OBTAINING AND PROCESSING OF CMM DATA FROM GEAR WHEEL MEASUREMENTS

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A non-contact, optical CMM with two translation axes and one rotation axis for measuring cylinder coordinates is introduced. It allows for considerably faster measurements than a conventional, tactile CMM. This enables in-process inspection of gear wheels, and other rather complex, axially symmetrical parts in both 2D and 3D. The traverse profile of a precision forged gear wheel, acquired with the new CMM, is used to exemplify the benefits. It is demonstrated, how sets of parameters are derived from the CMM data, in order to optimize subsequent production steps, such as pitch-grinding. Also, these sets of parameters can be used to establish control charts that enable the performance-based maintenance of individual forging tools, such as an entire forging die or single die inlets.

1. INTRODUCTION

1.1. New ways in gear wheel manufacturing

The transmission and transformation of torque and (input) speed is a core in mechanical engineering. Often it is accomplished using gear boxes with external and sometimes internal spur gear pairs or more frequently helical or even double helical gear pairs. Depending on their field of application high precision is essential to most gear wheels, i.e. virtually no tooth forming errors are allowed.

Until now, gear wheels are mostly made from round bars. A bore in the center of the raw material serves as a reference and enables chucking during further production steps. The preliminary toothing is form milled from raw material using special profile cutters. The gear wheel is completed by pitch-grinding or other processes.

Since form milling is a metal-cutting manufacturing process, it is very time-consuming and, therefore, only limited applicable in mass production such as in automotive industry. Consequently, faster processes are sought after such as casting or forging gear wheels, for instance.

At the University of Hanover, there new ways of precision forging high performance parts are investigated in general. In particular, gear wheels are precision forged in a closed forging die in order to improve accuracy. In this case, the forging die is equipped with ceramic die inlets to reduce abrasion and wear [2]. Thus, relatively precise gear wheels can be mass produced easily.

1.2. Impact on production engineering

However, due to its technology precision forging of gear wheels poses new challenges to production engineering. That is, because of uneven abrasion and wear of the forging die as well as inhomogeneous shrinkage during the cooling down of the part the center of the bore is not in the center of the tooth profile anymore [2, 3].

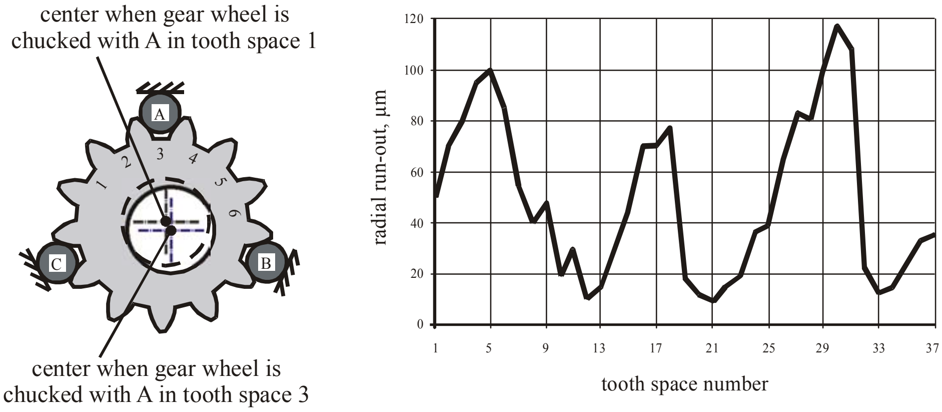

Fig. 1. Radial run-out of the bore of a forged gear wheel (from [3, 4])

It is demonstrated in figure 1, how the center of the bore of a forged gear wheel changes position, when the same clamping element (A) of the machine tool chucks the gear wheel in different tooth spaces (here tooth space number 1 and 3). The radial run-out of the bore is plotted against the tooth space number. It mostly stems from the excentricity of the bore related to the teeth of the forged gear wheel. Form errors of the bore as well as form and pitch errors of the teeth are marginal and, therefore, are unaccounted for. However, depending on which tooth space is chucked by the clamping element A, the radial run-out of the bore can be as high as 120 µm. If, in this case, the bore still serves as a reference and is used for chucking the gear wheel, the excentricity of the bore related to the teeth of the forged gear wheel is passed on the tooth profile. Consequently, this leads to a non-uniform material allowance, if no corrections are made prior to subsequent production steps.

The potential axial run-out of the abutting surface of the forged gear wheel affects the radial run-out up to 2 µm at the utmost, due to the stubby geometry of the gear wheel [3]. Consequently, it can be disregarded in this case.

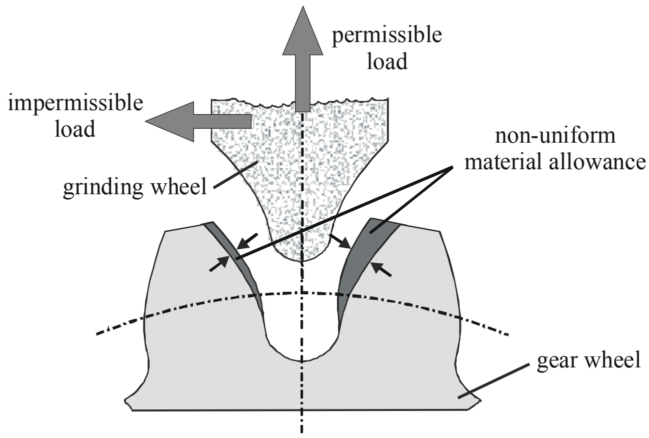

Fig. 2. Loads applied on the grinding wheel during pitch-grinding a forged gear wheel (from [3])

A non-uniform material allowance in turn has a tremendous impact on subsequent production steps as illustrated in figure 2. For example, the excess material on one flank of a tooth space puts an additional impermissible load on the grinding wheel during the process of pitch-grinding. While the grinding wheel can easily take the permissible load in radial direction, the impermissible load in axial direction near the rim causes the grinding wheel to bend. Thus, the quality of the toothing suffers severely. Besides, the durability of the grinding wheel is considerably reduced, too [3].

Accordingly, (numerical) corrections have to be made before using the bore of a forged gear wheel as a reference or for chucking. These corrections comprise an entire sequence of operations, namely chucking the gear wheel, taking at least one traverse profile measurement, calculating the center of the gear wheel from the traverse profile, relocating the gear wheel, and, thus, drilling the bore exactly in the center of the gear wheel. Now the bore can serve as a reference again during further production steps.

2. IN PROCESS CMM APPLICATION

2.1. Single probe CMM

It suffices to use just one distance gage and one rotation axis (see figure 3) for taking traverse profile measurements of gear wheels of the same size in cylinder coordinates. However, if one wants to take measurements of a variety of different parts (i.e. at least gear wheels of different size or shape) one has to tap into a flexible measuring technology. Here a coordinate measuring machine (CMM) comes in handy.

Conventional CMM usually consist of three translation axes (X, Y, Z) and one tactile probe. On the one hand, this allows for very flexible measuring strategies. On the other hand, measuring of very complex parts such as gear wheels takes a long time and provides only a low measuring point density. Consequently, for in process CMM inspection of gear wheels, a CMM with two (R, Z) or more (X, Y, Z) translation axes and one (additional) rotation axis (C) must be equipped with a non-contact (i.e. optical) probe replacing the conventional tactile probe. At least two translation axes are required to bring the optical probe in position.

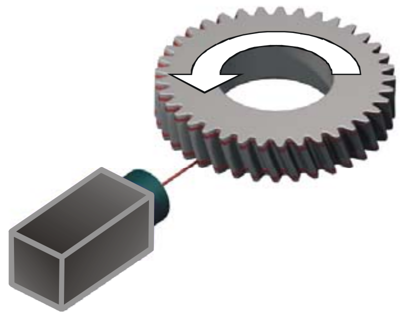

Fig. 3.
Taking a non-contact, optical traverse profile measurement of a precision forged gear wheel (from [3])

Figure 3 shows the non-contact, optical distance sensor in measuring ready position complying with the sensor's working range and standoff (also see figure 5). Moreover, the laser beam of the optical distance sensor has to intersect the axis of rotation virtually at an angle of exactly 90°. The specimen (gear wheel) is mounted on the rotation axis. Thus, a CMM can be upgraded easily to taking in process traverse profile measurements of gear wheels in cylinder coordinates.

Having a look at one tooth of the traverse profile of a gear wheel (see figure 4), one finds that it basically consists of the crest, a pair of tooth flanks, and the bottom of the tooth spaces.

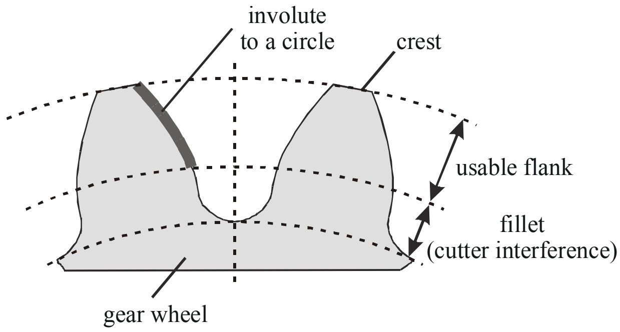

Fig. 4. Functional and non-functional surfaces

Talking about involute gear teeth, the functional surface, which is also referred to as usable flank, is an involute to a circle. It is confined by the crest at its top and by the fillet (most times with cutter interference) at its bottom, which both obviously are non-functional surfaces. A pair of opposite functional surfaces is called functional unit. A functional unit can either be a tooth or a tooth space depending on both whether one considers an external or internal gear and on the way the tooth flanks oppose each other.

2.2. Double probe CMM

Since the laser beam of the optical sensor virtually intersects the axis of rotation, the bottom of the tooth spaces might not be entirely accessible by this measurement strategy. This is especially true for gear wheels with cutter interference, undercut, or root relief.

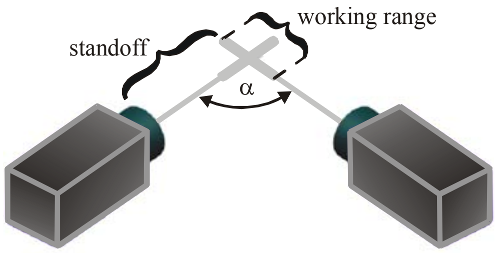

Fig. 5.
Set-up of a double probe non-contact, optical measuring system

It is exemplified in figure 5 how to simultaneously use two sensors in order to completely measure the traverse profile of a gear wheel inclusive of the entire bottom of the tooth spaces. The laser beams of both sensors have to intersect in or near their working range at an angle α, where $0° < \alpha < 90°$. Thus, one sensor takes measurements of one flank plus little more than half the bottom of tooth spaces, while the other sensor takes measurements of the opposite flank plus little more than the other half the bottom of tooth spaces. In so doing, one basically obtains two sets of right and left flanks that have to be merged to a traverse profiles of a gear wheel. The merging of measurement data from optical gear wheel measurements is addressed in [2], for example.

2.3. Multi purpose probe extension

As described above, the optical CMM qualifies for taking traverse profile measurements of external gears. Traverse profile measurements of internal gears, however, can be obtained in a similar way. But the optical distance sensor must be upgraded with special periscope-like optics first that allow for taking measurements from inside the internal gear.

A variety of extensions qualifying the optical distance sensor for other measuring tasks is also available.

3. CMM DATA PROCESSING

3.1. Specifying a substitute element

The first step of CMM data processing is the preparation of the obtained measurement data. It includes the decision of what is the substitute element the traverse profile of a forged gear wheel breaks down to. On the one hand, the substitute element might be an entire tooth or an entire tooth space inclusive of the crest or the bottom of the tooth spaces. On the other hand, the substitute element might be reduced to a functional unit, i.e. two opposite (usable) tooth flanks.

If the substitute element is a functional unit, one could take measurements only from the functional surfaces of a gear wheel in the first place. Alternatively, appropriate filter algorithms can be applied to the complete set of measurement data of a forged gear wheel (i.e. an entire traverse profile). In this case, the purge resolves the functional units the traverse profile breaks down to.

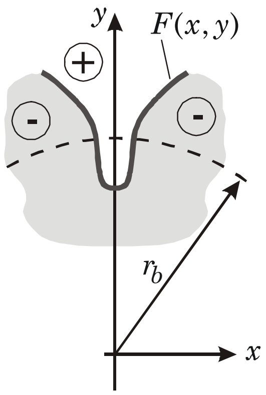

Fig. 6.
A substitute element (here a tooth space) described by an implicit mathematical function

Figure 6 shows a section of a traverse profile where the substitute element is an entire tooth space. The tooth space consists of two opposite tooth flanks as well as of the bottom of the tooth spaces and is graphed by the implicit mathematical function

$$F(x, y) = f(x) - y = 0 \tag{1}$$

where: x, y — CMM coordinates, mm, $f(x)$ — explicit function of x.

Considering the simplest case, the explicit function $f(x)$ might be a polynomial – second degree (parabola), for example. However, it even does not necessarily have to exist at all. Any implicit function $F(x, y)$ can be used to describe the shape of the forged (i.e. semi-finished) gear wheel. It comprises the (finished) tooth flank plus the material allowance necessary for subsequent production steps such as pitch-grinding, for instance.

One can easily calculate the orthogonal or Euclidian distance of the i^{th} measuring point $p(x_i, y_i)$ from any implicit function $F(x, y)$ [7, 8]:

$$d_i = \frac{F(x_i, y_i)}{\left|\operatorname{grad} F(x_i, y_i)\right|} \tag{2}$$

where: d — orthogonal distance, mm, x, y — CMM coordinates, mm.

If the substitute element is reduced to a functional unit of two opposite tooth flanks, or if the material allowance is reduced to zero (finished gear wheel), the involute to a circle can be used instead of an implicit function. The calculation of the orthogonal distance of a measuring point from an involute to a circle is addressed in [5] in extenso.

However, the sign of the distance has to be taken into account, too. As can be seen from figure 6, the orthogonal distance of the measuring points is positive ($d > 0$), if they lie above the implicit function, negative ($d < 0$), if they lie below the implicit function, or zero ($d = 0$) otherwise.

The orthogonal distances of the measuring points from the implicit function can be used for the calculation of the best-fit substitute element. The procedure, which also is referred to as orthogonal distance regression (ODR), is similar to the procedure used for the calculation of best-fit circles.

3.2. Best-fit circles

Different optimization criteria can be used to calculate a best-fit substitute element. Here best-fit circles serve as an easy example to introduce these criteria briefly.

The calculation of best-fit circles can always be put down to the minimization of an objective function which is a function of the parameter a of the circle. The parameter a comprises the coordinates of the center of the circle and, if necessary, in some cases its radius [1].

For an LSC, L1C, and MZC the estimated parameter of the best-fit circle $a = \left[x_C, y_C; r\right]$ is obtained using objective functions $Q(a)$ as follows:

LSC – least squares circle (according to Gauss)

$$Q(a) = \sum_i d_i^2 \xrightarrow{!} \min_a \tag{3}$$

L1C – least absolute values circle

$$Q(a) = \sum_i |d_i| \xrightarrow{!} \min_a \tag{4}$$

MZC – minimum zone circle (according to Chebyshev)

$$Q(a) = \max_i |d_i| \xrightarrow{!} \min_a \tag{5}$$

where: a — parameter, mm, d_i — distance of the i^{th} measuring point, mm.

For an MCC and MIC the minimal or maximal radius r is directly equivalent to the objective function. Thus, the estimated parameter of the best-fit circle $a = \left[x_C, y_C\right]$ is obtained using objective functions $Q(a)$ as follows:

MCC – minimum circumscribed circle

$$Q(a) = \max_i (r_i) \xrightarrow{!} \min_a \tag{6}$$

MIC – maximum inscribed circle

$$Q(a) = \max_i (-r_i) \xrightarrow{!} \min_a \tag{7}$$

where: a — parameter, mm, r_i — radius of the i^{th} measuring point, mm.

3.3. Best-fit substitute elements

The optimization criteria of equations (3) through (5) can directly be applied to calculating best-fit substitute elements (i.e. entire teeth or entire tooth spaces inclusive of crests or bottoms of the tooth spaces) of gear wheels. Though, the parameter a is composed quite differently. In a geometrical graphical way optimizing for a best-fit substitute element can be explained as properly turning and moving a reference substitute element. As a result, the estimated parameter for the best-fit substitute element is eventually obtained from the objective function. It comprises both the angle of rotation φ and the displacement $[\Delta x, \Delta y]$ of the substitute element.

However, there is a little twist to fitting a substitute element that complies with minimum circumscribed or maximum inscribed criteria, respectively. For an MCE and MIE the estimated parameter is obtained using objective functions $Q(a)$ as follows:

MCE – minimum circumscribed element

$$Q(a) = \max_i \frac{1}{d_i} \xrightarrow{!} \min_a \tag{8}$$

MIE – maximum inscribed element

$$Q(a) = \max_i \frac{1}{-d_i} \xrightarrow{!} \min_a \tag{9}$$

where: a — parameter; d_i — distance of the i^{th} measuring point, mm.

Further details about the objective functions of an MCE and MIE can be found in [6].

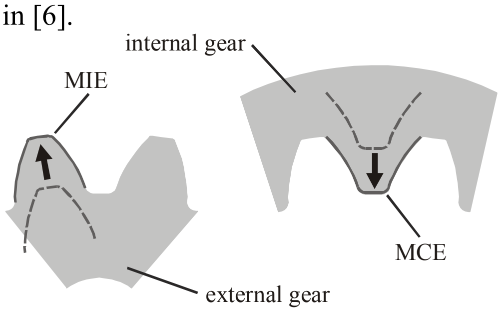

Fig. 7.
Fitting a Maximum Inscribed Element (MIE) to an external gear (left) and
fitting a Minimum Circumscribed Element (MCE) to an internal gear (right)

The procedure of fitting a substitute element in order to get the best-fit substitute element (here MIE and MCE) is exemplified in principle in figure 7. If one wants to determine whether or not the (finished) gear wheel can at all be manufactured from the forged (i.e. semi-finished) gear wheel, the best-fit substitute element has to be resolved from the material side of the part. Consequently, for an external gear the MIE must be determined, while for an internal gear the MCE has to be calculated.

4. QUALITY IMPROVEMENTS

4.1. Feedforward quality control

The output of calculating best-fit substitute elements are estimated parameters for each substitute element. They can be used to control subsequent production steps such as pitch-grinding, for instance, in order to improve both product quality and durability of tools.

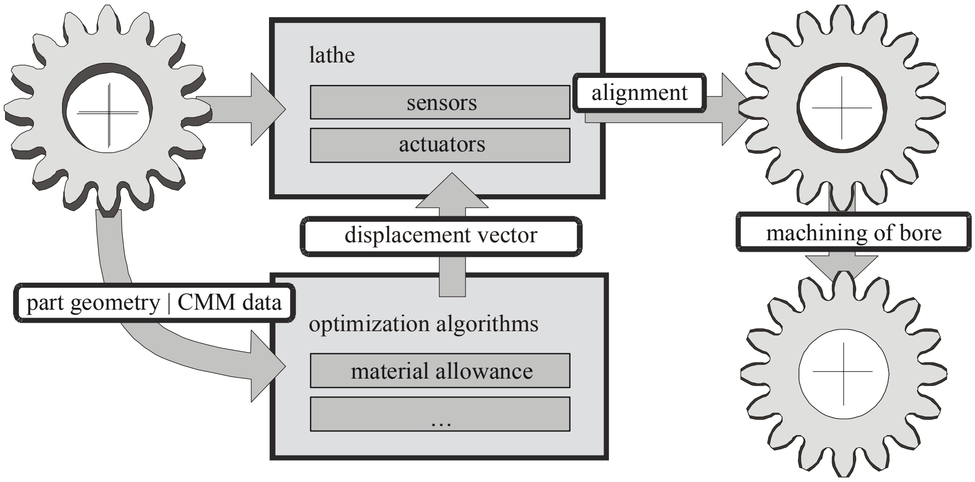

Fig. 8. Process optimization by means of feedforward quality control (from [4])

The scheme of feedforward quality control is shown in figure 8. The part geometry of the forged gear wheel is acquired utilizing the optical CMM that has been introduced. From the CMM data, the center of at least one traverse profile is determined employing optimization algorithms that are based upon the material allowance. The information about the position of the center of the traverse profile of the forged gear wheel is equivalent to a displacement vector that is transmitted to the sensor-actuator-system of the lathe (or any appropriate machine tool). Having chucked the forged gear wheel, it then is re-positioned by the actuators integrated into the lathe chuck according to the displacement vector. The re-positioning is carried out in a way that the center of the toothing of the gear wheel lines up with the axis of rotation of the machine tool. Eventually, the bore is machined in concentricity with the toothing of the forged gear wheel. Thus, a uniform distribution of the material allowance is guaranteed. So, the numerically corrected bore can serve as a reference or for chucking during further production steps as afore.

4.2. Feedback quality assurance (control charts)

Also, feedback quality assurance is feasible. That is, the estimated parameters of the best-fit substitute elements can be used to establish a control chart.

For example, a forging die is utilized for precision forging of an external gear. In order to reduce the abrasion and wear of the forging die, ceramic die inlets are put to use that form the tooth spaces of the gear wheel. For the traverse profile best-fit substitute elements (e.g. MCE or MIE) are calculated. If they are tooth spaces, they directly correspond to the die inlets. Consequently, the estimated parameters of the best-fit substitute element correlate with the abrasion and wear of the die inlets, too. Therefore, they can be used to establish a control chart for every single die inlet.

The information from the control chart can easily be exploited for both the performance based maintenance of the ceramic die inlets and the preventive maintenance of the entire forging die. Thus, permanent product quality is guaranteed while simultaneously reducing maintenance costs.

5. REFERENCES

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