Hard Finishing and Fine Finishing Part 2

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Editor's Note: Part I of this article dealing with the geometry of gear flanks, kinematics, and drive systems, tools, and computer assistance for hard and fine finishing, appeared in our last issue.

Operating Sequences and Machining Results

Fig. 1 shows the possible operating sequences for fine finishing and for hard finishing, integrated into the traditional sequences. It clearly follows from this table that the aims of fine finishing differ from those of hard finishing.

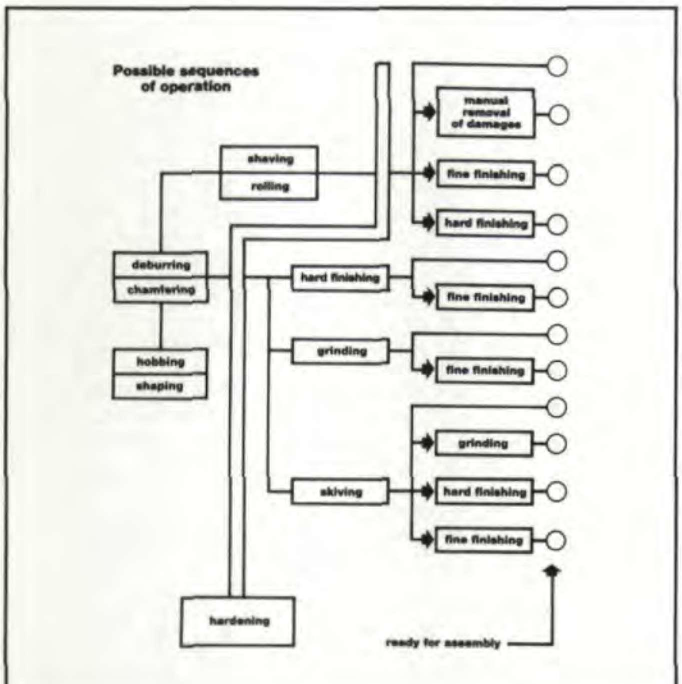

Fig. 1 – Operating sequences for fine finishing and for hard finishing.

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After shaping or hobbing, the tooth flanks must be either chamfered or deburred. Here it is paramount that the secondary burr produced will not be formed into the flank, but to the face of the gear, because during hardening, the secondary burr will straighten up and, due to its extreme hardness, will lead to excessive tool wear.

It is characteristic of all further operating sequences represented that the tooth gearings produced are ready for immediate assembly. Which of the operating sequences shown is optimal will depend on the quality required, on economic considerations, and on the circumstances of the sequences available.

Now we will show some examples of fine finishing and hard finishing. Along with conventional evaluations using the measurements of profiles, tooth traces, and pitch, statistical evaluations will be made to document the uniform output. To this end, workpieces are taken from manufacturing lines, and the results of profile and tooth trace measurements are plotted by using a point of reference. Thus, broom diagrams, whose range of tolerance is limited by preset windows, are set up. Further evaluations are obtained by means of the double flank total composite error test and by noise measurements.

Results of fine finishing are shown in Fig. 2. Damages shown on the double flank total composite error diagram have been removed, and a distinct reduction on the broom diagrams can be seen.

After removing the damages and improving the flank geometry, fine finishing is followed by a marked reduction of the generated noise.

Noise analyses are carried out in an unloaded condition. Noise emissions of car gear transmissions are particularly annoying in the lower load range, since they tend to override those of the engine.

As you will note in Fig. 1, another aim of fine finishing is to dispense with the noise test and the manual removal of damages after hardening of shaved or rolled gears. This may be illustrated by a hard finishing mode where work gears occur with damages at the flank sides of up to 350μm. The task is essentially to remove the defects in the marginal area of the flanks, while taking into account relatively large admissible radial deviations and wobbling of the gears. On a typical customer sample this procedure resulted in a tool life of a finishing tool in excess of 8000 parts and a cycle time of about 15 seconds per part. A considerable optimization of quality and cost for finished gears in mass production can be reached because of low production costs for green shaving or rolling, the elimination of the noise test and removal of defects, and the little effort required for fine finishing. The use of simple work conveyors also contributes to higher quality and lower costs, although these conveyors are not entirely safe from causing damage themselves.

An indispensable prerequisite is, however, that the heat treatment will not lead to excessive incalculable variations of the tooth geometry.

The fine finishing process also resulted in the percentage of gear boxes returned for reassembly dropping to a range of 0.3 per thousand, though the fine finishing was not followed by a noise test. The reason is that manual removal of defects involves many subjective imponderabilities, while fine finishing ensures that even the slightest damages will be definitely removed.

Inadmissible deviations of the teeth after hardening, such as

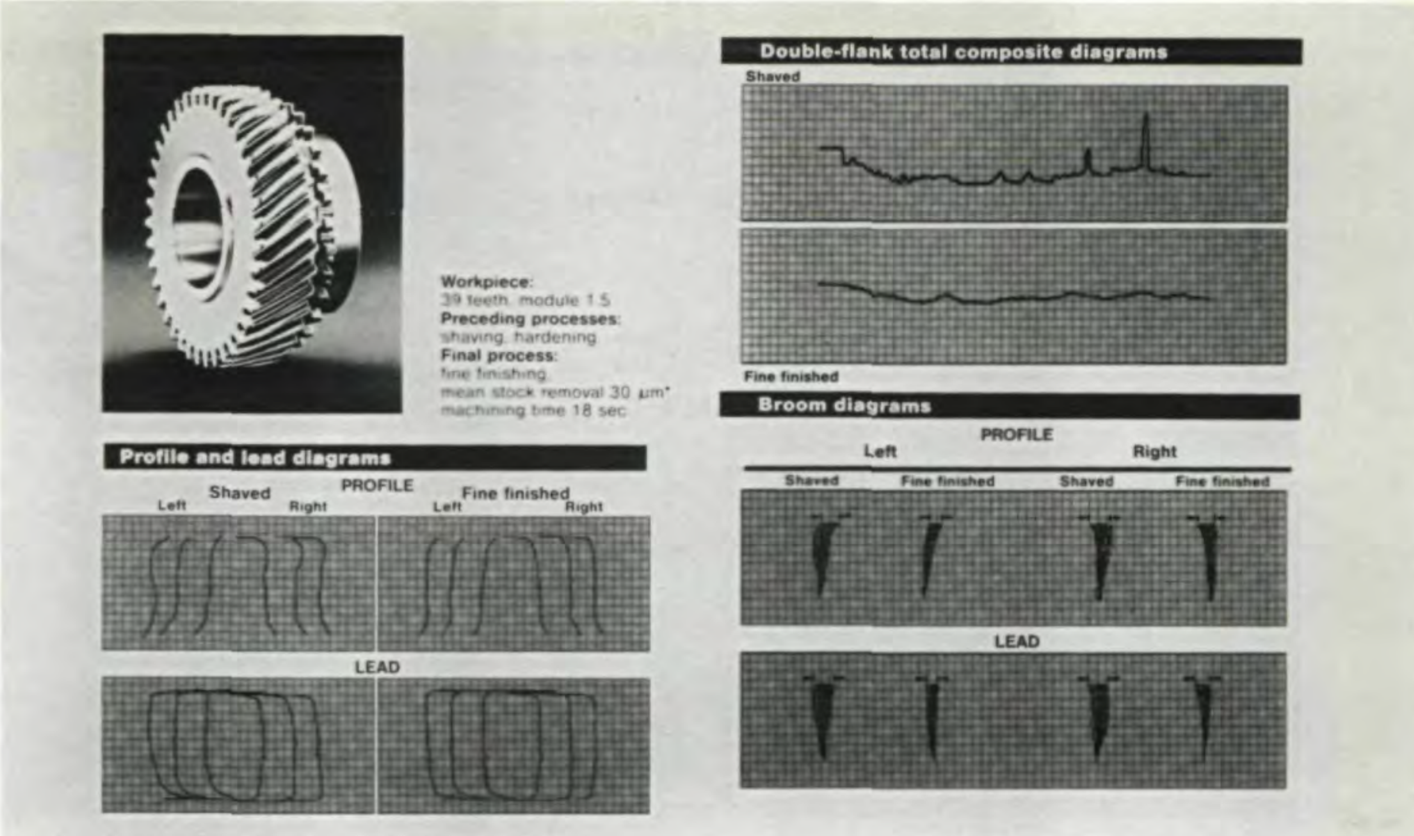

Fig. 2 – Working example of fine finishing a gear.

bent teeth, need, however, to be removed before fine finishing by means of an automatic two-flank rolling test.

Fig. 3 shows the macrogeometrical results before and after hard finishing with a CBN-coated tool. It can be seen that hard finishing will produce an entirely definite geometry of tooth flanks.

The desired gear flank has a slight profile bearing and face crowning, and it has been slightly modified at the addendum area. In this case, a stock removal per flank of 50μm will be sufficient.

Since any highly accurate hard machining process is always the most complicated and costly operation in the work flow of gear production, this production step should not be used in improper extension. A minimization of the required stock removal from the hardened flank is also appropriate for the necessary case-depth (1/10th mm of case-depth thickness will require a cementation time of about one hour) and in view of the reduction of hardness caused by the removal of excessive layers at the marginal areas.

It should be further noted that, for reasons of load capacity, the machining step in the root fillet should be as small as possible, or precutting should be carried out with the protuberance entering tangentially into the hard-finished flank.

The aim of minimizing the case depth also results from the requirement *not* to core-harden the synchro mesh gearing nor the tooth tips of addendum modified teeth with an extremely high tip and, consequently, a minimum thickness at the tip.

For the example shown the machining time was 48 seconds. As an average, quality grade 5 acc. DIN 3962 was obtained. For the roughness of the flanks we have $R_{ZD} = 3\ \mu m$, $R_a = 0.45\ \mu m$. The variation of the measurement over flanks is less than 20 μm.

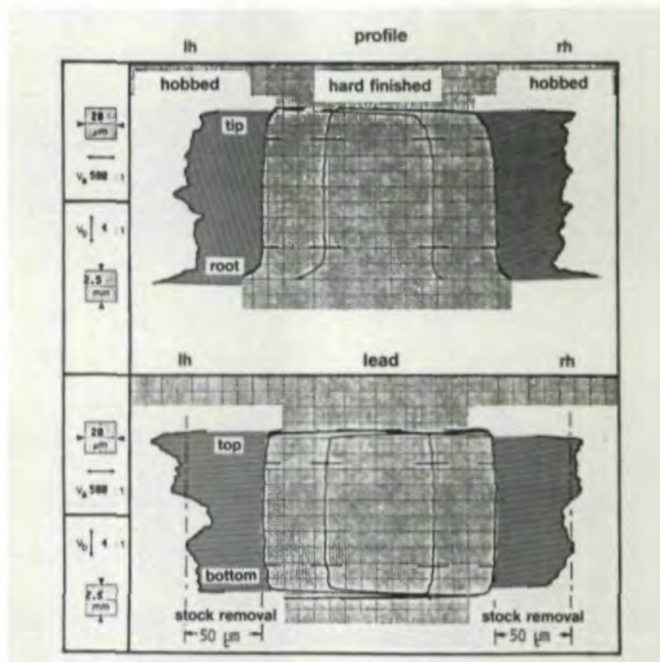

Fig. 3 – Profile and lead diagrams before and after hard finishing.

Results from hard finishing are presented in Tables 1 and 2 together with profile, lead, and pitch measurement records. (See Figs. 4-12.)

In the middle of the profile and lead records the required modifications are given.

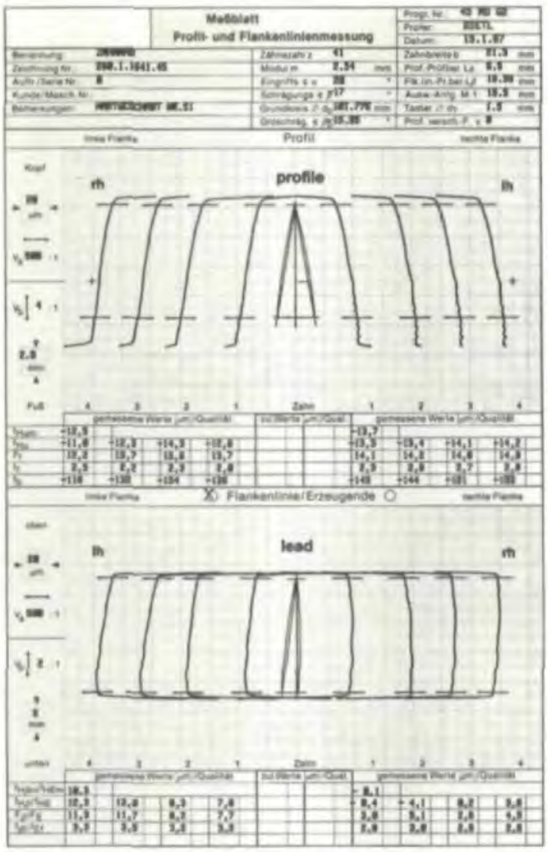

Fig. 4 – Machining example of hard finishing No. 1.

Table 1
Machining Examples of Hard Finishing

	Fig. 14/15 Example 1	Fig. 16/17 Example 2	Fig. 18/19 Example 3	Fig. 20/21/22 Example 4
Number of teeth	41	32	51	31
Module	2.54	1.75	2	1.75
Pressure angle	20°	15°	15°	17.5°
Helix angle	−17°	−25.75°	29.5°	−30.5°
Face width	21.5 mm	16.7 mm	17 mm	16.5 mm
Application	1st speed	3rd speed/ collar	1st speed	5th speed
Modification of pressure angle	lh/rh 12μm slanting	lh tip relief rh slanting by 4 μm	lh/rh tip relief	lh/rh tip relief
Profile crowning	lh/rh 2 μm	lh/rh 3 μm	lh/rh 3 μm	lh/rh 3 μm
Modification of helix angle	lh 10 μm rh 0 μm	lh 25 μm rh 12 μm	lh 8 μm rh face mod.	lh 7 μm rh 0 μm
Lead crowning	lh/rh 2 μm	lh/rh 4 μm	lh 4 μm rh 2 μm	lh/rh 5 μm
Cutting material	corundum	CBN	corundum	CBN
Bonding + blank	ceramic wheel	nickel + steel wheel	ceramic wheel	nickel + steel wheel
Premachining	pre-shaved	shaped	hobbed	hobbed
stock removal/flank	55 μm	45 μm	50 μm	50 μm
Quality acc. DIN 3962	5 to 6	5	6	6
Surface roughness R_{ZD}	2 μm	7 μm with subsequent fine finish.	3 μm	4 μm
Machining time	67 sec.	69 sec.	71 sec.	49 sec.
Tool life/per dressing cycle	30 off	total 8,000 off	25 off	total 7,300 off
Number of dressing cycles	35 off	–	30 off	–
Number of recoatings per tool	–	5	–	5

Experience with successful modifications for noise reduction in wide load ranges demonstrate that what matters is correctly chosen modifications of the pressure angle and helix angle with the least possible crowning. As a rule, the drive flank and the coast flank should be modified differently. Flank corrections in the lead-in and lead-out area are carried out degressively. In

Table 2
Main Characteristics of Fine Finishing and Hard Finishing

	Fine finishing	Hard finishing
Machine concept	• development from modular system of green shaving machine	• same
	• connected load 12 kVA	• connected load 15 kVA
	• part is driven and brake force applied to tool	• part and tool are kinematically locked to a master gear transmission
	• stored-program control	• CNC controlled, two axes
	• no additional motions during machining	• radial infeed
Tool	• external gear, outside diameter 230 mm	• same
	• corundum, synthetic resin bonded	• corundum, ceramic bonding or CBN coated
	• repeated dressing with diamond dresser is possible	• same
	• number of pieces per tool life depends on stock removed, number of work gear teeth, hardening distortion, radial deviation, quality of premachining, requirements on quality grade to be obtained	• same
	• example of tool life: $m = 2.2$, $Z = 35$ stock removal 2 ÷ 15 μm dressing cycle 100 ÷ 400 parts number of gears per tool life up to 8000 pcs.	• same stock removal 40 ÷ 150 μm dressing cycles 15 ÷ 60 parts number of gears per ceramic tool, up to 1200 pcs. number of gears per CBN tool, up to 10,000 pcs.
Feed and infeed	• no longitudinal feed no infeed constant distance between center lines	• same radial infeed
Meshing conditions	• continuous motion without traces of generated cut and feed	• same
	• crossed-axes angle 10 - 45°	• crossed-axes angle 6 - 20°
	• single-flank machining by reversing sense of rotation	• same
Part	• module 1.2 ÷ 6 mm	• 1 ÷ 4 mm
	• outside diameter 20 ÷ 280 mm	• 45 ÷ 250 mm
	• Width of tooth flank up to 50 mm	• up to 35 mm
	• helix angle 0° and ± 40°	• same
Tooth geometry	• depending on quality of precutting	• on an average better than quality grade 6 acc. DIN 3962
	• R_{ZD} smaller than 2 μm possible	as required: • R_{ZD} = 2 to 5 μm (ceramic) • R_{ZD} = 4 to 8 μm (CBN)
Machining time	• *about 0.5 min.*	• *depending on machining criteria, about 1 min.*

Fig. 5 — Machining example of hard finishing No. 1.

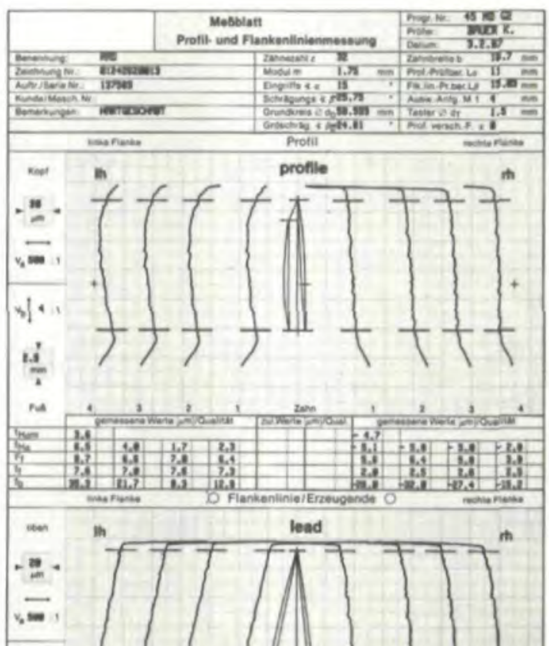

Fig. 6 — Machining example of hard finishing No. 2.

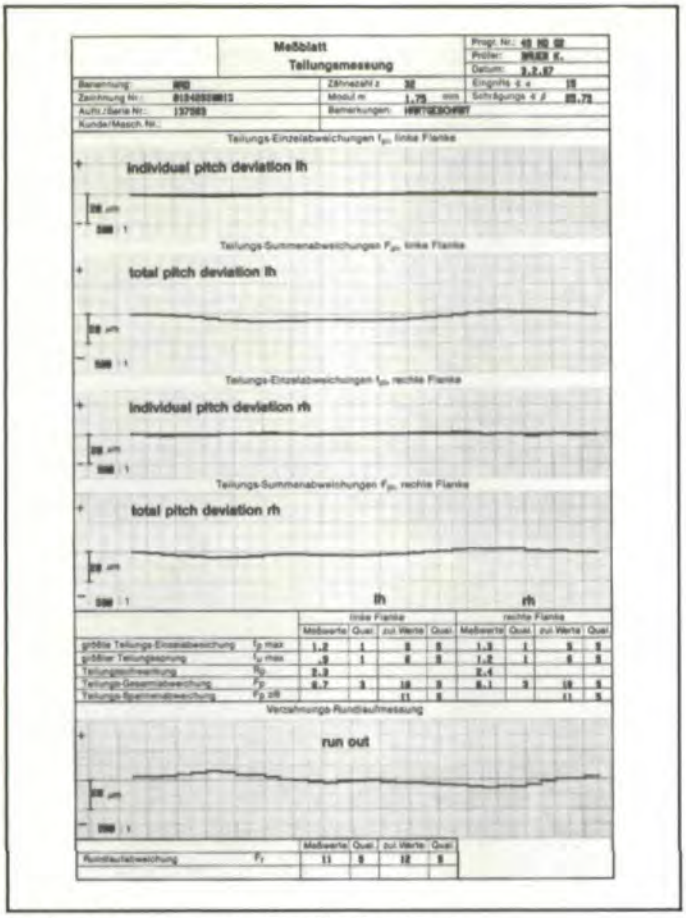

Fig. 7 – Machining example of hard finishing No. 2.

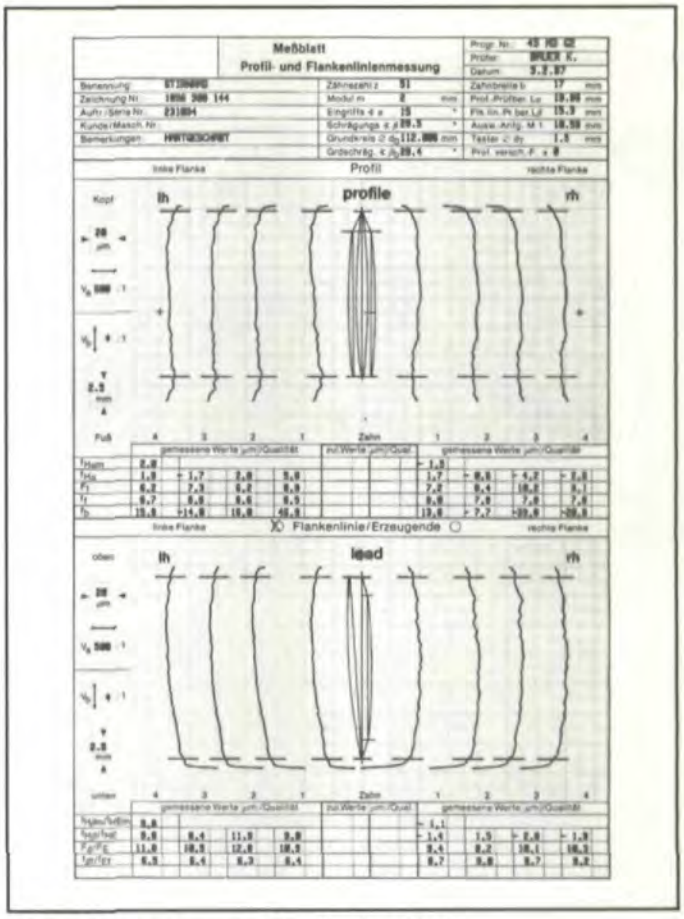

Fig. 8 – Machining example of hard finishing No. 3.

order to be able to use the least amount of crowning, the admissible pitch errors must be kept small. This will permit at the same time, the best possible distributions of contact and root fillet stresses in mesh for critically high load stages with the least possible influence of additional dynamic forces. In other words, apart from improvements on the noise sector, considerable increases of the load capacity will be obtained.

Gear Noise with Hard Finished and Fine Finished Gears

Fig. 13 schematically shows the possibilities offered by the hard machining processes in order to counter the noise generated.

A reduction of the gear noise will start with the implementation of tooth gearing data (face width, helix and pressure angle, addendum modification factor, and high tooth design, etc.).[3,6] The aim is to obtain a maximum contact ratio for smoothing the modulation of rigidity and to choose a contact ratio of an integral number of teeth, taking into account the contact conditions

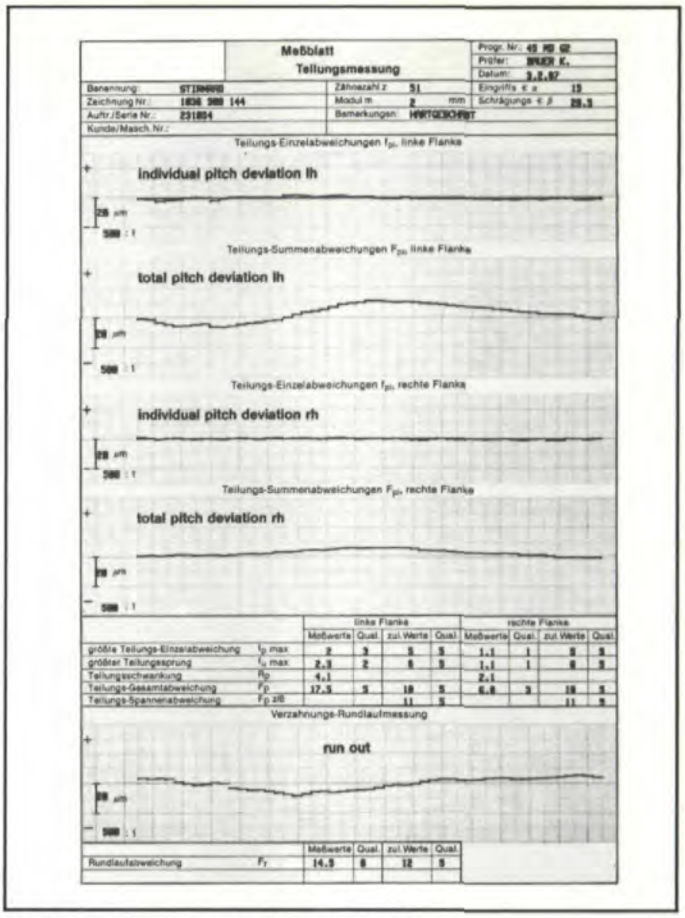

Fig. 9 – Machining example of hard finishing No. 3.

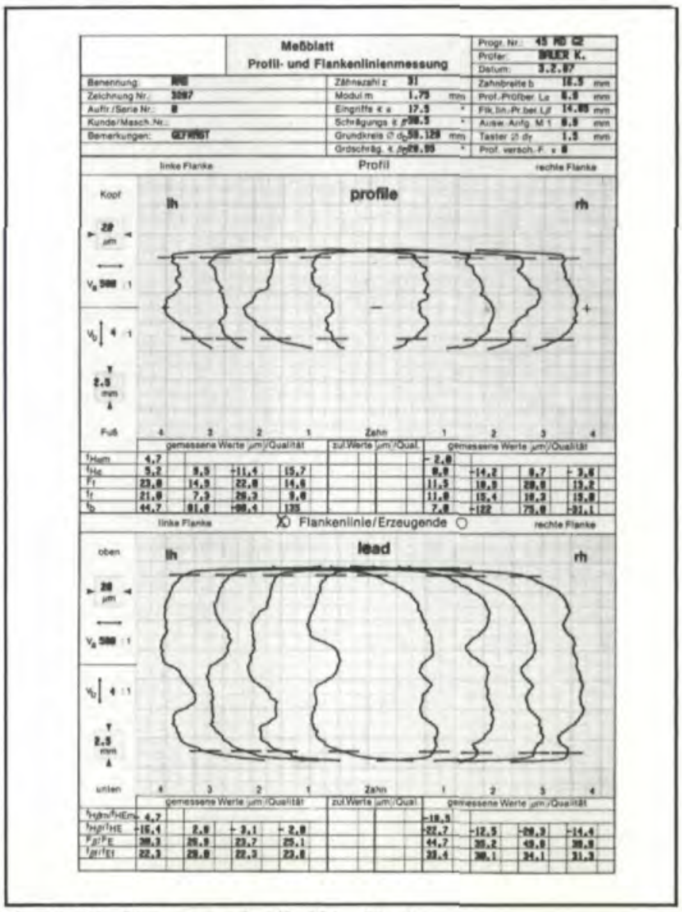

Fig. 10 – Machining example of hobbing No. 4.

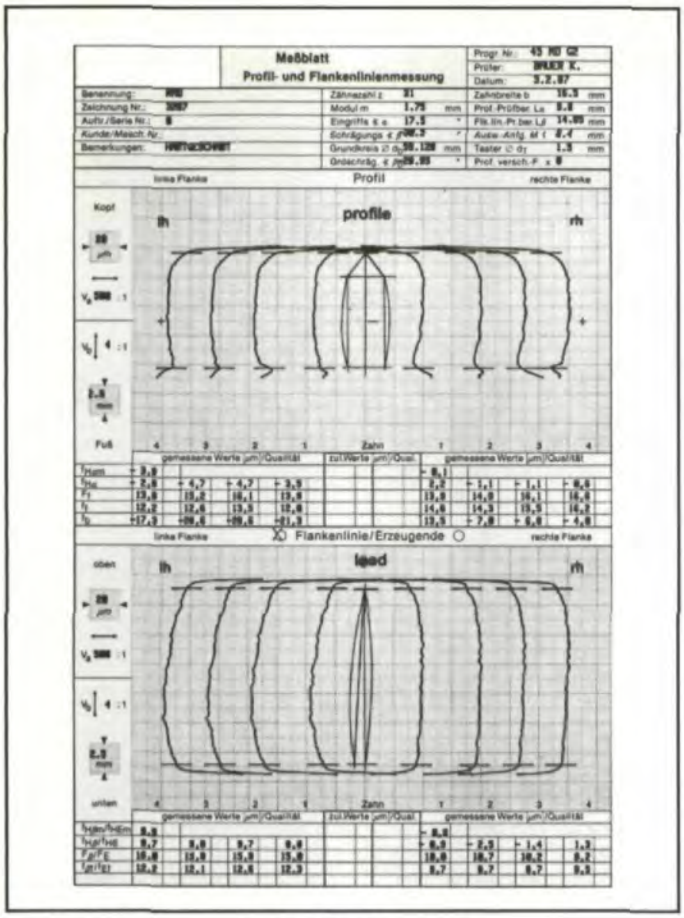

Fig. 11 – Machining example of hard finishing No. 4.

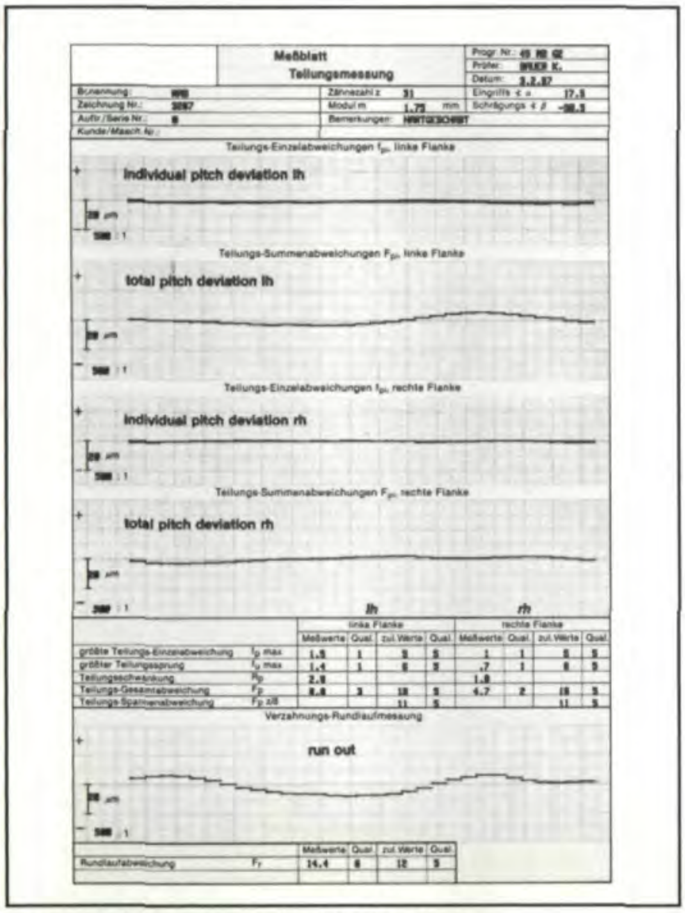

Fig. 12 – Machining example of hard finishing No. 4.

under load. The modification band width should permit a configuration of the tooth pattern that will allow no erratic variations of rigidity. Only a defined tooth bearing development will permit a modification of flanks for a wide-band load range. Otherwise heavy noise will be generated mainly in the partial load range, since the rather unyielding partial-load tooth pattern will result in a contact ratio of a non-integral number.

At the same time, the tooth contact pattern should have such an ease-off geometry that neutralizes deviations caused by manufacturing and faulty meshing due to the load is minimal.

A conclusion drawn from these circumstances is that only a tooth flank design specifically adapted to the possibility of a defined tooth pattern will be able to make full use of the essential advantages of hard finishing.

The practical procedure for defining the modifications can be ascertained by checking the tooth pattern, as with copper-plated gear flanks, with the gear unit in actual operation.

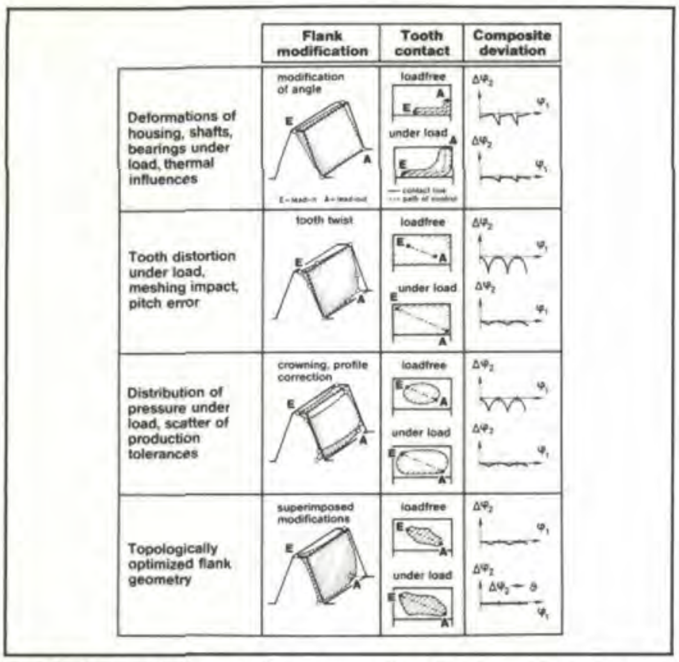

Fig. 13 – Systematic diagram of superimposed modifications of flanks for noise reduction.

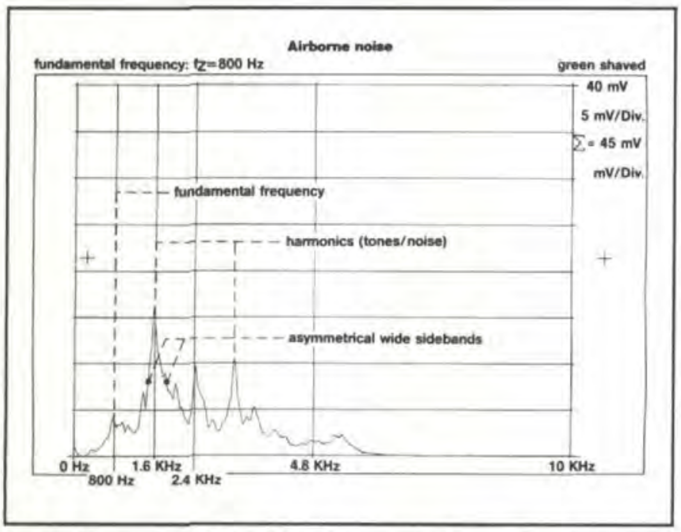

Fig. 14 – Frequency analysis of the airborne noise of green shaved gears.

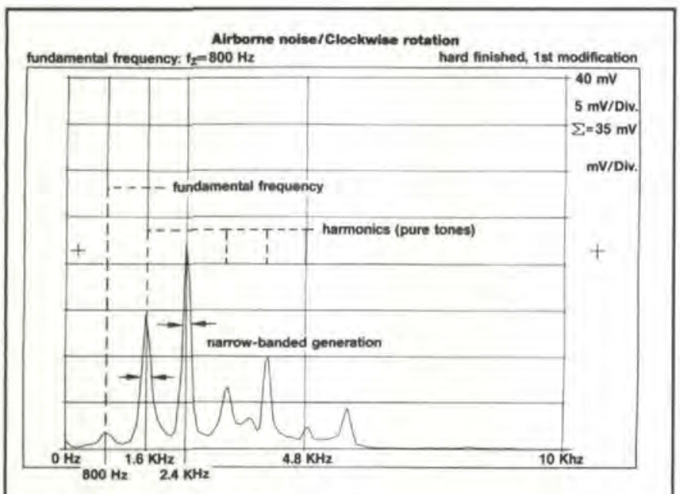

Fig. 15 – Frequency analysis of the airborne noise of hard-finished gears (first design of modifications).

The first step is to define the modifications of the helix and pressure angles.

These modifications differ for the drive and coast flank geometry according to the deformation behavior of the system of shafts and bearings, as well as of the gear housing.

Angle modifications are defined for a characteristic load stage of the gear set by evaluating the tooth patterns. According to a recognizable trend, a flexible grinding process is used to provide gears with modifications that will cover the estimated area of modification. These tests will be continued until satisfactory contact pattern (no noise behavior) is achieved.

The second step is to define modifications which will lay down the band width of the admissible load range and which will neutralize a scatter of deviations caused by manufacturing on account of production tolerances. Mainly, this would concern profile corrections in the lead-in and lead-out areas or addendum and dedendum areas and superimposed crownings.

The procedure is the same as explained above, though in this case the preset load range will be investigated step by step.

Effective modifications for noise reduction are characterized by an unerring choice of angle modifications and by the least possible superpositions of profile corrections and crownings in the range of a few μm.

The effectiveness of these modifications will essentially depend on the very close scatter of production tolerances of the gears. For instance, pitch, profile, and helix angle deviations could reduce and even neutralize the effect of such modifications.

In the following, a noise reduction on a test rig will be described by way of example. A frequency analysis of the airborne noise signals was carried out.

A green shaved pairing of gears is used as reference (Fig. 14).

With the frequency analysis, the partially stochastic distribution of amplitudes in Fig. 14 is striking. Though the first harmonic dominates, it is not noticed subjectively as such in the noise.

In the following, the gears were hard-finished with two different modifications.

The first design of modifications supplied the distribution of amplitudes shown in Fig. 15. The modifications were established from these green shaved gears running particularly smoothly. The amplitude with fundamental frequency (800 Hz) diminished markedly.

With the harmonics, however, a momentous narrow-banded rise of amplitudes occurred.

This narrow-banded generation, especially of the first harmonic, is subjectively disagreeable. The narrow-banded generation came into being due to an accurate gear, geometry (especially the very small pitch error) with unsuitable modifications.

So far, the transfer of modifications from green shaved gears has not been successful in all cases, since the necessary crownings required by hard finishing are much smaller than for green shaving, because for hard finishing correctly selected modifications of the helix and pressure angles with minimal crownings are of prime importance for getting best possible contact ratio. The second design of modifications will have the distribution of amplitudes shown in Fig. 16.

The marked drops of amplitude with only slight relative protruding amplitudes, and the consequential wide-band quality

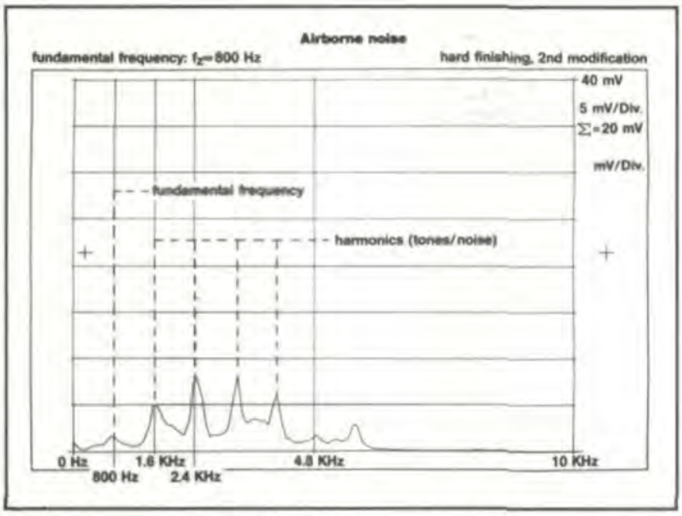

Fig. 16 – Frequency analysis of the airborne noise of hard-finished gears (second design of modifications).

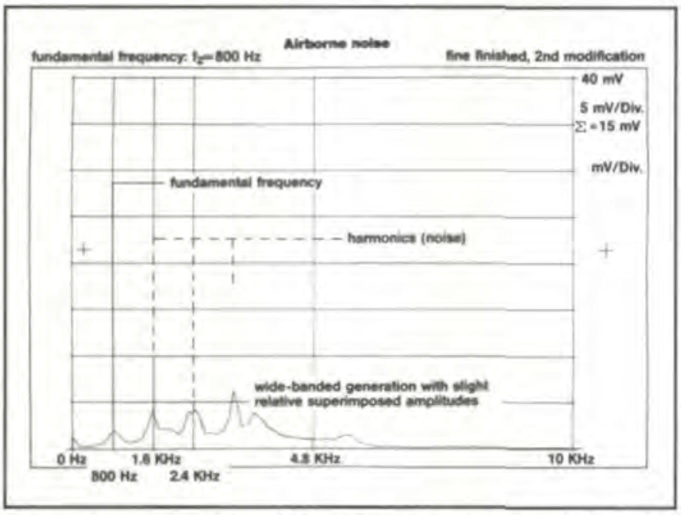

Fig. 17 – Frequency analysis of the airborne noise of hard-finished and fine finished gears.

provide a good subjective noise impression, since no individual tone made itself markedly heard.

In the next step of improvement the microstructure of flanks, with a roughness value $R_{ZD} \approx 3\ \mu m$ was reduced to $R_{ZD} \approx 1\ \mu m$ by fine finishing without changing the geometry. Fig. 17 shows the resulting frequency analysis.

The peaks of amplitudes with reference to Fig. 16 were further levelled. The subjective noise impression was especially improved for the well audible frequencies. If the noise relative to Fig. 16 still produced a sound impression, the noise relative to Fig. 17 increasingly merged into a noise similar to wide-banded rustle. The noise improvement, however, should not be primarily attributed to a reduction of surface roughness, but to the removal of microgeometrical meshing faults.

When investigating the deflections of gears on the test rig, marked acoustical differences were obtained in specific deflection and speed stages, requiring additional selective modifications of the flanks or damping methods for the natural frequencies of the gear blanks.

The strategy of defining modifications also consists in providing the results obtained under ideal testing conditions in such a way with a modification band width so that good results are obtained even in actual operation of the gear unit under various load stages. The modifications ultimately found and specific tooth gear quality parameters must be frequently kept at closer tolerances than required in the average quality specifications in order to obtain optimum noise results. Likewise, high demands must be made on the quality of the gear housing and to the systems of shafts and bearings if the noise reduction is to take a maximum effect.

Summary

Starting from the geometrical and qualitative requirements made on hard finishing methods of gears using geometrically undefined cutting edges, a brief survey was given on suitable tool configurations, the kinematical conditions, and possible drive modes for hard finishing and for fine finishing. (See Part I.)

The importance of tool manufacturing and the part played by computer assistance for tool design were dealt with. Machining results demonstrated the efficiency of the hard finishing methods of gears. Finally, the basic procedure to be followed for establishing tooth flank modifications for noise reduction were discussed.

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