the integration of measurement assemblies into the process chain is necessary, which is described in [3].

Conoscopic laser sensors are selected as the appropriate sensors, because measurements can be taken even at angles up to ±85° in every direction from the normal direction of the surface of the measured object. This is important while measuring the tooth flanks of the gearing. Additionally the measurement range, measurement uncertainty, and the stand off can be adapted flexibly by choosing an appropriate lens. Regarding the measurement of the gear shaft, two conoscopic laser sensors must be used. Technical and scientific informations about the conoscopic are described in [4].

To get line shaped profiles of the function elements, the distance data of the optical sensor must be synchronized with the data of the rotation axis or the data of the rotary encoder respectively [5]. Together with the height information - the z-axis of the formtester - the x-, y- and z-coordinates of the profile can be calculated and in the next step, the data can be prepared for the fitting process.

4. Data processing

The processing of the measured data for the successive analysis basically consists of two steps. First, the data is filtered by means of different criteria, like the signal noise ratio or the number of saturated pixels on the CCD-chip. The parameters of the criteria can be modified manually in a graphical user interface to react to different constrains like variable surfaces of the components or variable measure frequencies.

The second step is the extraction of the significant areas of the function elements. The measured data of the upper shaft for example can include points of grooves. These points must be removed from the data, because they would be interfering with the fitting process negatively. For the detection of points, which belong to a groove or the edges of a groove, the measured data is filtered by means of the radius. The distance of the points at the bottom of a groove varies from the general radius of the shaft, so that they can be excluded using a variation range. The angular range, in witch these points are found, can be used to exclude all the points on the groove including the edges of the groove.

The data of the gearing includes a complete profile. This means that the measured data contains the tooth flanks as well as tooth crests and bottoms of the tooth spaces. Important for the analysis are only the points of the tooth flanks, because these are critical for the transmission of the torque and the proper function elements of a gearing. The points of the tooth crests and the bottoms of the tooth spaces are eliminated through the addendum and dedendum circle and only the points of the tooth flanks remain. Figure 4 shows the extraction of the important data of the shaft and of the gearing in two dimensions.

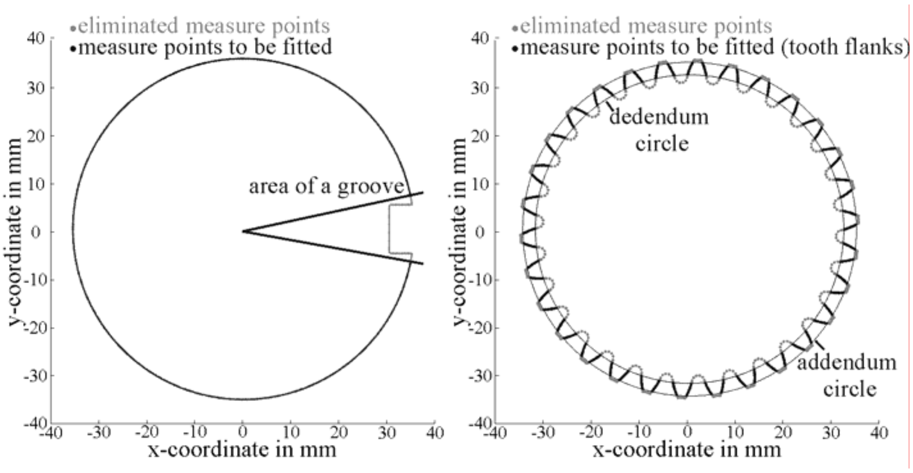

Fig. 4. Extraction of the important measure-data: shaft, gearing

5. Used Algorithms

After processing, the data can be fitted to a reference model. Therefore, different optimization criteria are used, which will be demonstrated on best-fit circles [6].

Best-fit circles can always be calculated by detecting a minimum of an objective function. This objective function uses the parameter a, which includes the coordinates of the centre of the circle and optionally its radius.

The different objective functions of the LSC, L1C, and MZC algorithm obtain the distances d_i of the measure point $p_i = \left[x_i, y_i\right]$ to the best-fit circle with the estimated parameter $a = \left[x_C, y_C; r\right]$ and have the following forms:

LSC – least squares circle (according to Gauss)

$$Q(a) = \sum_i d_i^2 \xrightarrow{!} \min_a \tag{1}$$

L1C – least absolute values circle

$$Q(a) = \sum_i \left|d_i\right| \xrightarrow{!} \min_a \tag{2}$$

MZC – minimum zone circle (according to Chebyshev)

$$Q(a) = \max_i \left|d_i\right| \xrightarrow{!} \min_a \tag{3}$$

where: a — parameter, mm, d_i — distance of the i^{th} measuring point, mm.

Figure 5 shows the best-fit circles of the three optimization criteria.

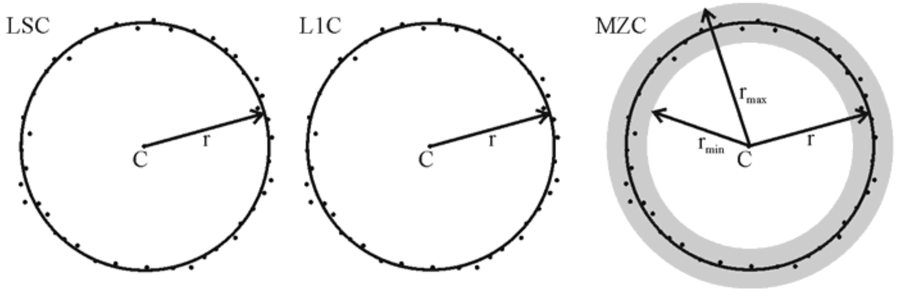

Fig. 5. Best-fit circles

To minimize the objective functions, the distances between best-fit elements and the measured points are necessary. For both function elements the Euclidian distances are calculated. The distance calculation between the involute tooth flanks and their best-fit element is shown in detail in [7]. With the calculation of the distances and the chosen optimization criterion, the adjustment vector can be calculated and transferred to the rotating clamping mechanism, which executes the necessary alignment, so that after machining of the upper shaft, the subsequent process of grinding of the gearing can be implemented optimally.

6. REFERENCES

[1] Bach, F.-W.; ea.: Sonderforschungsbereich 489 – Prozesskette zur Herstellung präzisionsgeschmiedeter Hochleistungsbauteile, Fortsetzungsantrag 2006-2007-2008. 2005

[2] Denkena, B.; Möhring. H.-C.; Immel J.; Möring, B.: Design an Optimization-Methods of an Adaptronic Chuck System. Adaptronic Congress 2007, 23-24 May, Göttingen 2007

[3] Gillhaus, R.; Kästner, M.; Seewig, J.; Reithmeier, E.: Sensorintegration zur Feinpositionierung von präzisionsgeschmiedeten Bauteilen. VDI-Tagung “Sensoren und Messsysteme 2008”, 11-12 März, Ludwigsburg 2008

[4] Kästner, M., Gillhaus, R., Seewig, J., Reithmeier, E., Frankowski, G.: Optische Multisensortechnik zur Geometrieerfassung präzisionsgeschmiedeter Bauteile. VDI-Tagung “Optische Messtechnik technischer Oberflächen in der Praxis”, 09.-10.10.2007 Hannover, VDI-Berichte 1996, S. 89-100

[5] Haase, R.: In-Process Quality Control in Gear Wheel Manufacturing by the means of Best-Fit Gear Wheels. 8th International Symposium on Measurement and Quality Control in Production. VDI-Berichte 1860, S. 401-408. Düsseldorf: VDI Verlag, 2004

[6] Weckenmann A., Gawande B.: Koordinatenmesstechnik. Flexible Messstrategien für Maß, Form und Lage. Carl Hanser Verlag 1999

[7] Günther, A.; Peters, J.; Goch, G.: Flächenhafte numerische Beschreibung, Ausrichtung und Auswertung von Zylinderrädern. Tm-Technisches Messen, heft 4, 2001