Efficient Hard Finishing of Asymmetric Tooth Profiles and Topological Modifications by Generating Grinding

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In order to improve load-carrying capacity and noise behavior, gears usually have profile and lead modifications. Furthermore, in gears where a specified tooth-flank load application direction (for drive and coast flanks) is a design enhancement, or even compulsory, the asymmetric tooth profile is a further solution. Nowadays, many gears need to be hard finished. Continuous generating grinding offers a very high process efficiency, but is this process able to grind all modifications, especially asymmetric gears? Yes, it is!

This technical paper will report about all new possibilities of modifications with the continuous generating grinding method, such as deviation-free topological grinding (DFT), generated end relief (GER), noise excitation optimized modification (NEO) and asymmetric gears

All of these modifications are indeed well-known in the gear industry, and tooth grinding methods are already established (namely profile grinding of asymmetric gears) to produce them. But now they can additionally be produced with, for certain parts, the faster—and therefore more economic—continuous generating grinding method.

Introduction

In the most modern transmission boxes, gears and shafts with profile and/or lead modifications can be found. With the help of these modifications, the efficiency and life time of the gears, and the transmission itself, can be increased. The running and noise behavior can also be improved.

Furthermore, the quality requirement of gears has been increased over the last 10 years. To fulfill the high-quality demands, it is necessary to hard finish the gears after their heat treatment. So nowadays, the hard finishing of gears is really established in a wide field of transmission applications like the automotive, truck, tractor and aerospace industries.

For these reasons, the gear production is always looking for a hard finishing method which is, on one hand, capable of creating all possible gear modifications, and on the other hand, as efficient as possible.

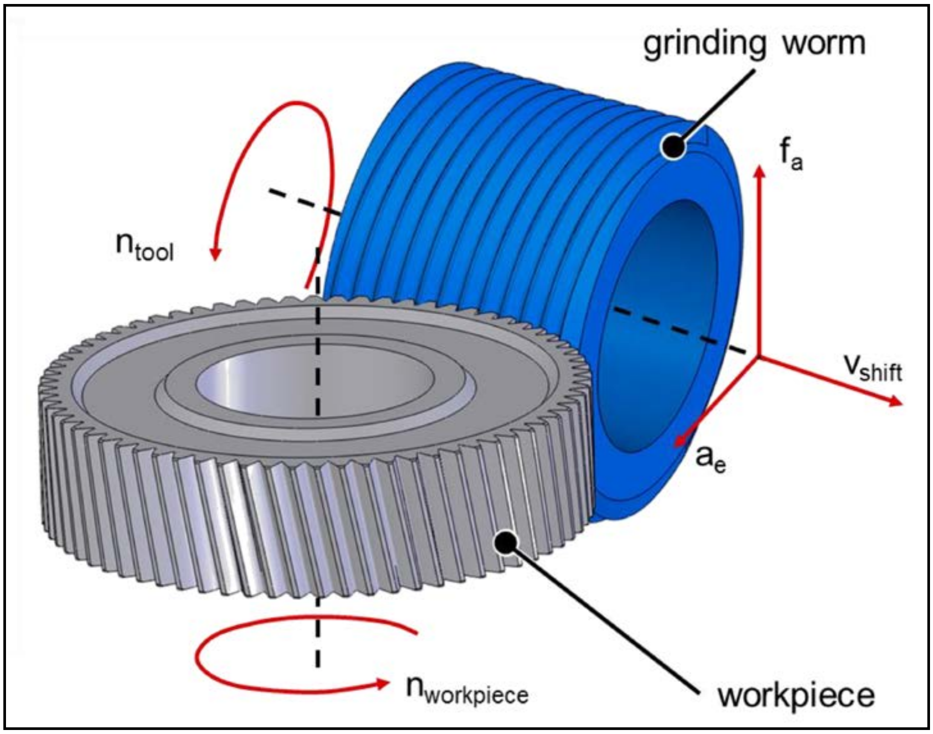


Figure 1 Kinematic principle of the continuous generating grinding (Ref. 1).

State of the Art

Generating Grinding. A very productive way to hard finish gears is the continuous generating grinding process. Its kinematic principle is shown (Fig. 1). The module range of external gears running in production is from 0.3 mm up to module 14 mm, and the latest developments of large gear generating grinding machines make it possible to grind gears with an outside diameter of 1,250 mm.

Due to the continuous rotary motion of the grinding worm (n_{tool}), which is always in a mating contact with the gear ($n_{workpiece}$), no time-consuming indexing from tooth to tooth appears. The grinding worm's high rotary speed leads to high cutting speed, and therefore also to a fast grinding time, so the stock removal rate on continuous generating grinding is sometimes higher than on other grinding processes.

Even with a high cutting speed of 80 to

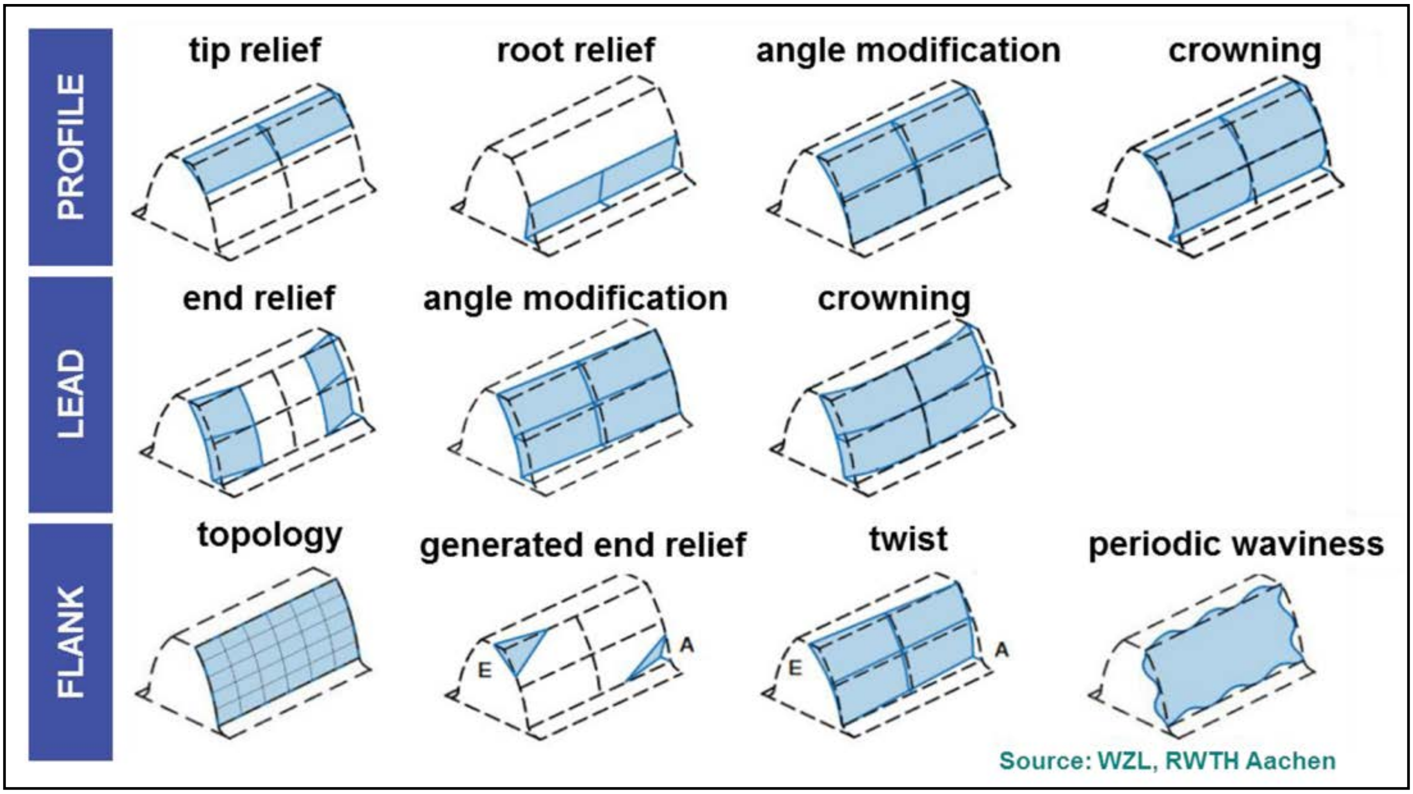


Figure 2 Overview of modifications (Ref. 6).

100 m/s — achievable with new types of abrasives and bonding systems — the risk for grinding burn is very low. The type of abrasive and the grinding technology have a big influence on thermal damage of the surface zone (Ref. 1), but recent studies show that these parameters can also have a positive influence on the load-carrying capacity on gear flanks (Ref. 2).

Modifications. Figure 2 shows all gear modifications possible on the profile, lead, and flank. This classification is based on DIN ISO 21771 (Ref. 3). All modifications have an influence on the tooth flank load-carrying capacity and the noise behavior (Refs. 4–5). The optimization of the gear design is always under the conflict of these two aims. This means that a modification which is useful for increasing the load-carrying capacity can have a more-or-less bad influence on the noise behavior.

Today the most commonly used are tip relief, profile and lead angle modifications in combination with crowning. In some special cases twist or twist-free grinding is applied. Recent scientific reports prove the optimization potential of topological modifications like twist (Ref. 6) and periodic waviness (Ref. 5) on a gear flank.

Twist-Free Grinding. Twist-free grinding with a profile angle-corrected worm used in a diagonal grinding method was invented in 1987 (Ref. 7). The aim of this method was to correct the natural twist that occurs during generating grinding of gear teeth featuring lead modifications, like lead crowning.

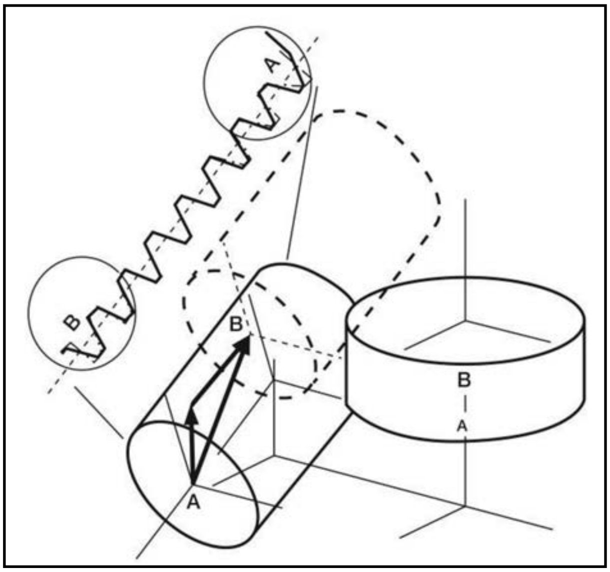


Figure 3 Principle of twist-free grinding (Ref. 7).

During the twist-free grinding process, the grinding worm moves diagonally; this means it is fed along the workpiece axis and at the same time, along its own axis from A to B (Fig. 3). This eliminates the twist or can be used to create a special twist. But this method does not eliminate geometrical errors over the total gear flank topology (Fig. 4). In Figure 4 (right) the twist has been corrected, but an unwanted concave crowning occurs in the profile.

Depending on the diagonal shift strategy, the number of parts-per-dressing cycle on the twist-free grinding is less in comparison to a conventional shift strategy. This reduced tool life affects the dressing time per part, which increases, and therefore the total cycle increases as well. The scientific report "Potential of Topological Grinding" (Ref. 6) investigated, besides the influence of the twist on the gear running behavior, also the hard finishing processes profile and generating grinding, with regard to productivity and costs. Here the result shows a cycle time increase of 20 to 25 percent for an automotive speed gear. Similar figures are known as a feedback from the industry. Optimization by using a two-sectioned

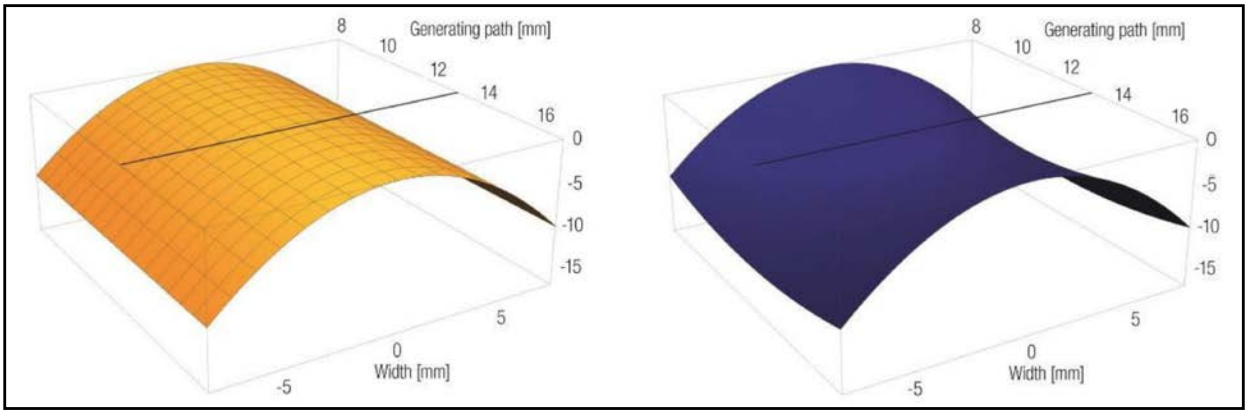


Figure 4 Twist-free nominal specification (left) and result (right).

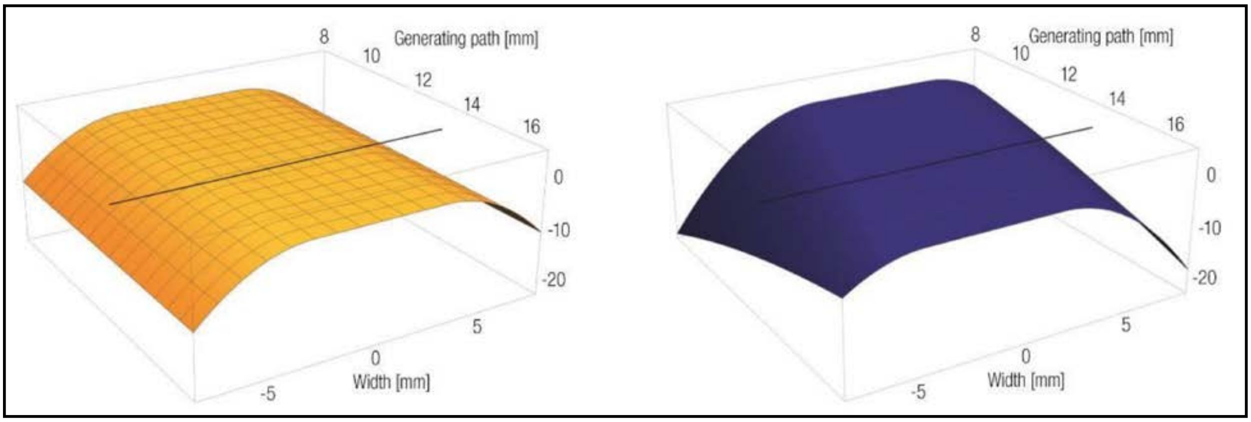


Figure 5 End relief nominal specification (left) and result (right).

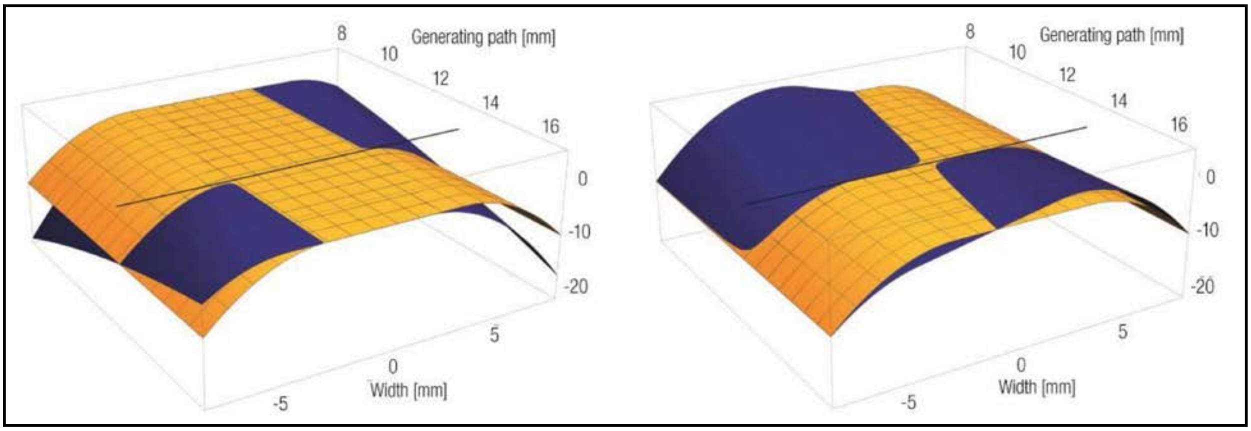


Figure 6 Illustration of the achieved end relief: conventional (left) and twist-free ground (right).

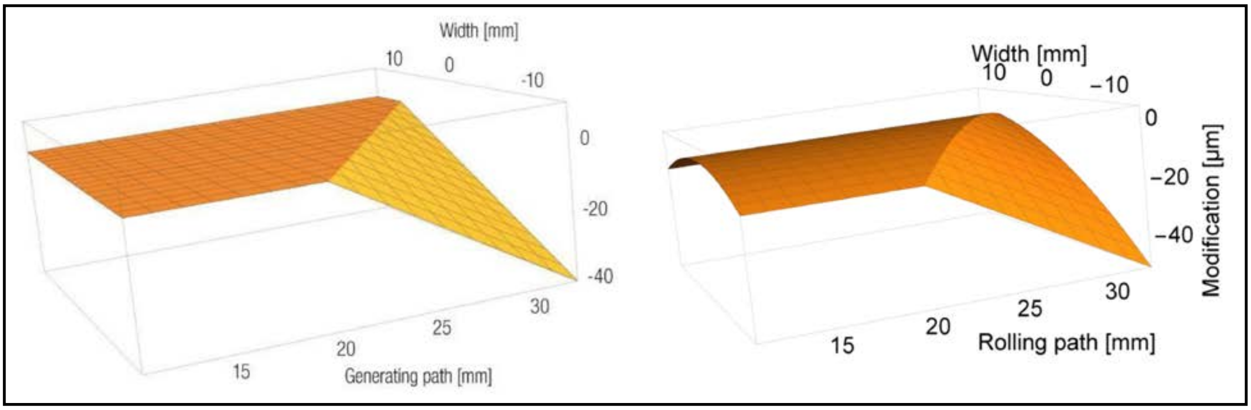


Figure 7 GER (left) and GER in combination with lead crowning (right).

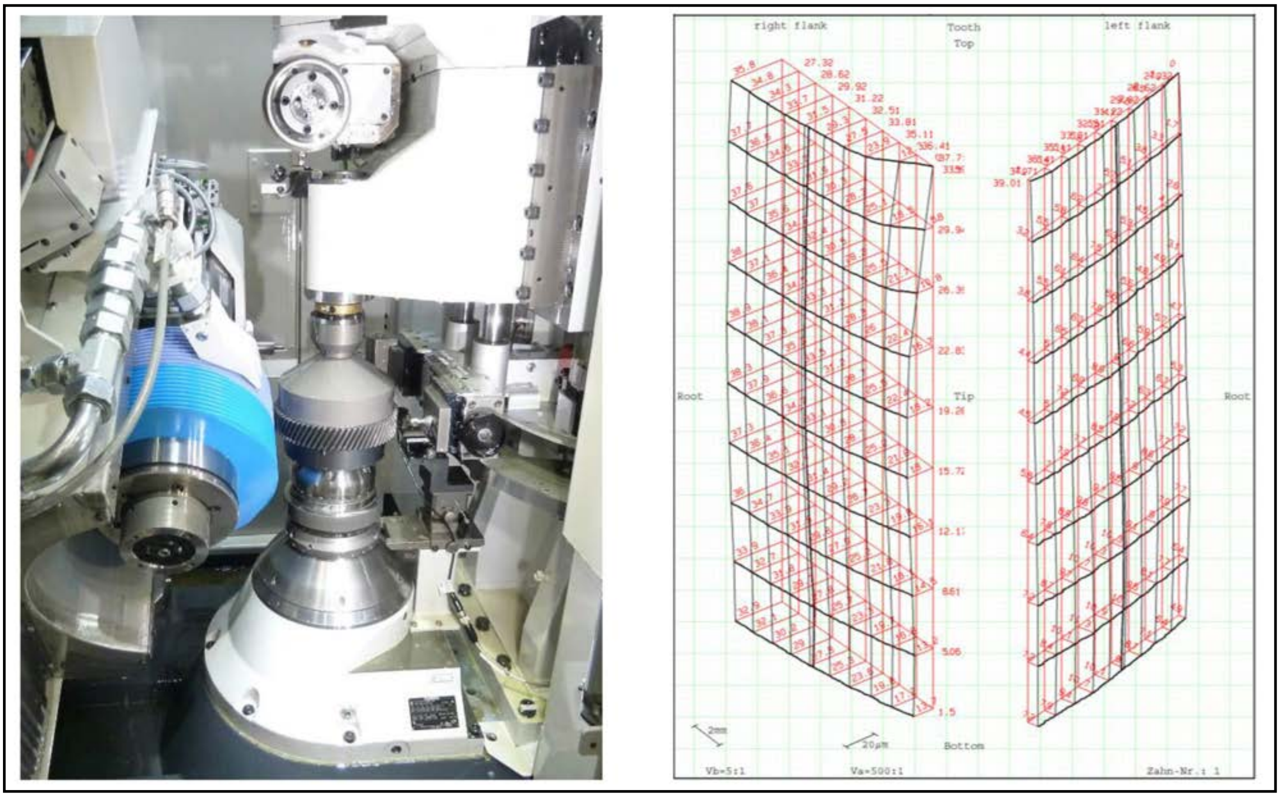


Figure 8 Grinding and polishing of a GER.

worm with a roughing and finishing zone improves the tool life, but still there is a small gap to the conventional grinding process.

Generating Grinding of an End Relief in the Lead. The generating grinding of an end relief in the lead is an established process (Ref. 8); but the conventional grinding shows that the nominal end relief is not achieved. There are distortions at the corners on the gear flank (Fig. 5, right) caused by the machine kinematics used for grinding. The root cause for this distortion is the same as that which creates the natural twist while grinding a lead crowing on helical gears, i.e. — the center distance and the corresponding generating point do not fit for all contact points.

Even using the twist-free grinding technology to compensate for the distortions at the gear tooth edges does not solve the problem completely. There are small discrepancies remaining and the modification is achieved correctly only on one diameter — the pitch diameter.

Deviation-Free Topological Grinding

The deviation free topological (DFT) grinding was developed exactly for this reason, to avoid the last unwanted distortions and geometrical errors on the gear flank.

Function Principle. Based on the old, but proven, twist-free grinding process, the deviation free topological (DFT) grinding was developed. The new grinding method (DFT) uses, during dressing and grinding, several CNC axes in addition to the profile angle-corrected grinding worm. A further advantage of DFT is working with standard dressing tools — no special or profile-corrected dressers are needed. Grinding and dressing time are equal to those occurring in twist-free grinding. For sure, the cycle time of the DFT is a little longer than a conventional grinding process, but it is still faster and more economic than the use of a topological, line-by-line dressed grinding worm.

Generated End Relief. In addition to grind and absolutely deviation-free lead modifications, the DFT grinding method can be adapted to enable generated end relief (GER) modifications as well. It is possible to superimpose the GER with all other modifications, such as lead crowning or twist.

Figure 8 shows an application example of the automotive industry. The differential gear with a module about 2.5 mm (DP 10) was ground and polished with a GER. Both the vitrified-bonded grinding and the elastic-bonded polishing worm section were dressed with the GER modification. And so it can be ensured that the triangular relief is also polished like the rest of the gear flank and the surface roughness is the same.

The benefits of such triangular end relief in terms of load capacity have been debated in the gear industry for many years. GER offers a targeted design of pressure distribution in meshing. This influences the maximum contact stress. Figure 9 shows an example of a truck speed gear under a constant torque. The gear width can be reduced by using a GER and adjusting the tip and root relief.

Noise Excitation Optimized Modification. Another application realizable with the DFT is excitation-enhanced modification. In the gear science the periodic waviness on gear flanks was investigated during the last few years. Time-variable gear tooth rigidity causes a periodic transmission error with amplitudes between two paired gears, which has a major impact on noise levels. To reduce the noise level a sinusoidal-shaped modification is ground on the gear flanks. The pos-

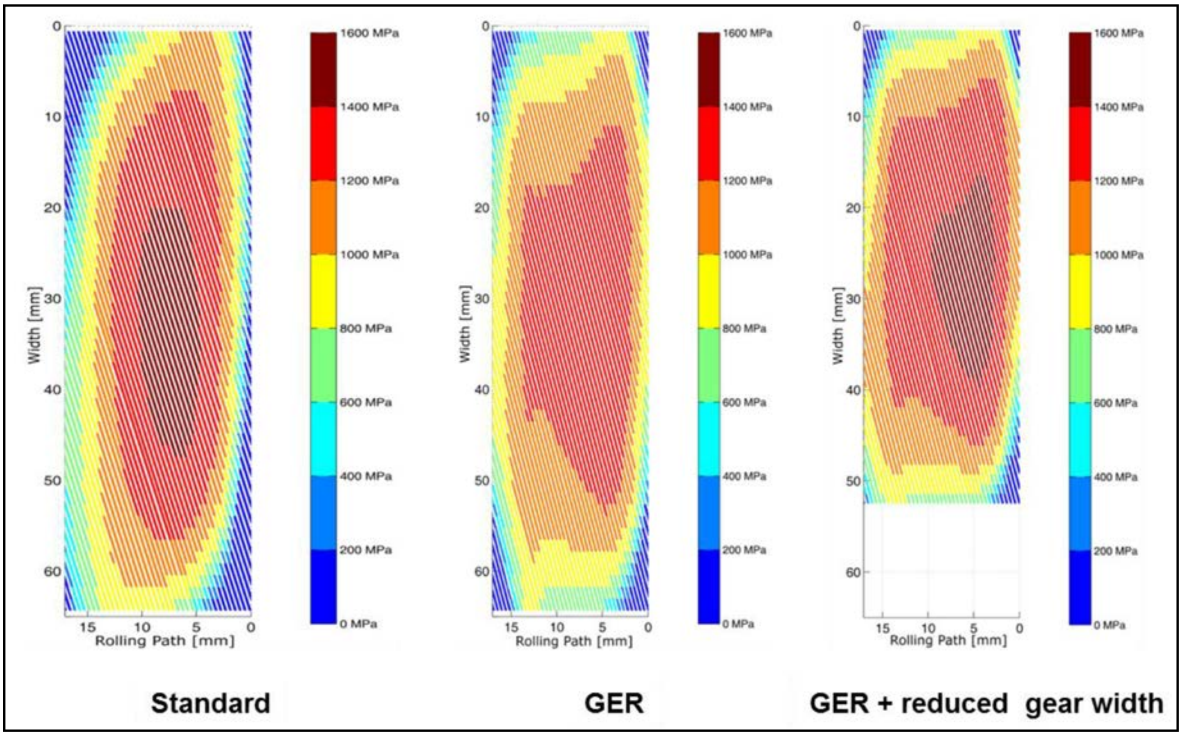


Figure 9 Reduced gear width by using a GER.

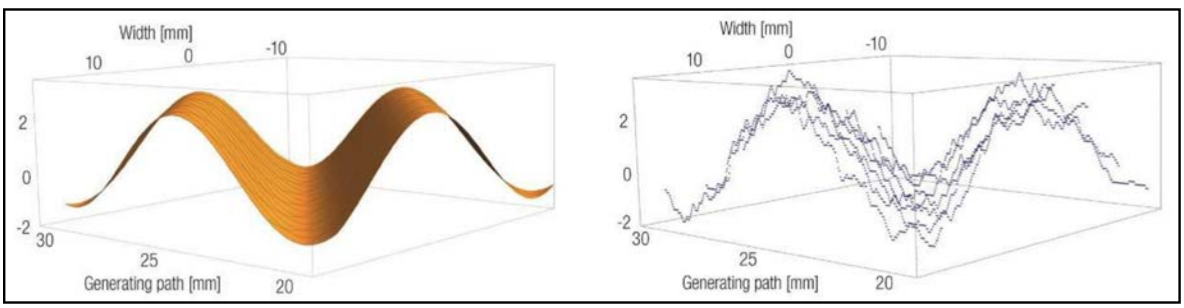


Figure 10 Sinusoidal-shaped modification: reference and DFT grinding result.

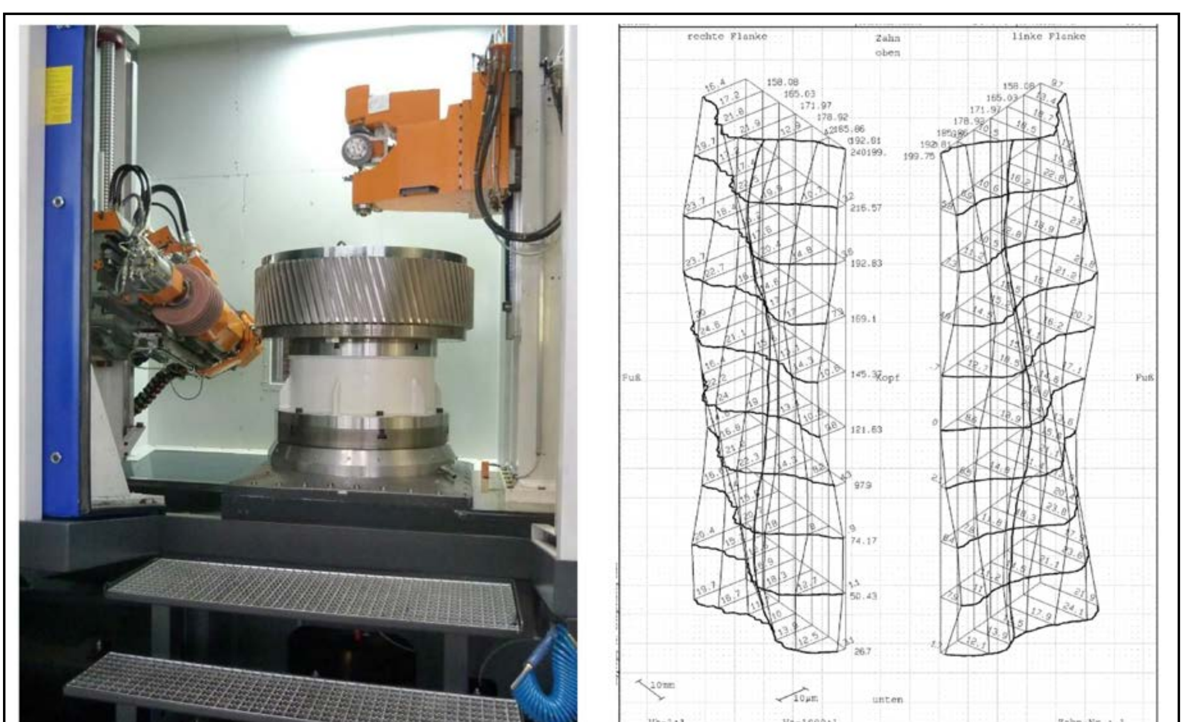


Figure 11 Grinding a NEO modification on a coarse module gear.

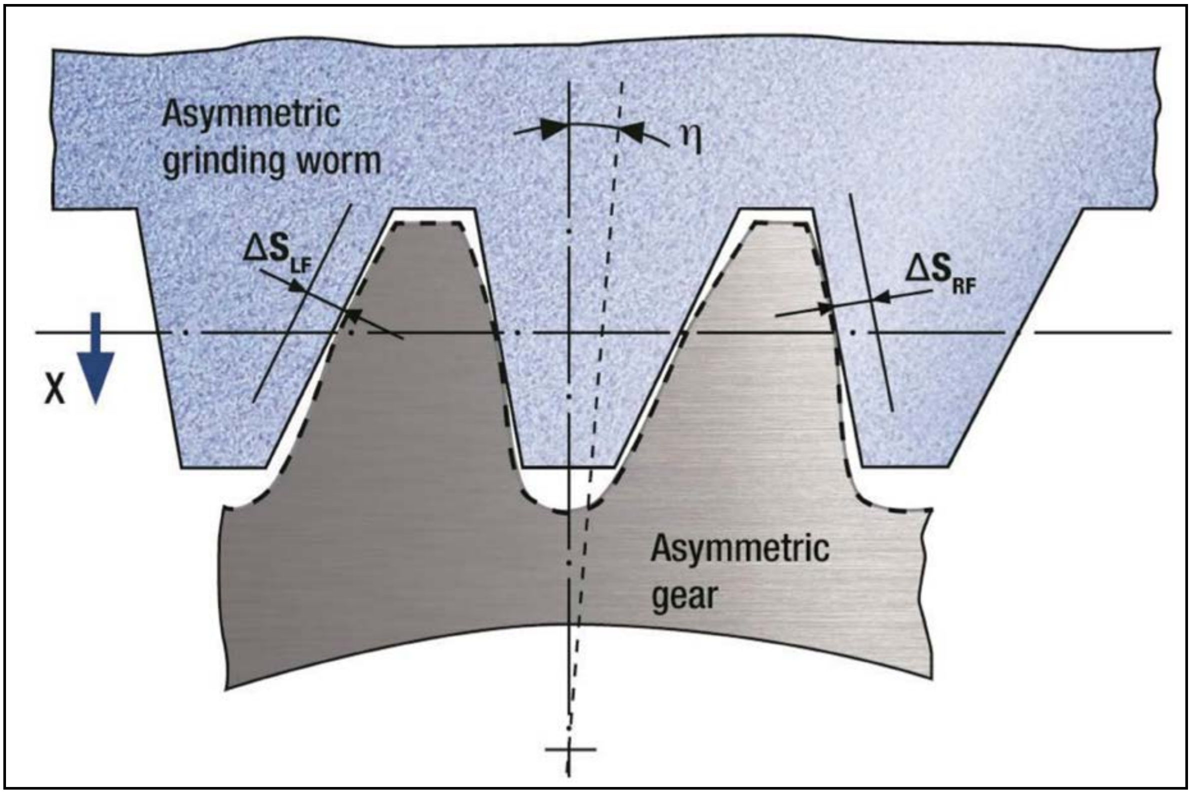


Figure 12 **Modified centering of an asymmetric gear and grinding worm.**

sible improvement has been conducted by the Gear Research Centre (FZG) at Munich Technical University's Institute for Machine Elements. This targeted degree of undulation, which typically has a μm-range amplitude, has no impact on load distribution.

This noise excitation-optimized (NEO) modification can be manufactured with the indexing generating grinding process as well, with a topological-dressed grinding worm used in the continuous generating grinding process. Both ways are very time-consuming and are therefore not economical enough for medium-to-mass production. Now with the new DFT grinding, a much faster and cost-effective production method is available. The method offers freedom in the design of the wave so the height of the amplitude, wave length, and orientation can be created on the demand of the application. Figure 11 shows a grinding result of a NEO modification on a gear with a module of 11 mm (DP 2.3). Due to the huge size of the gear, the amplitude of the wave should also have a higher amount. Therefore the periodic waviness is quite visible and gives a good impression as to what is really possible with this new grinding method.

Generating Grinding of Asymmetric Gears

The main advantage of asymmetric gears is contact stress reduction on the drive flanks. This results in higher torque density, i.e. — ratio of load capacity to gear size (Refs. 9–11). In the industry, hobbing, hardening and subsequent hard finishing (skive hobbing or profile grinding) have for years been a customary process chain for producing asymmetric gears. One important reason for the successful manufacture of asymmetric gears is the mathematical understanding of the gear size, as the machine operator must correct the measurement over balls and all cutting processes (Ref. 12).

Skive hobbing is effective, although it does not quite lead to maximum gear quality. Profile grinding achieves a significantly higher standard of quality than skive hobbing, but sometimes takes longer than a continuous generating method. Liebherr developed its asymmetric gear tooth generating grinding upon a customer request; this method combined high productivity with superior quality.

Technical Challenges and their Solutions. Asymmetric gear teeth, however, represent more of a challenge in terms of the generating grinding method and grinding and dressing tools than in terms of the grinding process itself. One key for success was to develop a dressing technology to produce an asymmetric grinding worm. For dressing purposes, the experts developed a software package that can work with asymmetric and symmetric dressing disks. The asymmetric dressing disk is ideal for a serial production. For prototype grinding, a symmetric dressing disc can be swiveled appropriately. A major challenge, as far as dressing, was to implement the complex mathematical calculations of the required swivel movement of the dressing unit. During the dressing process, the diameter of the grinding worm is reduced, which in turn necessitates a profile angle correction after each dressing sequence.

A quite different dynamic in respect of tooth-flank contact and contact order between the grinding worm and workpieces occurs during the grinding process itself, compared with conventional, symmetrical grinding processes (Ref. 13). Since stock removal on left and right tooth flank changes during the asymmetric grinding process, given differing pressure angles, an electronic correction is required. This degree of correction is determined by means of modified centering during the set-up procedure.

In the case of asymmetric gear teeth, this so called centering procedure, i.e. centered meshing of the grinding worm with the tooth gap, has to be slightly shifted by η during the radial feed *X* (Fig. 12) and maintained during the grinding process using precision monitoring and control technology. With this modified centering the different stock amount on the steep ΔS_{RF} and flat ΔS_{LF} gear flank can be nearly compensated. The cutting condition becomes more equal and now overloading the grinding worm with too high of a cutting removal rate on one flank can be avoided. This leads to a very low risk of grinding burn and no quality issues caused by tool wear.

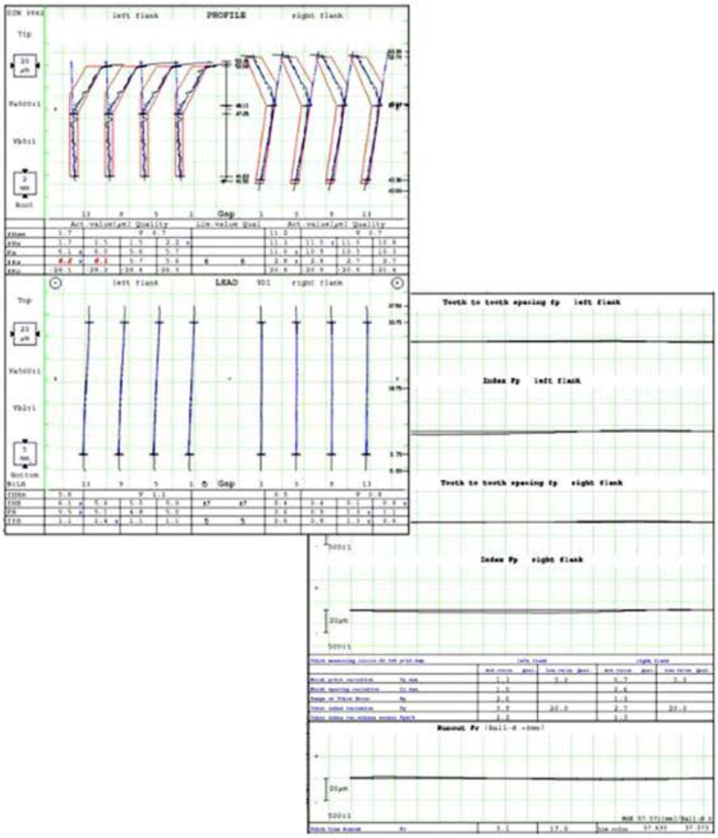
Application Example — Tractor Transmission. The generating grinding of asymmetric gears can now be reliably managed, and the first applications are running in series production. Figure 13 shows a drive shaft with four different gears. One of them has an asymmetric gear design. The challenge, beside the asymmetry, was that the grinding tool overrun was restricted. To grind the asymmetric gear, it was necessary to use a grinding worm with a maximum outside diameter of 75 mm. The achieved gear quality with the corresponding grinding technology is shown in Figure 14.

Gear Data and Tooling.

Workpiece:	
Module	2,5 mm
No. of teeth	17
Pressure angles	12° and 24°
Helix angle	25° (left hand)
Tip diameter	53 mm
Gear width	38 mm
Grinding worm:	
Dimension (D-L-B)	75-200-46
Type of abrasive	Cubitron II
Portion	30%
Grain size	+80
Grade	J
No. of starts	3

Figure 13 Drive shaft with asymmetric gear design.

Gear Quality, Grinding Technology, and Times.



Grinding technology:	
Cutting speed	25 m/s
Stock per flank	0.12 mm
Axial feed 1st cut	0.12 mm/tr
Axial feed 2nd cut	0.10 mm/tr
Axial feed 3rd cut	0.08 mm/tr
Times:	
Grinding time	95 s
Dressing time per part	12 s
Chip-to-chip time	18 s
Cycle time	125 s

Figure 14 Achieved gear quality by generating grinding

Summary

Nowadays with the continuous generating grinding method, there are increasingly more possibilities available to make even more complex tooth flank modifications. In this paper, it has been demonstrated that Liebherr has developed:

- Deviation-free topological grinding (DFT) to eliminate the minor distortions, which still can occur in end relief modification, and the twist-free grinding method. This has been solved by inducing multiple CNC-axes during grinding and has the further benefit of using standard dresser designs in twist-free grinding.
- Generated end relief (GER) is a further benefit of this DFT grinding, used to generate-grind a triangular shape end relief on helical gear applications, which can also be superimposed with profile- and lead-crowing shapes as well. GER enhances the designer's ability to increase load-carrying capacity by employing end-relief in the generating grinding applications.
- Noise excitation-optimized (NEO) modifications are also now possible in DFT grinding. In former times this type of sinusoidal flank modification was not possible with the continuous generating grinding method. This type of modification offers the designer the possibility to reduce noise emissions from time-variable tooth rigidity situations in a fast, economic gear grinding process.
- Asymmetric gears can also now be ground with the continuous generating method, thanks to software advancements in dressing and centering methods. The mathematics of differing pressure angles left to right flank, as well as pressure angle corrections necessitated in dressing as the tool diameter decreases, involves a complex technical challenge that has now been solved for industrial application.

Tooth flank modifications descried in this paper can now be produced with the established economic gear grinding process — the continuous generating grinding method.

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