New Technology for In-Line Quality Improvement of Gearwheels

In-line measurement and quality assurance of gearwheels

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Abstract

The common case hardening of automotive gearwheels often leads to distortions, geometry- and allowance variations. These influences can cause a malposition of gears in the chuck at the first clamping. This malposition leads to low quality gears or scrap in the following hard turning process.

The quality assurance in the manufacturing process of gears is based on production-related tactile measurements using coordinate measurement machines (CMM).

This paper shows the development of a new manufacturing technology, which allows the fast in-line (lathe integrated) measurements and precision positioning of gearwheels. The measurement system consists of an optical distance sensor, synchronization electronics and the data processing.

The synchronization electronics connect the rotary encoder of the machine spindle to the industrial PC and the conoscopic sensor. The measured distance data and the angle information of a rotary encoder are used in combination to reconstruct the geometry of the gearwheel. Using different new methods in data processing, clamping errors due to material allowance, eccentricity, distortion, geometry variations (deformation) and other possible errors can be detected before starting the cutting process.

The correction of the eccentricity using a mechatronic chuck is shown in an example concerning the automated manufacturing process of automotive gearwheels.

1. The manufacturing chain of automotive gears

The common manufacturing chain of automotive gears consists of different machining steps (fig.1). At first, raw parts are forged from round stocks. The next machining process is the manufacturing of the toothing using a hobbing machine. At this process step, there is still material allowance on the central bore or the flanks.

The following process is the heat treatment of the gears, usually with a case hardening process. The final manufacturing steps are the hard turning of the central bore and the grinding process of the toothing, where the central bore is used as a reference to assure a good quality of the radial run out.

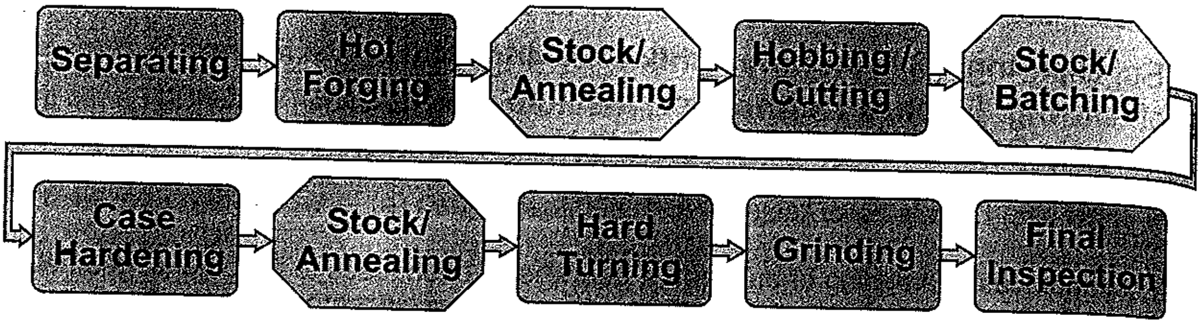

Fig. 1: Common manufacturing chain of automotive gears

The common quality assurance in the manufacturing process of gears is based on production-related tactile measurements using coordinate measurement machines (CMM) or special tactile gear measuring machines. Furthermore, optical measurement techniques such as the fringe projection (3D measurement) or laser triangulation (1D or 2D measurement) are getting more important for production-related gear measurements.

The disadvantages of production-related measurements are long cycle times and the additionally needed space for the measurement laboratories. Due to this, the quality assurance is limited to random testing during the manufacturing process and usually a complete final inspection of the fully manufactured gears.

The most critical manufacturing step is the case hardening. The hardening leads to significant (and detectable) distortions of the gears.

These influences can cause a malposition of gearwheels in the chuck at the first clamping, especially when there is no (fully manufactured) reference geometry because of the material allowance. This malposition leads to low quality gears or scrap in the following hard turning process. In case of an eccentric manufactured central bore, the grinding process of the flanks will lead to a low quality to the toothing, as well as tool wear and scrap.

2. In-line measurement equipment

The requirements for the in-line measurement system are fast measurement frequency, high accuracy, reliability and robustness. Tactile measurement methods have long measurement cycle times, especially for complex geometries like the toothing of gears. Thus, the fast optical measurement systems are more suitable concerning the cycle times. Remaining factors are robustness and reliability. The robustness of optical measurement system has significantly increased in the last years; several applications of optical measurement systems in industrial environments are known [1, 2, 3]. One critical factor of optical measurement technologies is the reliability. The accuracy, and thus the reliability, of optical measurements strictly depends on the optical cooperativity of the surface and other parameters [4, 5]. In most cases optical measurement systems need diffuse reflecting surfaces.

Surfaces, which can be easily captured by optical systems, are sand- and glass-blasted surfaces. Also, case harded surfaces, like the toothing of gears before the grinding process, can be captured with high confidence.

In contrast to the mentioned surfaces, high reflecting surfaces like line cutted surfaces are almost impossible to capture. These surfaces need additional treatments to allow the use of optical measurements [4].

Optical measurement techniques, which are already introduced into gear measurement, are technologies such as fringe projection (3D measurement), conocscopic holography (1D measurement) or laser triangulation (1D or 2D measurement) [1, 2, 6].

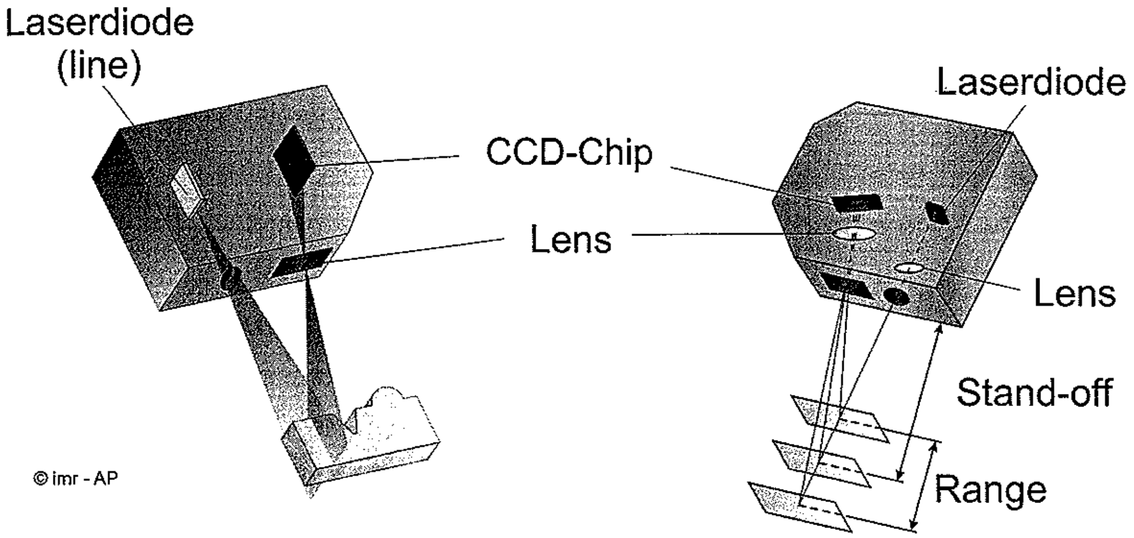

Fig. 2: Laser triangulation-sensors for 1D (right) and 2D (left) measurements

The used measurement equipment in this application consists of an optical distance sensor (1D, point distance sensor), the synchronization electronics and the data processing.

The fast and high-precision conoscopic laser sensor measures the toothing in a transverse plane during one revolution. The co-linear principal (the lighting of the measurement objective and the capturing of the reflected light are in one axis) of conoscopic holography allows measurements at angles of about ± 85 degrees orthogonal to the optical axis of the sensor. This great advantage compared to conventional optical principles, such as triangulation, allows to capture the complete gear-geometry in only one measurement position relative to the gear, including its functional elements (flanks). Manufacturer of this optical sensor is Optimet optical metrology Ltd. The stand-off and the possible resolution can easily be changed by using different accessory lenses.

The reachable accuracy of the sensor basically depends on these lenses. Other factors are the optical cooperativity of the workpiece-surface, the parameter adjustment of the sensor and finally the angle of the laser beam to the workpiece surface [2]. In the used test setup, the absolute accuracy with the chosen lens "50 extended" is specified with better than 6 µm with a reproducibility (1σ) << 1 µm. This lens provides a stand-off length of approximately 85 mm and a measuring range of about 8 mm.

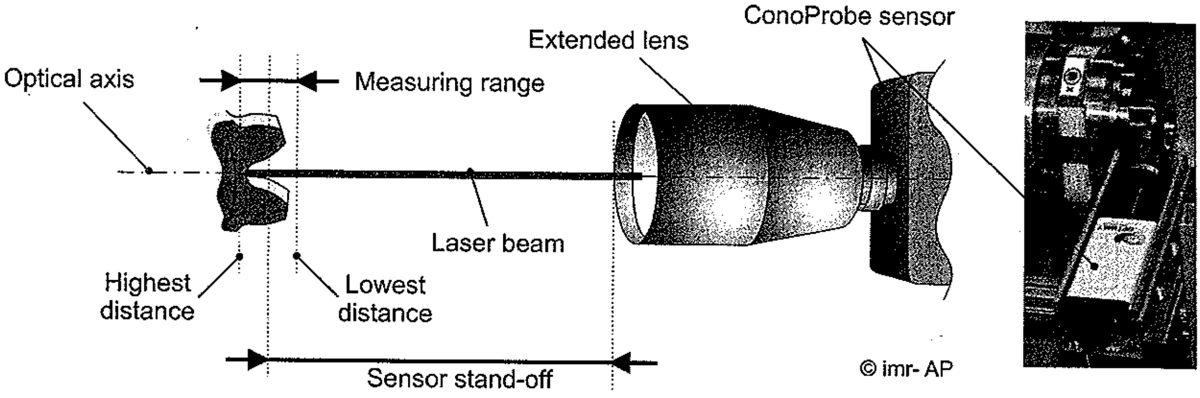

Fig. 3: Definitions of the conoscopic sensor ConoProbe with extended lens

The measurement frequency depends on the different versions. For the Mark III version, the frequency is limited to 3000 Hz, the Mark IV sensor version allows for measurements with up to 15000 Hz.

The optical sensor offers the opportunity to use information about the signal quality, amount of captured light and saturated CCD-pixel for filtering abroad the distance data transmitted. This information can be used to select the measurement points captured with high quality.

In order to reach an angle equidistant measurement and to establish new spectral analytic algorithms, the optical sensor is triggered by an incremental rotary encoder. This simple synchronization can be combined with a counter card to get additional angle information and a reference angle during one revolution [7].

3. Fast algorithms for gear inspection

The data processing consists of three parts: The preprocessing of the measured data (filtering), extraction of functional geometry elements and the evaluation algorithms.

Two characteristic geometry elements, the tip radius and the root radius, can be detected with a high signal to noise ratio. The functional geometry, the flanks, is hard to capture at the steep base circle.

In contrast to selective filters, where measurement points are extracted by the mentioned additional information given with the distance data, additional information like the absolute distance and the steadiness (important on the flanks) are used to hold as much points as possible. Detected measurement errors (bad points) are reconstructed by different inter- or extrapolation algorithms. The result of this filter is a complete transverse profile of the gear including all measurement information. Using the angle equidistant synchronization, there is one measurement point every chosen angle interval $\Delta\varphi$.

According to different manufacturing processes, different extraction algorithms (tip radius, flanks, root radius, pitch/tooth-thickness or complete gearwheel) had been developed. Depending on the manufacturing process, one of these algorithms can be used. Concerning the camshaft gear, the root radius is manufactured in the hobbing process of the toothing. Thus, the simple and very reliable algorithm for extracting the root radius is the common method for a fast characterization of the camshaft gear.

The last step is the post processing (or the evaluation algorithms) of the extracted data. The most limiting factor are the required short cycle times in automotive related gear manufacturing.

Instead of common iterative algorithms, a discrete Fourier transform (DFT) of the extracted data is used. In comparison to the fitting algorithms the spectral analytic methods reach deterministic and shorter computational effort. For fast in-line measurements of gears, the geometric data must be transformed into a “time” signal with equidistant sampling for using spectral analytic algorithms. The introduced synchronization with the rotary encoder allows the transformation of the taken measurement (measurement points every $\Delta\varphi$) into a time signal (measurement points every Δt). The angle equidistant measurement is now handled like a discrete time signal.

The frequency spectrum can be used for the characterization of the gearwheel. The simplest information is the eccentricity, which can be quantified with the basic oscillation (first frequency). Identified frequencies for distortion are the second and fourth oscillation. Using three jaws chucks, clamping errors can be detected by selecting the third oscillation. The common covering of some gear tooth because of the jaws can be compensated by interpolation.

4. Possibilities of eccentricity correction

In the CRC 489 a mechatronic chuck for turning processes was researched. This chuck has four integrated piezoelectric actuators, which can be used to compensate an eccentricity. In each direction, two actuators are placed in opposing-arrangement and can move the clamping system. This structure allows a positioning of the gear in two degrees of freedom (X- and Y-axis). The actuators offer a high stiffness to ensure a high precision turning process and an achievable compensation range of about 70 µm in each direction.

The power supply (inductive) and the data transmission (Bluetooth) are contactless and thus wear-free. In order to comply with industrial standards, the mechatronic chuck is connected to the machine spindle with a coned connection (DIN 55028) and cause of the light weight construction, a balancing class of G6,3 at 3000 rpm (DIN ISO 1940) can be reached [8].

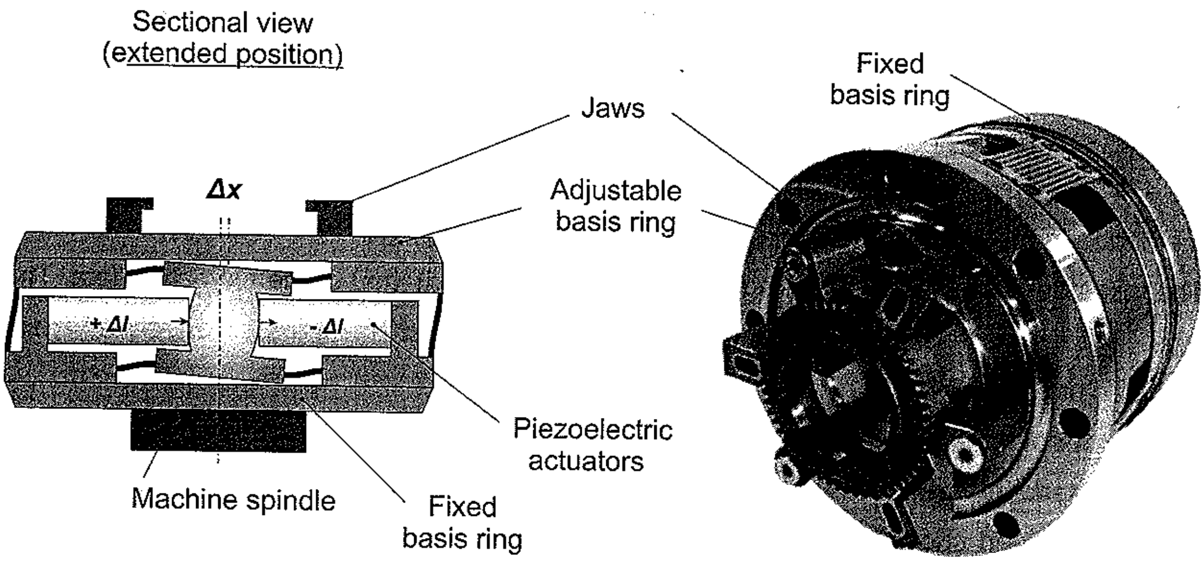

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Fig. 4: Principle of the mechatronic chuck [7]

The alternative way for compensating eccentricity is the use of machine's degrees of freedom combined with driven tools. In this case the turning process must be converted into a milling process. The gearwheel is fixed in a known position and the milling cutter corrects the eccentricity and manufactures the central bore. In machines with one directional radial feed, the angle of the ideal position must be in the direction of the radial feed for the described compensation [7].

5. Results

Accessible cycle times for measurements (3000 points per revolution at 3000 Hz measuring frequency), filtering and processing are about 2.5 seconds. Using the fast 15000 Hz ConoProbe Mark IV sensor, cycle times smaller than 1 second at 3000 points per revolution can be reached. The standard deviations at this configuration are < 0.5 µm (0.2 - 0.3 µm typ.) when choosing the most reliable tip- or root radius algorithms. The alternative algorithms, like the extraction and characterization of the flanks, reach standard deviations of about 1 µm.

In order to minimize additional time for the quality assurance, it is possible to use the acceleration phase of the machine spindle for measurement and data processing. Test runs with up to 2000 points per revolution have been successfully tested. Thus, the additional needed cycle time in this configuration is zero.

The additional time for the correction by the mechatronic chuck is about 5 seconds.

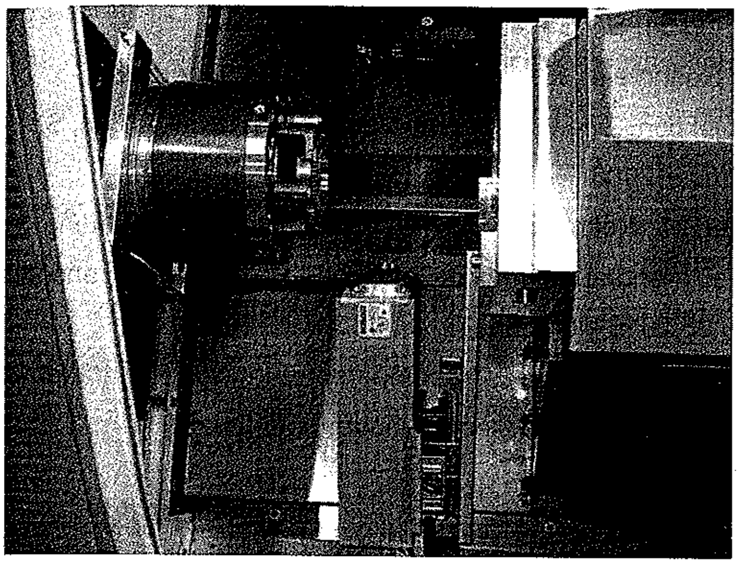

Fig. 3: System integration into a lathe (laser sensor inside housing)

The precision positioning system consisting of the optical sensor, the PC and the mechatronic chuck was integrated into a Gildemeister CTX 420 lathe. The data processing and the automatic control of the mechatronic chuck are written in C++ DLL`s, which are embedded into a LabVIEW – graphical user interface (GUI) called PiMPS (Process-integrated Measuring and Positioning Software).

The needed changes in the machine tool controller for automated process affect the CNC program and the communication interface. In the simplest configuration, the communication between the different process steps is done with digital Signals (DIO). Also a Profibus communication between the PC (using a systerra DRL-DPM-PCU Profibus DP card) and the lathe is possible.

In order to show the reliability of the precision positioning system several long term tests and the manufacturing of 500 camshaft gears had been done.

Acknowledgement

The authors would like to thank the German Research Foundation (DFG) for their support and funding of the presented research project CRC 489 –T4 and the complete CRC 489.

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