Closed Loop for Gears: Some Case Studies

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Introduction

The closed-loop concept has become widespread in recent years, especially in relation to the Industry 4.0 concept (Ref. 1). The term "closed loop" will be used herein to refer to the pairing of specifications and checking (Figure 1) which all ISO standards, starting with ISO 1 (Ref. 2), the "mother" of all standards, use in relation to GPS (Geometrical Product Specifications) (Ref. 3).

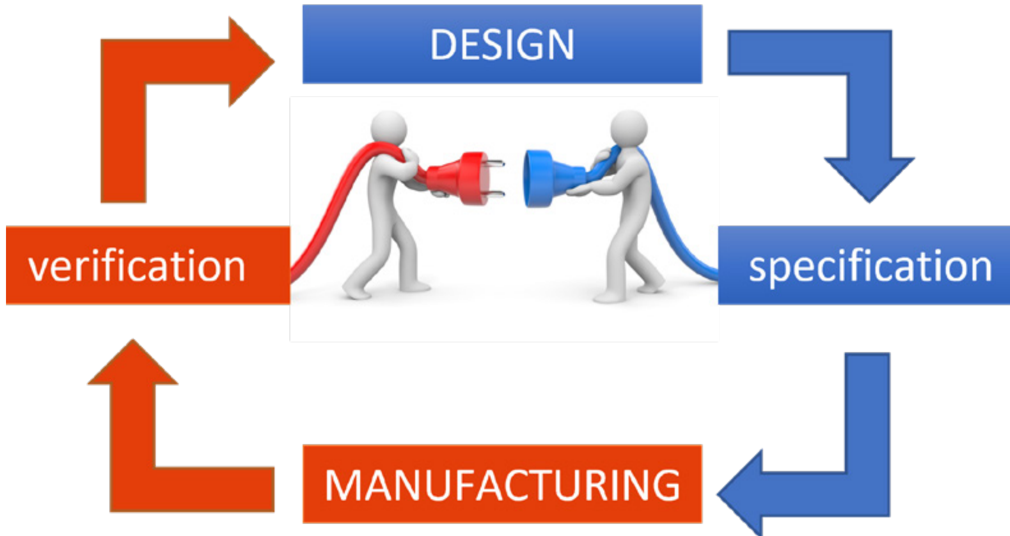


Figure 1—Closed loop.

The process of design of gears involves several steps, such as study of the market's requirements, general sizing using formulas, and numerical checking and optimization (Ref. 4), but it must end with the production of a drawing providing clear and unquestionable instructions for the manufacturer of the item. These are what are known as specifications.

On the other hand, manufacturing of gears also involves several steps (forging, cutting, heat treatment, finishing), but must end with checking that the product complies with requirements. That is called verification.

If specification is a two-dimensional design with 2D CAD dimensions, tables, and symbols, verification is a report with figures and tables generated by CMM or GMM, or compiled by an operator with the aid of hard-gauging.

The closed loop requires both specifications and verification to be complete, with no incomplete parts.

For example, the drawing of a gear listing only the number of teeth, module (without specifying whether normal or transversal), and helix angle cannot be defined as proper specification, and neither can a drawing whose table lists span measurements and measurements between rollers that do not correspond.

Likewise, the delivery of a batch of gears without a quality control report cannot be classed as a verification.

The closed-loop concept for design, manufacturing, measurement and testing of three types of gears with modified microgeometry for improved loaded tooth contact will be presented from several case studies to improve the documentation and performance of bevel, cylindrical, and worm gears.

Bevel Gears

Traditionally speaking, the closed loop for gear use were designed for bevel gears. The traditional cutting processes used for bevel gears, known as face-milling or face-hobbing, intrinsically involve adjustment of cutting and machine parameters, which is itself a closed loop. Modern cutting simulation techniques prior to checking the contact pattern on tester (Figure 2) have made production times quicker, but the concept has remained more or less unchanged, as described by Refs. 5 and 6.

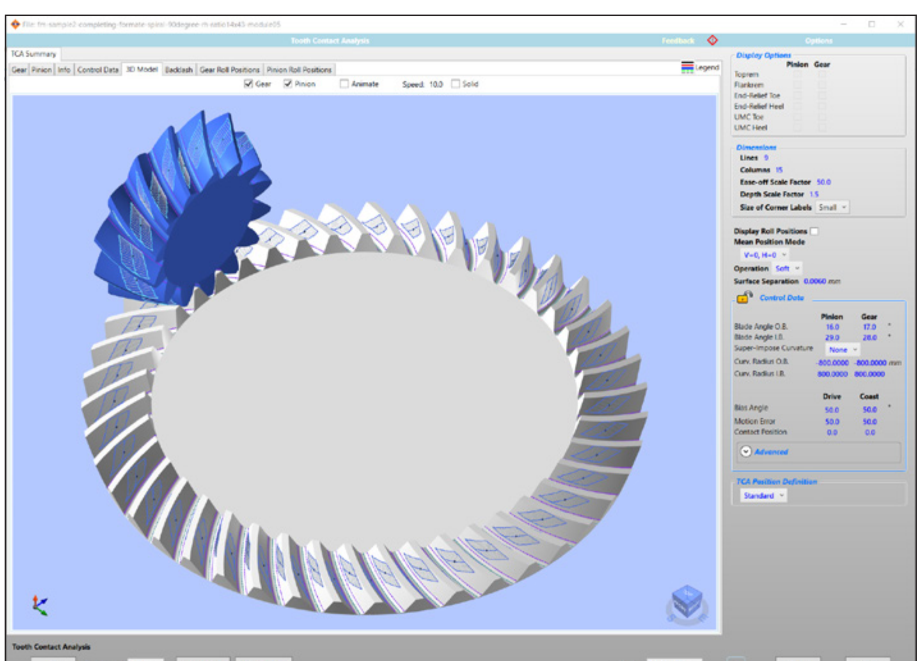


Figure 2—Simulation of the contact pattern (Ref. 7).

However, not all bevel gear designers have dedicated machine tool software.

In this case, they follow in the footsteps of Socrates: they know that they know nothing (Ref. 8). They can limit themselves, in the first instance, to only establishing the module and number of teeth, as well as the pressure angle (often 20 degrees or 22.5 degrees), the spiral angle (almost always 35 degrees), and face width (approximately one-third of the outer cone distance) values. It is almost embarrassing to think that the tooth thickness and tooth root radius, which are considered so carefully for cylindrical gear wheels and so important when calculating the bending strength, are ignored when designing bevel gears. Even if standards to calculate strength for both cylindrical (ISO 6336 and AGMA 2001) and bevel gears (ISO 10300 and AGMA 2003) require the values of both tooth thickness and tooth root radius or provide formulas to calculate them (AGMA 929), designer of bevel gears are not always able to fix these values in the drawings.

Most of the time, bevel gear designers that do not have dedicated machine tool software try to guess what the face angle of blank and the root angles will be, as well as tooth thickness, possibly wishing for a full radius for the tooth root. At the present time, the freely accessible bibliographical source offering the most realistic definition of the final geometry of spiral face milling is Ref. 9.

	A	B	C
Mean circular thickness pinion [mm]	7.85	7.60	7.01
Mean circular thickness gear [mm]	3.10	3.40	3.98
Whole depth	8.09	8.40	8.09
Edge radius used in strength—pinion [inch]	0.015	0.020	0.040
Edge radius used in strength—gear [inch]	0.060	0.035	0.045
Cutter radius [inch]	3.000	3.750	3.000
Geometry factor—Strength—J pinion	0.2878	0.2831	0.2769
Geometry factor—Strength—J gear	0.2909	0.2861	0.3440
Strength factor Q—pinion	10.889	11.071	11.318
Strength factor Q—gear	2.74577	2.79255	2.32188

Table 1—Three different cases of Duplex Helical Spiral Bevel with the same number of teeth (13–51), module (4.126), facewidth (30 mm), and pressure angle (22.5 degrees).

In some cases, the drawing comprises two stages and keeps track of the effect of the closed loop as shown in Figure 3. The top half shows the geometry defined by the designer, while the bottom half shows the actual geometry, taken from the dimension sheet generated by the workshop.

In other cases, the same drawing of the bevel gear pair with only basic data is sent to many suppliers. Each of them cuts according to different parameters (Table 1). The same spiral gear pair is manufacturing with different geometries and so with different strength. In this case, the technical department cannot send a realistic calculation report to customers or to certification bodies.

This primitive closed loop for bevel gears, which limits itself to intervening in the design process prior to part manufacture, in other words to intervening exclusively in the definition of specifications, could terminate with the microgeometry grid obtained by GMM being transferred to the design software.

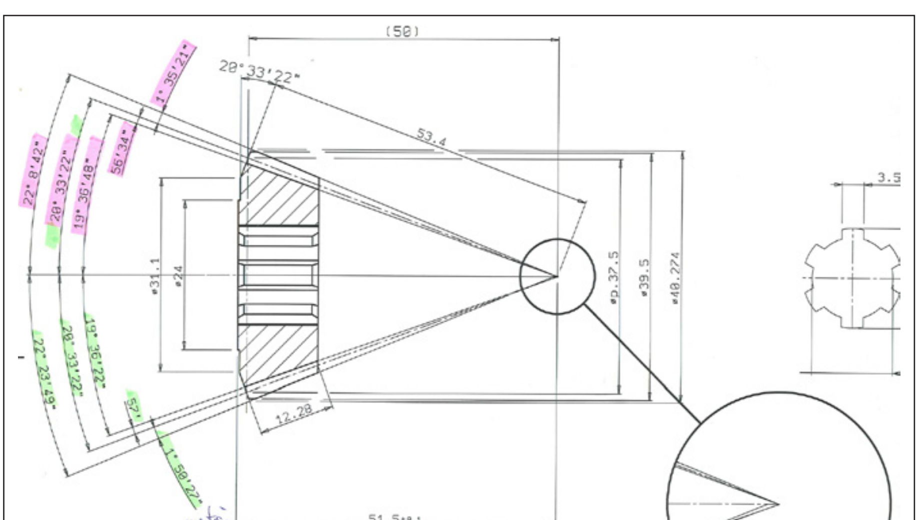


Figure 3—Drawing of a bevel gear: on the top side, there is the initial dimensioning (all apexes are in the same point). On the bottom, there are dimensions from the workshop.

Cylindrical Gears

Three different case histories can be found below in relation to cylindrical gears.

Manufacturing Twist

The first case history concerns an automotive transmission. A check was requested of the contact pattern under load of spiral gears. Given the main geometry of the two gears and deflection calculated by a multibody simulation software, analysis of contact under load with various types of microgeometry was requested:

- microgeometry defined in the drawings which included both profile and flank line crowning (Figure 4);
- microgeometry estimated by design and analysis software, which adds an unwanted yet inevitable twist due to the manufacturing process, when not compensated (Ref. 10);
- microgeometry estimated by grinding machine software applying a partial compensation method (Figure 5);
- microgeometry measured by GMM (Figure 6).

The last two were fairly similar as regards the twist, but the latter clearly is more "contaminated." In both cases, the grids could be accessed in an importable file format from the design and analysis software (Ref. 11).

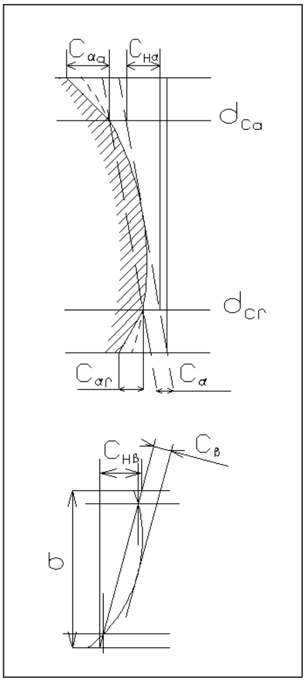


Figure 4—Profile and lead diagram not to scale, used to define micro-geometry in drawings.

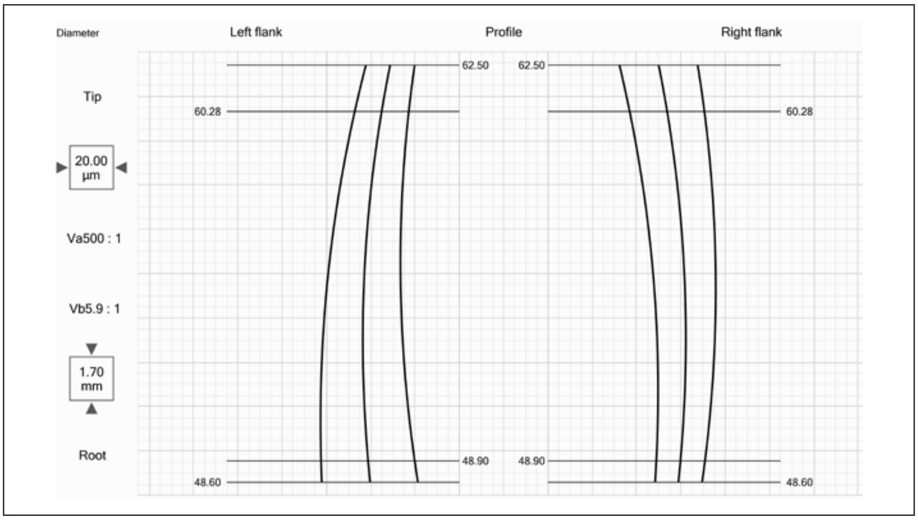


Figure 5—Profile and lead diagram, estimated by grinding control (values on axes are intentionally blank or without references).

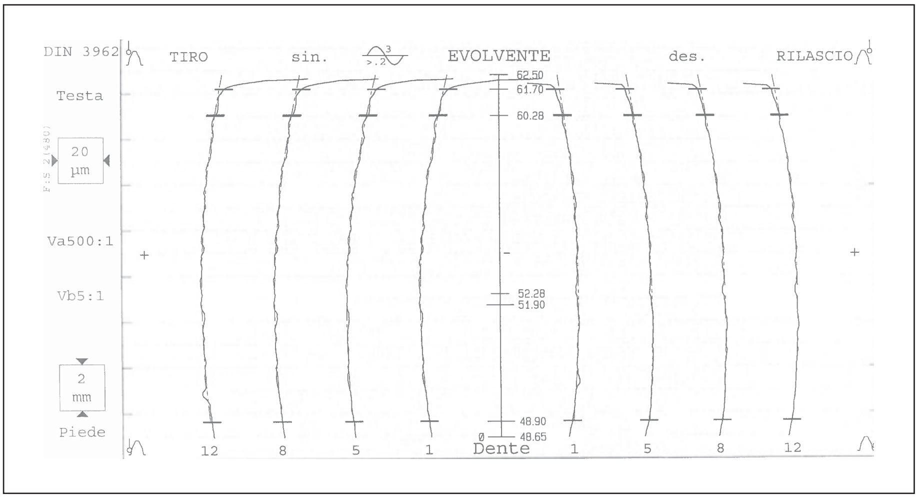


Figure 6—Profile and lead diagram, measured by GMM (values on axes are intentionally blank or without references).

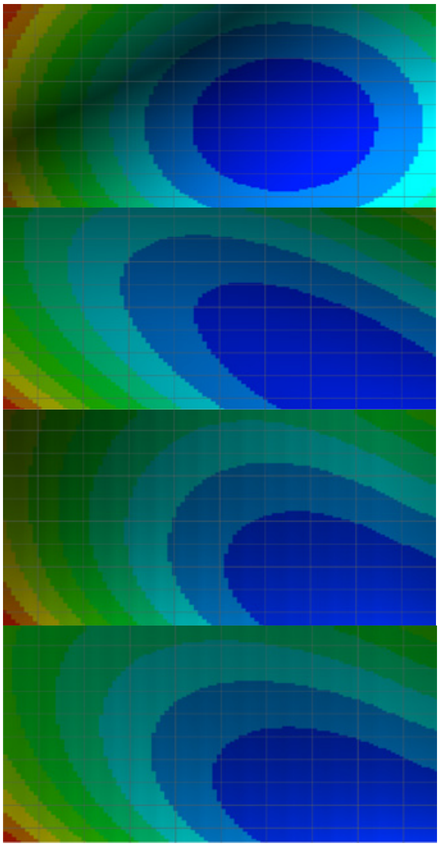


Figure 7—Some topography of the microgeometry. From top to bottom: defined in the drawing, estimated without compensation, estimated with compensation, measured (values on axes are intentionally blank or without references).

In this case, not only does the closed loop consist in being able to perform a LTCA on the measured microgeometry, but also in being able to design while taking into account the unwanted, yet clearly present, manufacturing twist.

K-chart

The second case history springs from the need to have a flexible tool to design and alter the K-profile with freedom of representation of the tolerance range. The designer needed to be able to check whether differences measured that exceeded the required tolerance were still acceptable. In this case, the technical office draws up an exemption and the design with the new tolerance area of the K-profile. These are the steps of this closed loop:

- design of cylindrical gears;
- drawings of gear, complete with K-profile with tolerance established in accordance with company specifications;
- manufacture and measurement of workpiece;
- in the event of a piece whose measurements exceed set limits, LTCA with new tolerance range;
- in the event of acceptance of results, drawing up of exemption and update of drawing with new K profile.

The tool shown in Figure 8 is an *Excel* worksheet, which reads formulation of the macro- and microgeometry from *KISSsoft* through COM interface and generates the DXF file of the K-profile for 2D drawings.

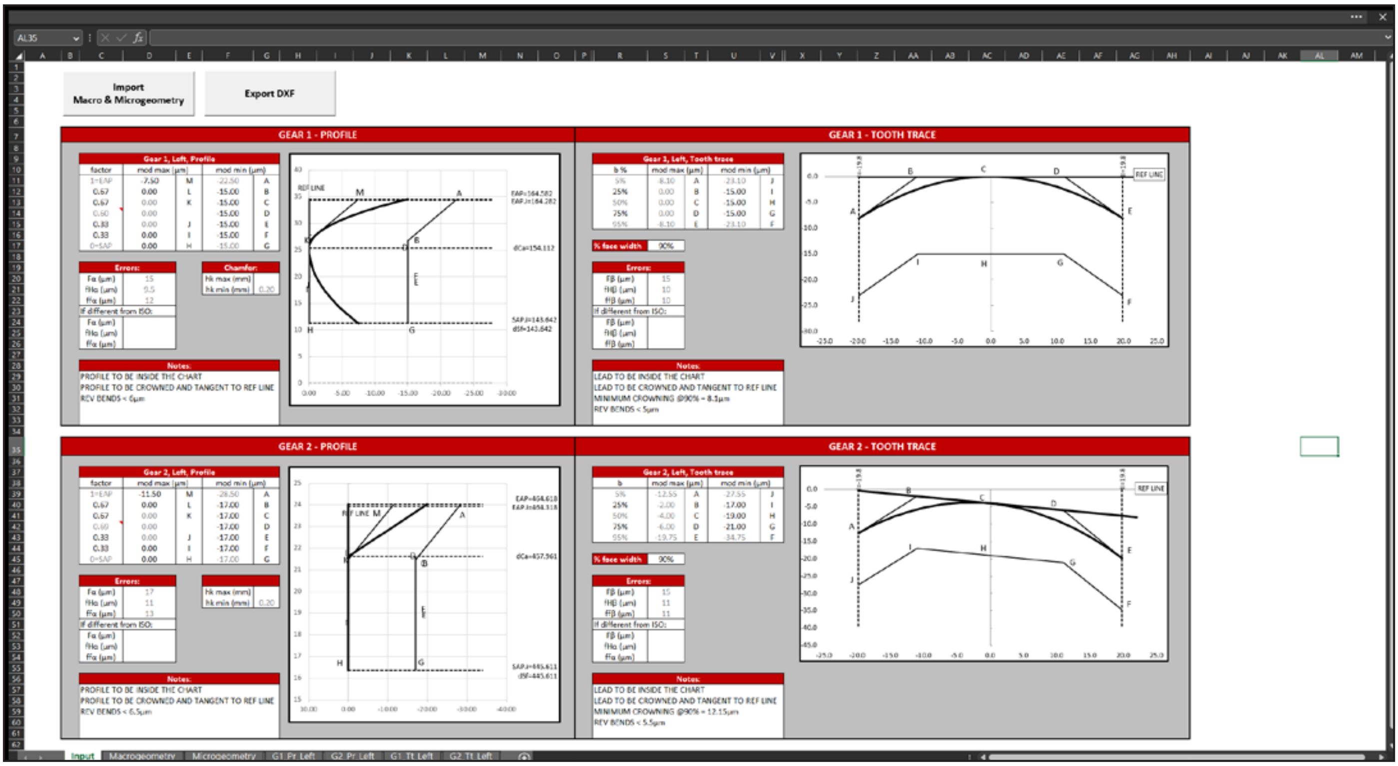
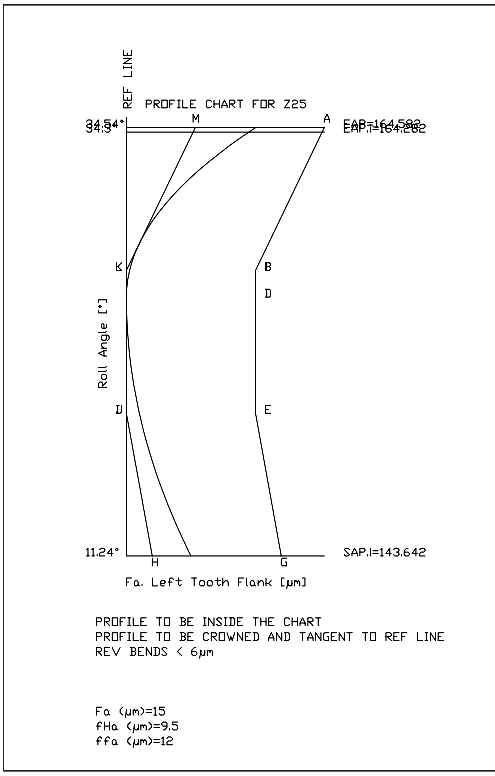


Figure 8—Excel tool to define K-chart tolerances.



	PROFILE CHART			
	Fa[µm]	xi [°]	Ly[mm]	d[mm]
A	-23	34.54	42.48	164.58
B	-15	26.77	32.93	155.58
C	-15	26.77	32.93	155.58
D	-15	25.33	31.15	154.11
E	-15	19.01	23.38	148.51
F	-15	19.01	23.38	148.51
G	-18	11.24	13.83	143.64
H	-3	11.24	13.83	143.64
I	0	19.01	23.38	148.51
J	0	19.01	23.38	148.51
K	0	26.77	32.93	155.58
L	0	26.77	32.93	155.58
M	-8	34.54	42.48	164.58

Figure 9—K-chart DXF file generated by the tool of the previous figure.

Waviness

The third case history concerns the need to limit the profile waviness (reverse bending), which some companies are showing on their drawings (Ref. 12).

A possible definition of waviness could be the distance between two peaks on involute profile measured in perpendicular direction with to the involute profile. Waviness w is measured only among peaks that are spaced at least 20 percent of the length of path of contact ($Lw > 0.2\ g_\alpha$). The maximum acceptable waviness could be defined by a fraction of the profile error (profile form deviation) $f_{f\alpha}$. However, no tolerance value has been yet standardized for these values (Ref. 13).

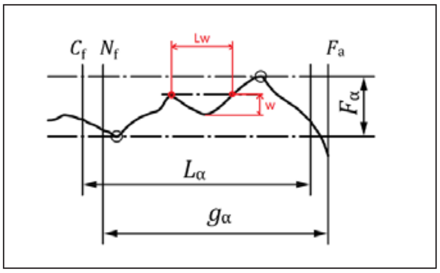


Figure 10—Waviness.

In this case, the closed loop consists of assessing the effect of the measured waviness on the transmission error.

The measured profile is then exported from GMM and imported into the design and analysis software (Figure 11). Waviness effects have been quantified with a loaded contact analysis (Figure 12). This type of analysis can be performed considering a single tooth or every tooth of the gear, using a fast GMM (Ref. 14), and a TCA software can manage different microgeometry for each tooth (Ref. 11).

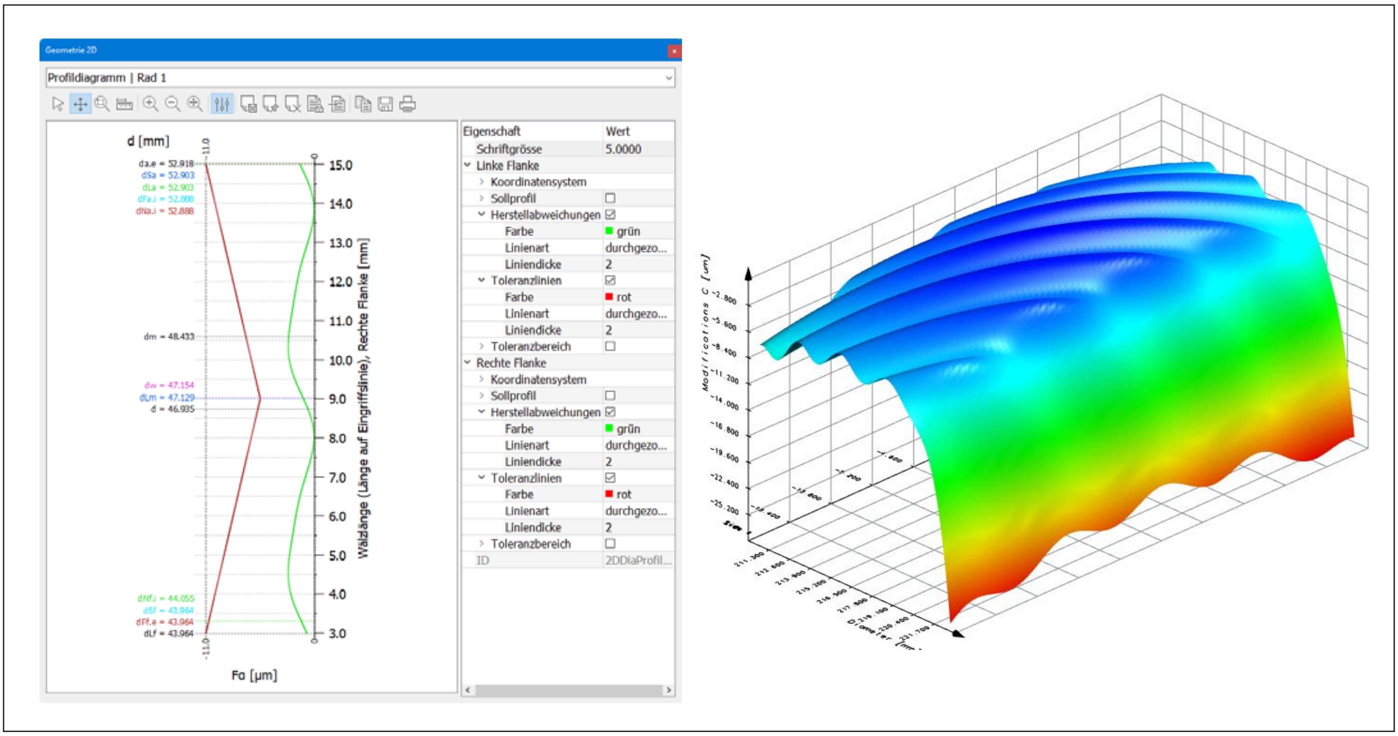


Figure 11—Measured profile with waviness imported into KISSsoft (Ref. 11).

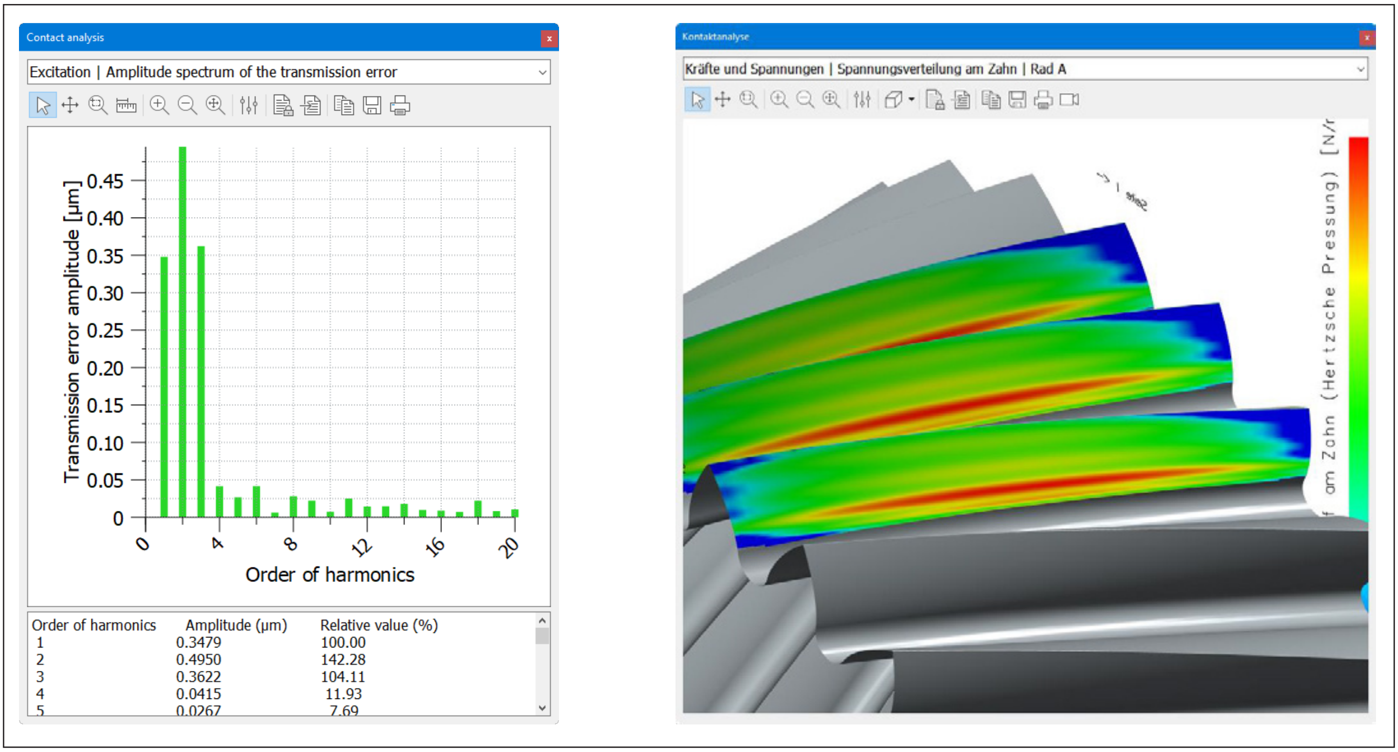
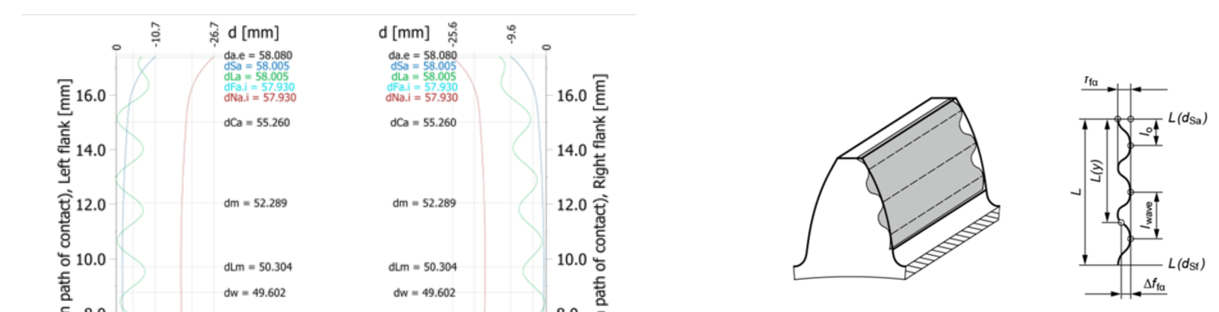


Figure 12—Results of the LTCA, considering the measured profile with waviness (Ref. 11).



d_{Sa}	profile form deviation, start, at tip	d_{Sf}	profile form deviation, end, at root
L	roll length	l_0	phase shift
l_{wave}	wave length	$f_{f\alpha}$	profile form deviation, value

	Value	Factor 1	Factor 2
Inputs	$f_{f\alpha}$	l_{wave}/m_n	l_0/m_n
Conditions	> 0	> 0	-
Equation	$\Delta f_{f\alpha} = \frac{f_{f\alpha}}{2} \cdot \left[1 - \sin\left(90^\circ + 360^\circ \cdot \left(\frac{L(y)}{Factor\ 1 \cdot m_n} - \frac{Factor\ 2}{Factor\ 1}\right)\right)\right]$		

Figure 13—$f_{f\alpha}$ modification to simulate waviness in the design process (Ref. 11).

However, before getting the measured profile form GMM, a first attempt to consider waviness during the design process could be made by adding the modification of profile form $f_{f\alpha}$ with analytic formulation (Figure 13).

Worm Wheels

The design (specification) for worm gearboxes often lacks specific information regarding crowning, hence regarding the contact pattern under load.

Suggestions concerning what the contact pattern should be like can be found in Ref. 15, as shown in Figure 14.

Generally speaking, crowning is obtained by oversizing the hobbing tool with regard to the worm dimensions (Refs. 16, 17) and by tilting it in relation to the worm's axis, at a clearly increased center distance.

Unlike cylindrical gears, whose microgeometrical adjustments are usually obtained during grinding, with specifically dressable tools, worm wheels, in bronze or cast iron, are finished by the hobbing. So the cutter's resharpening and changing the tool diameter also changes the contact pattern in the worm wheel.

These conditions must be complied with in order for meshing requisites to be met (Ref. 18).

$$d'_{m0} \cdot \sin\gamma'_0 = d_{m0} \cdot \sin\gamma_{m1} \qquad (1)$$

$$\eta = \gamma'_0 - \gamma_{m1} \qquad (2)$$

$$\tan\gamma''_0 = \frac{d'_{m0}}{d''_{m0}} \cdot \tan\gamma'_0 \qquad (3)$$

where

d_{m1} is the worm reference diameter

γ_{m1} is the reference lead angle of worm

d'_{m0} is the oversized hobber reference diameter

γ'_0 is the oversized hobber reference lead angle

d''_{m0} is the hobber reference diameter after resharpening

γ''_0 is the hobber reference lead angle after resharpening

η is the backing angle of the hobber

Some companies have recently adopted the closed loop for worm screw crowns by following the steps listed below:

- design of the worm gearbox (worm and worm wheel) providing for an oversize of the crown cutter (Figure 15);
- numerical and graphical check of contact pattern (Figure 16);
- generation of "hobber tip diameter | backing angle of the hobber | cutting center distance" table, taking into account that the hobber tip diameter decreases when resharpened (Table 2);
- exporting of grid for GMM without taking into account cutter oversize (digital master) (Figure 17);
- cutting as per listed parameters;
- measurement on GMM and comparison with digital master (Figure 18).

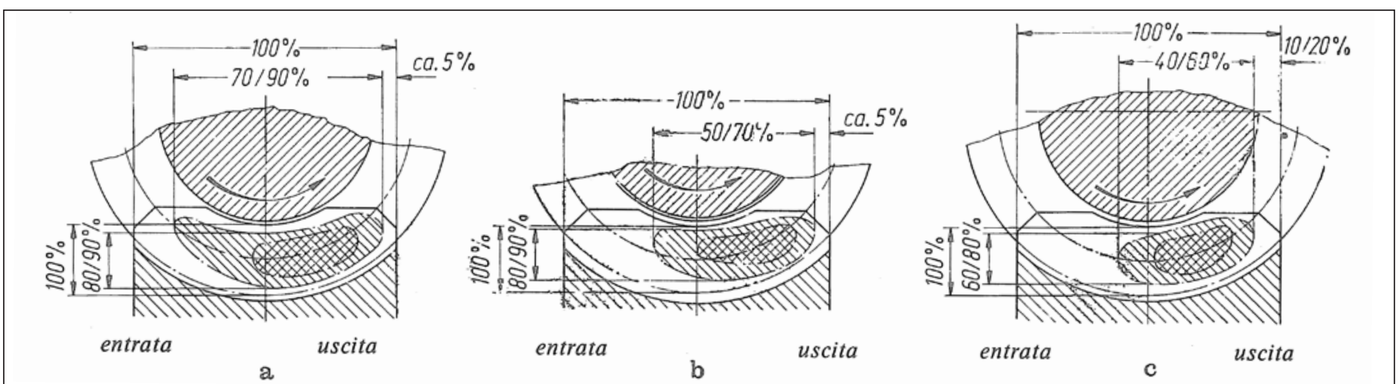


Figure 14—Proposal for the contact pattern in worm gearboxes (Ref. 15).

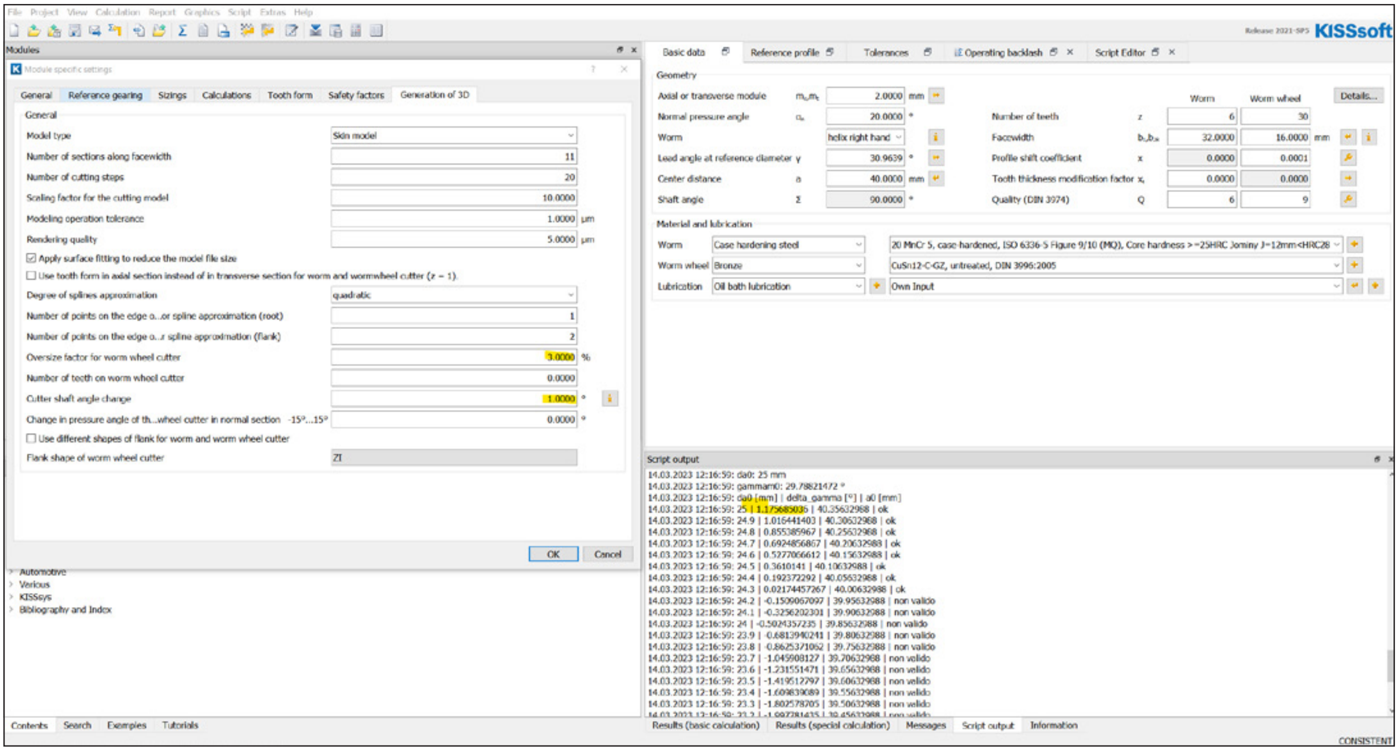


Figure 15—Design of the system worm and worm wheel with oversized hobber (Ref. 11).

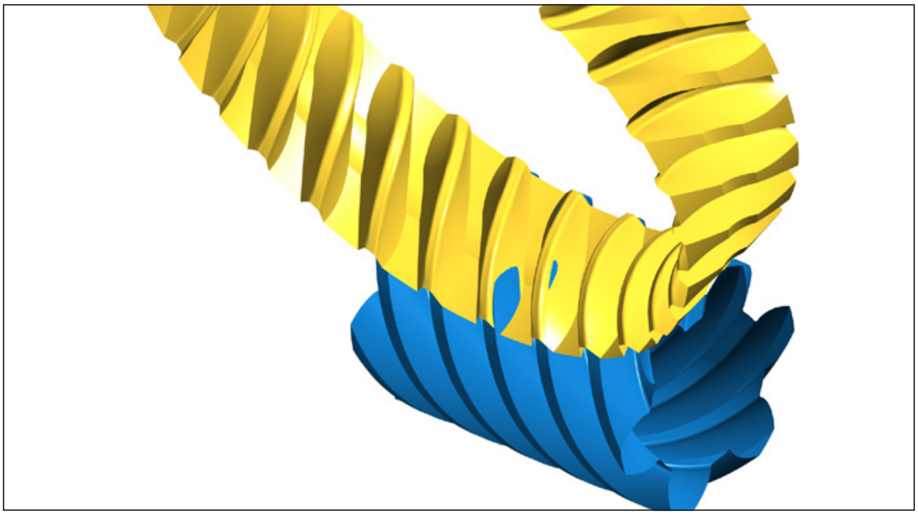


Figure 16—Check of the contact pattern on the design software (Ref. 11).

d_{a0} [mm]	η [°]	a [mm]	usability
24.887	0.996396079	40.30	✓
24.787	0.835111711	40.25	✓
24.687	0.671978307	40.20	✓
24.587	0.506961855	40.15	✓
24.487	0.340027451	40.10	✓
24.387	0.171139267	40.05	✓
24.287	0.000260518	40.00	✓
24.187	-0.172646576	39.95	χ

Table 2—Backing angle of the hobber and manufacturing center distance vs. resharpened hobber tip diameter.

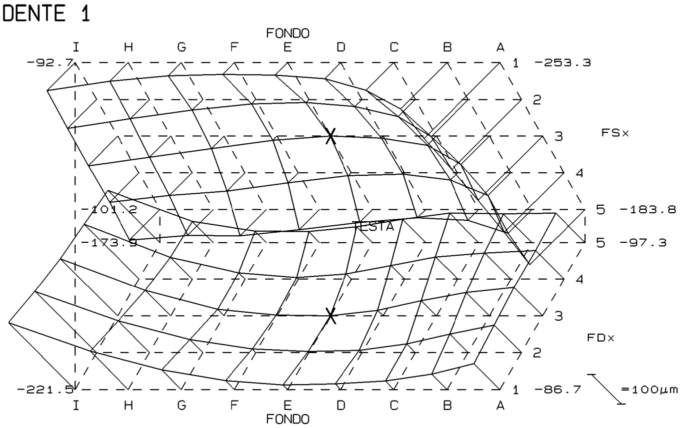
RECHTE FLANKE RAD
DATUM / ZEIT : 11.01.2022 / 11:54

IN SPALTE 5 / ZEILE 3 : ZAHNDICKENWINKEL = 0.119521 rad

J	I	XP	YP	ZP	XN	YN	ZN
1	1	-4.8699	-45.9436	-8.9981	-.8625	-.0671	.5014
1	2	-4.7820	-46.7550	-8.9981	-.8520	-.1153	.5105
1	3	-4.6463	-47.5668	-8.9981	-.8407	-.1648	.5157
1	4	-4.4665	-48.3772	-8.9981	-.8293	-.2071	.5189
1	5	-4.2429	-49.1910	-8.9981	-.8176	-.2429	.5219
2	1	-3.6710	-44.8900	-6.7486	-.8775	-.0654	.4750
2	2	-3.5530	-45.9931	-6.7486	-.8597	-.1182	.4969
2	3	-3.3669	-47.0950	-6.7486	-.8430	-.1715	.5096
2	4	-3.1057	-48.1983	-6.7486	-.8263	-.2253	.5160
2	5	-2.7704	-49.2985	-6.7486	-.8101	-.2721	.5192
3	1	-2.5962	-44.2012	-4.4991	-.8946	-.1266	.4284
3	2	-2.3974	-45.4065	-4.4991	-.8717	-.1647	.4614
3	3	-2.1437	-46.6103	-4.4991	-.8501	-.2011	.4865
3	4	-1.8276	-47.8081	-4.4991	-.8292	-.2435	.5029
3	5	-1.4350	-49.0099	-4.4991	-.8080	-.2909	.5122
4	1	-1.6439	-43.8121	-2.2495	-.9018	-.1931	.3863
4	2	-1.3700	-44.9346	-2.2495	-.8783	-.2313	.4183
4	3	-1.0504	-46.0619	-2.2495	-.8549	-.2583	.4497
4	4	-0.6948	-47.1785	-2.2495	-.8334	-.2807	.4759
4	5	-0.2979	-48.2897	-2.2495	-.8128	-.3070	.4949
5	1	-0.7733	-43.6874	0.0000	-.8978	-.2878	.3330
5	2	-0.4134	-44.7845	0.0000	-.8777	-.3132	.3624
5	3	0.0000	-45.8799	0.0000	-.8544	-.3394	.3933
5	4	0.4501	-46.9695	0.0000	-.8317	-.3564	.4256
5	5	0.9284	-48.0469	0.0000	-.8090	-.3716	.4553
6	1	0.0538	-43.8436	2.2495	-.8849	-.3771	.2730
6	2	0.5224	-44.9530	2.2495	-.8657	-.3939	.3087
6	3	1.0551	-46.0604	2.2495	-.8394	-.4245	.3391
6	4	1.6332	-47.1539	2.2495	-.8130	-.4476	.3722
6	5	2.2470	-48.2373	2.2495	-.7885	-.4581	.4102
7	1	0.8750	-44.2686	4.4991	-.8787	-.4232	.2207
7	2	1.4947	-45.4482	4.4991	-.8464	-.4770	.2366
7	3	2.1863	-46.6071	4.4991	-.8167	-.5139	.2621
7	4	2.9439	-47.7552	4.4991	-.7874	-.5430	.2916
7	5	3.7553	-48.8872	4.4991	-.7589	-.5632	.3268
8	1	1.7469	-45.0071	6.7486	-.8630	-.4810	.1543
8	2	2.4083	-46.0653	6.7486	-.8213	-.5499	.1513
8	3	3.1398	-47.1065	6.7486	-.7934	-.5852	.1670
8	4	3.9328	-48.1327	6.7486	-.7645	-.6176	.1844
8	5	4.7844	-49.1436	6.7486	-.7358	-.6451	.2057
9	1	2.7470	-46.1188	8.9981	-.8273	-.5540	.0926
9	2	3.3081	-46.8823	8.9981	-.7887	-.6086	.0854
9	3	3.9020	-47.6297	8.9981	-.7690	-.6317	.0970
9	4	4.5342	-48.3724	8.9981	-.7459	-.6574	.1062
9	5	5.2007	-49.1034	8.9981	-.7227	-.6812	.1161

Figure 17—Grid exported by the design software.

DENTE 1



Tpz:22.1 C Ta:23.3 C T: (#10.1) 1 mm

Grandezza caratteristica	teorica	reale	scost.	tol.inf.	tol.sup.	unità
Somma degli assoluti		3966.1				μm
Corda sez. front.	5.481	5.488	0.007			mm
(E3; R=45.880; Z=0.000)						mm
Dist. di montaggio	0.0000	0.0000	0.0000			mm

FONDO (FSx)

	I	H	G	F	E	D	C	B	A
1	-92.7	-62.5	-43.9	-39.1	-42.6	-54.0	-92.1	-153.9	-253.3
2	-96.4	-64.4	-35.3	-14.8	-10.8	-23.6	-57.1	-123.1	-233.1
3	-98.0	-70.5	-41.4	-13.7	0.0	-6.3	-30.4	-94.9	-214.2
4	-97.7	-75.6	-60.9	-33.6	-10.8	-4.5	-23.7	-75.1	-197.6
5	-101.2	-85.0	-87.3	-67.6	-42.6	-28.3	-36.7	-79.3	-183.8

FSx

TESTA

FDx

	I	H	G	F	E	D	C	B	A
5	-173.9	-69.9	-37.3	-35.7	-51.6	-76.7	-97.3	-95.0	-97.3
4	-182.7	-72.6	-21.1	-6.0	-17.9	-46.2	-74.3	-87.2	-95.1
3	-191.0	-84.6	-21.2	-2.6	0.0	-18.6	-50.8	-76.9	-95.1
2	-204.6	-105.3	-42.8	-11.6	-2.7	-7.9	-28.7	-61.8	-90.9
1	-221.5	-126.8	-65.2	-30.2	-15.2	-18.2	-28.3	-50.6	-86.7

FONDO (FDx)

Unità: [μm]

Figure 18—GMM measurement (A) and report (B).

The first result to check in the GMM report is the tooth thickness (chordal in transverse section): this is what makes it possible to keep a check on gearing backlash. Single-flank gear inspection was performed prior to adopting this procedure.

Figure 18B shows crowning until the tool reaches the end of its life. Crowning disappears at the precise moment when the tool takes on the worm's dimensions.

The operator has the same software in the workshop as used during design and can generate the grid (digital master) that takes into account the actual dimensions of the cutter that cut the wheel it is measuring. In this case, the drawing will not show crowning, but only any errors.

Conclusions

The goal of this paper was to help the reader improve the documentation and performance of bevel, cylindrical and worm gears. The closed loop is an improvement in the manufacturing process of gears, which connects design and production in a two-way manner. A necessary condition for its adoption is an awareness that specification and verification must also be connected. You cannot request what you cannot measure. The measurement process must be defined in a clear, unambiguous way, just as the measurements to be taken already are.

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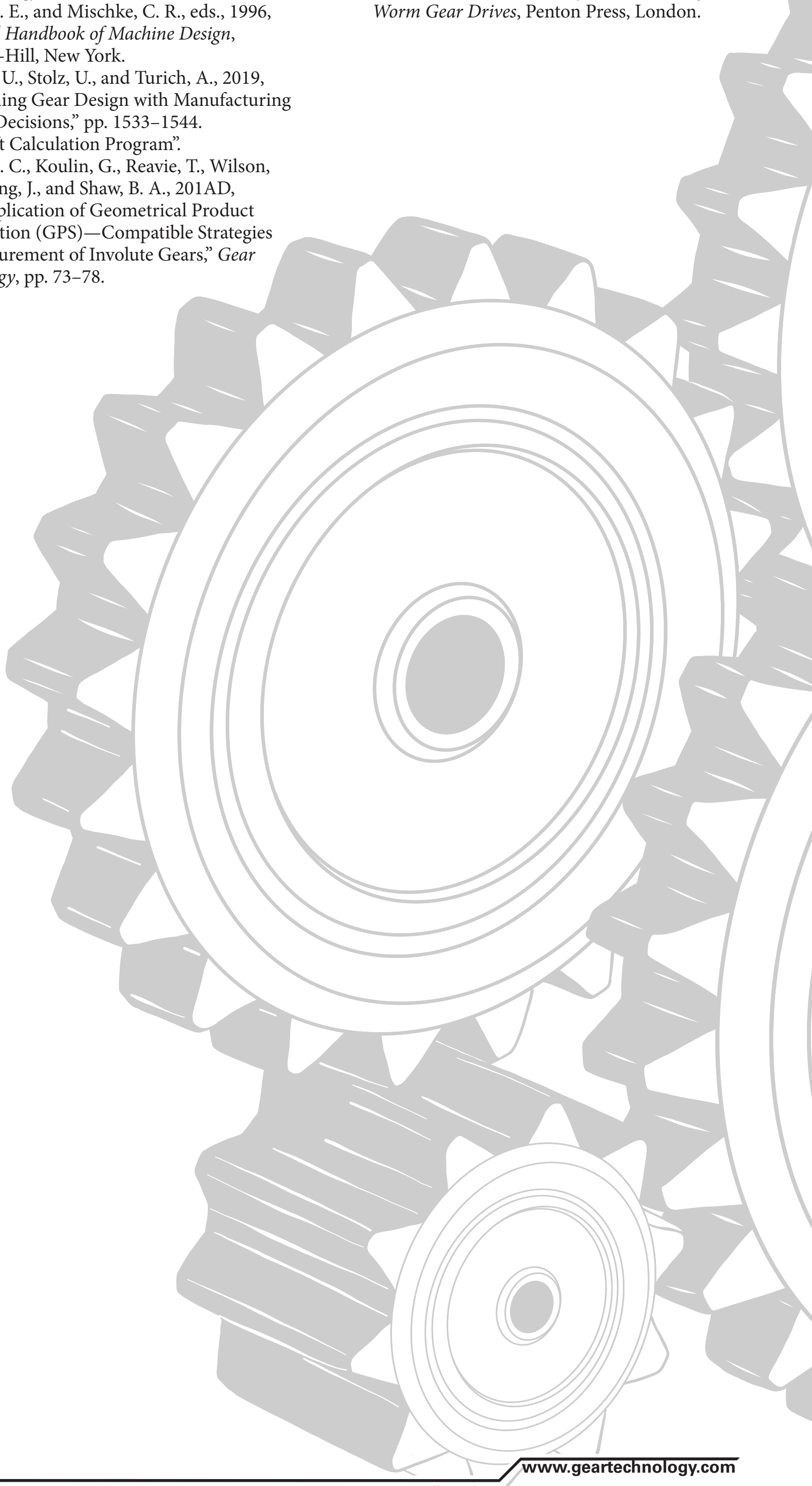

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