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## Automated noncontact sensor positioning


### Abstract

A multi-axis system (**30**) for positioning a workpiece measuring sensor (**54**) on a metrology machine. Preferably, each sensor is positionable via a system comprising movement along and/or about at least linear directions/axes (X, Z, A, B) so as to control linear and/or rotational movement of a sensor automatically to a predetermined position without operator intervention. The multi-axis positioning system allows faster setup times when a workpiece or tooling on a machine is changed.



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## Background/Summary

FIELD OF THE INVENTION

(1) The present invention relates primarily to the positioning of non-contact sensors for inspecting workpieces including gears and other toothed articles, particularly on functional measurement platforms that produce analytical test results.

BACKGROUND OF THE INVENTION

(2) For many years dimensional inspection (i.e. measurement) of gears and gear-like workpieces (e.g. cylindrical and bevel gears, worms) has mostly been carried out by two different methodologies, namely, (1) functional testing comprising meshing a gear or other toothed workpiece with a known master gear or mating gear, and (2) analytical testing using a coordinate measurement machine (CMM) or a gear measurement machine (GMM) such as the GMS line of gear measurement machines manufactured by, and commercially available from, the Applicant.

(3) Functional testing compares the measurement of a work piece against a master gear or a mating gear. Functional testing platforms for gears (i.e. roll testers) include those testers known as double flank testers and single flank testers. With single flank testing, mating gears roll together at their proper (fixed) center distance with backlash and with only one flank in contact. Gears can be tested in pairs or with a master gear. With double flank testing, mating gears are rolled together in tight

mesh which produces contact on both flanks. A work gear is meshed with master gear. By providing various encoders on the platform, the relative movement of gears (i.e. center distance variation) making up a collection or summary of gear errors is captured. For example, on a typical double flank gear roll testing machine, a work piece (e.g. cylindrical gear) is meshed with a known master part (e.g. cylindrical gear) and rotated. One of the gears is mounted on a fixed axis and other is mounted on a floating axis. The linear displacement between the axes is measured when the two gears are rotated. Composite errors from this functional testing, such as center distance variation, are reported and compared against required tolerances. Such a roll tester is also capable of reporting characteristics related to the size of gear teeth such as tooth thickness and diameter-over-pins (DOP).

(4) A typical CMM or GMM utilizes at least one contact probe. In recent years, a non-contact sensor (e.g. laser) has been used to inspect some gears as is disclosed in WO 2018/048872, the disclosure of which is hereby incorporated by reference. A contact probe is positioned at programmable locations on a gear tooth surface to measure its deviation from a theoretical tooth surface. A non-contact probe emits light on the tooth surface of a gear at a desired location to determine the same deviation.

(5) Analytical testing of gears may be done by either a GMM or CMM. These machines include a computer-controlled apparatus which includes a high-resolution touch sensor (e.g. tactile probe) and/or a non-contact probe. The machine of WO 2018/048872 is an example of an analytical machine for inspecting a gear workpiece utilizing a touch sensor and/or a laser sensor for inspection. Both sensors require repeatable positioning of the sensor for reliable and accurate measurement at desired locations on the gear tooth surface.

(6) CMM and GMM machines are both equipped with probes capable of measuring the location of points on the surface of workpieces. This is one of the core functions of these machines and is used to implement the full range of functionality available on these machines (e.g. measuring size, location, deviation from theoretical surface and form of geometric shapes). These measurements are checked against certain tolerances to ensure the correct fit and function of the measured workpieces.

(7) To measure a workpiece, the machine must convert the signal output from its probe (or probes) and the respective position of the relevant machine axes into the location of points on the surface of a workpiece. For this reason, the orientation of sensors to properly approach desired areas of a gear and the accurate calibration of sensors are very important. When a workpiece is changed to another workpiece having a different geometry, the positions of sensors will likely require adjustment for accurate measurement of the “different geometry” workpiece.

(8) In metrology systems such as disclosed by WO 2019/083932, the disclosure of which being hereby incorporated by reference, at least one non-contact sensor and preferably two non-contact sensors are utilized to measure gear artifacts. Preferably, two lasers are located in a manual set-up fixed position on a post and are oriented in such a way that each laser measures one flank of a gear.

(9) Prior art FIGS. **1**, **2** and **3** show a machine **50**, of the type as disclosed by WO 2019/083932, comprising at least one non-contact sensor assembly **52** on a functional testing platform for workpiece inspection and/or measurement. The machine **50** comprises a base portion having a top portion **8** (preferably a flat plate), production gear **16** (i.e. the workpiece) and master gear **14** mounted on respective workholding arbors **18** and **12**, such as mechanical, hydraulic or pneumatic arbors as is known to the skilled artisan. A slide plate **10** is affixed to slide **26** and arbor **12** is positioned on plate **10**. The production gear **16** may be located on either the left hand side or on the right hand side of the master gear **14** but is shown on the left side in FIG. **1**. The gear **16** rotates about a motorized axis W via motor **17**. The master gear **14** is mounted on right hand side (axis T) and is not motorized. The rotation of master gear **14** is provided by the driving motor **17** for axis W and the engagement with the production gear **16**.

(10) For functional testing, the master gear **14** is on a slide **26** (X axis) and is moveable in the

direction of the X axis (preferably horizontal) to allow coupling and decoupling of gears. Decoupling is required so that the production gear **16** can be removed and replaced with different workpieces either manually or via automation means. A linear scale **7** (FIG. **3**) is mounted to capture movement of the slide **26** in the X axis direction during operation. A rotary encoder **19** is mounted below the motorized production gear **16** (axis W) to capture rotary movement of the workpiece gear. Inputs of the rotary encoder and the linear scale are captured so that during rotation of gear pair, relative movement of gears (in the X direction) is measured with respect to the rotary position of the workpiece gear **16**.

(11) As shown in FIG. **1**, a non-contact sensor such as an optical sensor, for example a laser assembly **52**, is positioned on left side of the machine for analytical testing. A single laser **54** is mounted on a linearly adjustable post **56** having an adjustable mounting mechanism **58** whereby the laser **54** is movable and positionable in up to three linear directions X, Y, Z (preferably mutually perpendicular) and in up to three rotational directions, that is, about each of X, Y and Z for manually setting the operating position of the laser. In other words, laser **54** is preferably capable of six degree-of-freedom movement but only for set-up purposes. Such adjustability is preferable in order to orient the laser emission line **60** onto a gear tooth space whereby it can capture at least a portion of the tooth involute (i.e. profile direction) from root-to-tip for both tooth flanks of adjacent teeth.

(12) However, the only computer-controlled axis on the machine of FIG. **1** for analytical testing is the workpiece rotational axis W. The machine lacks the ability to re-position the probe via movement along and/or about one or more linear axes. Computer controlled positioning of a workpiece **16** relative to laser **54** via motion along or about one or more mutually perpendicular directions or axes X, Y and Z (i.e. three dimensional) is not possible and, hence, computer-controlled calibration of laser **54** via motion along or about one or more mutually perpendicular directions or axes is also not possible.

SUMMARY OF THE INVENTION

(13) The present invention is directed to a multi-directional positioning system for positioning a workpiece measuring sensor on a metrology machine. Preferably, each sensor is positionable via a system comprising movement in at least one linear direction and at least one rotary direction so as to control linear and/or rotational movement of a sensor automatically to a predetermined position without operator intervention. The multi-directional positioning system allows faster setup times when a workpiece or tooling on a machine is changed.

(14) The inventive multi-directional positioning system is preferably operable to provide linear motion in one or two directions (i.e. linear motions) and/or rotational/angular motion about one or two axes (i.e. rotary motions) with position feedback (e.g. linear and/or rotary encoders) which are controlled by motors (e.g. stepper or servo) to move each sensor in the necessary direction or directions whereby the sensor is properly positioned in order to measure a desired surface on a workpiece such as the tooth surface of a gear.

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## Description

BRIEF DESCRIPTION OF THE DRAWINGS

(1) FIG. **1** is a front view of a known machine showing two gears in rolling engagement and non-contact inspecting of one of the gears.

(2) FIG. **2** is an enlarged view of the non-contact sensor inspecting portion of FIG. **1**.

(3) FIG. **3** is a top view of the machine of FIG. **1**.

(4) FIG. **4** is a front view showing two inventive multi-directional positioning systems.

(5) FIG. **5** is a side view of the positioning systems of FIG. **4**.

(6) FIG. **6** is a top view of the positioning systems of FIG. **4**.

(7) FIG. **7** is a top view of two inventive positioning systems arranged on a functional gear testing platform.
(8) FIG. **8** is a front view of two inventive positioning systems arranged on a functional gear testing platform.
(9) FIG. **9** is a side view of two inventive positioning systems arranged on a functional gear testing platform.
(10) FIG. **10** illustrates a top view of two functional gear testing platforms arranged end-to end, with respect to their respective workpiece spindles, and including two inventive positioning systems arranged between the workpiece spindles.
(11) FIG. **11** illustrates a top view of two functional gear testing platforms arranged end-to end, with respect to their respective workpiece spindles, and including four inventive positioning systems arranged between the workpiece spindles.
(12) FIG. **12** is a side view of two inventive multi-axis positioning systems with the inclusion of a workpiece spindle.
(13) FIG. **13** diagrammatically illustrates the functional gear testing platform of FIG. **7** as being one part of a gear hard finishing or soft manufacturing cell.
(14) FIG. **14** diagrammatically illustrates the functional gear testing platform of FIG. **7** as being one part of a soft gear manufacturing cell including a chamfering and/or deburring machine.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

(15) The terms "invention," "the invention," and "the present invention" used in this specification are intended to refer broadly to all of the subject matter of this specification and any patent claims below. Statements containing these terms should not be understood to limit the subject matter described herein or to limit the meaning or scope of any patent claims below. Furthermore, this specification does not seek to describe or limit the subject matter covered by any claims in any particular part, paragraph, statement or drawing of the application. The subject matter should be understood by reference to the entire specification, all drawings and any claim below. The invention is capable of other constructions and of being practiced or being carried out in various ways. Also, it is understood that the phraseology and terminology used herein is for the purposes of description and should not be regarded as limiting.
(16) The details of the invention will now be discussed with reference to the accompanying drawings which illustrate the invention by way of example only. In the drawings, similar features or components will be referred to by like reference numbers. For a better understanding of the invention and ease of viewing, doors and any internal or external guarding have been omitted from the drawings.
(17) The use of "including", "having" and "comprising" and variations thereof herein is meant to encompass the items listed thereafter and equivalents thereof as well as additional items. The words "a" and "an" are understood to mean "one or more" unless a clear intent to limit to only one is specifically recited. The use of letters to identify elements of a machine, method or process is simply for identification and is not meant to indicate importance or significance, or that the elements/steps should be performed in a particular order. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items and may be abbreviated as "/".
(18) Although references may be made below to directions such as upper, lower, upward, downward, rearward, bottom, top, front, rear, etc., in describing the drawings, these references are made relative to the drawings (as normally viewed) for convenience. These directions are not intended to be taken literally or limit the present invention in any form. In addition, terms such as "first", "second", "third", etc., are used to herein for purposes of description and are not intended to indicate or imply importance or significance unless specifically recited.
(19) The invention comprises a multi-axis positioning system capable of moving a sensor and a workpiece relative to one another and addresses the heretofore inability to adequately re-position a

sensor automatically, particularly a non-contacting sensor such as an optical sensor, particularly a laser sensor, with respect to a workpiece such as a gear, shaft or other toothed article (collectively referred to hereafter as “gear”), using linear and rotary axes with no intervention from the machine operator.

(20) The inventive multi-directional positioning system is shown in a first embodiment by FIGS. **4-6** where two positioning systems **30** are illustrated in order to accommodate two non-contact, preferably optical (e.g. laser) sensors **54** for measuring a workpiece **16**. One sensor is positioned to scan tooth flanks on one side of the workpiece teeth and the other sensor is positioned to scan tooth flanks on the opposite side of the workpiece teeth as can be best seen in FIG. **5** wherein a laser emission line **60** is shown projecting from each sensor **54**. While the following description of the inventive position system will refer to only one positioning system **30**, it is understood that the description applies equally to additional positioning systems such as both positioning systems **30** in FIGS. **4-6**.

(21) Positioning system **30** comprises a column **32** on which slide **34** is positioned for Z-direction movement (preferably vertical as viewed in normal operation) on column **32** via guide rails **36**. Column **32** is attached to a rotary base **38** which is rotatable, as shown by arrow R.sub.A, about axis A (preferably oriented vertical as viewed in normal operation) thereby enabling column **32**, and sensor **54**, to be angularly adjustable/rotatable about the A-axis (see FIG. **6**). Base **38** is positioned on slide **40** which is movable in the X-direction (preferably horizontal as viewed in normal operation) on a base plate **43** via guide rails **42** (FIGS. **5**, **6**) so as to position column **32** in the X-direction. Direction Z lies in a first plane which, as normally viewed, is vertical (i.e. the plane of the page of FIG. **4**) and direction X lies in a second plane which, as normally viewed, is horizontal (i.e. the plane of the page of FIG. **6**) with the first and second planes being perpendicular to one another. Directions Z and X are preferably perpendicular to one another. The A-axis is preferably parallel to the Z direction, may lie in the first plane, and is preferably perpendicular to the X-direction. Base plate **43** is preferably attached to top portion **8** of the machine base.

(22) A rotatable mounting plate or disc **44** (i.e. rotary stage) is attached to slide **34** and is angularly adjustable/rotatable, as shown by arrow R.sub.B, about axis B (preferably oriented horizontal as viewed in normal operation, see FIGS. **5**, **6**) via a motorized drive or a worm and wheel drive for example. Preferably, the B-axis extends parallel to the second plane and is perpendicular to, intersects, and is angularly movable about the A-axis during the angular adjustment R.sub.A of column **32** about the A-axis (FIG. **6**). Laser sensor **54** is positioned on mounting plate **44** whereby the sensor is angularly adjustable/rotatable about the B-axis. A braking mechanism, preferably a disc brake mechanism comprising a caliper **46** and brake disc **47**, is preferably associated with rotary base **38** and/or rotatable mounting plate **44** for stopping rotary motion and securely maintaining the angular position of the rotary base **38** and/or rotatable mounting plate **44** during operation of the sensor. While the disc brake mechanism is preferred, other braking and/or clamping mechanisms may be utilized.

(23) Different motions, or combinations of motions, may be performed by the positioning system **30**, or elements thereof, in order to accommodate different workpiece geometries or the change from one workpiece geometry to another workpiece having a different geometry. Some examples (non-exhaustive list) include: Motions about the A axis, in the X-direction and about the workpiece spindle axis (W) may be performed to adjust the position and orientation of the sensor **54** relative to a workpiece in order to accommodate a range of parts with different modules, pitch diameters or outside diameters. Motion about the B-axis, and including motion about the A-axis as may be needed, may be carried out to adjust the orientation of the sensor **54** relative to a workpiece to accommodate for a range of parts with different helix angles and hands of rotation. Motion in the Z-direction may be performed to accommodate a range of parts with different face widths and spindle tooling lengths. Motions in the X-direction and about the A-axis may be performed to accommodate parts having teeth with different pressure angles.

With a sensor, or sensors, suitably positioned, the workpiece may be measured accurately.

(24) Movement of each of slide **34** in direction Z, column **32** in direction X, column **32** about axis A, mounting disc **44** about axis B and workpiece rotation about axis W is imparted by separate drive motors such as, for example, servo or stepper motors or worm and wheel drives (not shown). The above-named components are capable of independent movement with respect to one another or may move simultaneously with one another. Each of the respective motors is preferably associated a feedback device such as a linear or rotary encoder (not shown) as part of a CNC system which governs the operation of the drive motors in accordance with instructions input to a computer controller (i.e. CNC) which may be a dedicated computer control for the positioning system **30** or, for example, the computer control for a functional testing platform of the type shown in FIG. **1**.

(25) FIGS. **7**, **8** and **9** show two of the inventive positioning systems **30** located on a functional testing platform **50** of the type shown in FIG. **1**. For simplicity and ease of viewing, elements such as slide plate **10**, slide **26** and linear scale **7** have been omitted. However, instead of a non-contact sensor, such as a laser assembly **52**, requiring manual setup of axes positions to achieve the appropriate operating position relative to a workpiece **16** located on the functional testing platform **50**, the inventive positioning system **30** automatically achieves the appropriate operating position of the non-contact sensor (e.g. laser) **54** relative to workpiece **16**. The operating positioning being accomplished via the previously described positioning system comprising linear and/or rotational motions to automatically move the sensor to a predetermined position without operator intervention.

(26) FIG. **10** shows two functional testing platforms **50** arranged in an end-to-end manner whereby the inventive position system **30** (two shown) is located between the respective workpiece spindles **18** of the testing platforms. In this arrangement, one of the positioning systems **30** can be utilized to position a sensor relative to a workpiece on one platform **50** (e.g. right side in FIG. **10**) and the other positioning systems **30** can be utilized to position a sensor relative to a workpiece on the other platform **50** (e.g. left side in FIG. **10**). The ability of the positioning system **30** to be angularly positionable about the A-axis and linearly movable in the X-direction enable such functionality. Alternatively, both positioning systems **30** may be directed to a workpiece on one spindle, (e.g. right-side as shown in FIG. **10**), and then both positioning systems may be redirected to a workpiece on the other spindle (e.g. left-side spindle of FIG. **10**).

(27) FIG. **11** shows an arrangement of functional testing platforms **50** similar to FIG. **10** but with the inclusion of two sets (total of 4) positioning systems **30** wherein two positioning systems **30** are dedicated to the right-side functional testing platform and two positioning systems **30** are dedicated to the left-side functional testing platform. In the embodiment of FIG. **11**, two X-direction-oriented positioning systems share one set of X-direction guide rails **42**.

(28) While the above discussion has been directed to a positioning system for appropriately positioning a non-contact sensor, such as an optical sensor, for example a laser, relative to a workpiece, the inventive positioning system may also be operated in an active manner during a scanning (e.g. measuring/inspection) process. The positioning system may be operated to reposition the non-contact sensor during scanning in order to reposition the sensor, either continually, incrementally and/or intermittently, whereby a greater portion of a gear tooth flank surface in the profile direction (i.e. tooth height) and/or in the lead direction (i.e. tooth length) may be scanned compared to the scanned area of a fixed position sensor.

(29) Although the preferred orientation of axes (i.e. A, B) and directions of motion (i.e. X, Y) of the positioning system **30** are shown in FIGS. **4-6**, the invention is not limited thereto. For example, as best explained with reference to FIG. **7**, X-direction motion of the position system **30** relative to a workpiece **16** may be effected by the master gear **14** and workpiece **16** being movable in the X-direction instead of X-direction movement of the positioning system **30**. Alternatively, X-direction movement capability may be included with the positioning system **30** as well as with the master gear **14** and workpiece **16**.

(30) While the inventive positioning system has been discussed and illustrated in association with a functional testing platform for gears, the positioning system is not limited thereto. The inventive positioning system **30** may be associated with (e.g. located on) other types of machine tools such as, for example, other gear manufacturing machines such as gear cutting machines (e.g. hobbing, power skiving) or gear finishing machines (e.g. grinding, honing, power skiving, hard skiving, polishing). The X-direction of travel may function for infeeding and withdrawing a non-contact sensor, or another tool, relative to a workpiece.

(31) Additionally, the positioning system may be modified to include a workpiece spindle **68** such as shown in FIG. **12** thereby creating a standalone non-contact measuring apparatus for gears and/or other toothed articles.

(32) FIG. **13** represents a gear manufacturing cell **60** such as a hard finishing cell wherein a testing machine, such as the functional testing platform **50** of FIG. **7**, is one component of the cell. In the example of a hard finishing cell, block **80** represents a gear processing machine for finishing a previously cut workpiece. Examples of finishing include grinding (e.g. threaded-wheel and/or profile grinding), honing, power skiving, hard skiving, finish hobbing, and polishing. An automation system **70**, preferably a robotic system, for loading and unloading both machines **50** and **80**, and transferring workpieces between the machines, is located between the gear processing machine **80** and the testing platform **50**. Automation system **70** may also include additional devices for performing auxiliary processes such as, for example, part washing, laser marking, sorting, measuring and part handling in a stackable basket system. The gear manufacturing cell may be an automated closed-loop cell wherein part measurement information, particularly out-of-tolerance measurements, obtained by the functional testing platform **50** is communicated to the gear processing machine **80** and any process adjustments are automatically made to the operational settings of the gear processing machine to correct the detected deficiencies in the machined part. Preferably, 100 percent of parts processed by the machine **80** are measured and/or tested by the functional testing platform **50**.

(33) Although the gear manufacturing cell **60** of FIG. **13** has been discussed with regard to hard finishing, it is not limited thereto. Alternatively, the gear manufacturing cell **60** may be configured for non-hard finishing machining (e.g. “rough” or “soft” machining, collectively referred to hereafter as “soft”) wherein block **80** represents a machine for performing a soft operation such as, for example, rough (initial) hobbing, face milling or face hobbing of bevel gears, power skiving (soft), shaping and shaving. The soft gear manufacturing cell may also be an automated closed-loop cell wherein part measurement information, particularly out-of-tolerance measurements, obtained by the functional testing platform **50** is communicated to the gear processing machine **80** and any process adjustments are automatically made to the operational settings of the gear processing machine to correct the detected deficiencies in the machined part. Preferably, 100 percent of parts processed by the machine **80** are measured and/or tested by the functional testing platform **50**.

(34) The soft machining cell may further include means for chamfering and/or deburring a workpiece produced by a soft operation. Chamfering and/or deburring units may be incorporated within the machine **80** or the manufacturing cell may include an additional machine for chamfering and/or deburring. FIG. **14** shows an example of such a manufacturing cell **65** wherein block **90** represents a chamfering and/or deburring machine. Automation system **70**, preferably a robotic system, performs loading and unloading of machines **50**, **80** and **90**, and transfers workpieces between the machines. Such a soft manufacturing cell may also be configured as an automated closed-loop cell with 100 percent inspection of workpieces as discussed above.

(35) While the invention has been described with reference to preferred embodiments it is to be understood that the invention is not limited to the particulars thereof. The present invention is intended to include modifications not specifically detailed herein which would be apparent to those skilled in the art to which the subject matter pertains without deviating from the spirit and scope of the appended claims.

## Claims

1. A multi-directional positioning system for positioning a workpiece measuring and/or inspection non-contact sensor on a machine, said sensor being positionable via an automatic system comprising movement in at least one linear direction and at least one rotary direction so as to control linear and/or rotational movement of said sensor automatically to a predetermined position without operator intervention, said positioning system comprising a column having a first slide positioned on said column, said first slide being movable along said column in a first linear direction Z, said column being attached to a rotary base enabling rotary movement, RA, of said column about an axis A, with said axis A being parallel to said first linear direction Z, said sensor being attached to said first slide and being rotatable, RB, on said first slide about an axis B which extends perpendicular to and intersects said axis A, said rotary base being movable in a second linear direction X, said direction X and said direction Z being perpendicular to one another.
2. The multi-directional positioning system of claim 1 wherein the workpiece comprises a toothed article.
3. The multi-directional positioning system of claim 1 further including a workpiece spindle.
4. The multi-directional positioning system of claim 1 wherein at least one of said positioning system is located on a gear manufacturing, measuring and/or inspecting machine.
5. The multi-directional positioning system of claim 4 wherein said at least one of said positioning system is located on a measuring and/or inspecting machine comprising a functional testing platform.
6. The multi-directional positioning system of claim 5 wherein the functional testing platform comprises a master gear and a workpiece positioned thereon wherein the master gear and the workpiece are movable in the X direction.
7. The multi-directional positioning system of claim 5 wherein the functional testing platform is one machine of a plurality of machines defining a gear manufacturing cell.
8. The multi-directional positioning system of claim 1 wherein at least one of said positioning system is located between two functional testing platforms arranged end-to-end.
9. A gear metrology machine comprising the multi-directional positioning system of claim 1.
10. A method of measuring and/or inspecting a toothed article with at least one non-contact sensor wherein the at least one sensor and the toothed article are positioned relative to one another prior to measuring and/or inspecting wherein the method comprises: positioning said at least one sensor via an automatic system comprising the multi-directional positioning system of claim 1, measuring and/or inspecting at least one surface of said toothed article.
11. The method of claim 10 further including: moving said at least one sensor relative to the toothed article during the measuring and/or inspecting comprising moving the at least one sensor in at least one linear direction and at least one rotary direction in order to reposition the sensor, either continually, incrementally and/or intermittently, during the measuring and/or inspecting whereby a greater surface portion of the toothed article in a profile direction and/or in a lead direction may be measured and/or inspected.