Combining gear design with manufacturing process decisions

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Abstract

Gear manufacturing processes are continuously improved, pushed by the demand for higher quality and lower costs. Deciding which process is most appropriate, such as grinding, honing, or skiving, is difficult and requires specific expertise. Gear design engineers are expected to be knowledgeable with less manufacturing concerns today than they were 20 years ago.

Today, in many companies – mainly larger ones – design and manufacturing departments are separated and often manufacturing is provided by subcontractors. Additionally, gear transmission design continues to become more demanding and complex – achieving increased lifetime, lower noise, and lower losses are goals often at odd ends with each other. When a gearbox design is completed, and the designs of the components are transferred to manufacturing, it is usually too late for any modifications necessary for an optimal manufacturing process. The consequences are increased manufacturing costs.

In this paper the introduction of manufacturing knowledge into gear design software is described. Different methods, and how manufacturing options and restrictions can be considered in the design phase, are discussed:

- Use of available tools such as cutters, worm grinders, etc.
- Checking if economic production methods such as Power Skiving and Honing are applicable.
- Applying known manufacturing deviations such as manufacturing twist in the gear layout process.

1. 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.

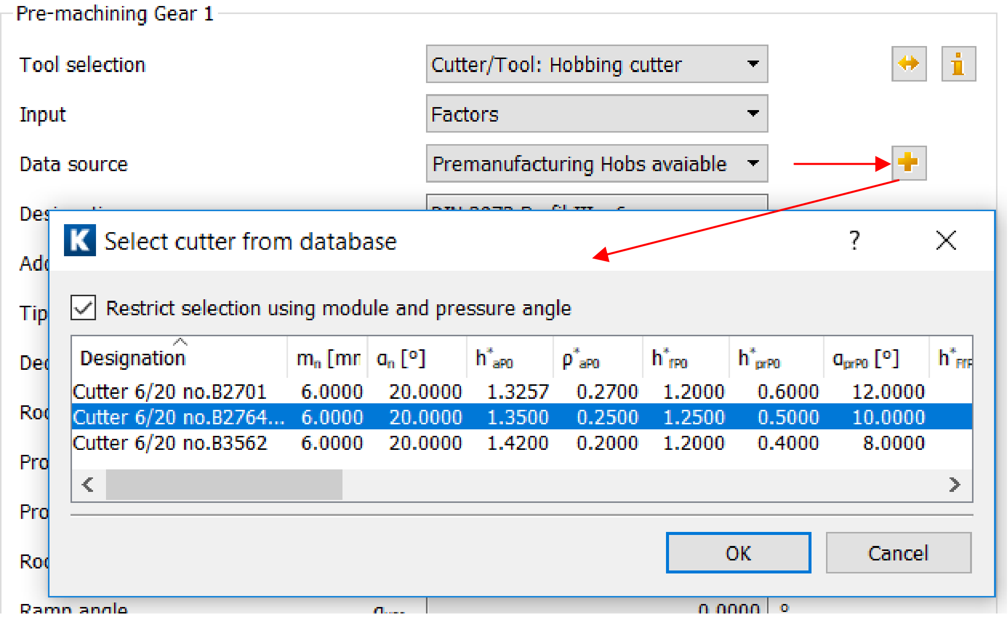
In this complex process, a design engineer is focused on finding the best gear layout and will not often consider manufacturing constraints. It's only after the manufacturing department gets the gear design data that the most efficient manufacturing process is evaluated and manufacturing costs are considered. 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 inefficient. Instead, an often-repeated request from production departments is to integrate certain manufacturing experience into the design process. Frequently designers are not intimate with manufacturing processes and so it is beneficial for him or her 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.

2. Selection of available tools during the gear design process

2.1. Choice of cutter or gear shapers

For companies producing special gear boxes in single-unit or in small batches, costs can be reduced if existing tools such as hobs or shaper cutters can be reused. The design software



Pre-machining Gear 1

Tool selection: Cutter/Tool: Hobbing cutter

Input: Factors

Data source: Premanufacturing Hobs avaiable

Select cutter from database

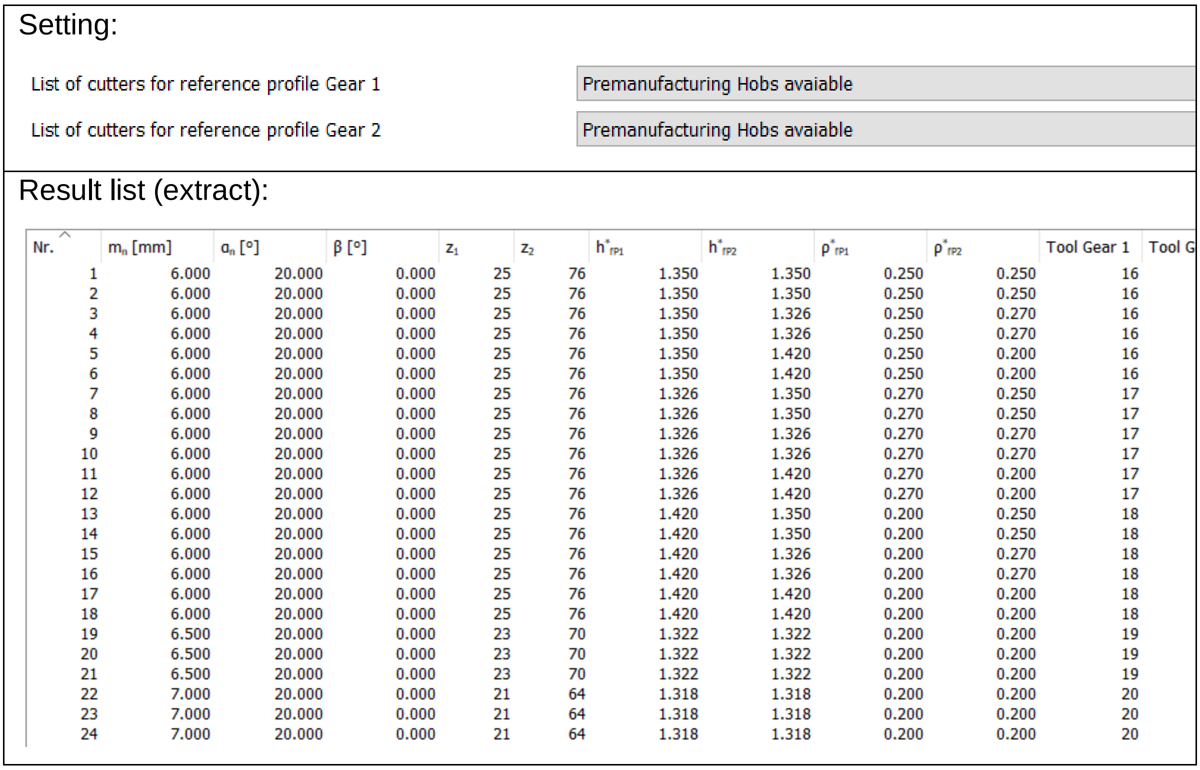
☑ Restrict selection using module and pressure angle

Designation	m_n [mr	α_n [°]	h^*_{aP0}	ρ^*_{aP0}	h^*_{FP0}	h^*_{prP0}	α_{prP0} [°]
Cutter 6/20 no.B2701	6.0000	20.0000	1.3257	0.2700	1.2000	0.6000	12.0000
Cutter 6/20 no.B2764...	6.0000	20.0000	1.3500	0.2500	1.2500	0.5000	10.0000
Cutter 6/20 no.B3562	6.0000	20.0000	1.4200	0.2000	1.2000	0.4000	8.0000

Figure 1: Selection of available cutters prefiltered from module and pressure angle (Symbols according ISO21771 [1])

can present a list of available tools when the gear geometry (reference profile) is defined. Such a task is simple to achieve if it is possible to add a list of available tools (Figure 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 [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.



Setting:

List of cutters for reference profile Gear 1: Premanufacturing Hobs avaiable

List of cutters for reference profile Gear 2: Premanufacturing Hobs avaiable

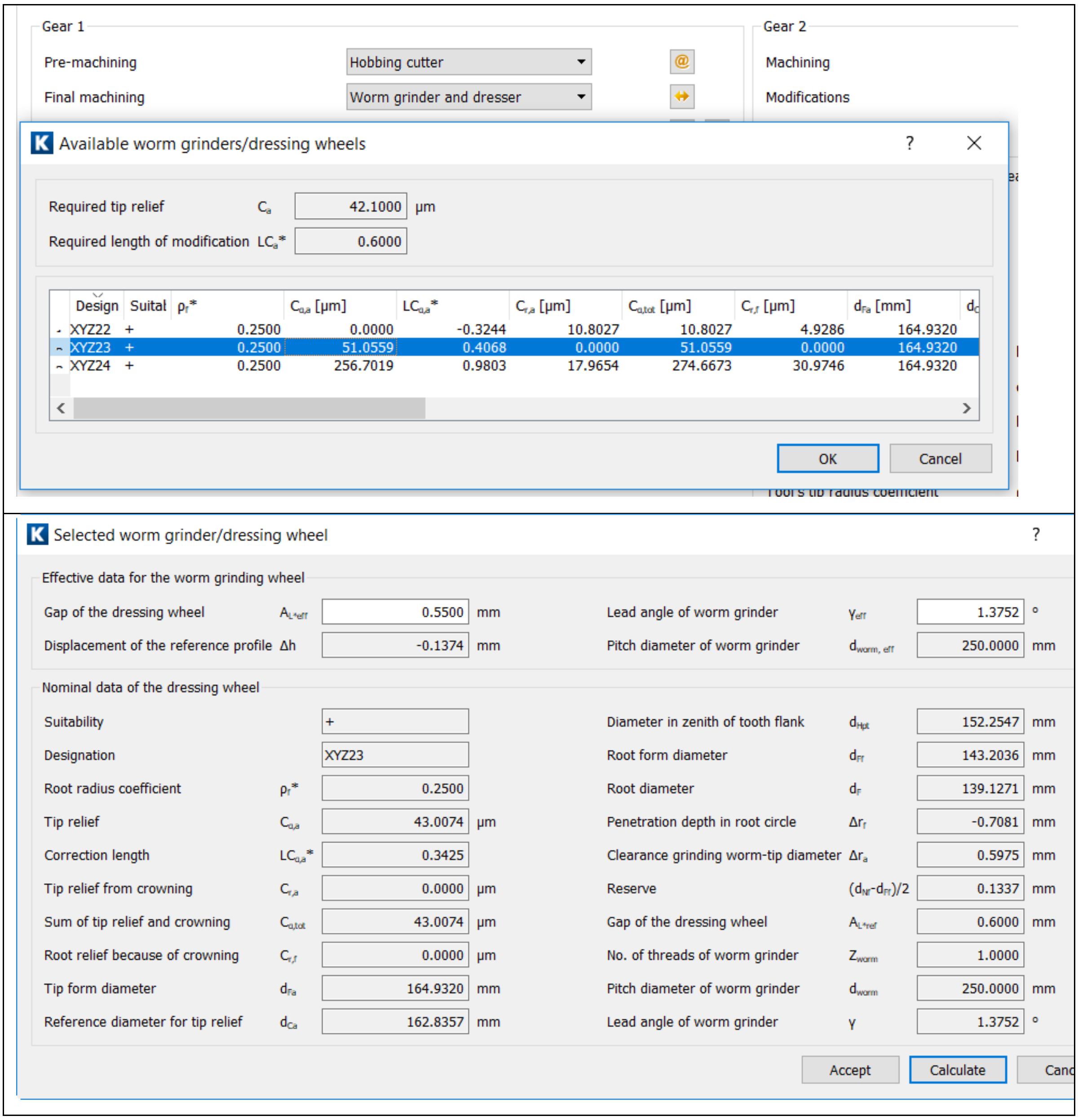
Result list (extract):

Nr.	m_n [mm]	α_n [°]	β [°]	z_1	z_2	h^*_{fP1}	h^*_{fP2}	ρ^*_{fP1}	ρ^*_{fP2}	Tool Gear 1	Tool G
1	6.000	20.000	0.000	25	76	1.350	1.350	0.250	0.250	16	
2	6.000	20.000	0.000	25	76	1.350	1.350	0.250	0.250	16	
3	6.000	20.000	0.000	25	76	1.350	1.326	0.250	0.270	16	
4	6.000	20.000	0.000	25	76	1.350	1.326	0.250	0.270	16	
5	6.000	20.000	0.000	25	76	1.350	1.420	0.250	0.200	16	
6	6.000	20.000	0.000	25	76	1.350	1.420	0.250	0.200	16	
7	6.000	20.000	0.000	25	76	1.326	1.350	0.270	0.250	17	
8	6.000	20.000	0.000	25	76	1.326	1.350	0.270	0.250	17	
9	6.000	20.000	0.000	25	76	1.326	1.326	0.270	0.270	17	
10	6.000	20.000	0.000	25	76	1.326	1.326	0.270	0.270	17	
11	6.000	20.000	0.000	25	76	1.326	1.420	0.270	0.200	17	
12	6.000	20.000	0.000	25	76	1.326	1.420	0.270	0.200	17	
13	6.000	20.000	0.000	25	76	1.420	1.350	0.200	0.250	18	
14	6.000	20.000	0.000	25	76	1.420	1.350	0.200	0.250	18	
15	6.000	20.000	0.000	25	76	1.420	1.326	0.200	0.270	18	
16	6.000	20.000	0.000	25	76	1.420	1.326	0.200	0.270	18	
17	6.000	20.000	0.000	25	76	1.420	1.420	0.200	0.200	18	
18	6.000	20.000	0.000	25	76	1.420	1.420	0.200	0.200	18	
19	6.500	20.000	0.000	23	70	1.322	1.322	0.200	0.200	19	
20	6.500	20.000	0.000	23	70	1.322	1.322	0.200	0.200	19	
21	6.500	20.000	0.000	23	70	1.322	1.322	0.200	0.200	19	
22	7.000	20.000	0.000	21	64	1.318	1.318	0.200	0.200	20	
23	7.000	20.000	0.000	21	64	1.318	1.318	0.200	0.200	20	
24	7.000	20.000	0.000	21	64	1.318	1.318	0.200	0.200	20	

Figure 2: Macro-geometry variants using only available cutters

2.2. 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 in figure 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 ($A_{L^{*}\mathrm{eff}}$).



Pre-machining: Hobbing cutter

Final machining: Worm grinder and dresser

Required tip relief C_a 42.1000 µm

Required length of modification LC_a^* 0.6000

	Design	Suitat	ρ_f^*	$C_{\alpha,a}$ [µm]	$LC_{\alpha,a}^*$	$C_{r,a}$ [µm]	$C_{\alpha,tot}$ [µm]	$C_{r,f}$ [µm]	d_{Fa} [mm]
-	XYZ22	+	0.2500	0.0000	-0.3244	10.8027	10.8027	4.9286	164.9320
~	XYZ23	+	0.2500	51.0559	0.4068	0.0000	51.0559	0.0000	164.9320
~	XYZ24	+	0.2500	256.7019	0.9803	17.9654	274.6673	30.9746	164.9320

Effective data for the worm grinding wheel

Gap of the dressing wheel	$A_{L^{*}eff}$	0.5500	mm	Lead angle of worm grinder	γ_{eff}	1.3752	°
Displacement of the reference profile	Δh	-0.1374	mm	Pitch diameter of worm grinder	$d_{worm,\ eff}$	250.0000	mm

Nominal data of the dressing wheel

Suitability		+		Diameter in zenith of tooth flank	d_{Hpt}	152.2547	mm
Designation		XYZ23		Root form diameter	d_{Ff}	143.2036	mm
Root radius coefficient	ρ_f^*	0.2500		Root diameter	d_F	139.1271	mm
Tip relief	$C_{\alpha,a}$	43.0074	µm	Penetration depth in root circle	Δr_f	-0.7081	mm
Correction length	$LC_{\alpha,a}^*$	0.3425		Clearance grinding worm-tip diameter	Δr_a	0.5975	mm
Tip relief from crowning	$C_{r,a}$	0.0000	µm	Reserve	$(d_{Nf}-d_{Ff})/2$	0.1337	mm
Sum of tip relief and crowning	$C_{\alpha,tot}$	43.0074	µm	Gap of the dressing wheel	$A_{L^{*}ref}$	0.6000	mm
Root relief because of crowning	$C_{r,f}$	0.0000	µm	No. of threads of worm grinder	Z_{worm}	1.0000	
Tip form diameter	d_{Fa}	164.9320	mm	Pitch diameter of worm grinder	d_{worm}	250.0000	mm
Reference diameter for tip relief	d_{Ca}	162.8357	mm	Lead angle of worm grinder	γ	1.3752	°

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 ($A_{L^{*}\mathrm{eff}}$), the requested tip relief amount ($C_{\alpha a}$) can be achieved.

3. 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.

3.1. Power Skiving

The Power Skiving process is a breakthrough in the production of gears [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 (Figure 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 special profiles such as cycloidal gears for robot applications.

Most gear cutting applications are placed somewhere between distinct production worlds: highly efficient mass 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 has 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 resharpening and technology consulting.

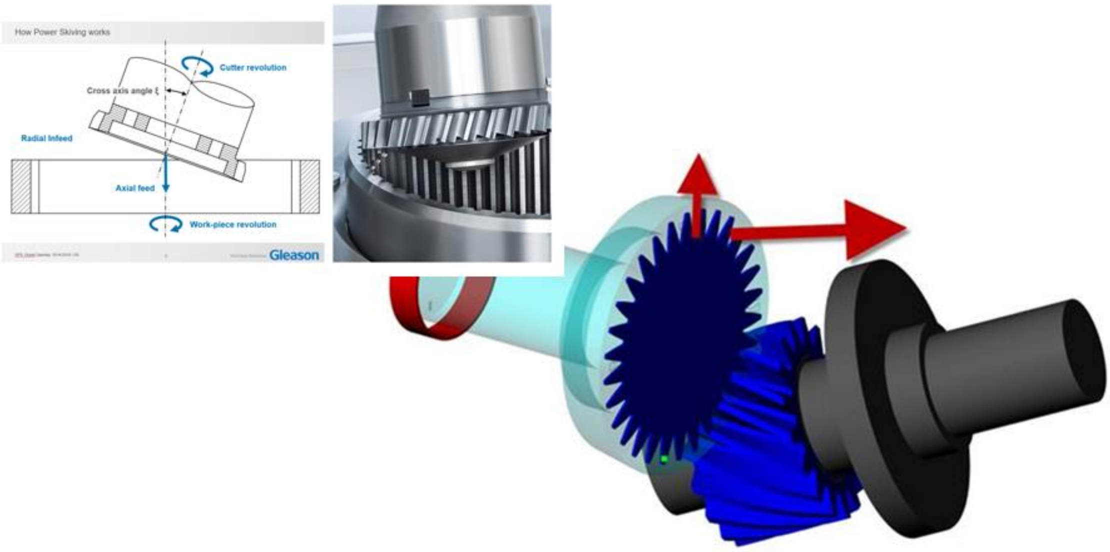
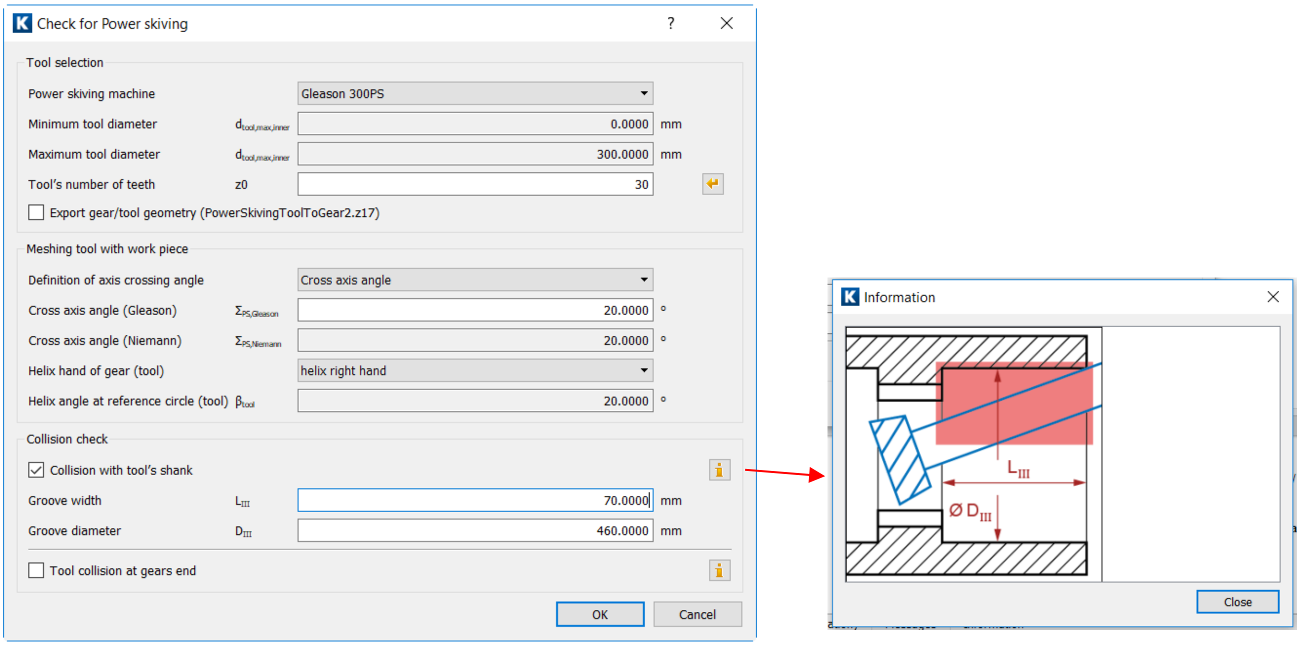


Figure 4: Left: Power Skiving Process Right: Visualization in KISSsoft [2]

3.2. 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: Power Skiving is possible / may be possible / is not possible.



Check for Power skiving

Tool selection

Power skiving machine		Gleason 300PS	
Minimum tool diameter	$d_{tool,max,inner}$	0.0000	mm
Maximum tool diameter	$d_{tool,max,inner}$	300.0000	mm
Tool's number of teeth	z0	30	

☐ Export gear/tool geometry (PowerSkivingToolToGear2.z17)

Meshing tool with work piece

Definition of axis crossing angle		Cross axis angle	
Cross axis angle (Gleason)	$\Sigma_{PS,Gleason}$	20.0000	°
Cross axis angle (Niemann)	$\Sigma_{PS,Niemann}$	20.0000	°
Helix hand of gear (tool)		helix right hand	
Helix angle at reference circle (tool)	β_{tool}	20.0000	°

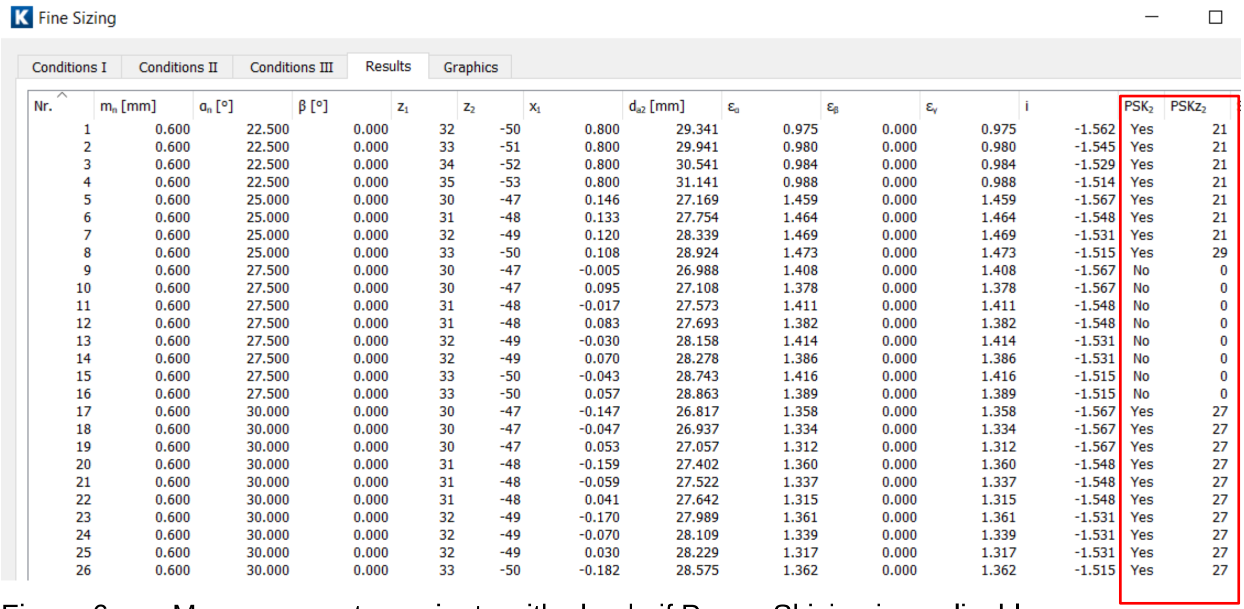
Collision check

☑ Collision with tool's shank

Groove width	L_{III}	70.0000	mm
Groove diameter	D_{III}	460.0000	mm

☐ Tool collision at gears end

Figure 5: Requested data for the check, if Power Skiving is applicable



Nr.	m_n [mm]	α_n [°]	β [°]	z_1	z_2	x_1	d_{a2} [mm]	ε_α	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

Figure 6: Macro-geometry variants with check, if Power Skiving is applicable

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 (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 [3], but the theory must be extended to inner gear pairs. In many cases, just by adjusting the tool tooth number, a valid combination can be found.

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 (Figure 6).

4. Consideration of known manufacturing deviations in the gear layout process

4.1. Manufacturing twist

When grinding helical gears and applying lead modifications such as lead crowning an undesired side effect results, the manufacturing twist [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 the contact line is 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 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.

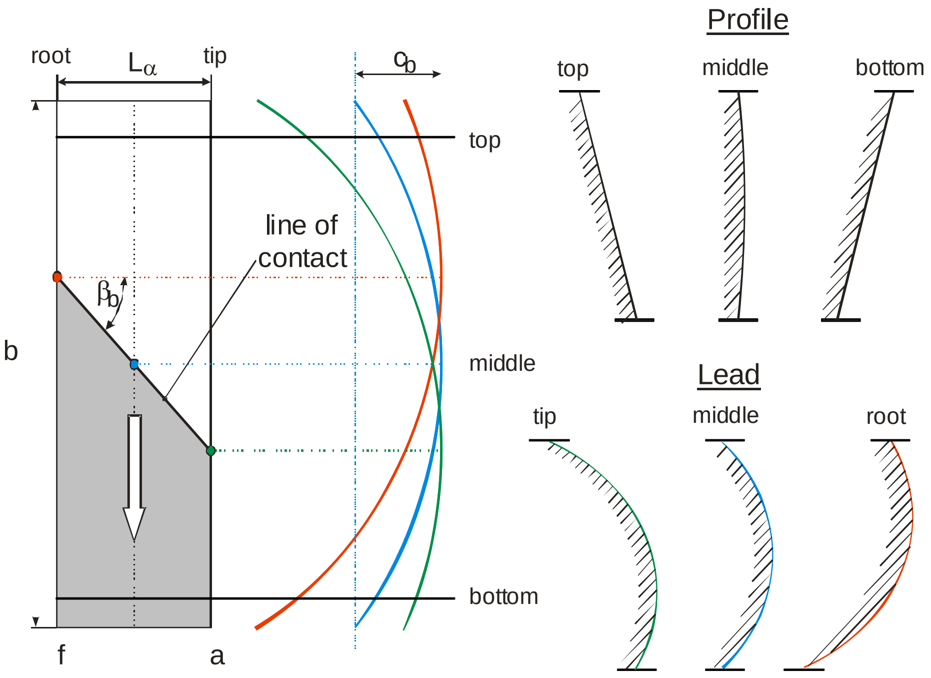
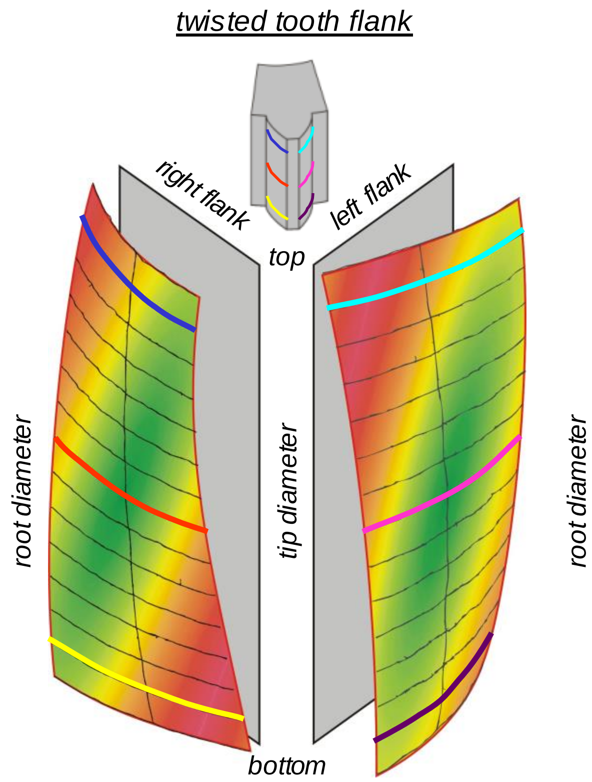
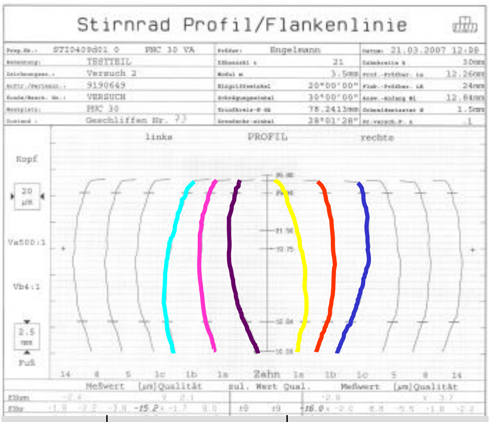


Figure 7: Contact line and twist generation in threaded wheel grinding

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.





$f_{H\alpha}$	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

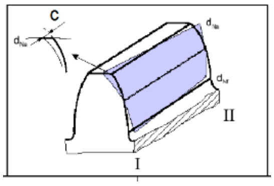
Figure 8: Twisted tooth flank

4.2. Considering manufacturing twist at design stage

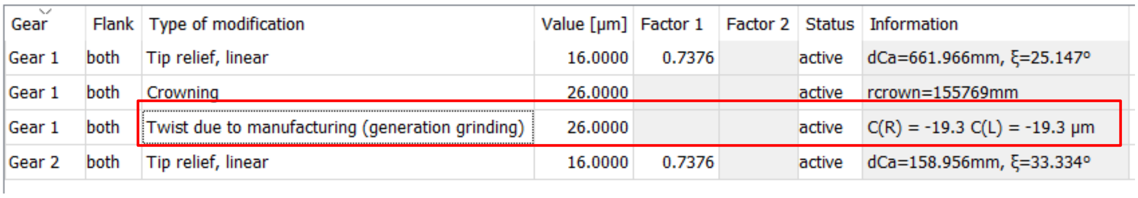
Today, it is possible with very modern grinding machines to compensate for this undesired effect [5]. But if such a machine is not available, manufacturing twist should be considered, when a loaded tooth contact analysis is executed during the gear design process. Hellmann [6] proposed an accurate formula 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 ISO21771 [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 (figure 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.



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 crowing of 26 µm.

5. 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.

References

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