Simulation of Deviations in Hobbing and Generation Grinding

Günther Gravel

The hobbing and generation grinding production processes are complex due to tool geometry and kinematics. Expert knowledge and extensive testing are required for a clear attribution of cause to workpiece deviations. A newly developed software tool now makes it possible to simulate the cutting procedure of the tool and superimpose systematic deviations on it. The performance of the simulation software is illustrated here with practical examples. The new simulation tool allows the user to accurately predict the effect of errors. With this knowledge, the user can design and operate optimal, robust gearing processes.

Introduction

The continuous machining of tooth flanks by a rolling motion process has long been a standard practice for manufacturing cost-effective gearing with high accuracy. This process is used for soft- and hard-machining by hobbing and generation grinding. The tool has the shape of a worm that is interrupted by gashes with hobs. Both tool and workpiece operate in a kinematic coupling with versatile motion options. In Figure 1 the possible influence categories are listed as possible reasons for deviations discovered in the scope of measuring a workpiece.

The tool may have deviations when it is new, or due to wear and damage. It can be set up in the machine incorrectly, thus indicating run-out deviations. The cutting process on the tooth flank is controlled by technology parameters such as feed rate and infeed; foreseeable deviations resulting from this are not only feed markings but also deviations in chip shape formation. Not surprising, given that the machine tool must implement and synchronize the different movements at a high precision. Here deviations also result from the control processes, deformation or position errors of the axes. The user therefore must deal with a complicated scenario of fault possibilities, and is pleased when he can assign the root cause of the fault to a category in order to then pursue out further checks or changes to the parameters.

With this in mind, simulation software now exists that mirrors the effects of typical faults stemming from hobbing and generation grinding to the workpiece,
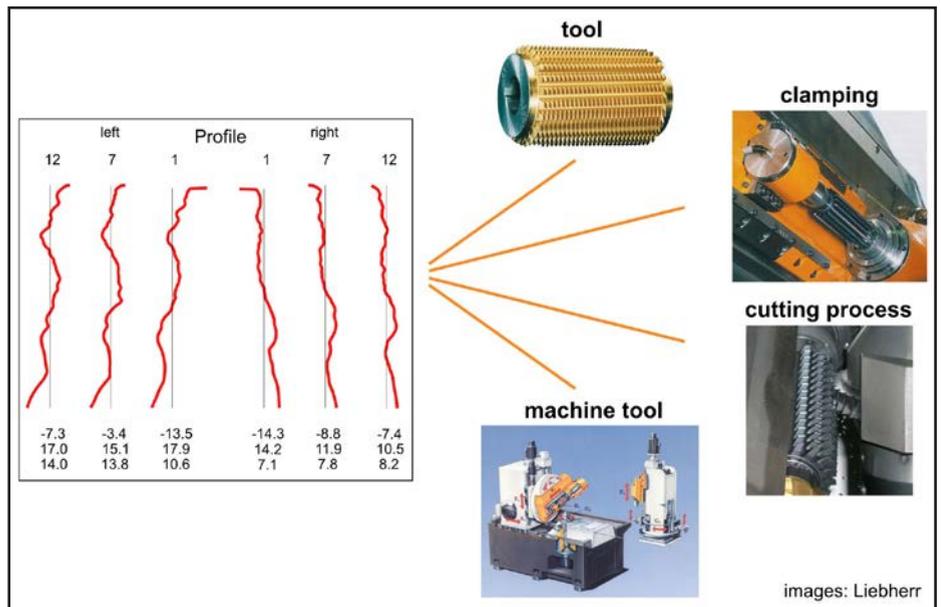

Figure 1   Causes of deviations.

and aids the user when searching for the cause. The following article presents the layout and function of this software in practical examples. Implementation requires only a simple operation and a quick and accurate calculation. With just a slight interpretation of the results, the simulation has been integrated in an analysis tool for gear measurement. The simulation results are represented in the same manner as the results of a gear measurement. Effort expended for development is reduced considerably by using the numerous calculation and output routines of the analysis software.

Layout of the Simulation Software

This simulation software provides representation of a rolling production by a worm-shaped tool. The only difference when considering hobs vs. grinding worms is that with hobs, the number of cutting edges is clearly determined, whereas with grinding worms the number is theoretically infinite but can still be effectively approximated in suitable quantity. As several deviations — such as the profile cut markings — only occur when hobbing and hobs are compared with grinding worms relatively easy to measure on gear measurement devices, only examples of hobbing shall be considered in the following; all possibilities of the software described here also apply to generation grinding.

The fundamental basis of the calculation is the consideration of points on the surface of the workpiece and the descrip-

tion of the tool cutting edge as a sequence of points. These points are equipped with possibilities for movement that adhere to defined dependencies. The workpiece points are treated as measuring points of a gear measurement that can then be used to calculate deviations using the conventional procedures of measuring technology. The tool cutting edges each have a cutting contour and description for the position of this contour. In their basic state these position parameters define the position of the cutting edge on the spiral-shaped tool body. All movements can only be implemented by changing these position parameters; in this way it is easy to represent many tool errors as position changes.

The possibility of moving the workpiece is only a rotation in the Z axis that is coupled with the tool rotation. The tool carries out an axial feed per rotation in the direction of the workpiece axis. The position of the tool in the direction of the tool axis is determined by the shift position. In this regard a diagonal shifting permits a movement during processing. The radial position of the tool to the workpiece axis is determined by the addendum modification. A movement during the machining is also possible here, for example, to generate a flank modification; the tool is rotated around the swiveling angle from the horizontal position that is determined from the helix angle of the workpiece gearing and the lead angle of the tool worm.

Indeed, in the course of simulation every single workpiece point is provided with an allowance and considered accordingly as to which cutting edge makes contact with it, and in which position. During cutting, the allowance is reduced to the clearance to the cutting edge (Fig. 3). On the measuring point considered here, the enlarged deviation curve of all measuring points is reduced rapidly, as with the removal of chips.

The implementation of the procedure described here is sufficient for an exact simulation, but leads to a response time that is impracticable when each point of the tool contour of every tool tooth meets in relation to each workpiece point in any possible position. For smooth performance, numerous guidelines have been implemented that in effect limit the tool teeth and cutting zones to the actu-
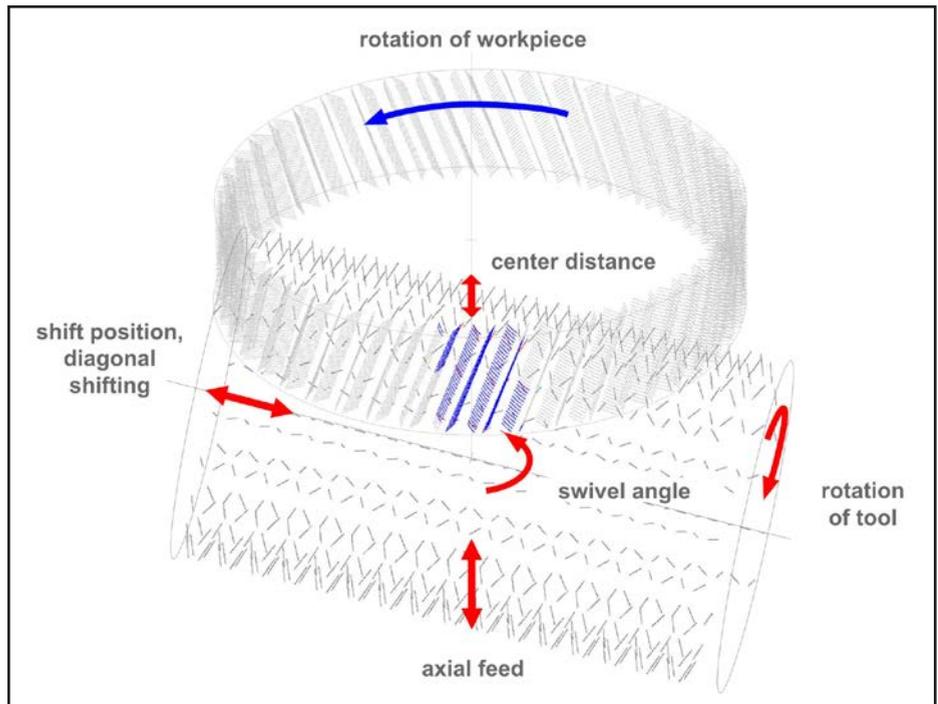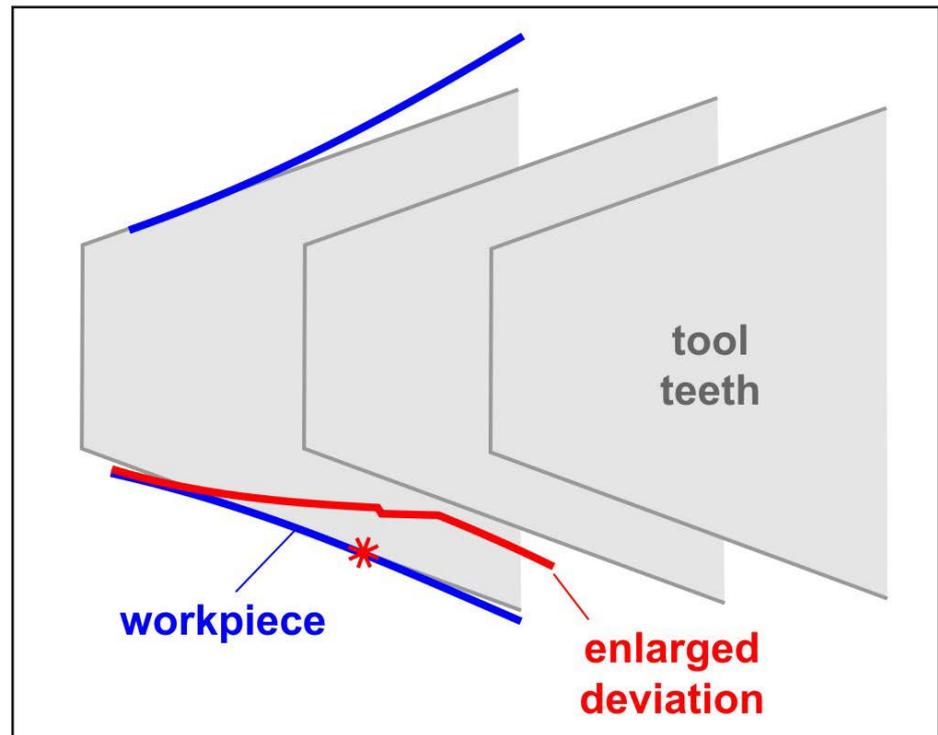

Figure 2   Description of the kinematics.

Figure 3   Calculation of cutting.

ally effective ones; in doing so, these rules also consider possible tool errors.

Simulation Results with Error-Free Processing

Figure 4 shows the results of the hobbing simulation of a workpiece; an error-free processing is carried out with a relatively high axial feed. Profile cuts and curves of the tooth trace on the right and left tooth flanks in the diagram — as well as pitch points on all teeth — are specified as measuring points according to a standard measurement on three distributed teeth. The markings of the axial feed arise on the tooth trace; the distance of the tips is equivalent with the feed rate. The crowning of the tooth trace results from the set-point specification of a crowned flank modification.
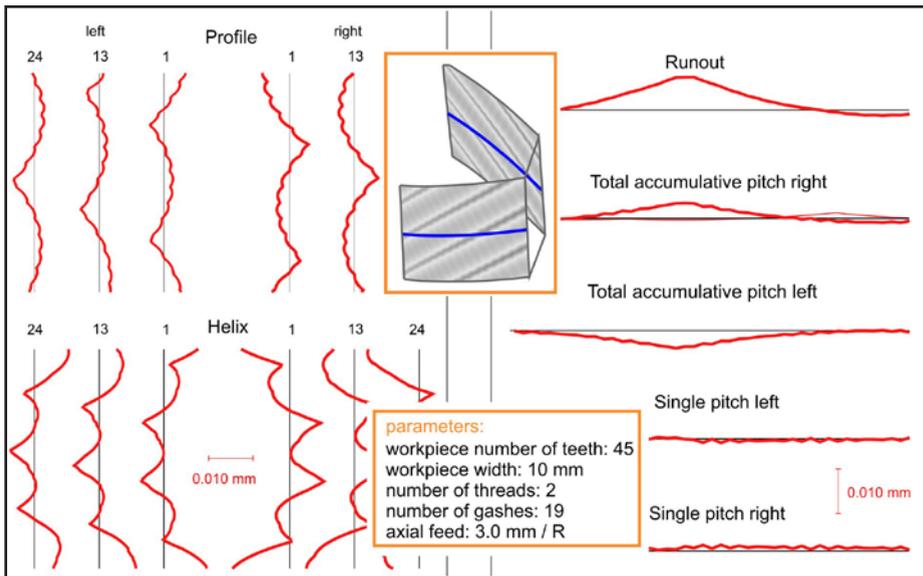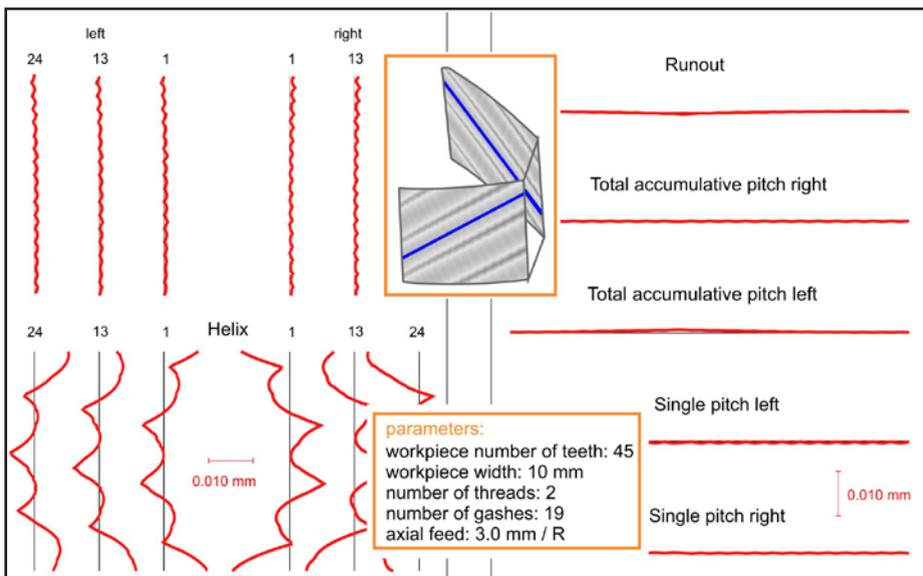
Figure 4   Standard measurement.

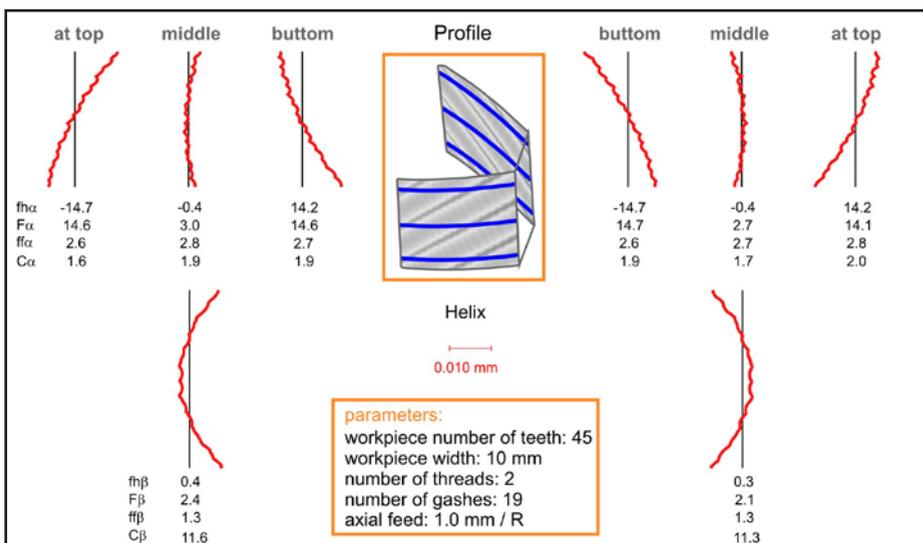**Figure 5   Measurement in the spiral of feed.**

Figure 6   Measurement of twist.

The 3D topography of a tooth is represented in the middle of Figure 4. An obliquely running ripple results over the tooth flank due to the axial feed. A typical profile measurement (blue line) is carried out in the transverse section and cuts this ripple effect, which also results in a ripple in the profile of the same amplitude. Moreover, the profile indicates a finer, higher-frequency ripple. These deviations result from the generating cuts after the cutting sequence of the individual cutting edges. They can be clearly seen due to the relatively small number of gashes-per-thread of this tool. As the ripples also move from tooth to tooth due to the axial feed, the pitch variation also indicates irregularities, depending on where the individual pitch point is located between peak and valley.

The deviation in form generated by the axial feed reflects the quality of the workpiece; but with regard to the manufacturing assessment, do not allow support statement about the accuracy of the profile generation or positional deviation of the gear teeth (radial run-out and pitch variation). It is therefore common on gear measurement devices to do a measurement in the spiral feed. With the profile and pitch measurements, the measuring probe then always scans in the base of the ripple (Fig. 5). The measuring points can also be distributed in this way in the simulation so that the deviations from the axial feed disappear and only the generating cut deviation remains in the profile.

As the position of the measuring points on the tooth flank can be freely selected, it is also possible to generate three profile cuts — common when measuring the twist. Figure 6 shows the deviations when using a considerably smaller axial feed during the simulation. The crowned contour of the tooth trace is generated by a correction of the axial distance during machining. As the tool is inclined by the swiveling angle, and thus does not only cut in the transverse section level of the workpiece, a tilting of the profile with changing signs results at the top and bottom that is designated as twist. Using the calculation of the standard characteristic values, the twist can also be output numerically. In practical tests, a good match with the values calculated is observed.

Figure 7 shows the results of the simulation of many more profile cuts as a color-coded representation of the deviations. On the figure's left side, error-free processing was done with a high axial feed and without crowned tooth trace. On the right side of the figure a positional deviation of the tool has also been specified in the form of a wobble. Whereas the right tooth flank of the workpiece shows almost no changes, the left tooth flank shows significant deviation patterns that can also be recognized visually on the tooth flanks of the manufactured gear. If the measurement diameter of a tooth trace measurement is modified here (displacement of a vertical cutting line to the outside or inside), then the form of the deviation curves can modify significantly. This effect is comprehensible only by means of a topographical representation. In this way the user of the simulation software is also able to analyze surface effects of the machining.

Consideration of Tool and Clamping Errors

In addition to error-free machining the cutting can be simulated using a defective tool. Figure 8 shows the possible tool errors that can easily be generated, as well as overlapped by a few mouse clicks. Corresponding to the clamping error in the hobbing or grinding machine, the tool can run wobbly or eccentrically — which is described on the reference collar by radial and axial run-out deviations. The tool can have a sinus-shaped thread lead deviation if the hob or grinding worm does not run to the reference collars, and a linear thread lead deviation if temperature expansion should occur. With multi-start tools, one thread can be axially displaced with respect to the others; after all, by specifying a deviation on a single cutting tooth, the effects of build-up edge, wear, or cutouts can be easily assessed upon the quality of a toothed gear manufactured in this way.

A hob has been purposely clamped eccentrically and a toothed gear has been machined with it to check the accuracy of the simulation. Figure 9 shows the results measured in blue that are compared with the red ones of the simulation results. The concentricity variation on the main and counter bearings, and their angular position to the machine axis have been
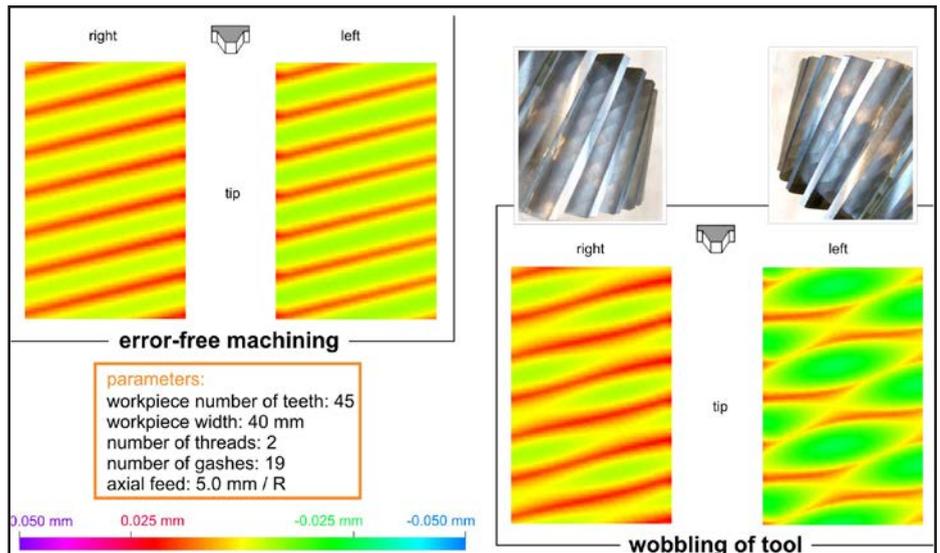

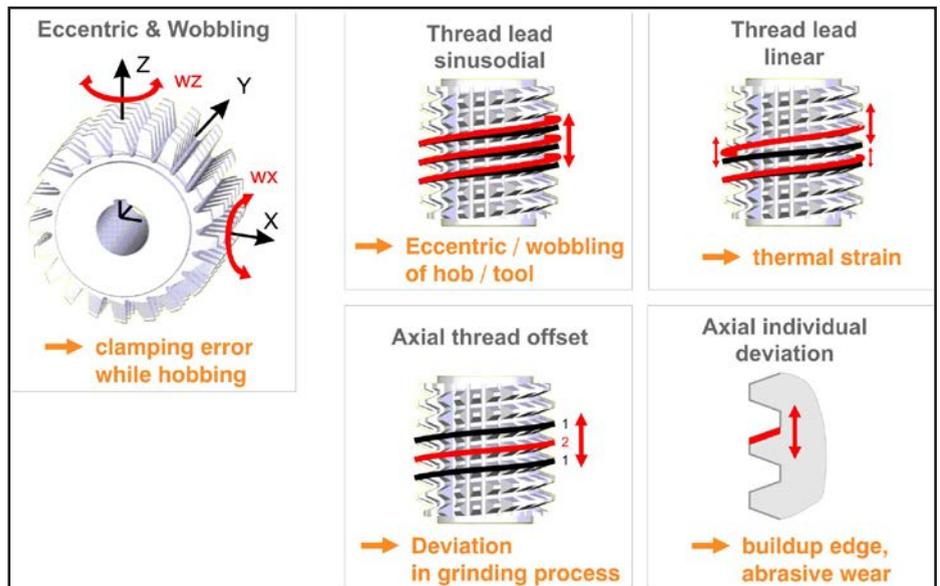Figure 7   Simulation of many sections and topography presentation.

Figure 8   Simulation of tool and clamping errors.

modified in the simulation step by step until the test settings — determined with a dial indicator — have been reached. The deviations — in the form of the measurement and calculation — correspond very well with one another.

It is obvious that not only typical, systemic errors must be considered in the simulation, but also the actual errors for each individual cutting edge, as they can be determined by measurement of the tool on a gear measurement device.

Figure 10 shows the measurement of a double-start hob; the profile deviation of the cutting edge, and the axial deviation of each tooth are transferred via an interface and used for the simulation. The differences of the deviation on the left and right tool flanks — and on the

threads between one another — lead to different profile and flank deviations on the workpiece that, at this ratio of workpiece teeth to the thread number, are the same on every-second gear tooth. In this calculation a diagonal feed rate of the tool has been entered that leads to a situation in which not all of the same tool teeth are active in the entire tooth trace. The result is greater deviations in form in this area — according to the hob deviations. The combination of simulation with hob measurement unleashes the possibility of predicting with great precision and detail the quality a hob-processed workpiece can attain in the most favorable circumstance. Clamping errors can then be overlapped here in the simulation as well.

Summary

- A new software tool is presented that provides high accuracy simulation of typical errors in the production of toothed gears by hobbing and generation grinding.
- This software enables consideration of any points on the tooth flank and represents all results in the form of a gear measurement familiar to the user.
- A 3D consideration of the twisting and of the topographical deviation pattern becomes possible.
- Comparison of the measured deviation on faulty components with the simulation results displays harmonious agreement. This provides users and planners of hobbing and generation grinder processes in construction and production with a high-performance tool that supports them in the dimensioning of processes and tools, and when looking for root cause deviations.
- With the option to edit the process parameters quickly and easily, the understanding of these complex machining processes and their influence categories is increased significantly. ◉

References

1. Pfauter, H. Pfauter - Wälzfräsen, Springer Verlag, 1976.
2. Abler, J., K. Felten, C. Kobialka, T. Lierse, A. Mundt, J. Pomp and G. Sulzer. Verzahntechnik - Informationen für die Praxis, Liebherr Verzahntechnik, 2004.
3. N., N. Seminarunterlagen Wälzfräsen, LMT Fette.
4. Mikoleizig, G. Aktuelle Tendenzen bei der Einzelfehlerbestimmung an Verzahnungen: Maschinentechnologie, Anwendungsspektrum, Auswerte Software, VDI Report 1880, 2005.
5. Trapp, H.J. "Mess- und Korrekturstrategien für den Closed Loop in der Zahnradfertigung," VDI Report 1673, 2002.
6. Gravel, G. "Simulation und Korrektur von Verzahnungsabweichungen - Qualitätsregelkreis Zahnradproduktion," VDI-Bericht 2148, 2011.
7. Mehr, A. "Möglichkeiten und Grenzen beim Wälz- und Profilschleifen," *GETPRO Kongress zur Getriebeproduktion*, 2009.
8. Türich, A. "Producing Profile and Lead Modifications in Threaded Wheel and Profile Grinding," *Gear Technology*, January/February 2010.
9. Winkel, O. "New Developments in Gear Hobbing," *Gear Technology*, March/April 2010.
10. Klocke, F., C. Gorgels, R. Schalaster and A. Stuckenberg. "An Innovative Way of Designing Gear Hobbing Processes," *International Conference on Gears*, VDI Report 2108, 2010.
11. VDI/VDE 2606. Messen von Verzahnungswerkzeugen - Messen von Wälzfräsern, 2010.
12. Kotlyar, Y. "Computerized Hob Inspection & Applications of Inspection Results, Parts I and II, *Gear Technology*, May/June, July/August 1994.
13. Cluff, B. W. "Effects of Hob Quality and Re-sharpening Errors on Generating Quality, *Gear Technology*, September/October 1987.
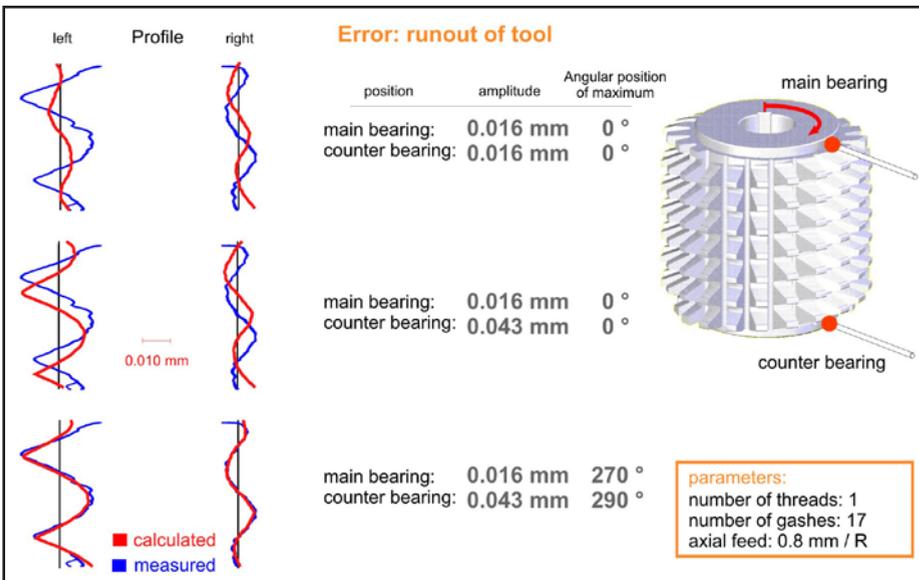
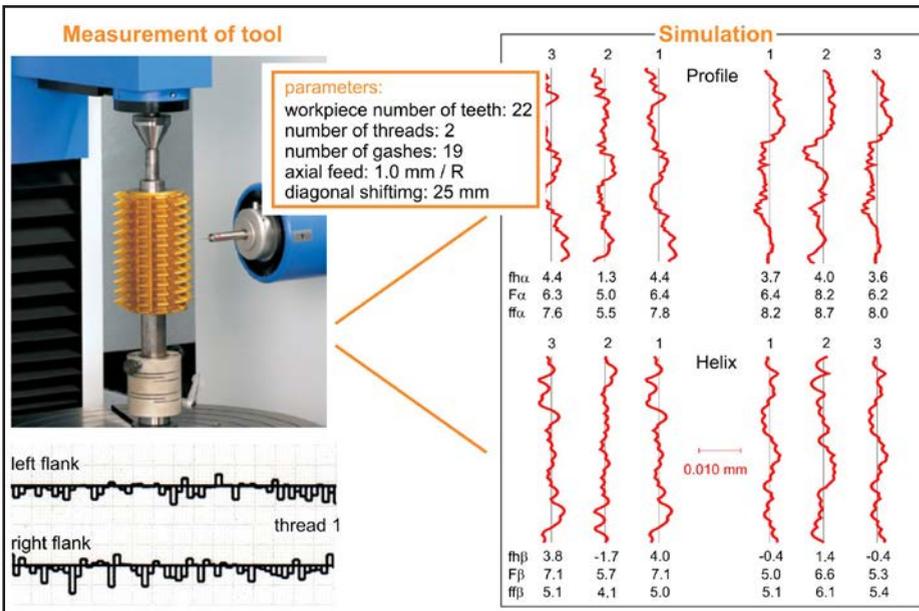**Figure 9   Comparison of measured and calculated profile deviations.**

Figure 10   Prediction of workpiece quality from a tool measurement.

Günther Gravel is professor for production engineering at the Hamburg University of Applied Sciences. He is the head of the Institute for Production Engineering. For more than 20 years, Dr. Gravel has studied the measurement of gears. He is now developing software for the analysis of gear measurement and for the simulation of errors in gear manufacturing processes; in fact the software mentioned in this article is part of a software deviation analysis suite. This software can be used to visualize deviations, simulate errors, calculate corrections for the manufacturing process, and evaluate ripples on a gear surface. It has been developed in cooperation with Liebherr and Klingelnberg and is available with all Klingelnberg measuring machines. For questions and practical applications contact *'www.klingelnberg.com'*.