Twist Control Grinding (TCG)

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This paper introduces the latest process developments for the hard-finishing of gears, specifically in regard to controlling the so-called flank twist. The purpose of twist control grinding (TCG) is to either eliminate twist, to introduce a counter-twist on purpose, or to add a specific twist to counteract the deformation of gears under load. By controlling twist, the contact bearing surfaces of meshing gear sets can be fully optimized, and therefore, the forces acting on the bearing surfaces can be ideally distributed. This leads to more efficient gears, both in terms of power density and fuel consumption. Today, in terms of grinding times, twist control grinding is on par with the standard continuous generating grinding which is well-established in the industry. High volume TCG production of twist-free gears, or gears with a defined twist, is now standard production practice at several automotive gearbox manufacturers.

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Introduction

This paper introduces the latest process developments for the hard-finishing of gears, specifically in regard to controlling the so-called flank twist, also known as bias. This paper only mentions twist control in reference to continuous generating grinding. Flank twist also occurs in profile grinding of helical gears with crowning. Demands on gears have always included the reliable transmission of high torque and the need for increased power density, low weight, and minimal noise emissions. Over recent years, greater efficiency, lower fuel consumption, and CO_2 output have been added to the growing list of demands. Emissions and fuel efficiency are becoming more stringent in all major market regions such as the USA, Europe, and China (Ref. 1; Fig. 1), and the car companies are facing huge technological and economic challenges to comply. These requirements can only be met by improvements in all aspects of motor vehicles, and specifically to the powertrain, i.e., the engine and the transmission. Additionally, research by Ford and Ricardo has shown that a reduction in fuel costs — via improved gearbox design — costs only half as much as similar economies realized by improvements to the internal combustion engine. According to one of many studies (Ref. 2), weight reduction can contribute a major share of the total fuel consumption reduction. Hence, modifying the flank twist by TCG allows modification to the contact pattern of gear teeth, thus leading to higher power density and a reduction in the overall weight of gears in general and, by extension, a weight reduction of the transmission itself. Furthermore, TCG-ground gears have shown noise reductions in transmissions of 2 to 3 decibel (dB).

Flank twist occurs as a matter of course when machining helical gears that feature lead modifications such as crowning. This phenomenon is brought about by the geometries and kinematics inherent in the continuous generating grinding of helical gears. Incidentally, profile grinding with a single rib wheel will also lead to flank twist, but this paper will focus on generating grinding only. Simply put, the purpose of twist control grinding

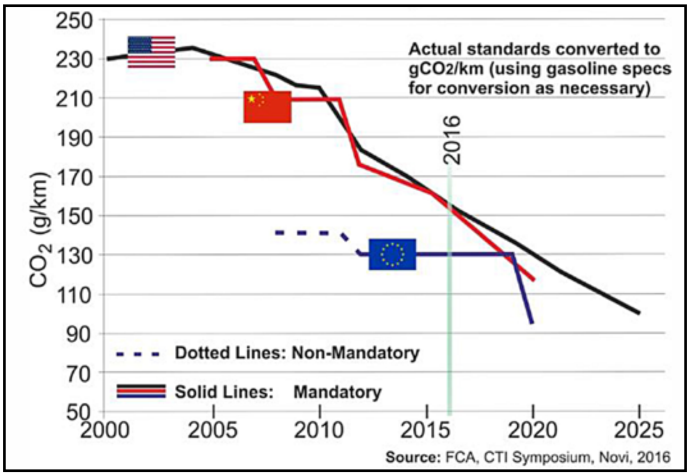

Figure 1 Legislation for CO_2 reduction.

is to either eliminate twist, to deliberately introduce a counter-twist, or to add a specific twist to counteract the deformation of gears under load. More often than not, twist has some negative connotations attached. However, with TCG grinding the word "twist" should be seen in a positive light, as it allows gear designers to use this phenomenon to fine-tune the gear geometry. Furthermore, the process, as presented in this paper, allows separate TCG on the left and right flank in the same grinding pass. By controlling twist the contact bearing patterns of meshing gear sets can be fully controlled and, therefore, the forces acting on the bearing surfaces can be ideally distributed, which leads to higher power density, more efficient transmission of power, and an increased longevity of gears. The TCG method gives gear design engineers a high degree of freedom to design gear flank geometries to match the demands made on automotive gears and to translate desired design features into an economical manufacturing process.

TCG is an added feature of the well-established, continuous generating gear grinding process. In principle, the kinematics of this process can be understood as a worm drive (Figs. 2 and 3), with an additional abrasive machining process consisting of an infeed *X*, a vertical feed-rate *Z*, and a lateral shifting motion *Y* — all working together simultaneously. The main difference to the standard continuous generating is that the grinding worm

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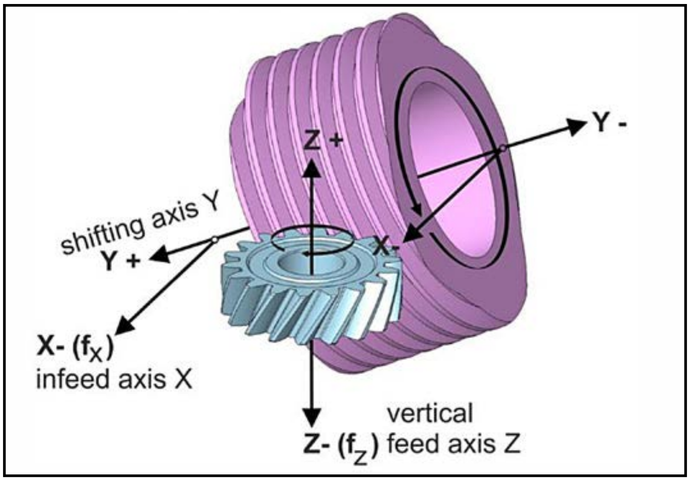

Figure 2 **Continuous generating grinding principle.**

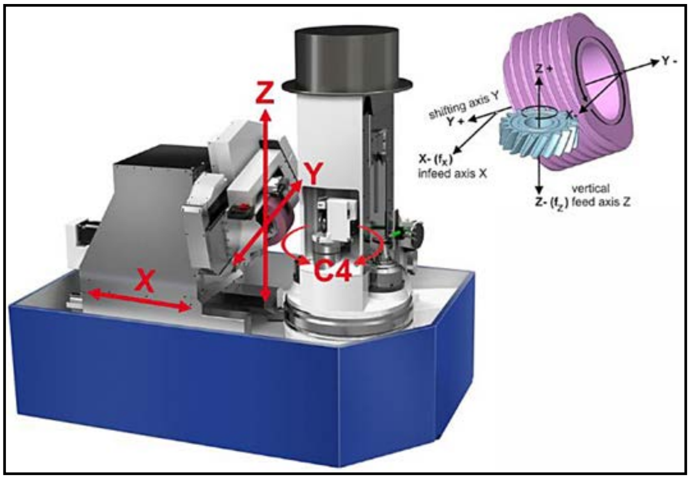

Figure 3 **Machine axis movements.**

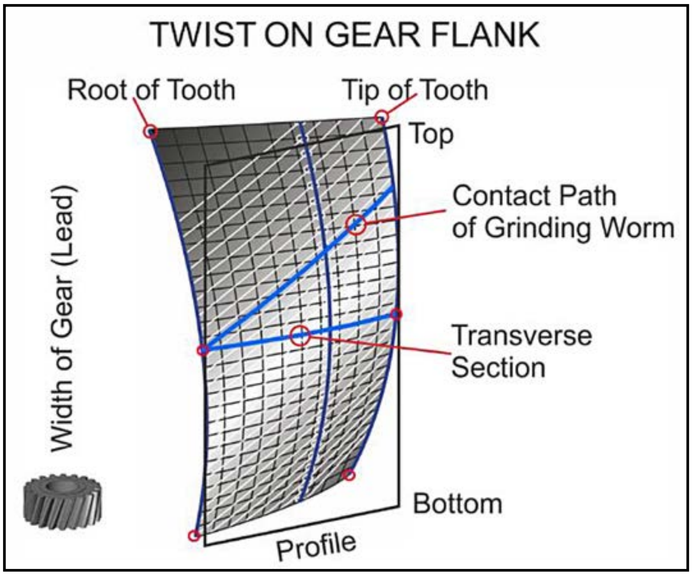

Figure 4 **Flank twist.**

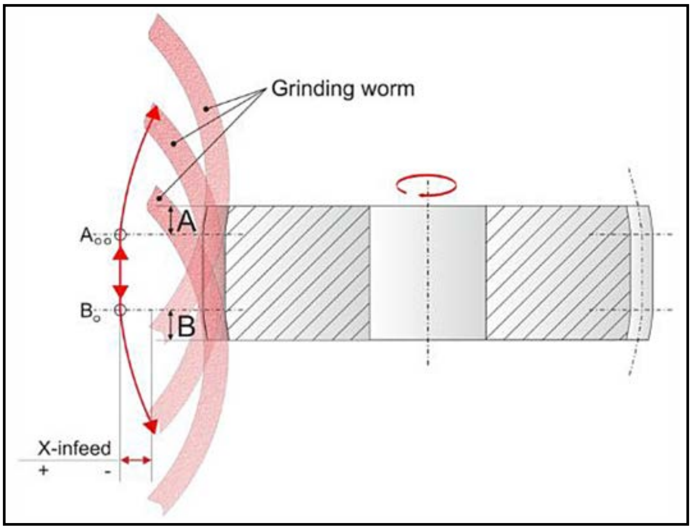

Figure 5 **Crowning and changing center distance.**

has to be modified across its width in terms of its pitch and/or its pressure angle. For this purpose the dressing unit (C4 axis) needs to be swiveled continuously as it moves laterally across the width of the grinding worm.

Defining Grinding Twist

Grinding twist is a continuous change of the profile angle ($f_{H\alpha}$) of the gear flank over the full width (Fig. 4). As previously mentioned, flank twist occurs as a matter of course when grinding lead-modified helical gears. The change in the profile angle $f_{H\alpha}$ occurs across the face width of the gear. Depending on the amount of lead crowning, twist can be minimal and often ignored, as the profile $f_{H\alpha}$ measurement is taken only across the transverse section in the middle of the lead (Fig. 4). For this reason the gear's teeth are produced within specified tolerances, despite some residual flank twist.

As Figure 4 illustrates, when grinding helical gears the contact path between the grinding worm and the part's tooth flank does not run on the transverse section of the part. (The transverse section is a cross-section perpendicular to the gear axis). The required modification of the tooth trace is defined and measured at the nominal base cylinder of the gear. The base cylinder corresponds to the base circle and is the cylinder from which the involute tooth surfaces are developed. When grinding the flank, depending on the helix angle and the direction of the stroke, the tip and root of a tooth flank's transverse section are not ground simultaneously. Modifications in lead direction, such as crowning or end relief (Fig. 5), are generally created by changing the center distance (*X*-infeed) between the grinding worm and the workpiece axes during the grinding process.

The change of the center distance between the grinding worm and the gear is also relative to the nominal base cylinder. The tooth's root and tip of a transverse section are ground at different revolutions of the gear. The contact paths are visible as feed marks (Fig. 6), so that between the grinding of the root and grinding of the tip, several revolutions of the gear to be ground have occurred. In generating grinding, this twisting effect is exacerbated by a more pronounced crowning or end relief, or by a greater helix angle of the gear flank. Particularly in the case of end relief configurations, in which the center distance changes radically over a relatively short distance, process-related tooth twist will occur.

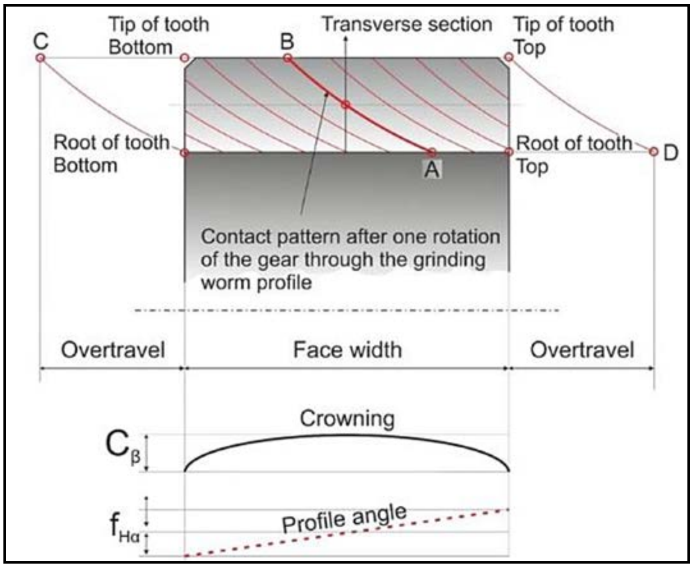

Figure 6 **Crowning and profile angle.**

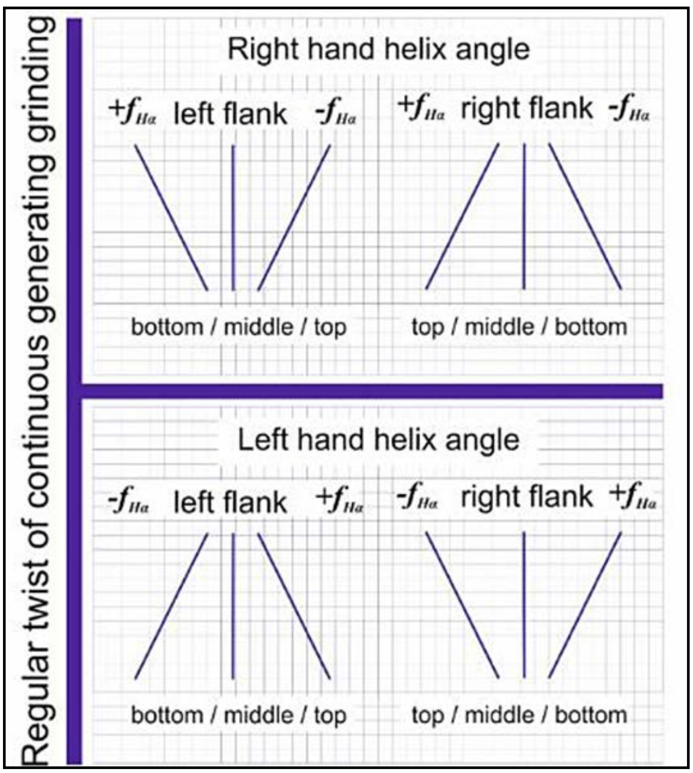

Figure 7 **Twist on opposing helix angles.**

While grinding crowning and end relief, the center axis distance changes during the grinding of the gear. Consequently, during one grinding stroke, while crowning and/or end relief has been generated, the direction of the center distance has been reversed. The resulting effect is that the tip on one side is in plus (+), and of the root on the opposite side is also in plus (+), creating the described flank twist effect (Fig. 7), which also shows this effect on opposing helix angles such as present on right- and left-hand gears. The measurements are always on one flank, in three locations across the face width of the gear.

Controlling Grinding Twist

TCG grinding takes place on modern existing continuous generating gear grinding machines that possess the necessary kinematics to control twist. Modification to the gear's base pitch can serve to compensate for any resulting twist, or serve to create a deliberately produced target twist. This modification is made possible by changing the pitch and/or the pressure angle across the width of the grinding worm (Fig. 8).

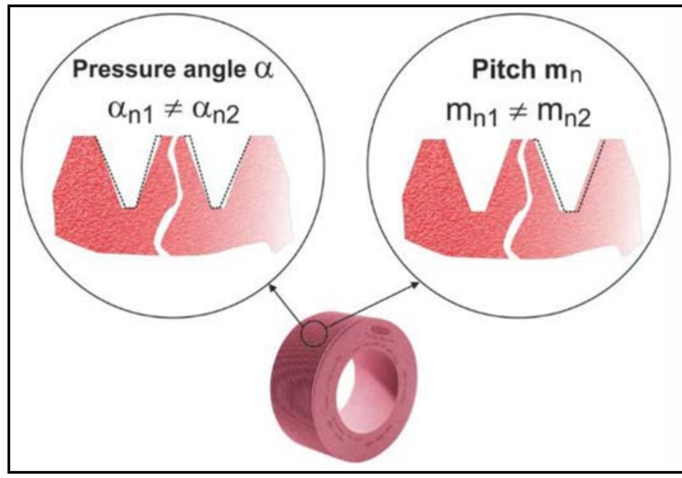

Figure 8 **Modification of the grinding worm.**

To control the twist that occurs in continuous generating grinding, a continuous change of the pressure angle on the grinding worm (Fig. 8) must be introduced across the shifting distance on the grinding worm width. This correction is only possible by applying diagonal generation grinding, such that the gear has a dedicated position on the width on the grinding worm in line with the changes of the pressure angle and the pitch across the grinding worm width. As mentioned previously, this can either occur by continuously changing the pressure angle or the pitch across the width of the grinding worm. TCG utilizes both modifications simultaneously, thus TCG can shorten the distance of the diagonal grinding pass in comparison if only one of the modifications were used at any one time. There are also machine tool builders that use only either pressure angle adjustments or pitch adjustment across the width of the threaded wheel. However, using both adjustments simultaneously has proven itself as the most effective TCG method in the automotive industry.

Figure 9 shows a typical layout of the grinding worm which, in this particular case, is divided into three distinct sections — one for roughing and two for finishing. The narrow ramp sections, $s_{\_1}$ to $s_{\_4}$, that are located in between the individual grinding sections, are not used and represent a safety area to ensure that the cycle start of finishing, for example, will not be in a transitional area between the roughing and finishing stroke.

Diamond Dressing of Grinding Wheel

TCG requires a double-taper diamond disc for the dressing of the grinding worm profile. Generating a defined tooth twist requires part-specific dressing tools, which, at any one time, dress only with one single flank due to the different geometries used for the right- and left-hand flanks (Ref. 4). This, of course, increases the overall dressing time, in comparison to conventional grinding in which both flanks are dressed in the same dressing stroke. In contrast to line dressing, profile dressing involves a linear contact between the grinding worm and the dressing tool, resulting in far shorter dressing times than line dressing. For line dressing, a flexible universal diamond dressing tool with defined radii dresses the profile of the grinding worm by using the machine axes on a line-by-line basis (Ref. 5). As there is only a point contact between the grinding worm and the dressing tool, the dressing times required for line profiling are relatively high. Line dressing is only relevant for prototyping gears, and so will not be further addressed in this paper. In addition to modifications and corrections of the twist and the profile angle, the profile dressing method also permits changes in profile crowning. Using the same dressing tool, the TCG process also allows separate profile crowning and flank twist corrections on each individual flank. To generate varying pressure angles on the grinding worm, the tool is swiveled during the dressing process using the machine's C4 axis (Fig. 10). So-called profile roll sets are available for outside diameter dressing or rounding off the tip of the grinding worm. These roll sets generate the required tooth tip profile of the grinding worm after both grinding worm flanks have been dressed.

Manufacturing Twist-Controlled Gears

An exemplary definition of twist-relevant data on a manufacturing drawing is shown (Fig. 11). In contrast to conventionally ground gears, TCG-ground gears need a precise indication as to the three measuring locations across the face width of the gear. In the case of the gear shown in Figure 11, the locations where the measurements have to be taken are as follows, starting from the top of the gear: 2.75 mm, 10.75 mm, 18.75 mm, with angle profile deviation ($f_{H\alpha}$) on the drive side being +10 µm at location 2.75, 0 at location 10.75, and −10 µm at location 18.75.

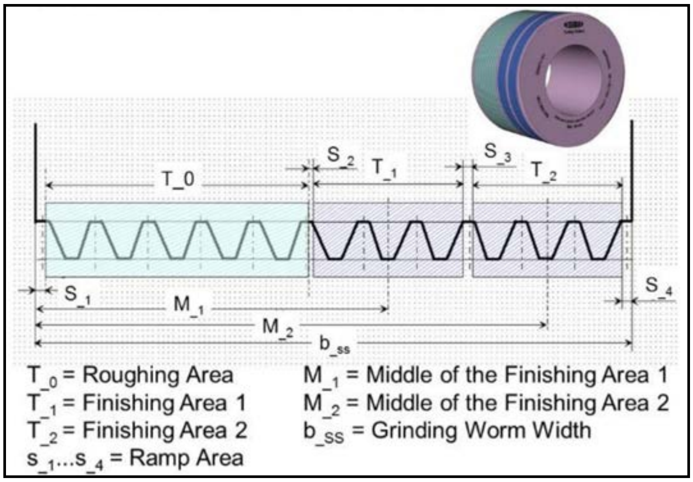

Figure 9 Grinding worm layout.

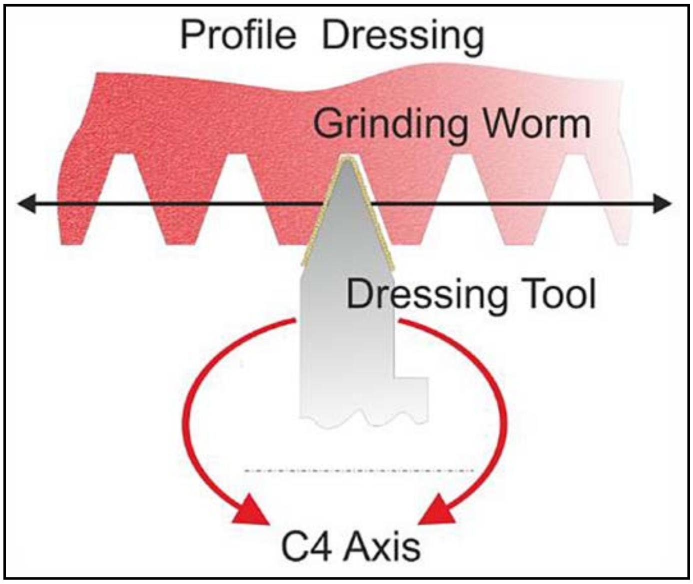

Figure 10 Dressing the grinding worm.

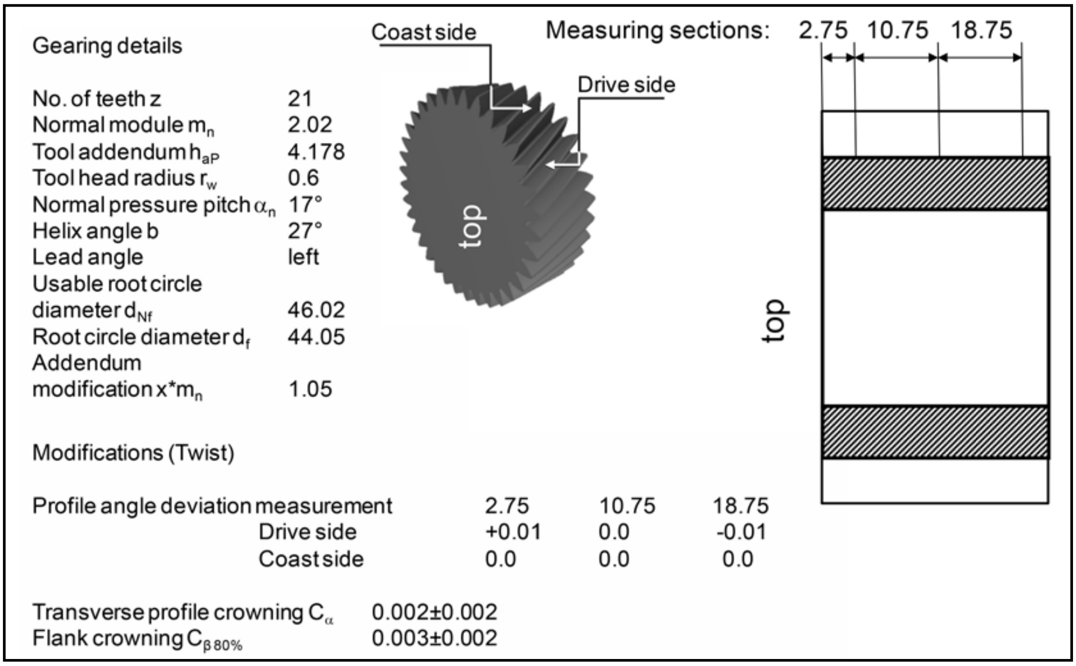

Figure 11 Exemplary definition of twist.

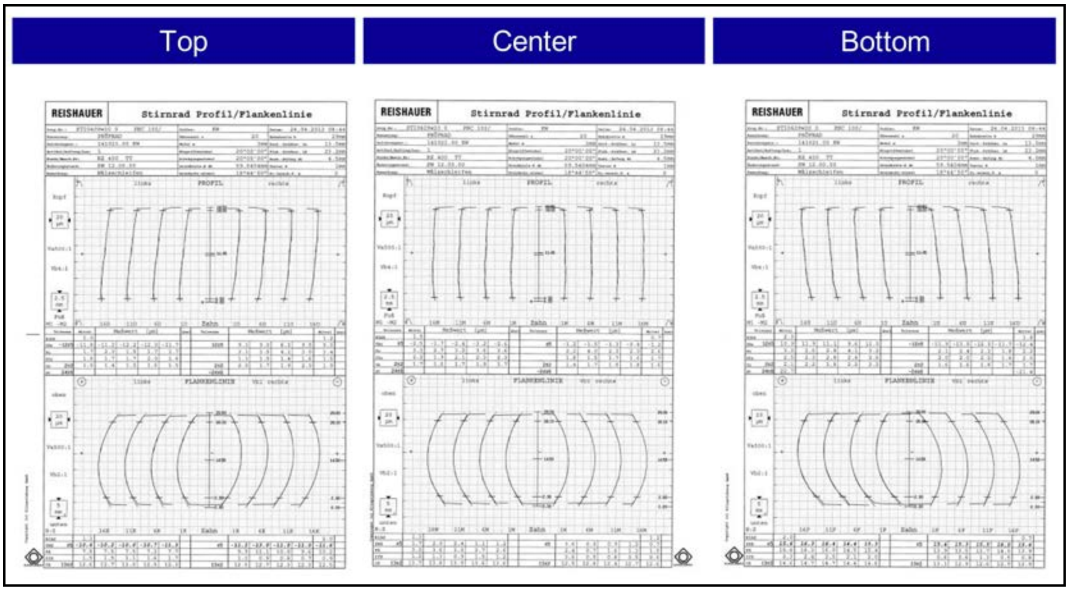

Figure 12 Gear ground with natural twist.

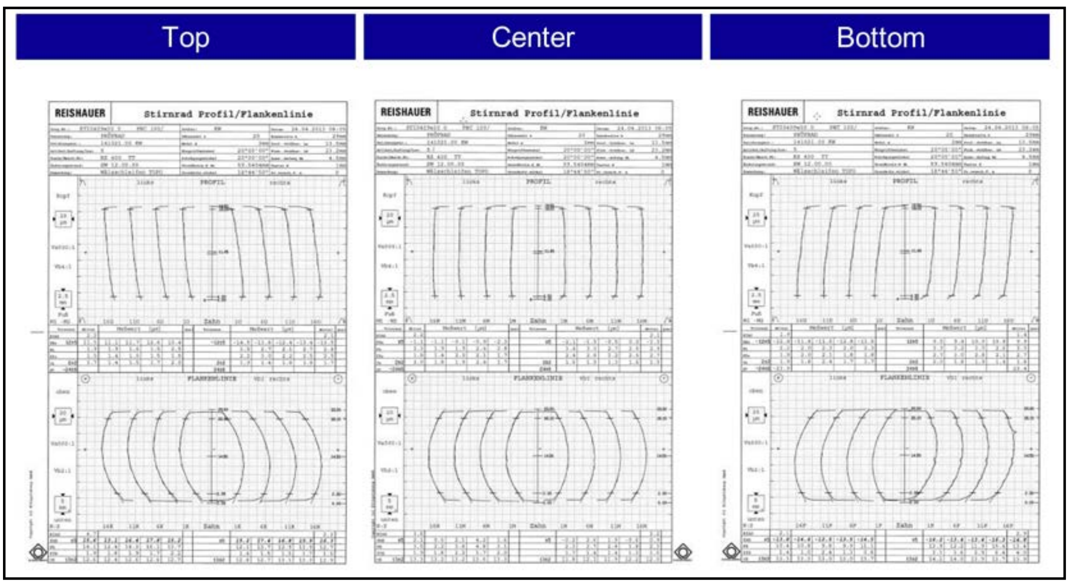

Figure 13 Gear ground with counter twist.

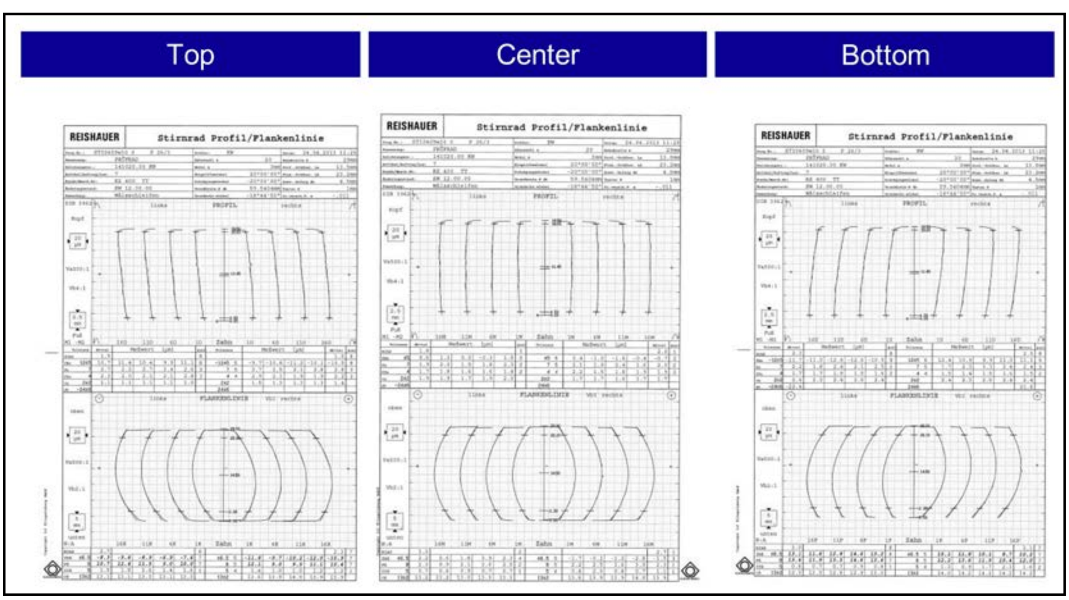

Figure 14 Mating gear ground with natural twist.

Effects of Twist

In order to show why grinding with a specified and controlled twist is worthwhile to pursue, the contact pattern of a gear wheel has been examined more closely (Ref. 6). A gear with the natural twist resulting from continuous generation grinding (Fig. 12) and one ground with TCG (Fig. 13) have been ground for this purpose. These gears have both been paired separately with the same mating gear, which had been ground with continuous generating grinding with a natural twist (Fig. 14). The resulting, different contact patterns are shown (Fig. 15). It can be seen that the contact pattern is less sloping in the pairing variant with the applied TCG. Furthermore, in this pairing the contact pattern is spread wider across both tooth flanks. Due to this wider contact pattern the torque load of the gear pair can be spread over a larger flank surface area. For this reason individual points of the flank would be subject to a lesser load which, correspondingly, would lead to an increased load-bearing capacity.

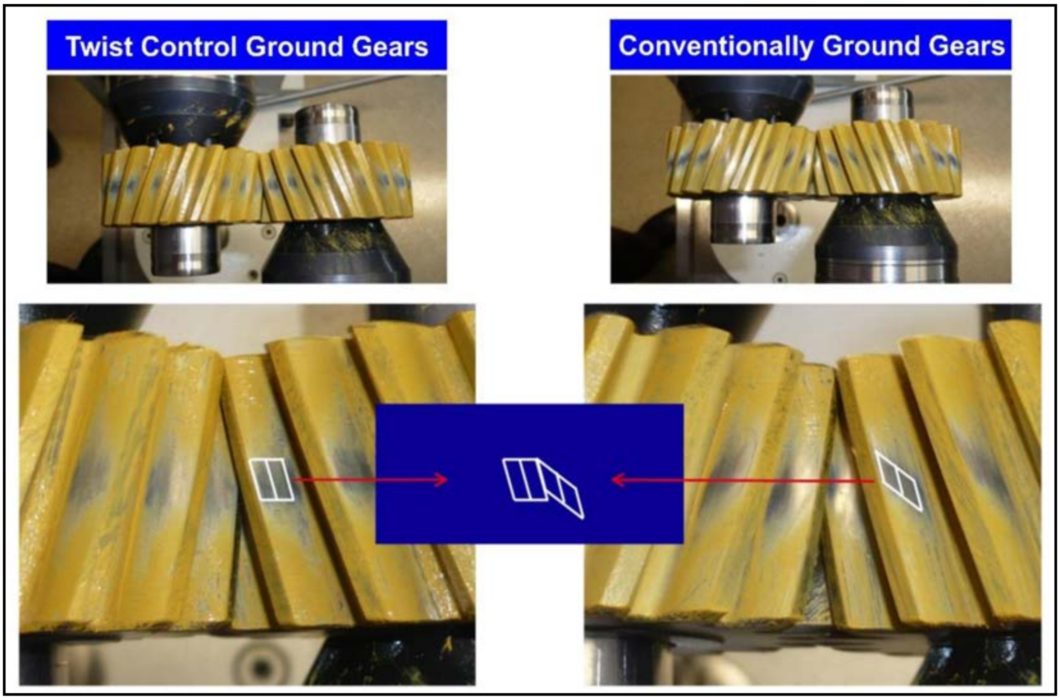

Figure 15 **Contact patterns of mating gears.**

Economic Considerations and Conclusion

The direct integration of TCG into the conventional continuous generating grinding process translates into minimal investment costs if customers already have Reishauer continuous generating gear grinding machines that feature a dressing unit with swivel capability. Furthermore, the diamond dressing tools remain the same as for many existing conventional processes. In addition, the TCG process requires minimal additional operator training if the operators already have experience with standard continuous generating grinding. Today, in terms of grinding cycle times, twist control grinding is on par with the standard continuous generating grinding which is well established in the industry. The number of workpieces per dress is also on par with standard continuous generating grinding. The benefits gained from controlling twist justify the small software investment and the influence of additional wheel dressing time. Following intensive research work and several years of industry application, Twist Control Grinding technology has proven itself in the marketplace and has, in many cases, eliminated gear honing, often thought to be the only method for large-scale twist-free hard finishing of gears. High volume TCG production of twist-free gears, or gears with a defined twist, is now standard production practice at several automotive transmission manufacturers. The higher process costs over conventional gear grinding are outweighed by the benefits of the reduction in torque loss, the increase in bearing capacity of TCG-ground gears, and higher resulting power density in transmissions. The main challenge which is presently addressed for TCG is the user friendliness of setting up the machine. Setting up a TCG process, or making corrections, must be simple and fast.

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After completing his toolmaking apprenticeship in 1974, **Walter Graf** worked for ten years in tool and mold making workshops. He subsequently he continued his studies in Australia and the UK and was awarded a Bachelor of Science Degree (Honors). In 1992, he began as a Product Manager for super-abrasive grinding and dressing tools at Winterthur Technology Group, Switzerland, and before the purchase of Winterthur by 3M in 2011, he held the position of Chief Marketing Officer for the entire Winterthur Group. At 3M, his role changed to Global Segment Leader for bonded abrasives. Since January 2014, he holds the position of Marketing Manager for gear grinding machines at Reishauer AG, Switzerland.