Combining Gear Design with Manufacturing Process Decisions

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Introduction

The layout of gear drives is a challenging process. Lifetime, noise, losses and other criteria must be considered. In the design process, first the overall geometry (e.g., center distance and outer dimensions of gear pairs) must be determined. Then macro geometry (e.g., module, helix angle, number of teeth, and reference profile) must be defined and optimized based on the requested design requirements. Finally, the micro geometry (e.g., profile and lead modifications) must be sized for optimum gear mesh behavior.

In this complex process a design engineer is focused on finding the best gear layout and will not often consider manufacturing constraints. It's only after the manufacturing department gets the gear design data that the most efficient manufacturing process is evaluated and manufacturing costs are considered. Today cost-efficient gear manufacturing processes are available. But whether a process — for example, power skiving or honing — is possible or not depends on certain gear and pinion geometry conditions and interference contours. Often, only a small change in the macro geometry would permit the use of a more productive or less-costly manufacturing process.

If the production department requests a change to the gear geometry, the design process often must be restarted, making the process time-consuming. Instead, an often-repeated request from production departments is to integrate certain manufacturing experience into the design process. Frequently designers are not familiar with manufacturing processes and so it is beneficial for them to have access to simple manufacturing information within their design software. This can, for example, determine if an intended manufacturing process is feasible or not.

Selection of Available Tools during the Gear Design Process

Choice of cutter or gear shapers. For companies producing special gearboxes in single-unit or small batches, costs can be reduced if existing tools such as hobs or shaper cutters can be reused. The design software can present a list of available tools when the gear geometry (ref-
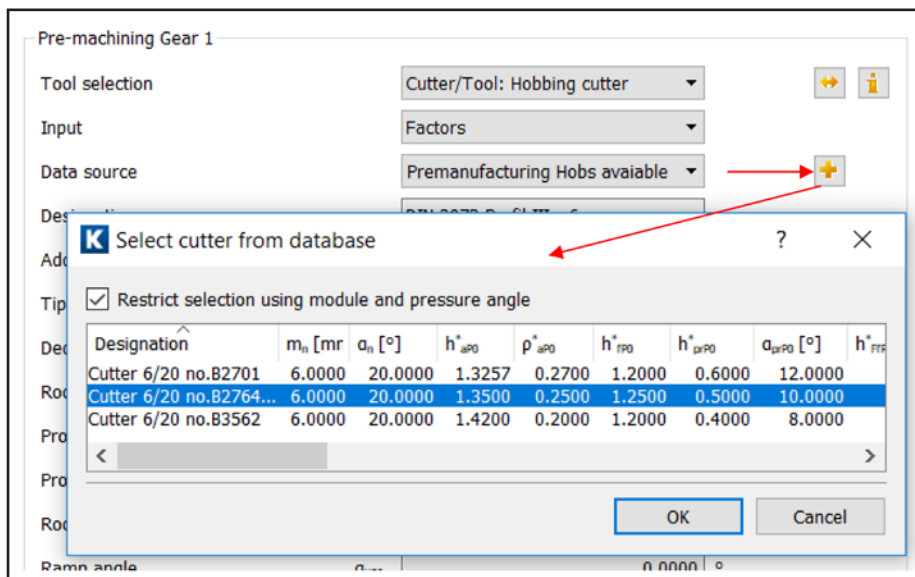

Figure 1   Selection of available cutters pre-filtered from module and pressure angle (symbols

Figure 2   Macro geometry variants using only available cutters.

erence profile) is defined. Such a task is simple to achieve if it is possible to add a list of available tools (Fig. 1) in the gear software.

A more advanced option is the integration of a list with available tools into a macro geometry variant generator. A tool called '*Finesizing*' in *KISSsoft* (Ref. 2) permits, while keeping the main parameters such as center distance and face width fixed, for a given gear reduction, iterating over a range of normal modules, pressure and helix angles, with different combinations of number of teeth and profile shift coefficients. If the option 'use only available tools' is activated, only solutions using existing tools are displayed (Fig. 2).

Use of available dresser/threaded grinding wheel combinations. Another efficient manufacturing process is threaded wheel grinding which is used normally as a finishing process of gears. For dressing the grinding wheel, an expensive dresser is required. For a gear designer, when working on a new gear set likely with profile modifications, it would be helpful to get a list of existing grinding tools/dressers with the resulting profile modifications that will be produced when they are used for new gear geometry. With this information available, an existing dresser can possibly be reused for a new project. As displayed (Fig. 3), in the first step all available dresser/grinding wheel combinations are displayed with the amount ($C_{\alpha a}$) and length ($L_{c\alpha a}$) of tip relief generated. After selecting the best fitting dresser, the tip relief amount can be further varied in the second step by the adaptation of the dresser wheel gap (A_{L*eff}).

Checking if Economic Production Methods are Applicable

To design cost-competitive products, it is worthwhile to make production method decisions early. Many different methods such as grinding, shaping, honing, broaching, etc. can be considered and evaluated. In this paper, the relatively new manufacturing method — power skiving — is used to explain the integration of manufacturing restrictions into the design process.

Power skiving. The power skiving process is a breakthrough in the production of gears (Ref. 7). It is several times faster than gear shaping and much more flexible

than gear broaching. Power skiving is setting ever-higher standards in the *machining of internal gears and/or gears with critical interfering contours* (Fig. 4).

Originally intended as a competitive alternative to gear shaping, and in some cases to broaching, for small-to-medium-sized, non-hardened cylindrical gears, its range of application has expanded

significantly. Today, we find power skiving solutions for soft and hard finishing of internal and external gears, for machining shafts and worms, as well as for special profiles such as cycloidal gears for robot applications.

Most gear cutting applications are placed somewhere between distinct production worlds, i.e.: highly efficient mass
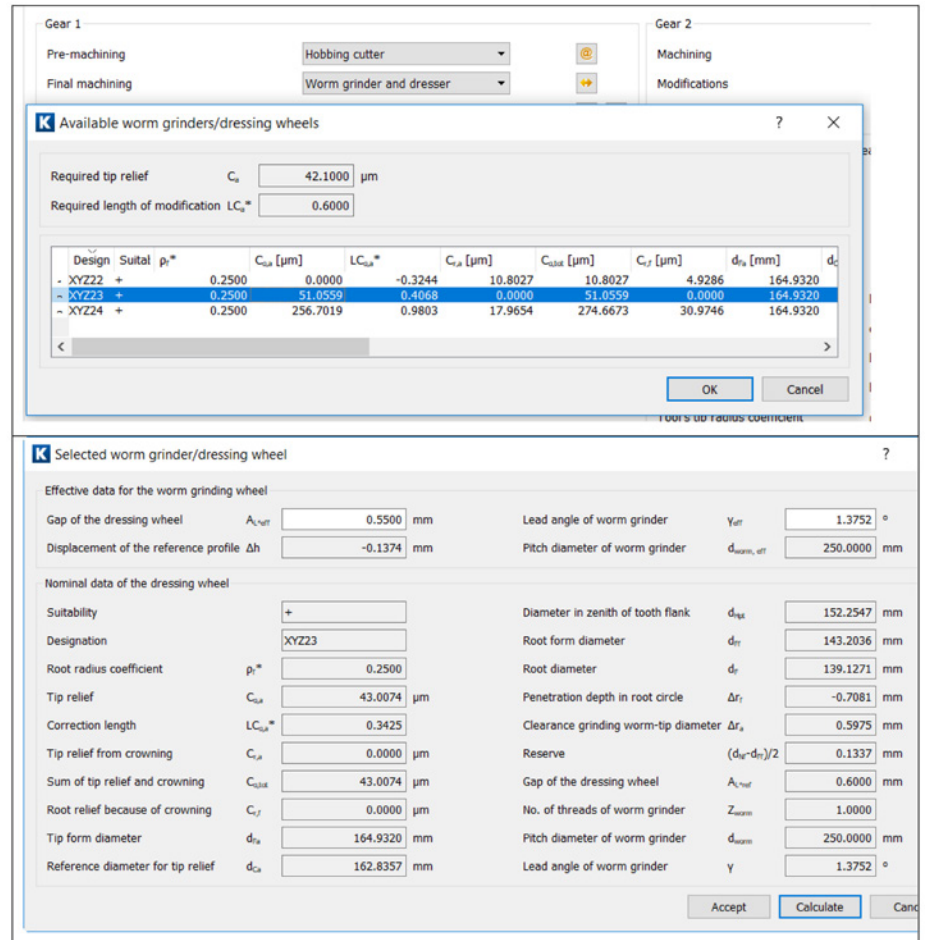

Figure 3   Selection of available dresser/threaded grinding wheel combinations. First step: selection of best fitting dresser; second step: due to a small change of the dresser wheel gap (AL*eff), the requested tip relief amount (Cαa) can be achieved.
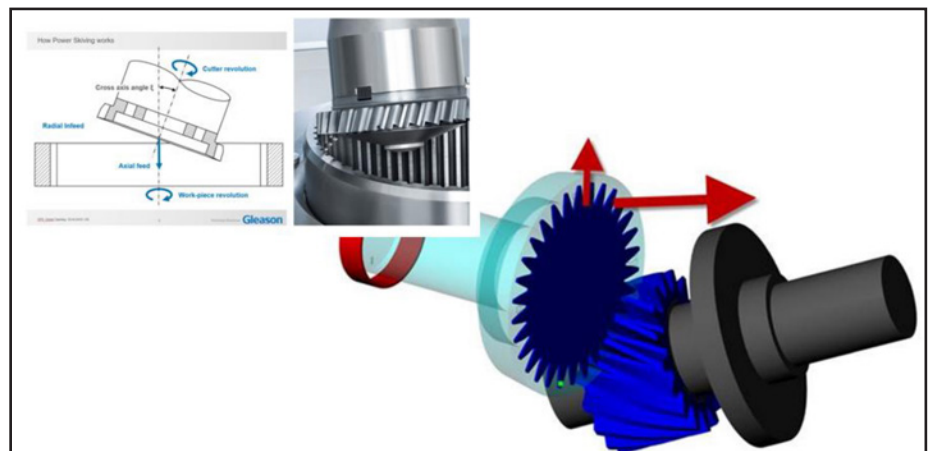

Figure 4   Left: power skiving process; Right: visualization in *KISSsoft* (Ref. 2).

production and flexible manufacturing of smaller, rapidly changing lots. Depending on the application, the power skiving process can be designed in such a way that it accommodates both requirements.

Demand for quieter gears and gear boxes and/or higher torque are increasingly determining requirements of the finishing methods for hardened gears. However, so far there has been no economical hard finishing solution for small to medium-sized internal gears on the market. Hard power skiving provides the potential for a particularly economical alternative to the traditional hard finishing processes.

The combination of extremely stiff latest-generation machines with direct drives in all relevant axes, integrated stock division, simulation software, process expertise and modern carbide tools have made hard power skiving a competitive production method for hardened gears. The quality and surface roughness which can be achieved are perfectly adequate for most

applications, and so a further finishing process step is usually not required.

Up until a few years ago, the boundaries of the skiving process were unknown. The process could only be optimized in advance to an unsatisfactory extent. In order to optimize the production output with respect to productivity and manufacturing costs, integrated solutions are becoming more important. These new, smart systems include gear design, process simulation, manufacturing and metrology equipment, workholdings, tools and support services such as re-sharpening and technology consulting.

Verification of power skiving possibility. Clearly, in gear design software, only basic manufacturing knowledge can be expected from a design engineer; therefore, only simple inputs can be imposed. This implies that not all data for a complete check of manufacturability is available. The check is therefore simplified and so there are cases where a reliable result cannot be achieved. The results of the

check can be in one of three categories: 1) power skiving is possible; 2) may be possible; 3) is not possible.

Whether power skiving is possible depends on different collision scenarios between the tool and gear (tool head, tool back or tool shaft) and on some geometric restrictions, e.g. — minimum length of involute on tool tooth, total overlap ratio, etc. The gear-tool setting is a classic crossed helical gear mesh, as defined by Niemann (Ref. 3), but the theory must be extended to inner gear pairs. In many cases, a valid combination can be found just by adjusting the tool tooth number.

If such a check is available in a gear variant generator — showing macro geometry variants for a given gear stage — then it is easy for a gear designer to find a suitable variant which can be manufactured by power skiving (Fig. 6).

Consideration of Known Manufacturing Deviations in the Gear Layout Process

Manufacturing twist. When grinding helical gears and applying lead modifications such as lead crowning an undesired side effect results — the manufacturing twist (Ref. 4). It is therefore critical when designing the lead modifications to consider this usually unwanted side effect.

The root cause for the manufacturing twist is the contact line between the workpiece and the grinding wheel along the flank which is being ground. The contact line shape depends on the process, whether it is profile or threaded wheel grinding and the gear data itself. What both processes have in common is that the contact line for helical gears runs diagonally across the flank. However, the contact line in profile grinding is curved and oriented the other way around, compared to threaded wheel grinding where the contact line is straight but diagonal. Only on spur gears is the contact line straight and parallel to the top section of the gear — which is the reason why manufacturing twist does not appear on spur gears.

The effect of manufacturing twist is described as follows using the example of threaded wheel grinding. Figure 7 shows the diagonal line of contact on a simplified gear tooth. All points along this line, are generated at the same time. So, in case of grinding a symmetric lead crowning, the machine infeed axis must follow a
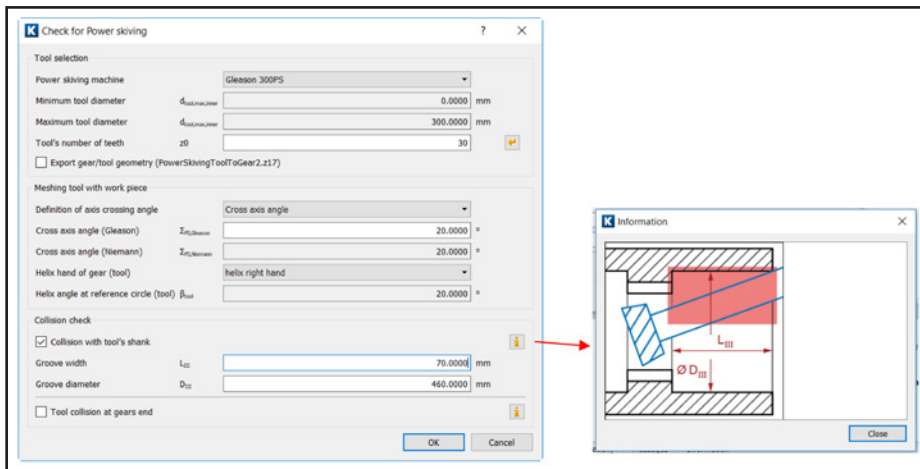

Figure 5   Requested data for the check, if power skiving is applicable.

Figure 6   Macro geometry variants with check, if power skiving is applicable.

Nr.	m_n [mm]	a_n [°]	β [°]	z_1	z_2	x_1	d_{a2} [mm]	ε_a	ε_β	ε_γ	i	PSK_2	$PSKz_2$
1	0.600	22.500	0.000	32	-50	0.800	29.341	0.975	0.000	0.975	-1.562	Yes	21
2	0.600	22.500	0.000	33	-51	0.800	29.941	0.980	0.000	0.980	-1.545	Yes	21
3	0.600	22.500	0.000	34	-52	0.800	30.541	0.984	0.000	0.984	-1.529	Yes	21
4	0.600	22.500	0.000	35	-53	0.800	31.141	0.988	0.000	0.988	-1.514	Yes	21
5	0.600	25.000	0.000	30	-47	0.146	27.169	1.459	0.000	1.459	-1.567	Yes	21
6	0.600	25.000	0.000	31	-48	0.133	27.754	1.464	0.000	1.464	-1.548	Yes	21
7	0.600	25.000	0.000	32	-49	0.120	28.339	1.469	0.000	1.469	-1.531	Yes	21
8	0.600	25.000	0.000	33	-50	0.108	28.924	1.473	0.000	1.473	-1.515	Yes	29
9	0.600	27.500	0.000	30	-47	-0.005	26.988	1.408	0.000	1.408	-1.567	No	0
10	0.600	27.500	0.000	30	-47	0.095	27.108	1.378	0.000	1.378	-1.567	No	0
11	0.600	27.500	0.000	31	-48	-0.017	27.573	1.411	0.000	1.411	-1.548	No	0
12	0.600	27.500	0.000	31	-48	0.083	27.693	1.382	0.000	1.382	-1.548	No	0
13	0.600	27.500	0.000	32	-49	-0.030	28.158	1.414	0.000	1.414	-1.531	No	0
14	0.600	27.500	0.000	32	-49	0.070	28.278	1.386	0.000	1.386	-1.531	No	0
15	0.600	27.500	0.000	33	-50	-0.043	28.743	1.416	0.000	1.416	-1.515	No	0
16	0.600	27.500	0.000	33	-50	0.057	28.863	1.389	0.000	1.389	-1.515	No	0
17	0.600	30.000	0.000	30	-47	-0.147	26.817	1.358	0.000	1.358	-1.567	Yes	27
18	0.600	30.000	0.000	30	-47	-0.047	26.937	1.334	0.000	1.334	-1.567	Yes	27
19	0.600	30.000	0.000	30	-47	0.053	27.057	1.312	0.000	1.312	-1.567	Yes	27
20	0.600	30.000	0.000	31	-48	-0.159	27.402	1.360	0.000	1.360	-1.548	Yes	27
21	0.600	30.000	0.000	31	-48	-0.059	27.522	1.337	0.000	1.337	-1.548	Yes	27
22	0.600	30.000	0.000	31	-48	0.041	27.642	1.315	0.000	1.315	-1.548	Yes	27
23	0.600	30.000	0.000	32	-49	-0.170	27.989	1.361	0.000	1.361	-1.531	Yes	27
24	0.600	30.000	0.000	32	-49	-0.070	28.109	1.339	0.000	1.339	-1.531	Yes	27
25	0.600	30.000	0.000	32	-49	0.030	28.229	1.317	0.000	1.317	-1.531	Yes	27
26	0.600	30.000	0.000	33	-50	-0.182	28.575	1.362	0.000	1.362	-1.515	Yes	27

parabolic function $x(z)$ and will result in a change of radial infeed over the face width "b" of the gear. Usually the highpoint of a crowning is set to the middle of the tooth face width represented by the blue point in Figure 7. Since all points along the line of contact are ground (generated) at the same time, this results in the root area, represented by the red point, achieving its crowning highpoint shifted towards the top of the gear. The tip area, which is represented by the green point, achieves its highpoint displaced towards the bottom of the gear. Thus, the lead crowning is only symmetrical in the middle of the gear. When measuring the lead line in the root (red line) and tip area (green line), the crowning also shows a lead angle error while simultaneously affecting the profile modification. The middle section has no profile error but a slight crowning being affected by the lead crowning. The top and bottom profile lines show a clear profile angle error.

Figure 8 shows a grinding result where this effect can be seen. The amount of twist error, which is defined as the absolute change in profile angle error from top to the bottom, is for this example about 25 μm and much more than the allowed tolerance.

Considering manufacturing twist at design stage. Today, it is possible with very modern grinding machines to compensate for this undesired effect (Ref. 5). But if such a machine is not available, manufacturing twist should be considered, when a loaded tooth contact analysis is executed during the gear design process. Hellmann (Ref. 6) proposed an accurate formula to get the amount of twist when a crowning in generation grinding is produced.

$$C = 8 * C_\beta * \tan(\beta_b) * L_\alpha / b \qquad (1)$$

(Symbols according to ISO21771 (Ref. 1). C: Twist; C_β: Crowning amount; β_b: Base helix angle; L_α: Involute length; b: Face width.)

Based on this formula, the generated manufacturing twist can be determined by the gear design software (Fig. 9). The twist is automatically calculated and considered in the contact analysis and the 3D display. The design engineer is therefore able to decide if the unwanted twist is acceptable or if additional profile and/or flank line modifications are necessary to compensate for this error.
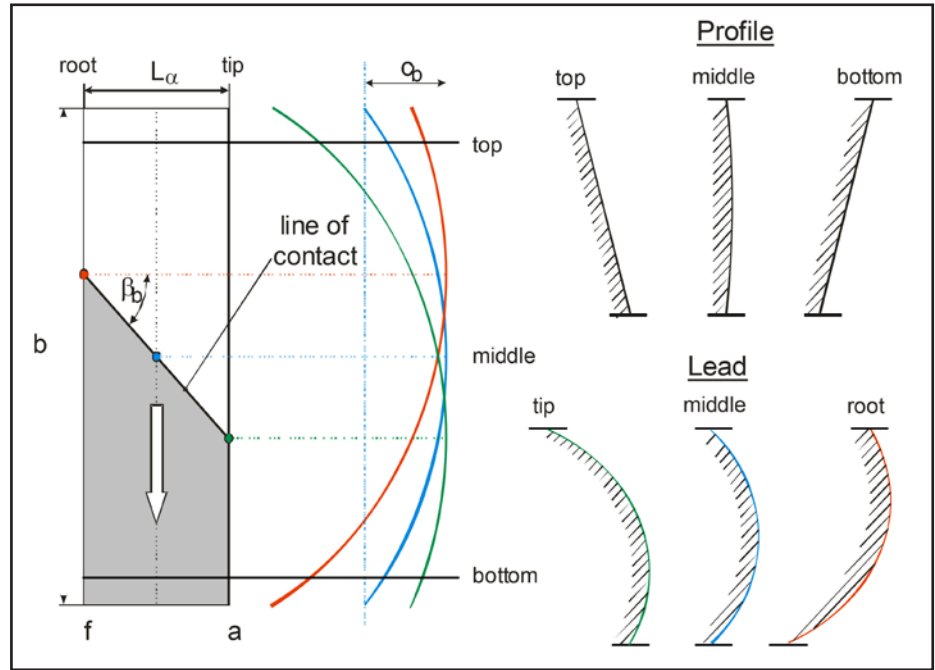

Figure 7   Contact line and twist generation in threaded wheel grinding.

Figure 8   Twisted tooth flank.

$f_{H\alpha}$	left flank (LF)	right flank (RF)
top	-15μm	+9μm
middle	-2μm	-2μm
bottom	+8μm	-16μm
amount of twist s_α		
s_α	$f_{H\alpha\,top} - f_{H\alpha\,bottom}$	$f_{H\alpha\,bottom} - f_{H\alpha\,top}$
s_α	-24μm	-25μm

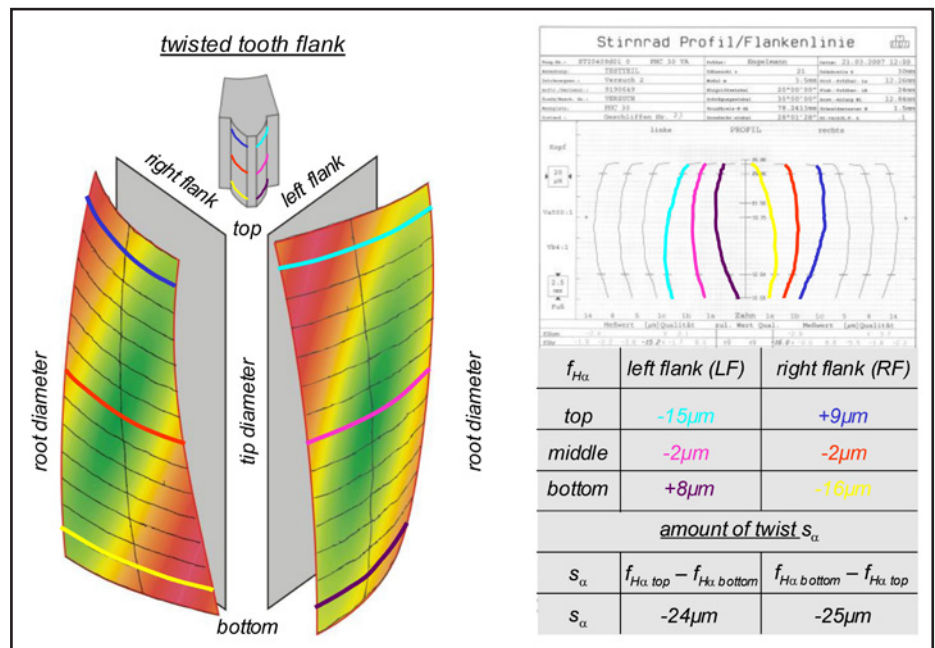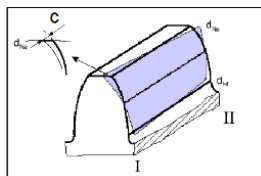## Conclusion

The integration of manufacturing information into gear design software reduces cost during the design process by avoiding time-consuming back and forth between the design and manufacturing departments. The challenging task for such software is ensuring the design engineer does not need specific manufacturing expertise. Otherwise he or she would be overwhelmed and not use such a feature. **PTE**

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Gear	Flank	Type of modification	Value [µm]	Factor 1	Factor 2	Status	Information
Gear 1	both	Tip relief, linear	16.0000	0.7376		active	dCa=661.966mm, ξ=25.147°
Gear 1	both	Crowning	26.0000			active	rcrown=155769mm
Gear 1	both	Twist due to manufacturing (generation grinding)	26.0000			active	C(R) = -19.3 C(L) = -19.3 µm
Gear 2	both	Tip relief, linear	16.0000	0.7376		active	dCa=158.956mm, ξ=33.334°

Figure 9   Gear with helix angle 23° and face width 180 mm; manufacturing twist is 19.3 µm for a crowning of 26 µm.

Dr. Ulrich Kissling studied machine engineering (1976-1980) at the Swiss Technical University (ETH), where he also completed his doctoral thesis — "Pneumatic Weft Insertion on Weaving Machines. In 1981 he started his professional career as calculation engineer for a gearbox manufacturing company in Zurich, progressing there to technical manager and ultimately managing director. As a calculation engineer for gearbox design, he began developing software for gear, bearing and shaft layout. In 1985 he branded this software 'KISSsoft' and started to market it, selling its first license in 1986. In 1998 he founded his own company — KISSsoft AG — concentrating on software development and growing staff from three people in 1998 to workers in 2017. Today, aided by the contributions of partner and managing director Dr. Stefan Beermann, KISSsoft is the leading drivetrain design software, used by more than 3,000 companies on all continents. An internationally respected gear expert, Dr. Kissling is chairman of the TK25 committee (gears) of the Swiss Standards Association (SNV) and a voting member for Switzerland in the ISO TC 60 committee. He actively participates in different work groups of ISO for the development of international standards.

Udo Stolz studied (1980 – 1985) Studied mechanical engineering at Transylvania University in Brasov, Romania – graduation as Dipl. Ing. From 1993 – 1994, he enrolled in marketing studies for engineers at Free University of Berlin, Germany, graduating as master of business marketing. Since 1987 he has held several positions in the technical and sales departments at Hermann Pfauter GmbH, Gleason-Pfauter GmbH and Gleason Corporation. Stolz since 2009 has served as vice president, Worldwide Sales & Marketing, for Gleason Corporation.

Dr. –Ing. Antoine Türich studied mechanical enigineering (1990-1996) at the University of Hannover, and from 1996-2001he was a research assistant at the Institute of Production Engineering and Machine Tools, University of Hannover, Germany. He earned his Ph.D. in 2005 at the University of Hannover: Werkzeug-Profilerzeugung für das Verzahnungsschleifen. Türich has been with Gleason Corporation (Hurth, Munich) since 2002, serving in roles including manager of technology development and,, currently, as director of product management—hard finishing solutions.