Measurement System and Algorithms for the Finepositioning of Precision Forged Pinion Shafts

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Abstract

The project A5 „Material Allowance Based Finepositioning“ of the Collaborative Research Center 489 (CRC 489) "Process Chain for the Production of Precision-Forged High-Performance Components" researchs among other things a process-integrated measurement system. This determines the optimal position of the precision forged pinion shaft which features a certain allowance before the hard machining. Because of this, errors in position of the functional elements toothing and shaft due to the appearing deviations in form, size, and position can be detected and corrected. For this, conoscopic sensors are used which are properly positioned at the measurement component by a linear axis within the lathe. Through the analysis of the captured data the optimal position for processing the functional surfaces is determined.

Keywords:
Inline-measurement, conoscopic sensor, finepositioning, fitting algorithms

1 INTRODUCTION

The project A5 „Material Allowance Based Finepositioning“ has the ambition to clamp, to measure, to positioning and to finish precision forged high perfomance components which have a minimal material allowance. Form and position deviations, which result from the forging process, are not corrected by increasing the material allowance. Rather the produced component is aligned in an optimal position for the machining process of the functional elements. The subproject A5 consists of two scopes. On the one hand the actuating elements and on the other hand the sensor systems are researched. The sensor system consists of a process integrated measurement system and the algorithms for calculating the optimal position for machining.

1.1 Setup of the process-integrated measurement system

Precision forging defined as the near-net-shaped, flash-free forging produces simultaneously both functional elements of a pinion shaft, i. e. the shaft and the gearing which subsequently receive heat treatment from the forging heat. The appearing geometry deviations result in incorrect positioning like eccentricity- and tilt-failures. These have an influence on the following finishing process of the grinding of the gearing and are displayed in figure 1.

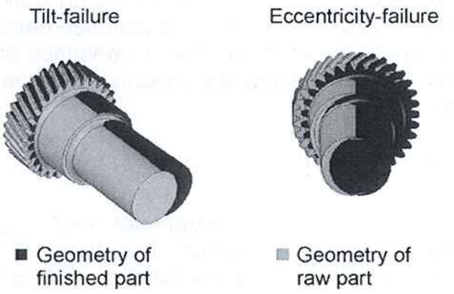

Figure 1: Eccentricity- and tilt-failures of a pinion shaft (super elevated), © IMR

If the processed surface of the shaft is used as reference for the grinding-process, an uneven abrasion of gearing material is caused. E. g. in case of an eccentricity-failure, on one side more material than needed is removed, while on the other side there might be no effect of the worm grinding wheel.

In order to implement the initial reference for precision forged pinions shafts a process for fine positioning which adjusts the rotary axis of the workpiece according to the rotary axis of the machine is mandatory. Both a translational as well as rotational displacement is necessary for this approach. For the fine positioning process the measurement equipment needs to be integrated into the process as displayed in figure 2.

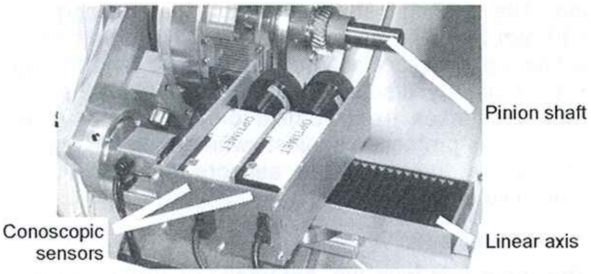

Figure 2: Process integrated measurement system, © IMR

1.2 Conoscopic sensor

For capturing the measurement data two conoscopic sensors from the Inc. Optimet Ltd. are used. The point sensors which operate on the principle of holographic interferometry are very suitable for recording the gearing, since they are able to capture data on an angle of up to ± 85° to the surface normal of the test object.

As displayed in figure 3, a beam generated by a laser diode falls via a beam splitter and a lens system on the surface of the measurement object. From here it is reflected back and after passing the lens system and other optical components it hits a birefringent crystal in a certain angle, which depends upon the distance to the measurement object. The crystal features differing indices of refraction for different directions of polarization of the light. Subject to the direction of polarization the incoming beam is split into an ordinary and extraordinary beam by the crystal. Due to the birefringence these two beams show an optical path difference which is dependent on the incident angle and thus from the distance of the measurement object. According to the optical path difference the interference of these two beams creates a certain interference form of concentric circles which is projected on a CCD sensor. The closer the measurement object is to the sensor, the larger the distance between the circles of the interference patterns becomes. Enlarging the distance between the measurement object and the sensor results in smaller distances between the circles of the interference pattern. The Fourier transformation is used to analyze the frequency of the periodic ring structure on the CCD sensor and after a range calibration it is possible to assign a value for the distance between the measurement object and the detector to each frequency of the ring structure. The technical specifications and further details are described in [1], [2], and [3].

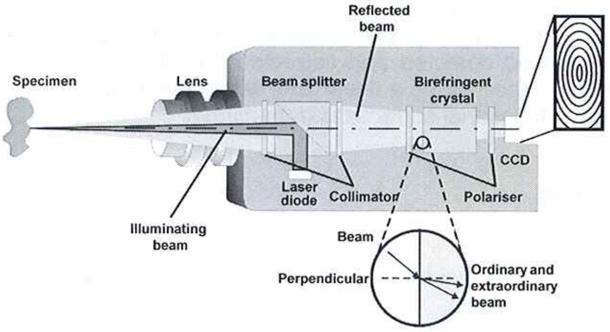

Figure 3: Functionality of the conoscopic sensor, [4]

The conoscopic sensors operate with a frequency of 850 Hz and can be used in a temperature range between 18-35°C. Additional technical specifications are dependent on the used lens system. For example, a lens system of 75 mm length of focus shows an extended standard uncertainty of measurement of about 10 µm, a repeatability of 2 µm and a measurement range of 18 mm. The working distance of 65 mm can be increased to 130 mm by using an extended lens system. In order to achieve a sufficient accuracy and to be able to capture both geometry elements, two conoscopic sensors with extended lenses are used next to each other as shown in figure 2. As protection against swarf during the machining process of the shaft the sensors are encased in a protective cover.

1.3 Linear axis

The linear axis from Inc. Aerotech Ltd. which can also be seen in figure 2 possesses a traverse path of 150 mm with a resolution of 0.1 µm and an accuracy of 0.75 µm. It is used to position the conoscopic sensors in the longitudinal direction of the shaft. Consequently, it is possible to perform one or multiple line shaped measurements per functional element. The linear axis is protected by a gaiter from the swarf.

1.4 Capturing of line shaped measurements

The measurement system as described above consisting of two conoscopic sensors and a linear axis can capture the functional elements of a precision forged pinion shaft during the process. Figure 4 shows the setup for the acquisition of measurement data.

The pinion shaft rotates around the rotary axis of the machine. Due to the low frequency of the conoscopic sensor it is not possible to use the idle-running speed of the machine; instead a dc motor spins the pinion shaft with a speed of 100°/s, so that enough measurement data can be recorded over the circumference. The conoscopic sensors are positioned by the linear axis and measure the distance to the measurement object.

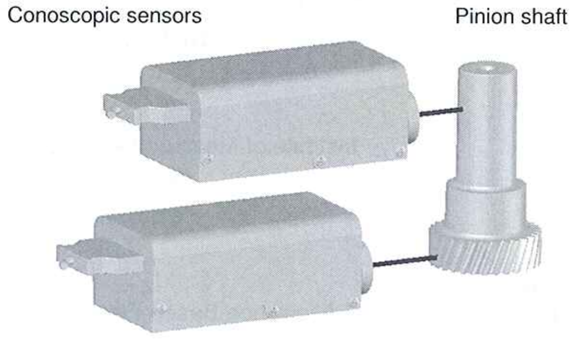

Figure 4: Line shaped measurements, © IMR

To generate cartesian coordinates which can be used for the analysis, the recorded distance data has to be synchronized with the angular position signal and the linear axis position.

2 ALGORITHM FOR THE ANALYSIS OF THE FINE-POSITIONING OF PINION SHAFTS

2.1 Processing of the measured data

Before the measurement data can be analyzed it has to be preprocessed. This contains two process steps. In a first step the data is filtered according to different criteria, e. g. certain data can be eliminated due to the signal-noise-ratio or the light intensity. The values of these parameters can be defined with a user interface to meet the circumstances like the characteristics of the component's surface or the frequency of the measurement. During the second step irrelevant data is removed. On the one hand statistical outliers are detected and on the other hand the data for the tooth crests and the bottoms of the tooth spaces are removed because only the data for the tooth flanks are needed for the analysis of the toothing.

2.2 Data analysis

For the alignment of the produced pinion shaft a three dimensional adjustment vector has to be calculated, which contains the necessary translation and rotation. After supplying this information to the fine positioning systems the required translation and rotation is performed by the according actuators [5, 6]. The calculation of the adjustment vector is done by fitting the measured data onto a reference geometry which lies in a constant fixed coordinate system. Generally, the determination of the deviations and the calculation of the correction vector can be formulated as an optimization problem, for which in this case the distance between the reference model and the measured workpiece are to be minimized. Mathematically, the objective function can be stated as

$$Q(\underline{a}) = \xrightarrow{!} \min_{\underline{a}} \tag{1}$$

The solution supplies the parameter vector $\underline{a}$, which minimizes the objective function. The objective function $Q(\underline{a})$ can have different characteristics. Regarding the adjustment of the pinion shaft three iterative approaches (numerical fitting) that are typical for this field of application were implemented.

The objective function of the Tschebbyscheff fitting (L_∞-Norm) has the general form

$$Q(\underline{a}) = \max_{i} \left| d_i(\underline{a}) \right| \xrightarrow{!} \min_{\underline{a}} . \tag{2}$$

It determines the absolute maximum distance of all distances d_i of the measurement data to the Tschebbyscheff element. The Tschebbyscheff fitting is used, e. g., for the inspection of components confirming standard ISO 1101 in the coordinate metrology and also the creation of references accords to DIN ISO 5459. Consequently, this adjustment determines a minimal zone, which contains all measurement points and is twice as wide as the absolute distance of all measurement points' distances d_i.

A less common strategy is the Manhattan fitting (L_1-Norm) with the general objective function

$$Q(\underline{a}) = \sum_i \left| d_i(\underline{a}) \right| \xrightarrow{!} \min_{\underline{a}} . \tag{3}$$

Accordingly, the sum of all absolute measurement points' distances d_i is minimized. Another adjustment algorithm which was implemented is the fitting according to Gauss (L_2-Norm). It is very common in coordinate metrology; its objective function is

$$Q(\underline{a}) = \sum_i d_i(\underline{a})^2 \xrightarrow{!} \min_{\underline{a}} . \tag{4}$$

It minimizes the square root of the sum of the squared distances of the measurement points.

For all fitting types the perpendicular distances between the reference model and the measurement data is determined. Because of the simultaneous adjustment of the shaft data and the gearing data an optimal distribution of allowance and the corresponding adjustment vector can be calculated. Figure 5 shows the result of an exemplary analysis of a pinion shaft.

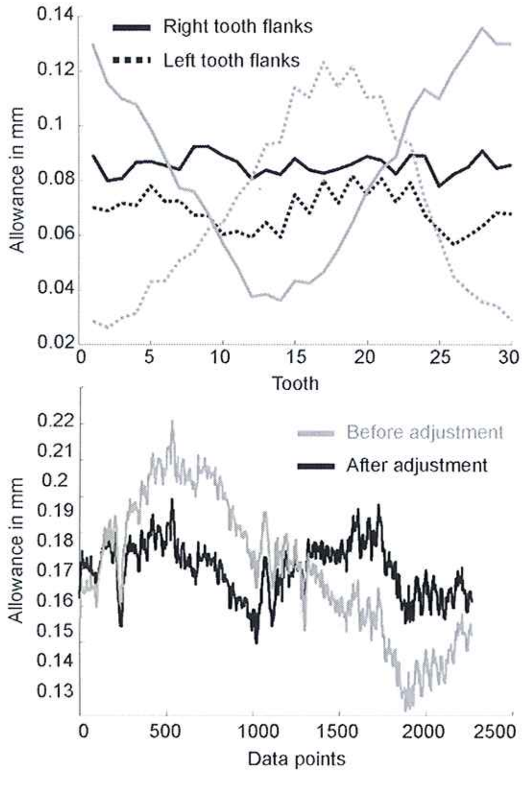

Figure 5: Material allowance before and after adjustment on the toothing and the bearing seat, © IMR

The allowance on both functional elements is distributed considerably more homogenous after the adjustment than before. For this example the adjustment vector as stated in table 1 was required for the alignment of the pinion shaft.

Pinion shaft 91	x	y	z
Rotation	-31"	72"	(6073")
Translation	-41 µm	-30 µm	(0 µm)

Table 1: Necessary corrections for the alignment, © IMR

This adjustment vector was subsequently relayed to the fine positioning mechanism so the pinion shaft can be processed in the optimal position.

3 SUMMARY

The process-integrated metrology enables the optimal alignment of precision forged pinion shafts, which show deviations in form, size and position within a hard machining process. In order to do this, the measurement system was integrated into the process chain to be able to inspect 100% of all produced components. After being preprocessed, the captured measurement data is analyzed according to technologically reasonable criteria, i. e. an equidistantly distributed allowance on all functional elements. As a result an adjustment vector is calculated supplying the necessary displacement and tilting of the pinion shaft before the processing of the shaft. The processed bearing seat is used as the primary reference element during the subsequent step of the grinding of the toothing.

4 ACKKNOWLEDGEMENT

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