Grinding Wheel Wear, Dressing, Tip Advance and Work Phase Angle Adjustment after Corrections: Are there Rules to Aid in Grinding Process Optimization?

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The following is another chapter from Dr. Hermann J. Stadtfeld's new book, *Practical Gear Technology*, part of an ongoing series of installments excerpted from the book. Designed for easy understanding and supported with helpful illustrations and graphic material, the e-book can be accessed for free *at Gleason.com*.

The question about rules for bevel gear grinding was asked many times, and also the question if a help tab could be developed which aids to solve the problems on a grinding machine For example, a setup person or manufacturing engineer experiences a problem like losing size after grinding only a few slots, without that the spacing and size compensation could help. There are rules and hints to improve bevel gear grinding results. This chapter is a compilation of practical grinding experiences which will be the basis of help tabs which are being developed for Gleason machines.

Adjustment and Optimization of the Dresser Speed Ratio.

The dresser speed ratio is calculated by dividing the dress roller surface speed by the grinding wheel surface speed. The diagrams of dresser speed ratio versus surface roughness (Fig. 1, top) and dresser speed ratio versus the force between the grinding wheel and the ground flank surfaces (Fig. 1, bottom) show two interesting graphs which are non-linear and not intuitive. Preferred areas in the two diagrams are between –0.65 and –0.85 for highest surface finish and between +0.65 and +0.85 for highest productivity.

There is no optimal compromise between the two areas to the contrary, in the center of the diagrams is a large area; where dressing is not possible. The first extreme point in Figure 1 is at dresser speed ratio of 0.0, where the dress roller is not rotating and will be destroyed if dressing at this setting is conducted. The second extreme point is at a dresser speed ratio of 1.0, where a pure crushing of the grinding grit out of the ceramic wheel bond occurs. It has to be noted at this point, that the kind and composition of the grinding wheel will influence the optimal dresser speed ratio. Some highly optimized grinding wheel types like for example Cubitron II might require to reverse the sign of the dresser speed

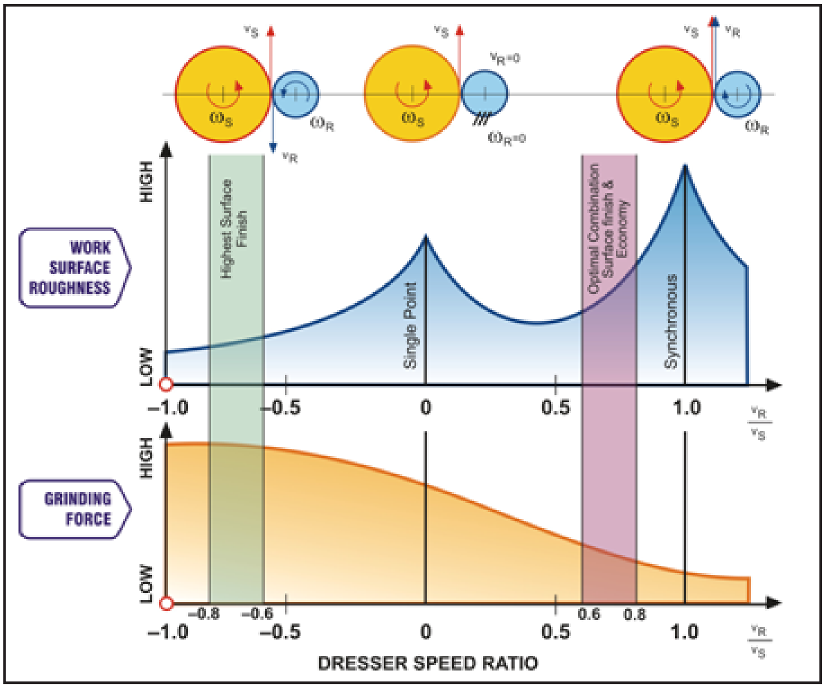

Figure 1 Dresser speed ratio versus surface roughness and grinding force.

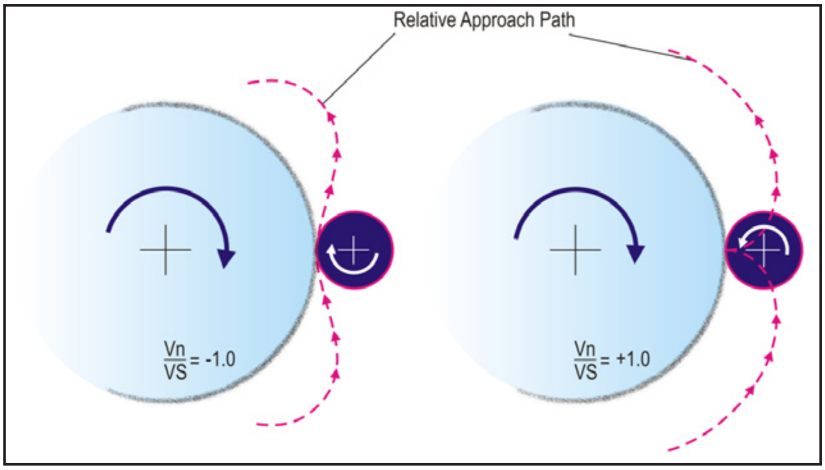

Figure 2 Pure shearing (left) and pure crushing (right).

ratio although the original setting worked well for a traditional style grinding wheel.

A comparison of the approach paths in case of a dresser speed ratio of −1.0 and +1.0 is shown (Fig. 2). The left side graphic in Figure 2 demonstrates a pure shearing of the abrasive grit particles with a trochoidal shaped relative approach path between dresser particle and wheel grit particles. This results in a dull, but stable wheel surface. (See the shearing fracture in Fig. 3). Such a wheel surface can be advantageous in the last cycle "stations" of an aircraft grinding cycle. It will achieve an excellent surface finish and a precise flank surface as long as material removal amount per time unit is very low. The right side graphic in Figure 2 demonstrates a relative approach path with the shape of an epicycloid. The result is a splitting of the abrasive grains or a levering effect which will remove entire grain particles out of the ceramic bond. Levering or crushing will not only consume the grinding wheel fast; it will also result in a not very stable bond of the grit on the wheel surface, leading to flank form inaccuracies (Ref. 1).

The following rules are based on the physical effects explained above and will help to find a better suitable dresser speed ratio in connection with other important grinding parameters:

Grinding of non-generated gears using Waguri	▶	• Start with negative dresser speed ratio depending on wheel type positive dresser speed ratio may be optimal
Grinding of generated gears without Waguri	▶	• Positive dresser speed ratio
Pinion grinding without Waguri	▶	• Positive dresser speed ratio
If the surface finish is too rough	▶	• Reduce the dress roller traversing feed rate • Move to the left side of the dress roller speed ratio band • Change to negative dress roller speed ratio, but now go first to the right side of the dress roller speed ratio band and use high dress roller traversing feed rate to preserve some open poor surface structure • Apply a dual rotation cycle without redressing
If spacing of first to last tooth is bad	▶	• Increase dress roller traversing feed rate • Move to the right side of the dress roller speed ratio band • Change to positive dress roller speed ratio,but now go first to the left side of the dress roller speed ratio band and use a low dress roller traversing feed rate to preserve a high surface finish
Burn marks on pinion surface or root	▶	• Increase dress roller traversing feed rate • Move to the right side of the dress roller speed ratio band • Change to positive dress roller speed ratio, but now go first to the left side of the dress roller speed ratio band and use a low dress roller traversing feed rate to preserve a high surface finish
Burn marks on Formate gear surface or root	▶	• Increase dress roller traversing feed rate • Move to the right side of the dress roller speed ratio band • Reduce grinding plunge feed rates
Grinding from solid	▶	• Requires a sharp wheel surface with open pores – dresser speed ratio between +0.8 and +0.9 • Wheel wear will be high in order to achieve sufficient material removal • Dressing after 3 to 6 slots required • Rough grinding to full depth in one rotation with higher dress frequency is most efficient

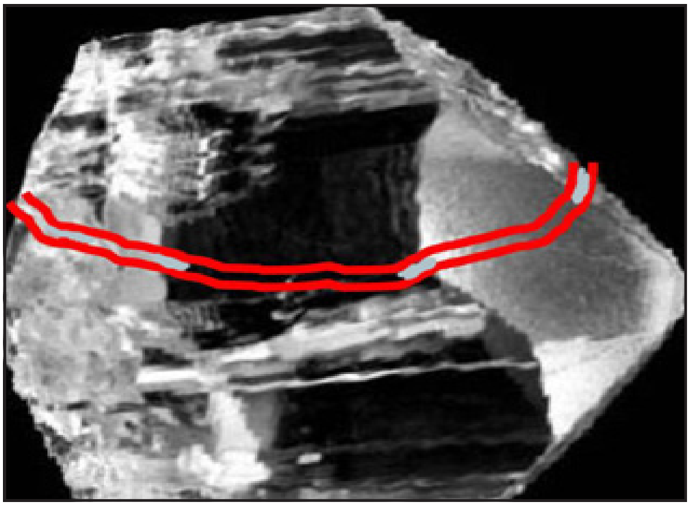

Figure 3 Principal appearance of a grain shear fracture.

The Grinding Wheel Tries to Tell You Something!

Keys to efficient grinding are the abrasive material and the abrasive bond. Recommended for bevel gear grinding are grinding wheels with an 80 grit sintered aluminum oxide abrasive with an open pore, soft ceramic bond. Results of extensive process development have shown that non-uniform particle size, e.g., 80 grit wheel specification which contains particles between 80 and 240 size, increase the grinding wheel wear and the need for redressing. Uniform particle size e.g. between 80 and 120 grit (for an 80 grit wheel specification) require fewer re-dressings because the grinding wheel keeps its shape and dimension longer (Ref. 2).

The automatic re-sharpening effect of a wheel is based on the radial and tangential cutting forces onto the abrasive grinding grain. The causes of wheel wear are:

Case 1	▶	Grain breaks out of ceramic bond, e.g. — (bulk wear) (wheel stays sharp but loses size)
Case 2	▶	Grain dulls (attritions wear) (wheel keeps dimension, surface finish improves, grinding force is high, risk of burning)
Case 3	▶	Grain fracture of mono crystal (fracture wear) (wheel dulls somewhat and loses dimension somewhat)
Case 4	▶	Grain fracture along particle boundaries of sintered grain (dimension is stable, wheel is always very sharp)

Case 1	If the dresser speed ratio has already been optimized, then a wheel which is sintered with higher temperatures or higher force with a harder ceramic specification will solve the encountered problem.
Case 2	Grain hardness might be too high in combination with too high bonding forces. If increasing a positive dresser speed ratio shows no improvement, then grinding wheel with different specification (softer bond).
Case 3	Wear like in Figure 3. Change to sintered aluminum oxide instead of mono crystal is recommended.
Case 4	Is the desirable case which can be achieved in most cases with sintered aluminum oxide grains in connection with an optimized dresser speed ratio.

Dressing of Profiles with Blended Toprem.

Blended Toprem with small Toprem radii and large Toprem depth creates a profile clean-up problem, especially when the profile pressure angles are low (below 15°). Figure 4 shows that only a significant increase of the dressing amount can help to solve this problem.

The proof that the grinding wheel profile cleaned up during the dressing cycle can be obtained by using fast-drying blue shop spray paint which is applied to a section of the wheel at the inside and outside profile before re-dressing. In case of insufficient clean-up, witness marks of the paint will be visible in the area marked "Undercut of Intermediate Dressing Profile" (Fig. 4). The required axial dress amount can be a multiple of the dressing amount required to re-sharpen and re-shape the wheel in case of a lack of blended Toprem.

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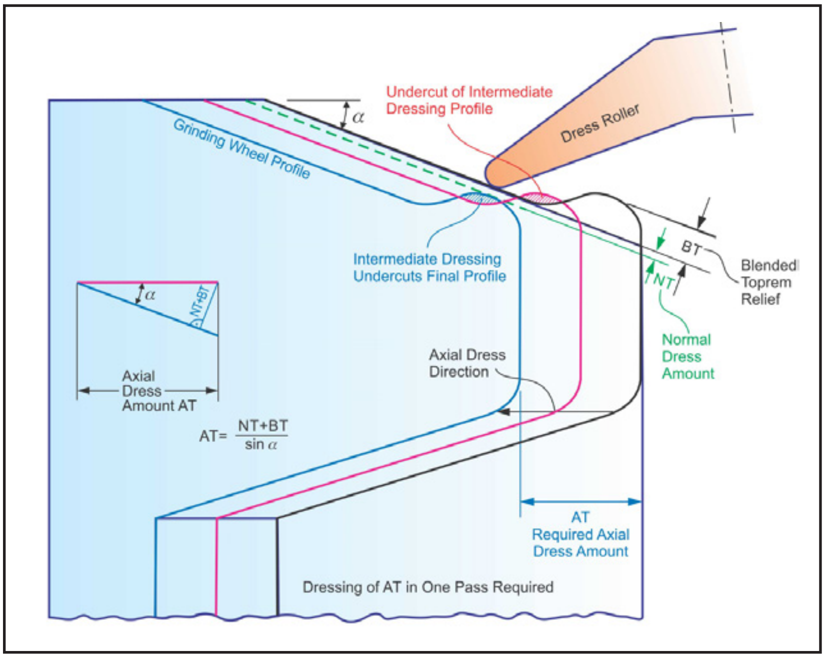

Figure 4 Undercut on grinding wheel profile due to blended toprem.

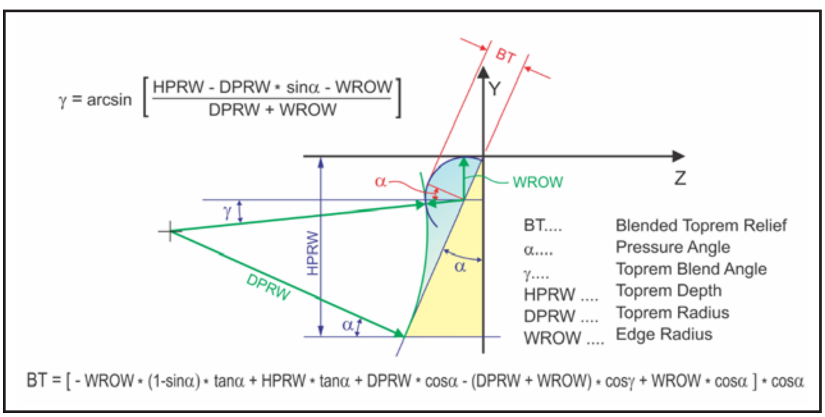

Figure 5 Calculation of minimal dressing amount to avoid undercut.

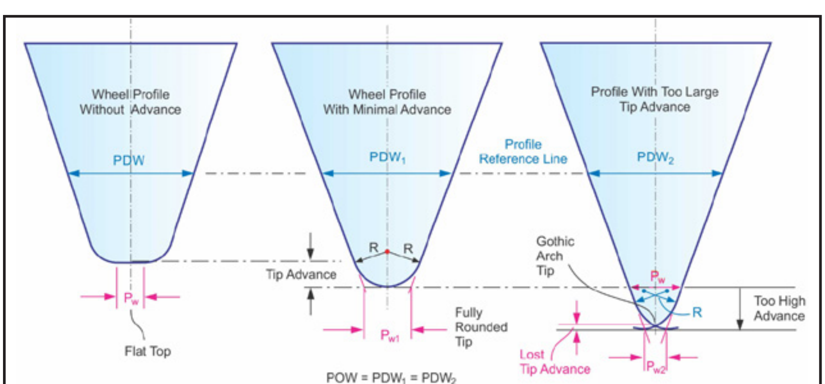

Figure 6 Wheel tip truncation due to tip advance.

The blended Toprem relief BT has to be added to the minimal required dressing amount NT. The result is divided by the sin of the wheel pressure angle, resulting in the axial dressing amount AT (see formula in Fig. 4). If this amount appears too large for an optimal wheel dressing, then it is not possible to dress the wheel in two or more passes. The purple profile (Fig. 4) shows how an intermediate dressing step would not clean up the profile and will in addition cause that the final profile (blue in Fig. 4) will not clean up.

The only possibility to reduce the normal or axial dressing amount is to reduce the blended Toprem radius or the blended Toprem depth or both. It is advisable in cases where a change of more than 10% Toprem radius or Toprem depth is required to redevelop the blended Toprem parameters in the design program in order to avoid an undesirable change in the gear set performance.

In order to calculate the axial dressing amount AT, the precise value of the blended Toprem relief is required in addition to the normal dressing amount. The mathematical relationship between Toprem relief BT and the Toprem parameters depth and radius has been derived in Figure 5. The formula appears complicated and long for a rather simple appearing task. However, the geometrical relationship of a blended Toprem circle blending with the tip edge radius on the one side and the main cutting edge on the other side is complicated. Simplified, approximate calculations have been tried out but showed not to be reliable.

Dressing of a Tip Advance.

The Gleason design and summary calculation programs determine the largest edge radius which fits the tip of a cutting blade or grinding wheel (Dimension Sheet). If this "Max. Radius - Cutter Blades" is applied to the grinding wheel, then the wheel tip will show a fully rounded tip (Fig. 6, center). Only in the case of smaller tip radii than the maximal limit of the Dimension sheet (tip with flat top, Fig. 5, left), a tip advance is possible, to the point, where the flat top has disappeared and the wheel tip is fully rounded (transition from left to center in Fig. 6).

Wheel tip advances beyond this point will cause a truncated wheel tip, which not only deliver an unsatisfactory root appearance, but also cause fast tip break down, reduced tooth depth and possible burning in the root during the grinding process.

Work Phase Angle Adjustment after G-AGE Correction.

Formate ring gears require after each flank form correction for example with *G-AGE* an adjustment of the work phase angle in order to re-establish the correct stock division. Of course this applies only to grinding, but it is time- consuming and disturbs the grinding production. A correction of the work axis phase angle *A* is used to re-establish a correct stock division position.

It is difficult to analyze from the *G-AGE* corrections, which different elements of corrective settings have been superimposed in order to eliminate flank form deviations. In a first step the phase angle influence of the two most common corrections, spiral angle and pressure angle changes is captured (Fig. 7) and a correction value ΔA is calculated.

In a second step, root angle changes in connection with a machine center to crossing point change and the changes from Figure 7 have been analyzed with the graphic in Figure 8. From the V-H setting changes in Figure 8 a formula which is valid for all cases was developed. The A-axis angular position is corrected after each *G-AGE* correction by adding the value ΔA. The work axis correction is calculated in the machine control and applied automatically.

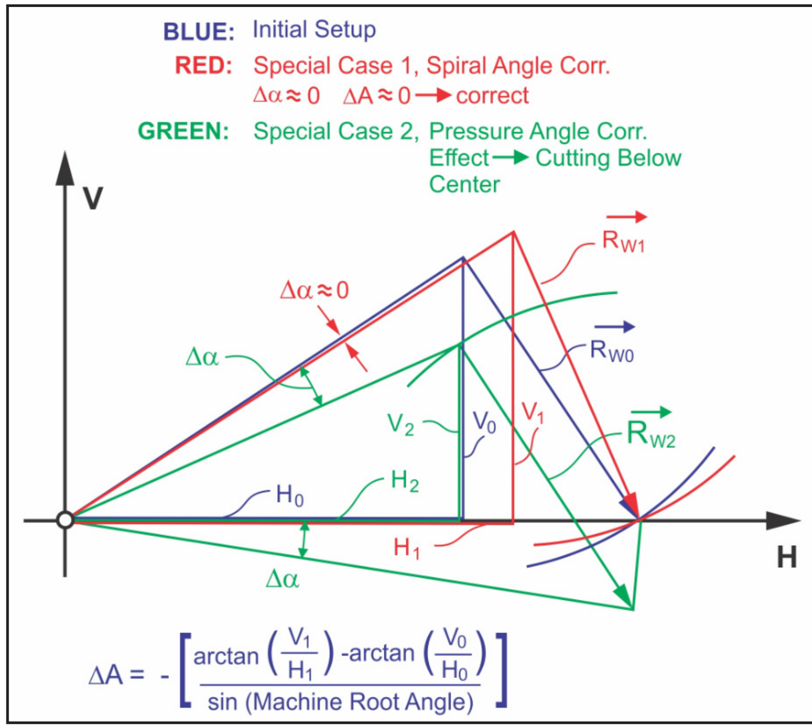

Figure 7 Only V-H corrections.

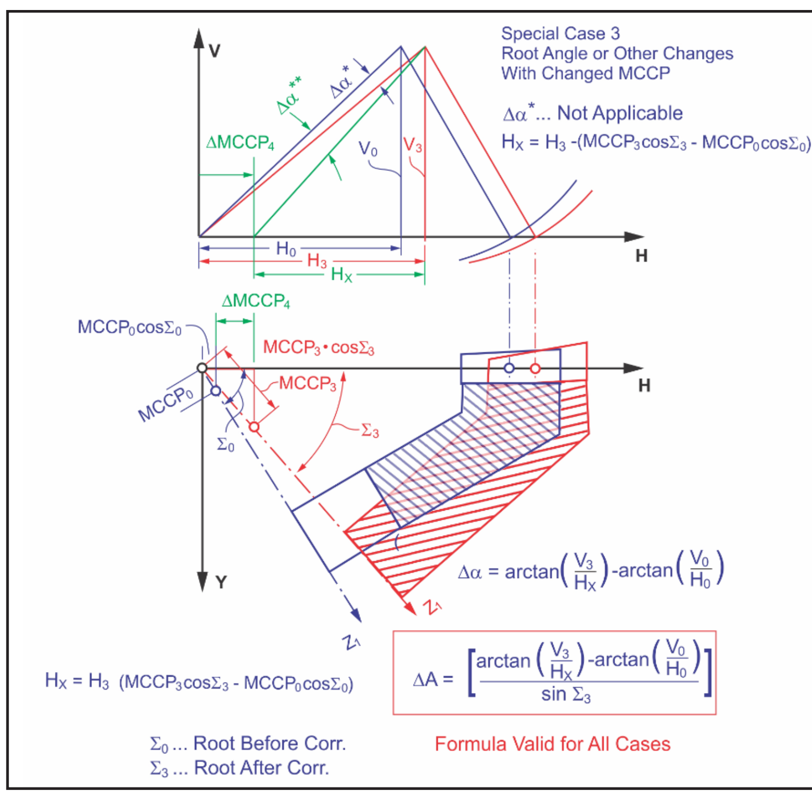

Figure 8 Universal phase angle adjustment.

Summary

This chapter was written to answer the frequently asked questions about the influence of the grinding wheel dressing parameters to the grinding process performance and features like surface finish, root blends and surfaces without thermal damages. Of course, the characteristics of wheel breakdown are also vital to the produced part quality. The wheel wear compensation will eliminate the spacing and tooth thickness variation, but only if a "healthy" fast wear and total wear are exhibited.

Spacing errors and tooth depth errors are not the only result of a not well compensated wheel breakdown. A tip breakdown which is common in cases of small wheel point width and wrong dressing parameters in combination with none optimal grinding wheel specifications cannot be compensated during the grinding of the slots of a single part. Even after one part is finished, the restoration of the wheel tip might require 2 or three dressing cycles in order to re-establish the correct tip specifications.

Wheel specification and wheel dressing are the key factors for a robust grinding process. The machine summary is created in the grinding summary program and delivers more than a good starting point. The technological data input in the summary program should reflect an experienced based control of the parameters like surface speed, roll rates and plunge feed rates. It is recommended to use the process data from developed processes, which worked efficient and delivered stable part quality. If such technological data are applied in the grinding technology data input of similar gearset designs, then a successful grinding of a brand new design will be the result, provided that the coolant application and the grinding wheel specification also reflects the best practices from other successfully ground jobs.

However, many factors concerning the grinding wheel condition are not captured in the grinding summary. The different sections in this chapter try to give hints and provide rules for the grinding wheel observation and help to find conclusions for the optimization of the wheel dressing and the grinding conditions. Many of those rules and conclusion are "soft facts" and are therefore not always obvious and straight forward.

In order to sustain the effort of giving the manufacturing engineers and the machine setup specialists useful hints for the improvement of the bevel gear grinding process, a help function on Gleason grinding machines is being developed, containing the information and illustrations in this chapter, and making them easily accessible during a process optimization.

For more information. Questions or comments regarding this paper? Contact Hermann Stadtfeld at *hstadtfeld@gleason.com.*

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Dr. Hermann J. Stadtfeld is the Vice President of Bevel Gear Technology and R&D at the Gleason Corporation and Professor of the Technical University of Ilmenau, Germany. As one of the world's most respected experts in Bevel Gear Technology, he has published more than 300 technical papers and 10 books in this field. Likewise, he has filed international patent applications for more than 60 inventions based upon new gearing systems, gear manufacturing methods as well as cutting tools and gear manufacturing machines. Under his leadership and guidance, the world of bevel gear cutting has converted to, environmentally friendly, dry machining of gears with significantly increased power density due to non-linear machine motions and new processes. Those developments also lower the noise emission level and reduce the degree of energy consumption. Over a span of over 35 years, Dr. Stadtfeld has had a remarkable career within the field of Bevel Gear Technology. Having received his Ph.D. with summa cum laude in 1987 at the Technical University in Aachen, Germany, he became the Head of Development & Engineering at Oerlikon-Bührle in Switzerland. Dr. Stadtfeld held a Professor position at the Rochester Institute of Technology in Rochester, New York From 1992 to 1994. In 2000 as Vice President R&D he received in the name of The Gleason Works two Automotive Pace Awards, one for his high speed dry cutting development and one for the successful development and implementation of the Universal Motion Concept (UMC). The UMC brought the conventional bevel gear geometry and its physical properties to a new level. In 2015, the Rochester Intellectual property Law Association elected Dr. Stadtfeld the "Distinguished Inventor of the Year" by. Between 2015 and 2016 CNN-Networks featured him as "Tech Hero" in a Website dedicated to technical innovators for his accomplishments regarding environmentally friendly gear manufacturing and technical advancements in gear efficiency. Currently, he continues next to his Senior Management position at Gleason Corporation to mentor and advice graduate level Gleason employees, and he supervises Gleason sponsored Master Thesis programs as Professor of the Technical University of Ilmenau, helping to shape the future of Gear Technology.