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Optische Messtechniken zur Geometrieprüfung präzisionsgeschmiedeter Ritzelwellen

Optical Measurement techniques for precision-forged high-performance pinion shafts

by

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Optical Measurement Techniques for Precision-forged High-performance Pinion Shafts

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Abstract

During the precision-forging of pinion shafts geometry deviations are created randomly on the component's surface due to the molding of the die. In general, these cannot be detected by conventional tactile measurements. A solution is offered by the fringe projection as an areal triangulation method. A complete areal capture of the functional surfaces after the precision-forging with an integrated heat-treatment builds the foundation for a near-process coherent analysis of the deviation of the gearing and the bearing seat of pinion shafts. By capturing the geometry before and after the hardening process distortions due to hardening can also be detected. A process-integrated measurement 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 from, 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 the processing of the functional surfaces is determined.

Keywords

Fringe projection, quality control, precision forging, inline-measurement, conoscopic sensors

Introduction

The automotive industry is one of the most important industry branches in Germany. The quality of the produced vehicles is the foundation for staying competitive in the international markets. Especially the end consumer demands a long lifespan and long service intervals in regard to automotives and their components. In contrast, the automotive industry and its suppliers face an increasing cost pressure.

In regard to the power train, a "process chain for the production of precision-forged high-performance parts" has been designed at the Leibniz Universität Hannover as part of the Collaborative Research Centre 489 (CRC 489). Helical pinion shafts have been chosen to serve as sample components. Conventional process chains include to a great extent expensive metal cutting steps for the production of pinion shafts. In contrast, the process chain as introduced by the CRC 489 offers a considerable reduction due to innovative process steps. For example, the precision forging and the integrated heat treatment, which can be performed with the forging heat, are integrated into a single process step. Consequently, the cycle time as well as the cost per part can be reduced significantly.

Due to the metal shaping steps in the production, singular geometry variations are randomly generated on the component's surface. These variations can notably influence the quality of the produced component, but they cannot be detected with conventional tactile measurement procedures in an acceptable period of time. In order to guarantee the final machining during the terminal quality-decisive grinding of the toothing the pinion shafts have small material allowances regarding to their functional elements. Concerning the geometrical inspection of precision-forged pinion shafts it is important that the gearing and the shaft are formed simultaneously.

The forging process with the integrated heat treatment can result in distortions because of thermal effects. Due to these distortions the axes of the shaft and the gearing do not match. Consequently, the shaft cannot be used as the main reference for the following process steps, or respectively, as a reference for a function based inspection of the geometry. Therefore, for the geometrical inspection of precision-forged pinion shafts a production-oriented reference system is chosen based on the axis of the bearing seat. For the geometrical inspection of the functional surfaces of these precision-forged components the fringe projection as an imaging triangulation method is used.

In order to detect the variances two metrological subprojects are integrated in the CRC. The subproject B5 "Geometry Analysis" investigates an areal capturing of functional surfaces of random part samples to supply information to the producing process steps about the distribution of the material allowance of the components and parameters for the production-related correction of systematic variances. On the other hand, as part of the subproject A5 "fine positioning based on material allowance" the line shape of every produced component is measured before the machining process, so that it can be aligned optimally on the basis of the collected geometric information. Due to the varying objectives, both subprojects make different demands on the sensor systems, methods and strategies of data analysis which will be presented in this paper.

Setup of the Accompanying Measurement System

For the geometrical inspection of precision-forged pinion shafts the measurement system, which consists of a fringe projection sensor made by GF Messtechnik GmbH, a precision rotation axis with air pressure-bearing from LT Ultra Precision Technology GmbH and a fixture for the workpiece, is integrated into a coordinate measurement device from Werth Messtechnik GmbH (figure 1). Using the precision guidance of the coordinate measurement device enables a high-precision positioning of the fringe projection sensor at the required position for capturing the functional surfaces.

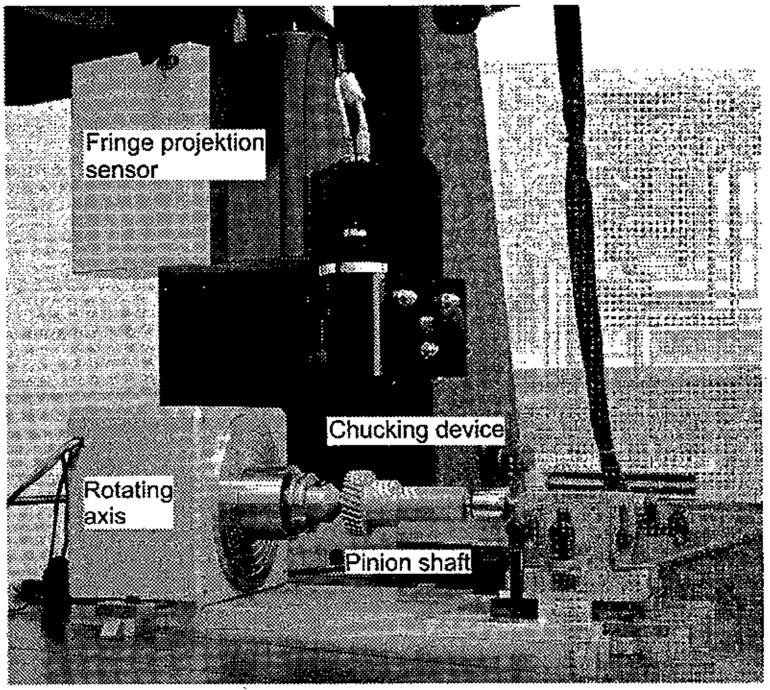

Fig. 1: Setup of the accompanying measurement system

Fringe projection system

The fringe projection system which is used possesses a digital micro mirror array with 1024 x 768 single mirrors for the creation of the fringe sequences. The system features a cold light source, which is coupled into the projection unit through an optical fiber in order to prevent thermal effects.

The fringe sequences, which are projected onto the test object, are displayed on the detection area of a CCD camera type 641F from Basler AG via a telecentric objective made by Sill Optics GmbH & Co. KG. The camera features 1600 x 1200 pixels. The dimensions of the measurement area are about 47.6 mm x 35.2 mm with a vertical measurement range of about ±9 mm. By synchronizing the projection of the fringe sequences with the image capturing of the camera, measurement periods of about 2 seconds can be achieved for 3D-recordings. The calculation time of the height information is highly dependent on the pc computing power and ranges about 6 seconds.

Rotation Axis

The used hinge is of prime importance for the measurement procedure. It serves the high-precision rotatory positioning of the pinion shaft in the measurement capacity of the fringe projection sensor. The hinge is mounted on an air-bearing, possesses a servo drive and a high resolution incremental rotary encoder with a resolution of 0.4". With this setup a rotary insecurity of ± 3.6" is achieved. The concentric accuracy is specified to be < 0.5 µm. Consequently, this results in a maximum error for the hinge of ca. 1.4 µm regarding the pinion shafts to test, which have a gearing with a divided circle radius of about 40 mm. This impreciseness is in reference to the measuring objective negligible and does not contribute noticeably to the measurement impreciseness of the whole system.

Capturing of the workpiece's geometry

Since the uncertainty of measurement of fringe projection sensors is proportional to the length of the diagonal of the measurement area, the fringe projection system, which is implemented to capture the workpiece's geometry, has a measurement capacity which is adjusted to the component's dimensions [1]. By using a minimal measurement capacity and because of the relative position of the pinion's functional surfaces the capturing of the workpiece's geometry is performed in two consecutive steps (figure 2). Initially, the bearing seat of the pinion is captured in 16 angle positions distributed equidistantly over the full circle of the shaft. Subsequently, the geometry of the gearing is recorded. During this step, a measurement is performed for every tooth gap. The workpiece is rotated in between two of these measurements by the angular pitch. Because of this approach many parts of the gearing are captured redundantly. Areas with a high gradient, which contribute considerably to the measurement insecurity, can be eliminated, since especially these parts are contained in adjacent records given optically favorable circumstances.

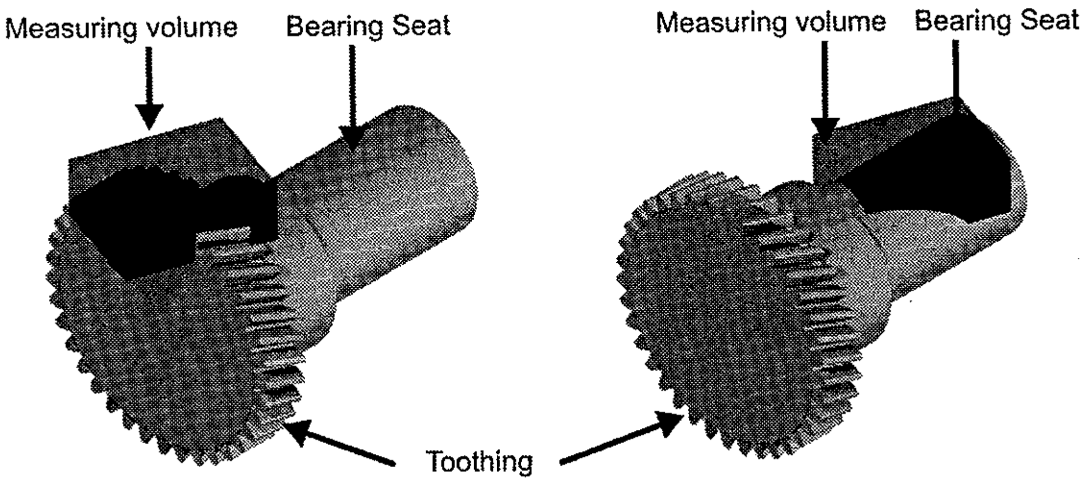

Fig. 2: Acquisition of the functional surfaces

The creation of the whole geometry results from the purely geometrical transformation of the measurement points, so complex matching operations are not necessary. This approach demands a very exact determination of the rotary axis, around which the measurement object is rotated during the measurement. In order to identify the rotary axis, the previously measured datasets of the bearing seat are used, by fitting cylinders onto each of them as substitute geometries. The rotary axis is determined by building the average of the axes of the calculated substitute cylinders [2].

Areal analysis of Deviations

Definition of the component's axis

The bearing seat of a pinion shaft is the primary reference element for the final cutting of a component. For this reason and the fact that the cylinder axis of the bearing seat can be determined fast and securely through numeric adjustment methods, the axis of the bearing seat is subsequently defined as the component's axis. Alternatively it is possible to choose the axis of the gearing as the component's axis. However, the required adjustment of the gear measurement data onto a reference geometry is numerically a lot more complex and time-consuming than the analysis of cylinders. Moreover, precision-forged gearings show more often bigger geometrical variances than cylinder segments because of the considerably more demanding forming process. Consequently, a component's axis based upon the gearing axis is not as securely determinable as when based upon the axis of the bearing seat due to the characteristics of variances.

Separate analysis of the functional components

The recombined models of the functional components built from the separate datasets are fitted onto ideal geometrical models of the gearing and the bearing seat respectively in order to determine the geometric deviation. Subsequent to the adjustment, the deviation of the measurement data to the reference geometry is calculated orthogonally to the models' surface. The results of the optical examination of the geometry can be displayed as three-dimensional images of deviation (cf. figure 3). Using this displaying method already enables a qualitative rating of the geometrical deviations. Specifically, the local and randomly spread geometry deviations, which are typical for precision forging, as well as temperature, related systematic variances can be detected.

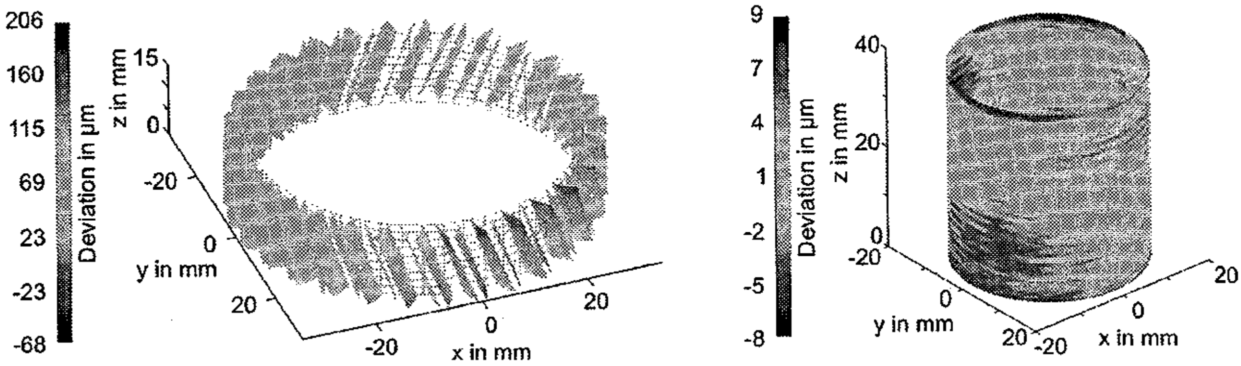

Fig. 3: 3D illustration of the deviations on the functional surfaces

Consideration of the holistic component

Next to the analysis of the deviations of the bearing seat and the gearing as functional components an examination of the whole workpiece is mandatory for a comprehensive inspection of the geometry. This makes it possible to gather detailed information about the geometry deviations caused by the production process and to deduct selective measures for the correction of the parameters of the forging process and the heat treatment respectively. Initially, for the analysis of the whole workpiece the axis of the bearing seat is defined as the component's axis. Apart from the deviation of the gearing which can be determined by the inspection of the gearing independent of the geometry of the whole workpiece, the deviations which are caused by the tilting of the gearing axis in respect to the workpiece's axis also have to be considered. Figure 4 shows the deviation of the functional surfaces of the whole workpiece from the reference geometry [3].

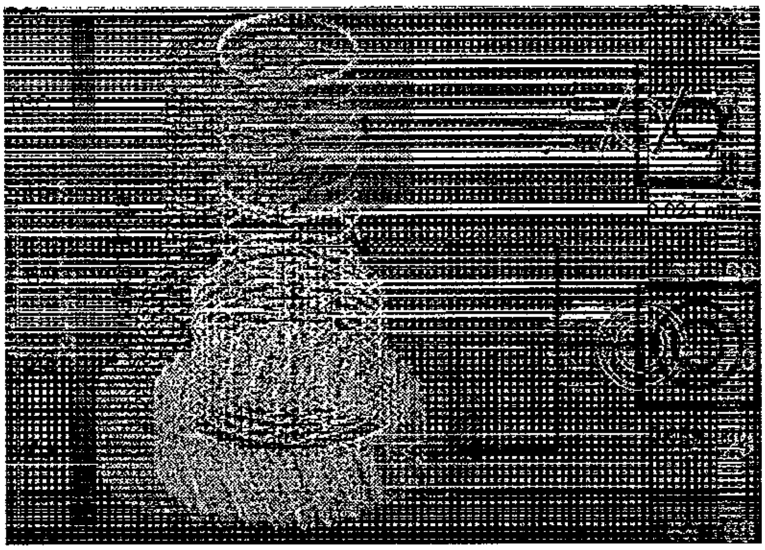

Fig. 4: 3D illustration of the deviations on the functional surfaces of the whole component

A quantitative analysis of the geometry errors with the aim of an objective examination, the definition of tolerances, and the feedback of assembly errors is performed based on the gearing through surface related parameters [4]. The quantification of the deviation of the bearing seat is conducted based on the determination of the cylindricity and the bearing seat radius. As a characteristic for the analysis of the tilting of the bearing seat's and the gearing's axis their coaxiality is employed. The characterization of the geometry information based on these parameters suppliers information about the kind and specification of the deviation and supplies actual data for the process control. This way, the wear of the machining tools or the shape errors due to the heat treatment can be specifically detected and corrected by appropriate correction parameters.

Examination of distortion

To characterize the distortions due to the hardening of the pinion shafts it is necessary to capture the geometry of the investigated components before and after the heat treatment with a fringe projection sensor. The recorded geometry information has to be compared for a calculation of the distortion related geometry deviation. In order to be able to perform this comparison with the Polyworks module IMInspect the conversion of the recorded geometry data, which is available as pointclouds, into polygon models is necessary.

Using the Polyworks module IMInspect the polygon model of the measurement data after the heat treatment is fitted onto the polygon model of the measurement data before the heat treatment, which serves as reference. The deviations between the two models are subsequently calculated orthogonally to the surface of the reference model and deliver information about the distortion caused by heat treatment.

For a qualitative analysis of the distortions due to hardening a color-coded 3D-display of the geometry deviations is very suitable, analogous to the inspection of distortion for the gearing. Hereby, systematic deviations which are typical for distortions due to hardening can be detected in a fast and highly deterministic manner. Additionally, their characteristics can be analyzed and evaluated.

Fig. 5: Color-coded illustration of the deviations caused by hardening

Figure 5 shows the geometry variations caused by the distortion of a pinion shaft hardened with spray cooling as a three dimensional color-coded geometry model. The gearing of the pinion shaft shows a homogenous and minor distortion. The low deviation of the helix angle is noticeable. In the left part of the toothing of the pinion shaft the helix angle of the hardened toothing is bigger than the helix angle of the non hardened reference. In the right part of the toothing the opposite behavior can be observed. The maximum geometry deviations of the gearing range around 75 µm. Additionally, the bearing seat's radius of the pinion shaft after the hardening is approximately 30 µm smaller than before the hardening.

In order to quantify the deviations of the gearing of the pinion shaft caused by distortions methods for interpreting the profile lines and analyzing of the changes of the head and foot radius can be used. The distortions due to hardening of the bearing seat can be characterized by determining the cylindricity as well as the inspection of the cylinder radius. For the examination of the distortions of the whole component an analysis of the coaxiality of the axes of the bearing seat and the gearing can be employed. For the inspection of the pinion shaft as displayed in figure 5 the parameters before and after the hardening as stated in table 1 were discovered. Apparently, the deviation of the coaxiality of the bearing seat and the gearing axes is increased considerably during the hardening process, whereas the difference between the bearing seat radius and the cylinder form is decreased. Additionally, the bearing seat radius is smaller after the hardening. This effect can be presumably explained by changes of the internal stress relation inside the component due to the heat treatment.

Parameter	Not hardened	Hardened
Radius bearing seat in mm	17.787	17.746
Cylindricity in mm	0.024	0.017
Coaxiality in mm	0.089	0.123

Tab. 1: Parameters to quantify geometry deviations of the bearing seat and the toothing before and after hardening

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 wrongful 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 6.

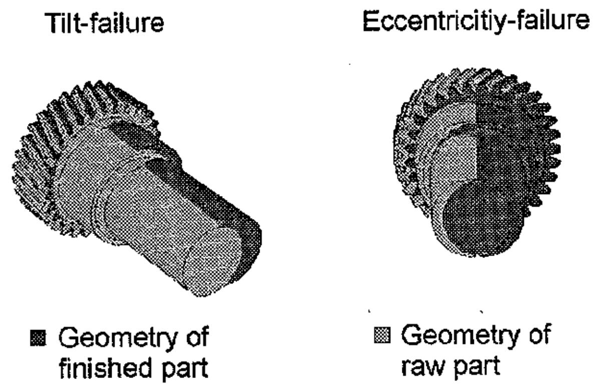

Fig. 6: Eccentricity- and tilt-failures of a pinion shaft (super elevated)

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 rotatory 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 7.

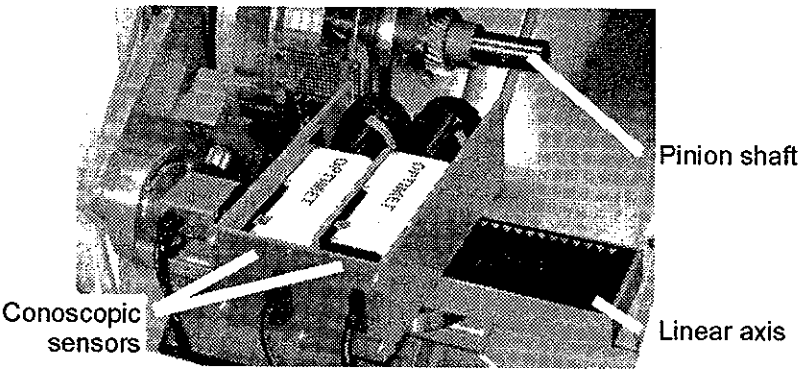

Fig. 7: Process integrated measurement system

As illustrated in figure 7 it comprises of two conoscopic sensors, which are mounted on a linear axis, in order to be able to capture both functional elements, the gearing and the shaft with multiple measurements.

Conoscopic sensor

For the capturing of 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 8, 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 in 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 [5], [6], and [7].

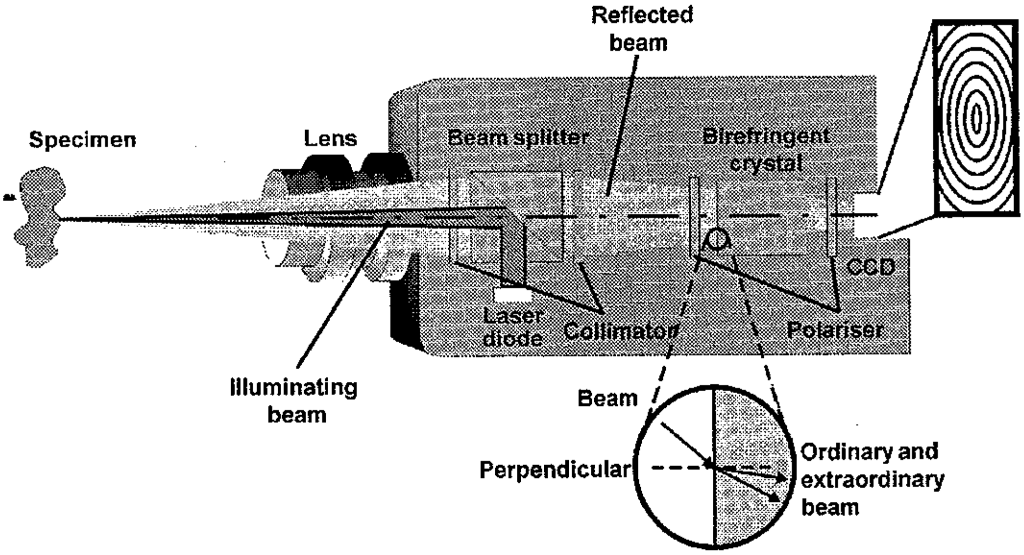

Fig. 8: Functionality of the conoscopic sensor [8]

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 insecurity 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 7. As protection against swarf during the machining process of the shaft the sensors are encased in a protective cover.

Linear Axis

The linear axis from Inc. Aerotech Ltd. which can also be seen in figure 7 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.

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 9 shows the setup for the acquisition of measurement data.

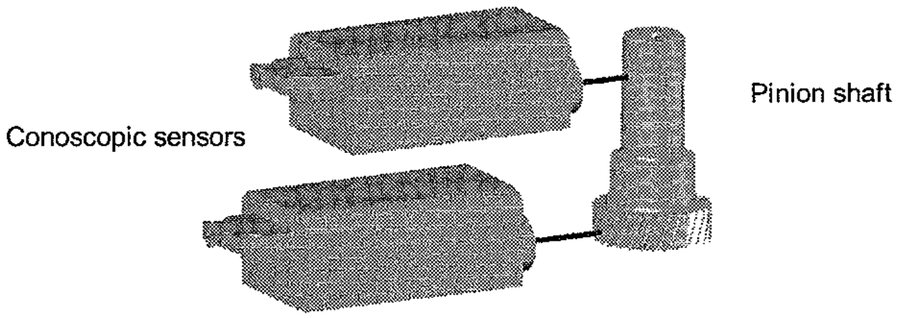

Fig. 9: Capturing of the line shaped measurements

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

Algorithm for the Analysis of fine positioning of pinion shafts

Processing of the measurement 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.

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 [9, 10]. 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

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

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

$$Q(\underline{a}) = \max_i |d_i(\underline{a})| \xrightarrow{!} \min_{\underline{a}} .$$

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

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

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

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

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 10 shows the result of an exemplary analysis of a pinion shaft.

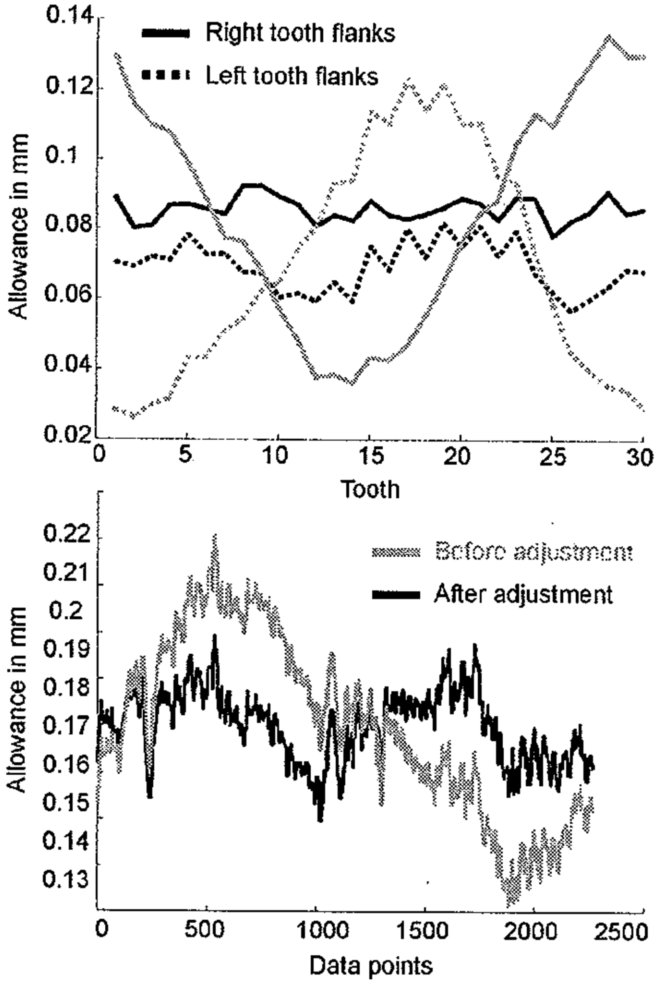

Fig. 10: Material allowance before and after adjustment on the toothing and the bearing seat

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 2 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)

Tab. 2: Necessary corrections for the alignment

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

Summary

Based on the total areal capture with a fringe projection system a complete analysis of the deviation of functional surfaces of pinion shafts could be performed. Due to the color coded display of the deviations on a geometry model of the pinion shaft, random as well as systematic deviations can be detected fast and securely. A quantification of the deviation can be made by examining the cylindricity and the actual radius of the bearing seat and the coaxiality of the axes of the bearing seat and the gearing. Distortions due to hardening can be evaluated by a comparison of the geometry data of the pinion shaft before and after the hardening.

The process-integrated metrology enables the optimal alignment of precision forged pinion shafts, which show deviations in form, size, and position, for the hard machining. 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.

Acknowledgement

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