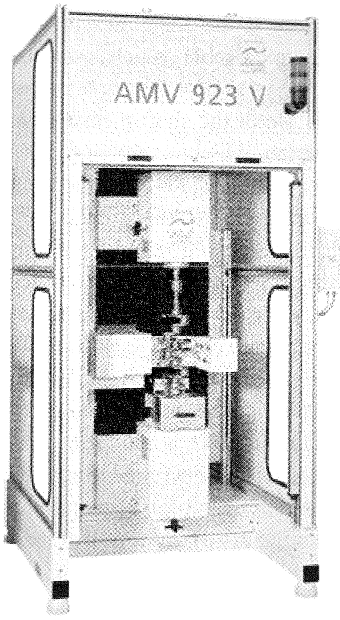

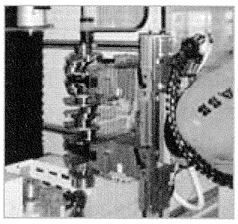

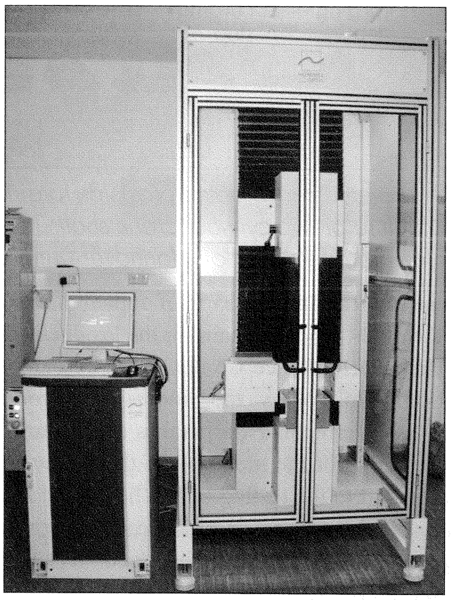

Geometry Inspection of Precision-Forged Crank Shafts Based on Optical Multisensor Techniques

by M. Kaestner, R. Gillhaus, and E. Reithmeier

Within the scope of the "Process Chain for the Production of Precision-Forged High-Performance Components" project, which is being researched at the University of Leibniz in Hanover, Germany, is the reshaping production of highly stressed components of the drive chain of automobiles, which results in individual and randomly distributed deviations and variations of the material allowance. Furthermore, thermally induced internal strains during the heat treatment of precision-forged parts cause distortions, which particularly result in form deviations of long parts.

For a fast and production-related geometric inspection of the functional surfaces of these parts, fringe projection is used as an imaging-triangulation technique. By means of the recombination of the areal measurement data in forming a complete model of the functional surfaces, an analysis of the geometric errors is made possible, based on a nominal value comparison. The analysis of the geometric data provides information about characteristics of the deviations and delivers the actual data for process control. By this means the wear of the forming tools or form deviations caused by the heat treatment can be detected.

For the geometric inspection of crank shafts, a contour projection system is used in addition to the fringe projection sensor for the acquisition of the outline of the work piece. Based on an envelope of the work piece, which consists of a multiplicity of work piece outlines, an analysis of shape, dimension, and position parameters is carried out.

A further optical sensor, the conoscopic sensor, is used to measure the undercuts of the geometrical element crank web, which cannot be acquired with the other sensor systems. The undercuts are captured with a high number of single line-shaped measurements. This way a similar data density is achieved, compared to the other measurements.

By merging the areal measurement data of the fringe projection sensor with the envelope of the work piece and the undercuts acquired with the conoscopic sensor, a volumetric analysis of the crank shaft is made possible. Thus the mass distribution and the centre of mass can be calculated. Based on these results the unbalance, which is a significant parameter for the manufacture of crank shafts, can be estimated.

Parameters for the adjustment of the subsequent process steps can be defined based on the detected process-related geometric errors and the results of the volumetric analysis. These parameters can also be used as an indicator to determine the performance of the prior process steps.

INTRODUCTION

Multisensor techniques are commonly applied in modern coordinate measuring technology. In the last years modern coordinate measuring machines (CMM) are often equipped with optical sensors, in addition to the tactile probe. These are usually video sensors used for the acquisition and analysis of work piece contours using image processing or point- or line-based distance sensors, which work on the basis of the autofocus principle or laser triangulation. By means of multisensor techniques, the objective to precisely measure work piece geometries in a short time with one universal measuring system can often be realized much better than with conventional tactile CMMs.[1]

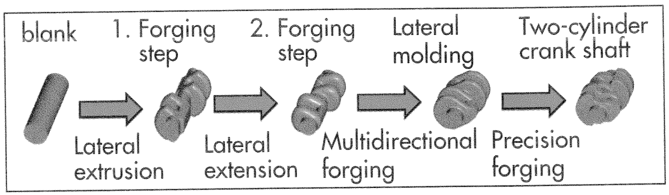

Figure 1. The four stages of the precision-forging process for the manufacture of two-cylinder crank shafts (Source: Institute of Integrated Production Hannover GmbH [IPH])

An ideal application for the use of optical multisensor systems is offered by the "Process Chain for the Production of Precision-Forged High-Performance Components" research. Concerning the position of metrology, the process- and production-related testing of the intermediate parts takes center stage. In this case the requirements for the precision of the measuring system are lower compared to the testing of finished parts. Besides the fast acquisition of the geometric elements of the precision-forged work piece, the areal analysis of the functional surfaces is of high interest. Furthermore, the surfaces of these work pieces show diffuse reflexion, unlike machined parts. This is advantageous for the application of optical measuring techniques.

The current work piece, which is used for the representation of the process chain, is a two-cylinder crank shaft. The geometry of the crank shaft is adapted to the material flow during the forging process. For the manufacture of the crank shaft, a four-stage forging process is employed, as seen in figure 1.

In the first and second stage of the forging process the blank is compressed in the axial direction and gets an eccentric unbalance due to a lateral material flow. In the third operation, the work piece is compressed along its main axis by multidirectional forging. Through this the pin bearings are displaced relative to the main axis. The last precision-forging step ensures that the form of the work piece shows only minor deviations compared to the nominal geometry.[2] Figure 2 shows a precision-forged two-cylinder crank shaft.

SETUP OF THE OPTICAL MULTISENSOR SYSTEM

For the acquisition of the geometry of crank shafts, a multisensor system consisting of three different sensors is used.[3] The basic element of this system is the shaft measurement system AMV 923V by Hommel Etamic GmbH, which is seen in the figure at the top of the article.

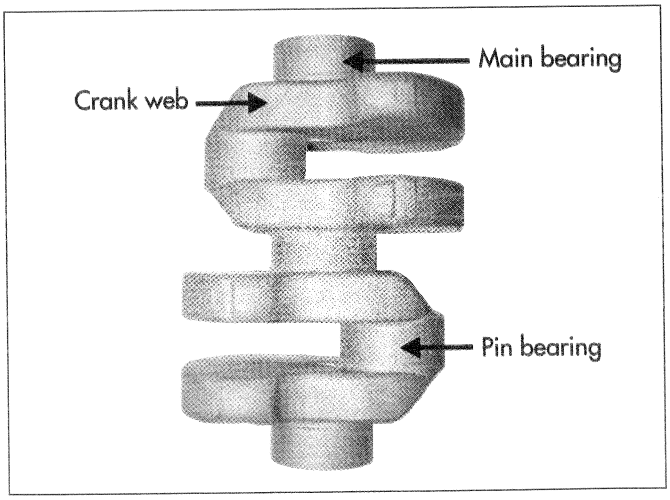

Figure 2. Precision-forged two-cylinder crank shaft

The measurement principle of the shaft measurement system is based on contour projection, which is seen in figure 3.

The measurement object is illuminated by a telecentric projection of infrared light, as seen in figure 3a. On the other side CCD line scan cameras, which are also equipped with telecentric objectives, are used to detect the shadow of the object, as seen in figure 3b. The necessary accuracy for the measurement is achieved by analysis of the light-dark boundary on the CCD chip and the application of subpixel methods, as seen in figure 3c. When a defined threshold for the digitalization of the interpolated distribution of light intensity on the CCD elements is reached, the light-dark boundary can be determined with subpixel accuracy. In this way, the contour of the measurement object can be acquired.

Figure 4 shows a few characteristics of the shaft measurement system AMV 923V.

The second measurement system, used to acquire the geometry of precision-forged crank shafts, is a fringe projection system. Its mode of operation, which allows for a fast data acquisition of about 106 measuring points during one exposure time of about six seconds, is seen in figure 5.

The fringe projection system uses a digital micro mirror array with 1024 × 768 single mirrors for the creation of the fringe sequences. To prevent thermal effects, a cold-light source, which is coupled into the projection unit through an optical fiber, is utilized. The fringe patterns, which are projected onto the measurement object, are displayed on the detection area of a CCD camera with 1600 × 1200 pixels via a telecentric objective. The dimensions of the measurement area are approximately 47.6 mm × 35.2 mm with a vertical measurement range of ±9 mm. The measuring uncertainty of imaging triangulation sensors is

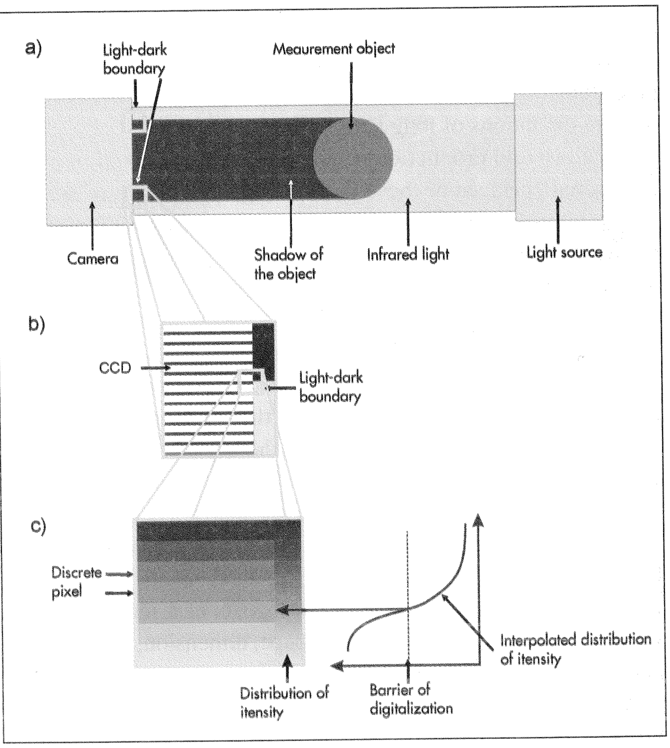

Figure 3. The contour projection principle

AMV 923V	
Measurement capacity: length	900 mm
Measurement capacity: diameter	230 mm
Deviation: length	± (5 + L[mm]/100) μm
Deviation: diameter	± (2 + D[mm]/100) μm
Standard deviation: length	± 5 μm
Standard deviation: diameter	± 1 μm

Figure 4. Characteristics of the shaft measurement system AMV 923V

proportional to the length of the diagonal of the measuring field[4] and is here about ±6 μm.

The third measurement system used is a conoscopic sensor, based on the principle of conoscopic holography. The mode of operation of the conoscopic sensor is seen in figure 6.

A beam, generated by a laser diode, falls via a beam splitter and a lens system on the surface of the measurement object. The reflected beam passes the lens system and other optical components and hits a birefringent crystal at a certain angle, which depends on the distance to the measurement object. The crystal features differing indexes 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 feature 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 pattern in the form of concentric circles, which are projected on a CCD sensor. The closer the measurement object is to the sensor, the larger becomes the distance between the circles of the interference pattern. As the distances between the circles of the interference pattern are smaller, the distance between the measurement object and the sensor become greater. This interference pattern is analyzed and delivers a measure for the distance to the measuring object.

The conoscopic sensor, which is used for the measurements, works with a frequency of 1000 Hz and a lens system of 100 mm length of focus, and shows a precision of less than 15 μm, a reproducibility of less than 4 μm, and a measurement range of 35 mm. Further technical specifications and details are available.[5,6,7]

The complete measurement system to capture the geometry of crank shafts is seen in figure 7.

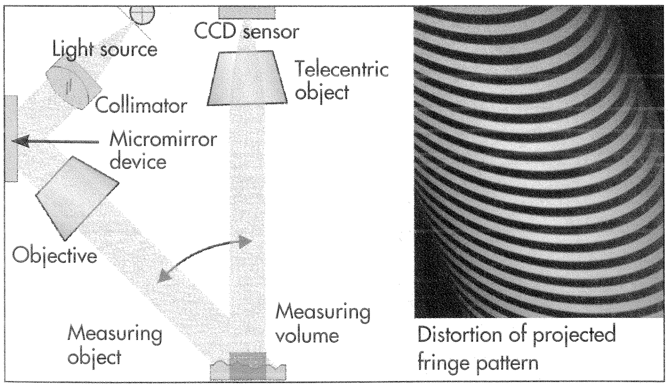

Figure 5. Mode of operation of the fringe projection system

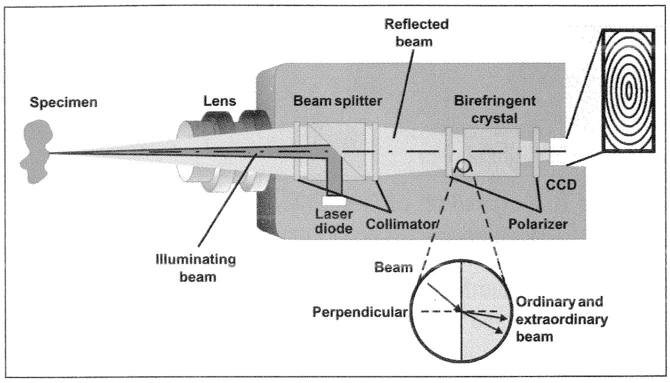

Figure 6. Mode of operation of the conoscopic sensor

DATA ACQUISITION

Acquisition of an envelope of the work piece

For identification of form, dimension, and position parameters of the geometric elements of precision-forged crank shafts, an accurate knowledge of the work-piece geometry is mandatory. A fast and almost complete acquisition of the geometry of crank shafts, except for the undercuts at the crank webs, can be carried out with the contour projection technique with high precision. For the acquisition of the geometry of precision-forged crank shafts it is necessary to acquire a large number of work piece contours (~103) in different angular positions along the rotation axis, as seen in figure 8.

An envelope of the work piece can be combined by a large number of contours, as seen in figure 9. With the geometric information obtained this way, important parameters like concentric run, concentricity, and eccentricity of the bearing seats can be determined. Furthermore, an analysis of the roundness, respectively the cylindricity of the bearing seats, a determination of the eccentricity of the pin bearing, and a testing of the parallelism of the axes of the pin bearings and the rotation axis of the crank shaft, is made possible.

For a quick determination of form and dimension of selected geometric elements of precision-forged crank shafts, the work piece contour can initially be acquired in a few defined angular positions with the contour projection system. This way dimensions like the diameter and the width of the bearing seats can be deter-

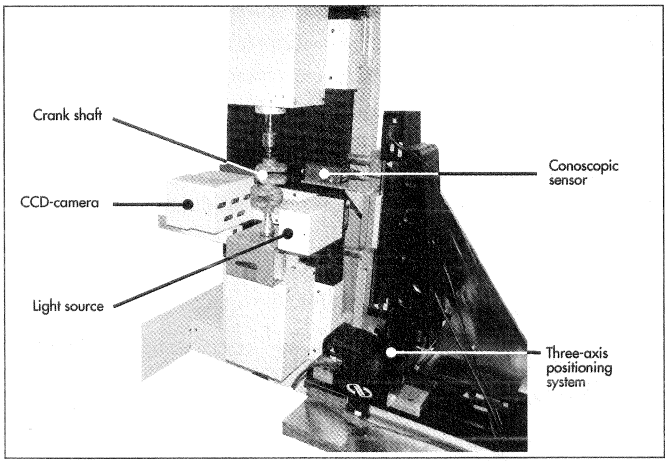

Figure 7. Measurement system (exemplarily shown with conoscopic sensor)

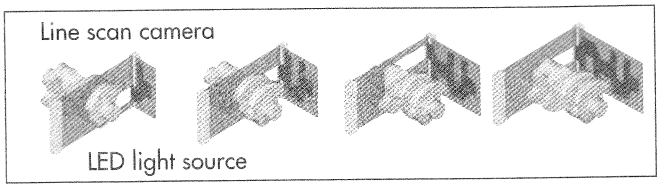

Figure 8. Acquisition of the contour of a crank shaft along its rotation axis using contour projection

mined quickly. Furthermore, a testing of the rectangularity between the crank webs and the rotation axis is rendered possible.

Acquisition of the functional surfaces

On the functional surfaces, namely the main and pin bearings of precision-forged crank shafts, individual and randomly distributed geometric errors occur due to the forging process. To assure the completion of the bearing seats, it must be verified that an adequate material allowance is available for the finishing operation. To test this requirement, it is necessary to acquire the complete functional surfaces with high density. Because of the diffuse reflection, the surfaces of precision-forged parts are particularly applicable for the fringe projection technique. For a gapless acquisition of the main bearings, several measurements in different equidistant angular positions have to be carried out. These positions can be set up with a motorized rotation stage. For a precise acquisition of the pin bearings, the fringe projection sensor has to be made to follow-up the bearing subject to the angular position.

Acquisition of the undercuts of the crank webs

Crank webs often feature undercuts or areas with transconductance and these can't be captured with the fringe and/or shadow projection system. To measure the whole geometry a conoscopic sensor is used. The essential advantage of this sensor is that it can capture data with an angle of up to ±85° to the surface normal of the measurement object. But to capture the whole crank web, this feature isn't sufficient, because of the undercuts. To measure the complete crank web, a measurement strategy must be developed, which is seen in figure 10.

By means of a linear axis the conoscopic sensor can be moved and thereby achieves different positions relative to the object axis. Figure 10a shows the conventional measurement position, where the sensor cuts the rotation axis orthogonally. In this position the undercuts of the crank webs can't be captured (figure 10b). By moving the sensor a position can be achieved, where one undercut can be measured, but not the other undercut (figure 10c and 10d). So a third measurement position, seen in figure 10e, must be approached.

After the three measurements the measurement data is merged. Figure 11 shows an exemplarily combined dataset.

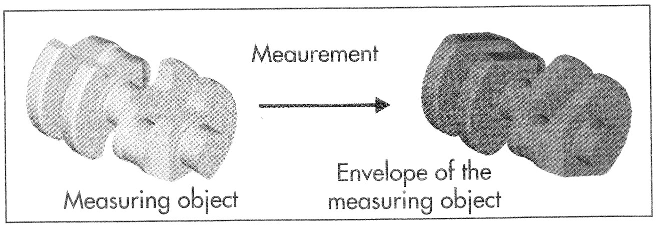

Figure 9. Acquisition of an envelope of the measuring object using contour projection

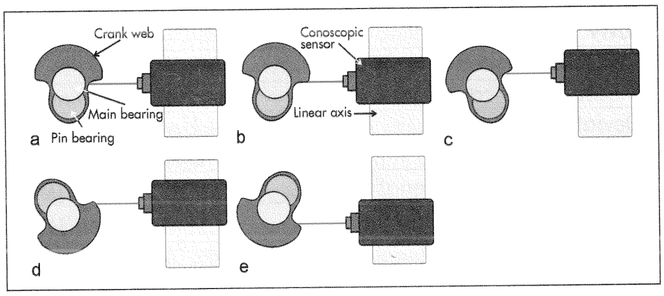

Figure 10. Strategy to measure the complete crank web with the conoscopic sensor

Evaluation of the deviations

On the basis of the acquisition of the geometry of precision-forged crank shafts using the optical measuring techniques mentioned previously, the deviations from the nominal geometry can be calculated. Figure 12 shows the deviations on the functional surfaces of a precision-forged two-cylinder crank shaft.

The top and the bottom main bearing show a high positive deviation from the nominal geometry. This is caused by the material allowance needed for the finishing operation. The center main bearing shows only small deviations. Noticeable is the displacement of both pin bearings in positive direction of the x-axis, which is caused by the distortion of the crank shaft due to the forging process. The table in figure 13 shows deviations of the bearing seats of the measured crank shaft concerning radius, cylindricity, and coaxility.

The denoted standard deviation of all values relates to 10 measurements. Conspicuous is the considerable variety of the concentricity, which indicates a methodic error in the production process.

ESTIMATION OF THE UNBALANCES

Before an estimation of the unbalances based on optical measuring data can be carried out, it is necessary to approximate the volume of the crank shaft. For this purpose, the geo-

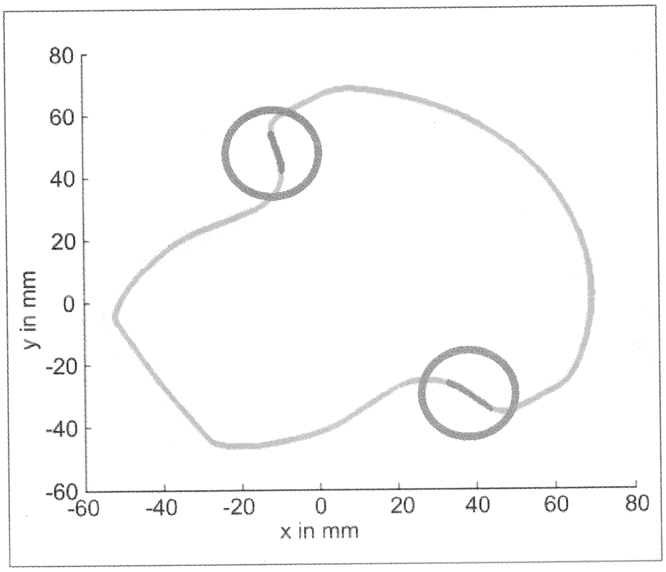

Figure 11. Combined crank web contour based on three measurements with a conoscopic sensor

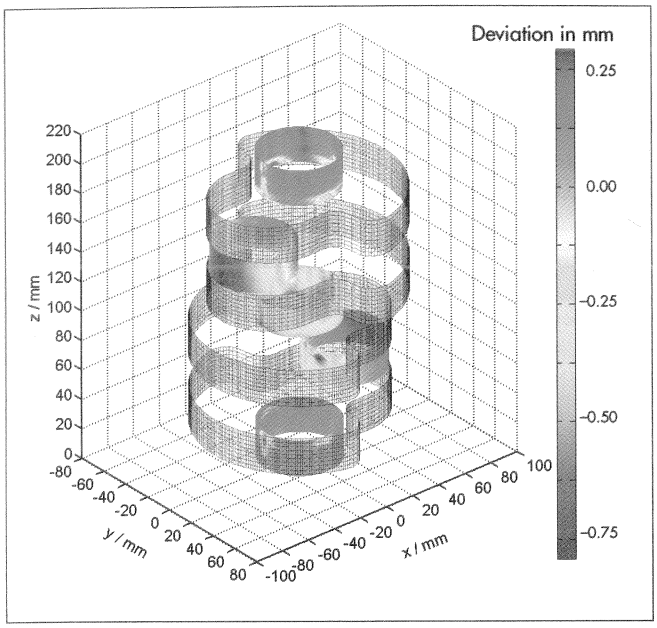

Figure 12. Deviations on the surface of a precision-forged two-cylinder crank shaft

metric elements main bearing, pin bearing, and crank web are examined separately. In the first step contours of the particular geometric element are extracted. By means of these contours, equidistant cross-sections that are oriented orthogonally to the axis of the crank shaft and cover the complete height of the geometric element are created. The vertical distance between these cross-sections is approximately 40 μm. Before the calculation of the volume can be carried out, it is necessary to determine the area of the cross-sections, which is achieved by interpolating the boundary points of the cross-section with cubic splines and calculating the area integral of the enclosed area. Through the multiplication of the vertical distance of the cross-sections with their particular area, the volume of the geometric elements of crank shafts can be estimated. For the calculation of the mass of the crank shaft, its volume has to be multiplied with the density of the used material. Based on the actual center of mass, which is determined based on the mass distribution, the static unbalance of the crank shaft can be calculated.

Figure 14 shows the deviation of the actual center of mass from the nominal center of mass of a machined one-cylinder crank shaft. The difference of the calculated mass and the nominal mass of this crank shaft is 0.52 g.[8] This result underlines the capability of the described method for machined crank shafts with small deviations from the nominal geometry.

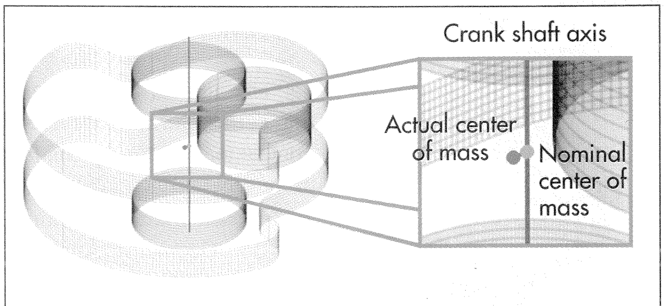

Figure 14. Determination of the deviation of the center of mass of a machined one-cylinder crank shaft using optical measuring data

Figure 15 shows the geometric data used to calculate the mass distribution of a precision-forged two-cylinder crank shaft. These data are a combination of optical measuring data from the fringe projection system (bearings) and the contour projection system (bearings and crank webs). Because the undercuts at the crank webs cannot be acquired with these measuring devices, synthetic data based on the nominal geometry is used for these areas.

Because of a tilt of the crank webs caused by distortions due to the forging process, the width of the crank webs is overestimated by the contour projection system. This also results in an overestimation of the volume and the mass of the crank shaft of about 2.4 percent.

To avoid the overestimation of the crank shafts mass, methods for determination of the tilt of the crank webs are planned based on the measuring data of the contour projection system. Furthermore, it is intended to replace the synthetic data at the undercuts of the crank webs by the measuring data of a conoscopic sensor. Therefore, a large number of line-shaped profiles of the crank webs will be measured with the conoscopic sensor, as seen in figure 16. Due to these measures a much more precise estimation of the mass distribution of precision-forged crank shafts can be carried out.

CONCLUSION AND OUTLOOK

This article introduces an optical multisensor system for the measurement of complex geometries such as precision-forged crank shafts. For this purpose three different optical sensor systems are used. This way, a comprehensive geometry inspection of the measurement object can be accomplished.

After capturing the geometrical elements, the measurement data is merged to analyze geometry deviations on the one hand and the unbalance of the measurement object on the other. The data fusion of two sensor systems is already conducted. The next step is to replace the synthetic data of the crank webs by measuring data of the conoscopic sensor for a better approximation of the volume of precision-forged crank shafts. Furthermore, the estimation of uncertainties of the whole measurement is also an actual object of research.

	Radius in mm	Cylindricity in mm	Concentricity in mm
Main bearing 1	25.6839 ±0.0003	0.2817 ±0.0004	0.3044 ±0.0006
Main bearing 2	25.7403 ±0.0003	0.1688 ±0.0002	0.6329 ±0.0002
Main bearing 3	25.6525 ±0.0002	0.1755 ±0.0005	0.0963 ±0.0001
Pin bearing 1	25.7416 ±0.0024	0.1653 ±0.0005	0.0424 ±0.0001
Pin bearing 2	25.7942 ±0.0007	0.1662 ±0.0003	0.0677 ±0.0002

Figure 13. Deviations on the bearing seats of a precision-forged two-cylinder crank shaft

ACKNOWLEDGEMENTS

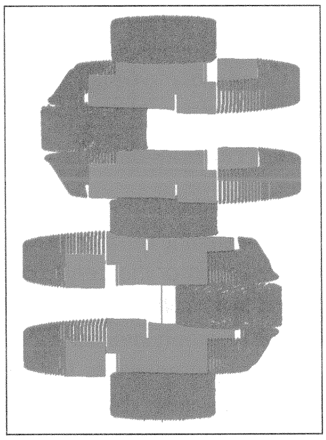

Figure 15. Combination of optical measuring data (blue) and synthetic data at the undercuts (red) as basis for the volumetric analysis

The authors would like to thank the German Research Foundation (DFG) for funding the projects A5 "Material Allowance-Based Fine Positioning" and B5 "Geometric Analysis" within the CRC 489.

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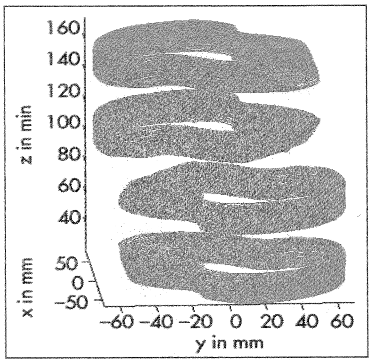

Figure 16. Acquistion of the crank webs of a precision-forged two-cyclinder crank shaft with a conoscopic sensor

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