Surface Roughness Measurements of Cylindrical Gears and Bevel Gears on Gear Inspection Machines

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Alongside the macro test parameters on tooth flanks for profile and tooth traces, surface properties (roughness) play a decisive role in ensuring proper toothed gear function. This article addresses roughness measurement systems on tooth flanks. In addition to universal test equipment, modified test equipment based on the profile method for use on gears is addressed in particular. The equipment application here refers to cylindrical gear flanks and bevel gear flanks. The most important roughness parameters, as well as the implementation of the precise measurement procedure will also be described under consideration of the applicable DIN EN ISO standards as well as the current VDI/VDE Directive 2612 Sheet 5.

Introduction

Alongside the macro test parameters on tooth flanks for profile and tooth traces, surface properties (roughness) play a decisive role in ensuring proper toothed gear function. The generally increased load stresses on gear teeth can only be implemented by maintaining precisely defined roughness parameters. Roughness measurements are therefore conducted on the gearing flanks in all highly developed drives, in the automotive industry, aircraft industry, or the area of wind energy drives, for example.

This article addresses roughness measurement systems on tooth flanks. In addition to universal test equipment, modified test equipment based on the profile method for use on gears is addressed in particular. The equipment application here refers to cylindrical gear flanks and bevel gear flanks. The most important roughness parameters, as well as the implementation of the precise measurement procedure will also be described under consideration of the applicable DIN EN ISO standards as well as the current VDI/VDE Directive 2612 Sheet 5.

The Purpose of Roughness Measurement on Toothed Gear Flanks

Alongside the macro test parameters on tooth flanks for profile and flank lines, surface properties (roughness) play a decisive role in ensuring proper toothed gear function. Unlike general functional surfaces, the particular shape (curvature) and the slide-roll effect during meshing come into play with tooth flanks. Thus the surface roughness affects the following properties:

- Flank load capacity
- Tooth root load capacity
- Wear load capacity
- Load capacity involving heavy scoring
- Lubrication conditions
- Noise behavior
- Approach behavior

When determining the gearing quality according to DIN/AGMA/ISO standards via profile and tooth trace, an impression of the existing roughness is also obtained, but this is in no way comparable to roughness measurement performed according to the standard. The correlation is clear when the various probe elements for the measurement are taken into account, for example (Fig. 1). A standard gear measurement is performed with a 1.5 mm probe (radius 750 μm); for a roughness measurement, however, a diamond tip with a radius of 2 μm or 5 μm is used. A roughness measurement therefore measures significantly finer structures on the surfaces. Along with the macro test parameters on tooth flanks

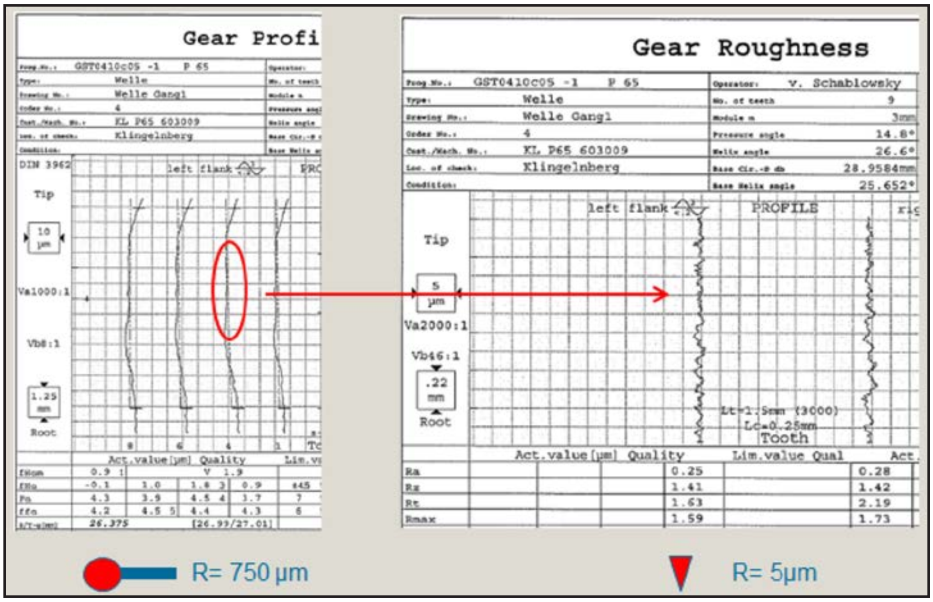


Figure 1 Comparison of measuring results.

according to the gear standards for cylindrical gears, surface properties (roughness) plays an important role in ensuring a proper toothed gear function.

Overview of Roughness Parameters

The general roughness parameters are defined in the DIN EN ISO 4287 standard. An application of this standard for tooth flank measurements is described in the current VDI/VDE 2612 Sheet 5. In a general roughness measurement, the unfiltered P profile (Ref. 2) is obtained initially. Filtering then produces the long-wave deviation (W profile) or the short-wave deviation (R profile). The short-wave deviations form the basis for the general roughness parameters used (Fig. 2).

During filtering of the recorded profiles, DIN ISO 16610-21 specifications apply, including measuring paths and cut-off wavelength (Fig. 3).

The profiles relevant for the roughness measurement are limited by the lambda C filter (waviness cut-off) and the lambda S filter (cut-off for even finer structures) (Fig. 4).

The most important roughness parameters for flank measurements are shown in Figure 5.

The arithmetic mean roughness value *Ra* is the ordinate value of the roughness profile within a single measurement path *lr*. The individual roughness depth *Rz* is the sum of the distance between the profile peak and profile valley within a single measurement path *lr*. Like *Ra*, the averaged roughness profile *Rz* is determined as an arithmetic mean from the individual measurement paths.

The total height of the roughness profile *Rt* is the sum of the height of the largest profile peak and the depth of the largest profile valley within the measurement path *ln*. The maximum individual roughness depth *Rmax* is the largest individual roughness depths *Rz*. The stock portion *Rmr* is the ratio of the sum of the stock-filled lengths *Ml*1-*Mli* for the total measuring path ln as a percent value.

The core roughness depth *Rk* is the depth of the roughness core profile. The reduced peak height *Rpk* is the height determined from the peaks projecting beyond the core area. The reduced peak depth *Rvk* is the height determined

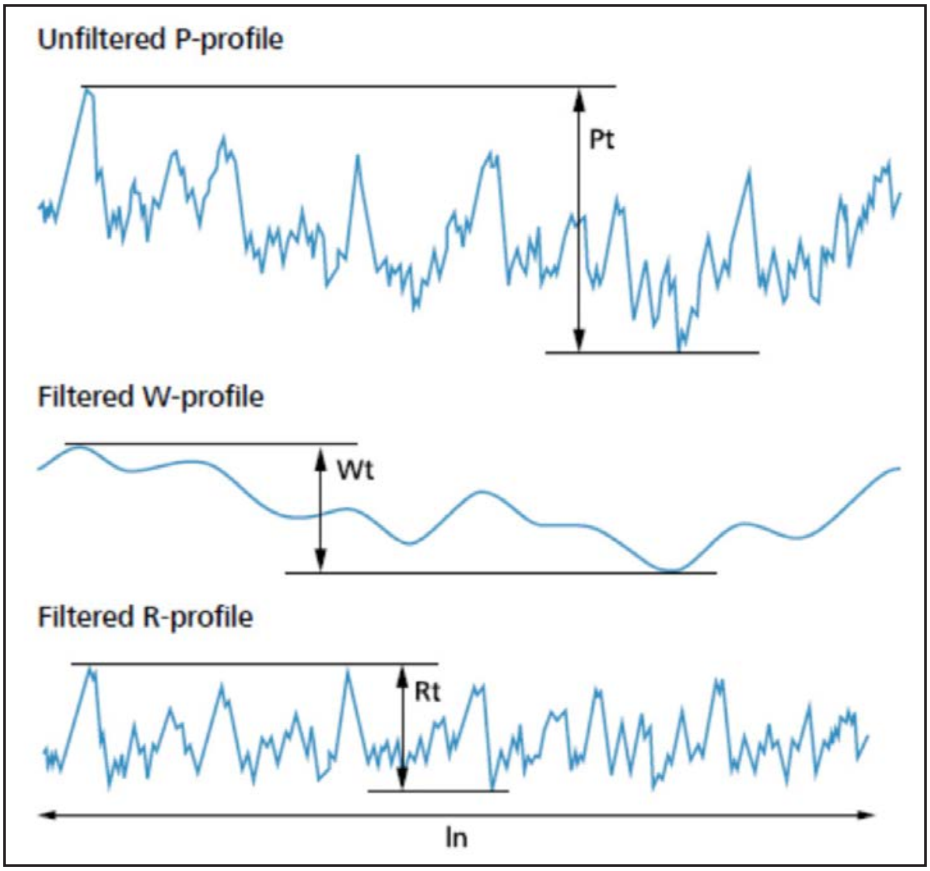


Figure 2 Division of a surface.

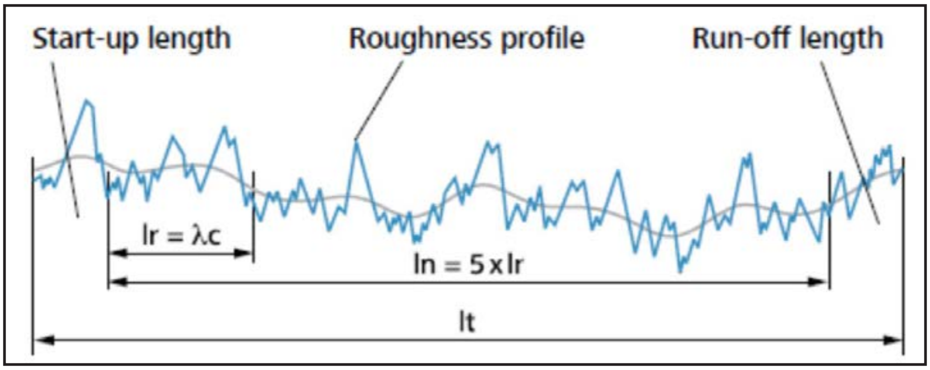
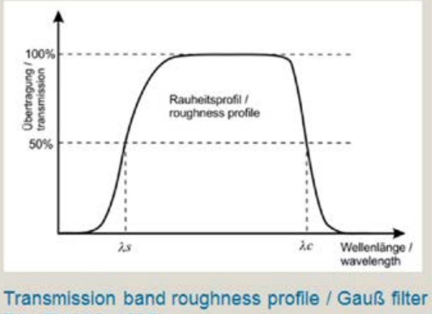


Figure 3 Evaluation lengths-cut off.

λc in mm	λs in µm	≈λc/λs	Stylus tip radius max. in µm	Measuring point distribution max. in µm
0,08	2,5	30	2	0,5
0,25	2,5	100	2	0,5
0,8	2,5	300	2 (oder 5)[a)]	0,5
2,5	8	300	5	1,5
8	25	300	10	5

Filter parameter roughness according DIN EN ISO 3274

→ Suitable parameters for grounded gears



Transmission band roughness profile / Gauß filter DIN EN ISO 4287

Figure 4 Filter parameters and transmission band for roughness profiles.

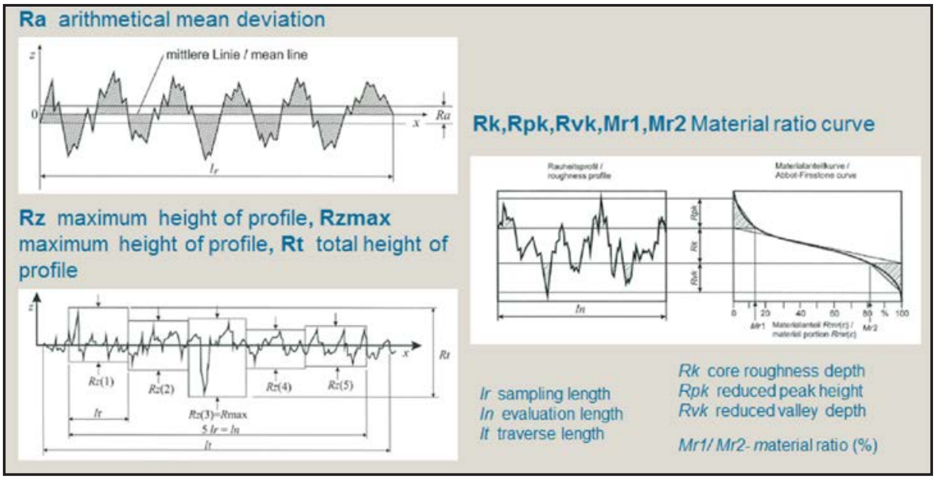


Figure 5 Roughness parameters according to DIN EN ISO 4287/13565.

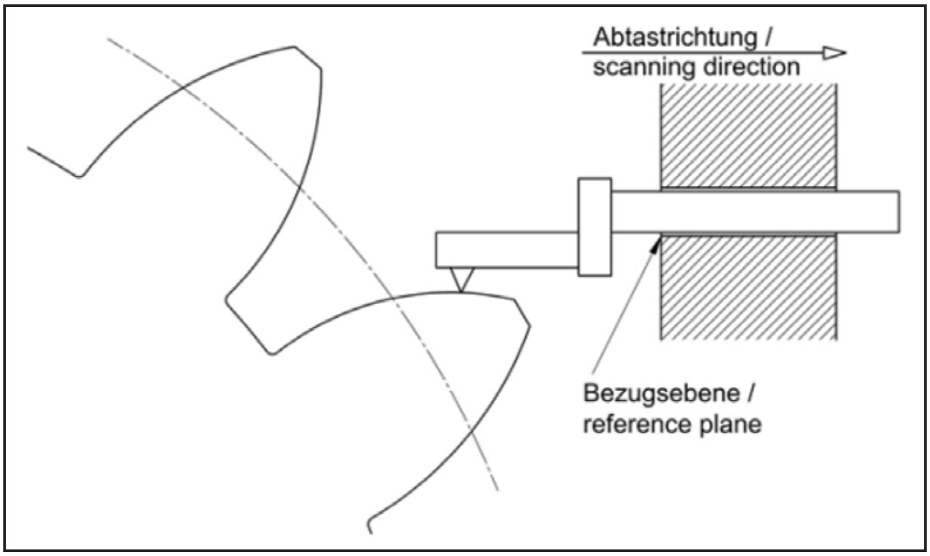


Figure 6 Skid less probing system with plane reference.

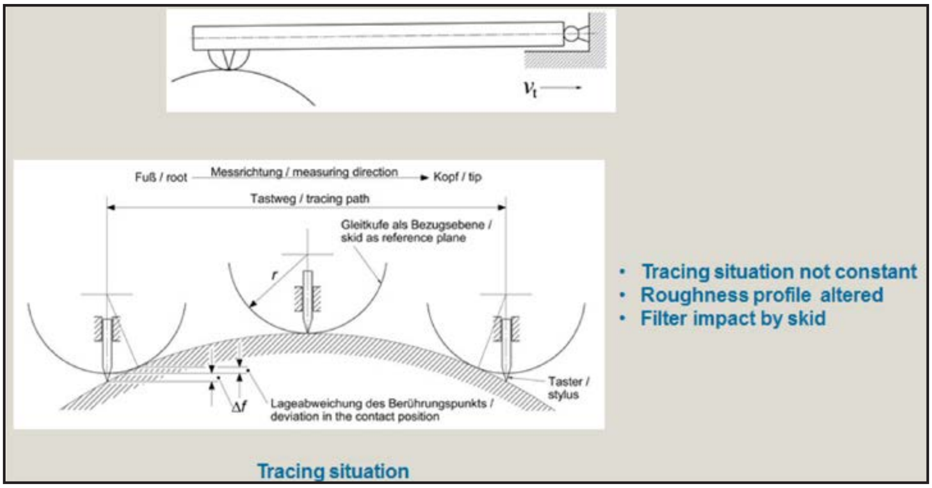


Figure 7 Probe system with side mounted skid probe (VDI/VDE 2612 Sheet 5).

for the striations extending from the core area into the stock. The parameters *Mr*1and *Mr*2 of the stock percentage curve characterize the stock content at the limits of the roughness profile *Mr*.

Measuring Methods and Measuring Equipment for Roughness Measurement

In the VDI/VDE 2602 directive, and the DIN EN ISO 4287 and DIN EN ISO 16610-21 standard, these are profile methods that describe the properties of the profile equipment and the general-case measurement conditions for roughness measurements of surfaces.

Skid-less probing systems and instruments with lateral skid (at the side off) are typically used to measure flank roughness (Ref. 1).

Figure 6 shows the tracing situation of a skid-less probing system in the tooth space. The profile here must be aligned as parallel as possible to the tracing direction of the test device. In the result, however, there is always a difference between the straight trace direction and the curved flank. The overall profile must therefore be corrected with a compensation arc, or residual errors must be eliminated with the lambda C profile filter. The possible trace path is limited due to the curved profile surface and the measuring range of the roughness probe.

The probing conditions of a skid system are shown in Figure 7. The side-mounted probe skid follows the profile of the tooth flank. A deviation due to changing contact conditions during the roughness measurement must be taken into account here. The deviations are relatively small, however, and are largely eliminated due to profile filtering.

For roughness measurement on cylindrical gear flanks, measuring devices with an involute reference (Fig. 8) offer certain advantages. Logging of measured values in profile generation mode on the tooth flank (involute) ensures that the probe tip is always aligned perpendicular to the surface; thus the roughness can theoretically be scanned over the entire profile length. The disadvantage of this type of contact operation, however, is that the scanning speed for measured value logging is not constant, nor is a uniform measuring point distance ensured. But this is a minor disadvantage, resulting in measured value differences of up to 10%.

On current gear measuring centers, the involute reference is generated via CNC path control and can be used in principle in conjunction with skid-less systems and skid systems. For special profiles and bevel gear flanks with other profile forms, for instance, the CNC-guided path control can also execute reference profiles.

Roughness Measurement Procedure in Practice

The measuring conditions (Ref. 1) must first be defined in order to achieve generally comparable results. The following points must be taken into account to avoid measurement deviations:

- Probe system
- Profile filter
- Alignment of test specimen
- Environmental influences

Refer to Table 1 to select appropriate individual measurement paths and cut-off. As finish-machined surfaces on tooth flanks in particular must be tested, the highlighted values should be used preferentially. The measuring direction for the roughness measurement should be selected according to Table 2, based on the machining method and the resulting structures.

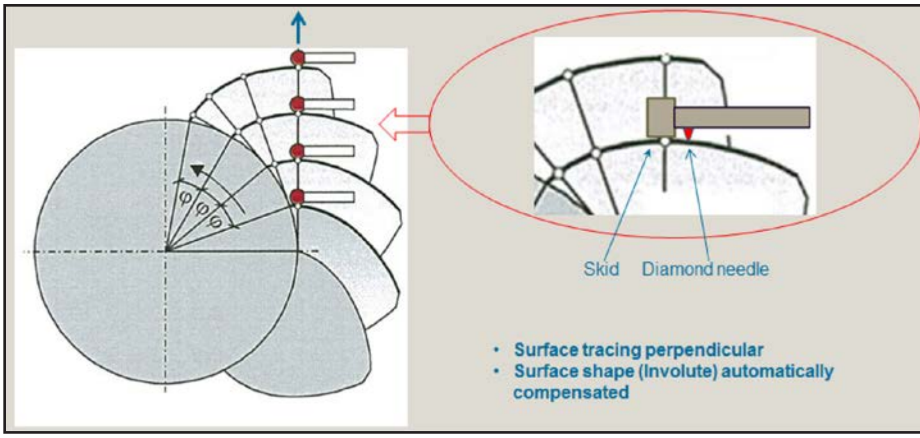


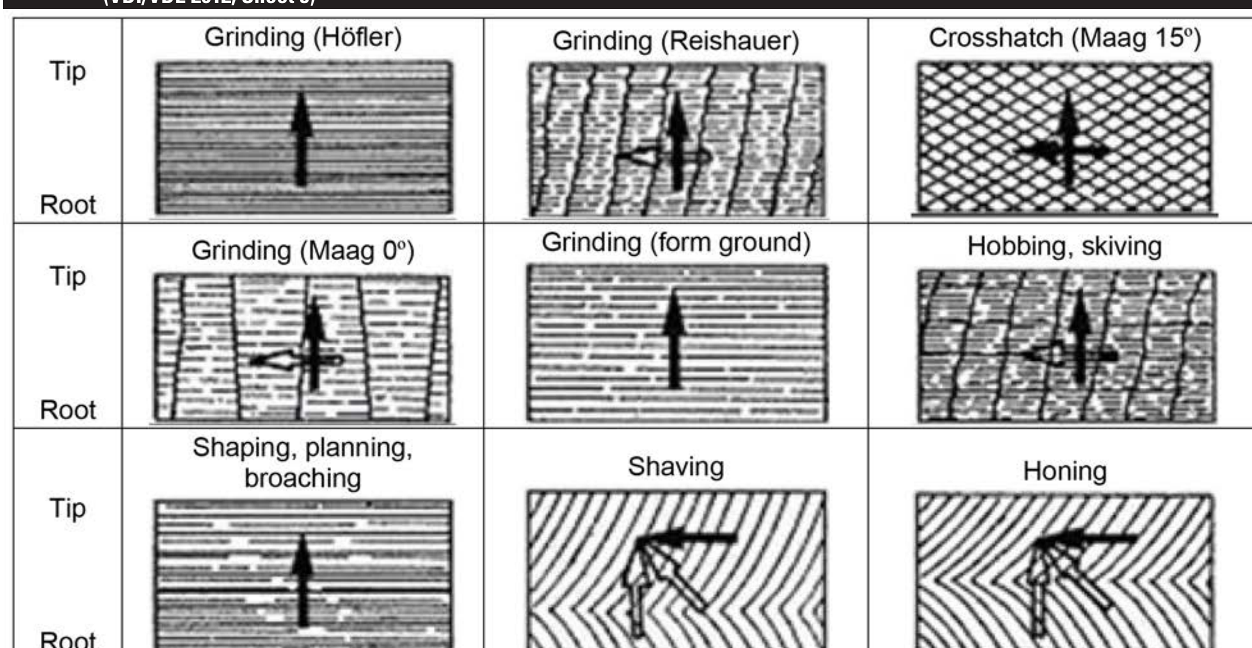
Figure 8 **Skid probe system with involute reference (VDI/VDE 2612 Sheet 5).**

Table 1 **Selection of individual measuring paths/cut-offs according to DIN EN ISO 4288 periodic profile**

Periodic profile ***RSm***, mm	Non-periodic profile		**Cut-off[1)] λc, mm**	Sampling length (***lr***)/ Evaluation length (***ln***)[1)] ***lr/ln***, mm
	Rz, µm	***Ra***, µm		
> 0.013 to 0.04	> -0.025 to 0.1	> -0.006 to 0.02	0.08	0.08/0.40
> 0.04 to 0.13	> 0.1 to 0.5	> 0.02 to 0.1	0.25	0.25/1.25
> 0.13 to 0.4[2)]	> 0.5 to 10[2)]	> 0.1 to 2[2)]	0.80[2)]	0.8/4.0[2)]
> 0.4 to 1.3	> 10 to 50	> 2 to 10	2.5	2.5/12.5
> 1.3 to 4.0	> 50 to 200	> 10 to 80	8.0	8.0/40

NOTES:
1) Sampling length, evaluation and cut-off according to DIN EN ISO 4288
2) Suitable parameters for grounded gears

Table 2 **Selection of measuring direction based on machining method showing recommended tracing direction (based on process) (VDI/VDE 2612; Sheet 5)**



NOTES:
➡ Preferred tracing direction
⇨ Tracing direction for additional information (feed marks)

When selecting the appropriate parameters for the roughness measurement on tooth flanks, the stress on these surfaces due to compression and sliding must be taken into account. The parameter *Rmax* has little meaning for this stress, as individually projecting peaks, which are of little relevance for the load capacity, are taken into account here. The arithmetic mean raw value *Ra* is greatly distributed, but correlates the least with the function parameters and therefore should not be used. The preferred parameter for roughness on flank surfaces is *Rz*, as it provides a high degree of clarity and makes it possible to draw accurate conclusions about the height of the roughness profile.

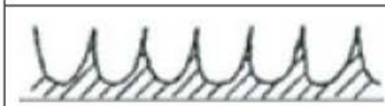
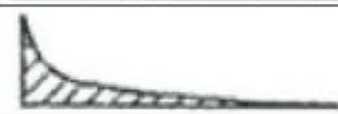
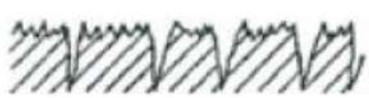
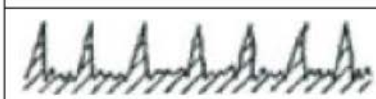
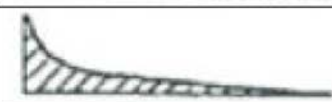
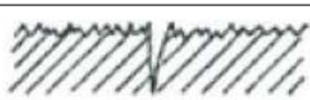
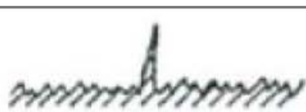
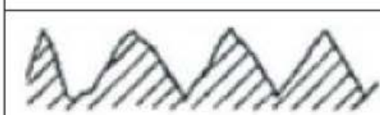
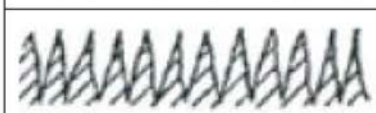
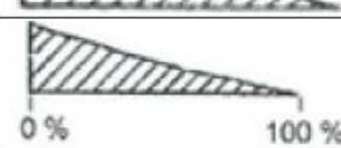
In addition to the parameters that describe only the vertical expansion of the roughness profile, it is important to determine the roughness structure in order to determine the wear behavior or load capacity of a tooth flank. The stock percentage curve (Abbott-Firestone) and the resulting parameters *Rk*, *Rpk* and *Rvk* are appropriate for determining the structure of the roughness profile. A nearly S-shaped pattern in the stock percentage curve is ideal. Another appropriate parameter for the stock percentage is *Rmr* (*c*). See Table 3 for a comparison of roughness parameters and stock percentage curves.

A standard roughness testing device (Ref. 3) is shown in Figure 9. In addition to a feed mechanism with a microprobe system, the device also features a cross-slide to position and test the workpiece. An additional clamping fixture is generally needed to test toothed gears. According to the figure detail, compact reference area probe systems with an application range from module 0.5 can be used here. A PC computing system with high-performance software is available to control and evaluate the roughness measurements. The evaluation software takes into account a large number of established roughness measurement standards. A report printout of the measuring results can be custom-designed.

One advantage of the device presented is that general workpieces can also be tested, and a higher standard overall is provided for roughness measurement. It does, however, require more set-up for flank measurements and the device is not suitable for large and heavy workpieces (500 mm in diameter, for example).

Application example: cylindrical gear/bevel gear measurement on gear measuring centers. Gear measuring centers are typically equipped with a rotary table for testing rotationally symmetrical workpieces and are suitable for measured value logging on small to very large

Table 3 Evaluation of roughness profiles and associated stock percentage curves

Roughness profile	*Rt*	*Rmax*	*Rz*	*Ra*	*Rmr* (0.25)	Abbott curve
	1	1	1	0.25	75%	
	1	1	1	0.25	15%	
	1	1	1	0.20	85%	
	1	1	1	0.20	20%	
	1	1	0.4	0.08	88%	
	1	1	0.4	0.08	7%	
	1	1	1	0.20	25%	
	1	1	1	0.30	38%	

NOTES:

\+ *Ra*

++ *Rz*

+++ *Rk, Rpk, Rvk*

workpieces, in conjunction with a model series. As previously described, the measuring method used here is the involute reference in combination with a skid system.

For roughness measurement a special probe system on the adapter plate of the measuring machine's macro probe system is adapted (Fig. 10). An additional electrical connection is provided for transferring the measured values from the integrated micro-probe system for the roughness measurement. For measured value logging in the profile direction, the probe skid rests on the flank to be tested and executes a movement similar to a normal profile measurement for the macrostructure of the flank. As it does so, a diamond needle located in front of the probe skid logs the measured values for the roughness measurement. The probe system represented here is also suitable for measured value logging in the tooth trace direction. The roughness probe system also features an adjustment mechanism enabling the probe needle to be aligned perpendicular to the surface for helical cylindrical gears as well.

Thus in conjunction with an automatic probe change rack, a fully automatic process can be carried out for the roughness measurement in combination with other gear measurements. Because the measured value logging is controlled by the CNC-guided measuring axes, this results in highly precise positional accuracy and reproducibility for the measuring positions. The most important technical data for the integrated roughness test equipment are shown in Table 4.

To document the measuring results, the roughness parameters can also be documented on the standard measuring sheet for profile and reference tooth traces, or they can be printed as a separate measuring sheet including diagrams (Fig. 11).

Comparable to measured value logging on cylindrical gears, roughness measurements can also be conducted on bevel gears. The profile measurement here takes place based on the calculated nominal data, which are available in high resolution for measuring the macrostructure. Various probe systems are used for measured value logging, depending on

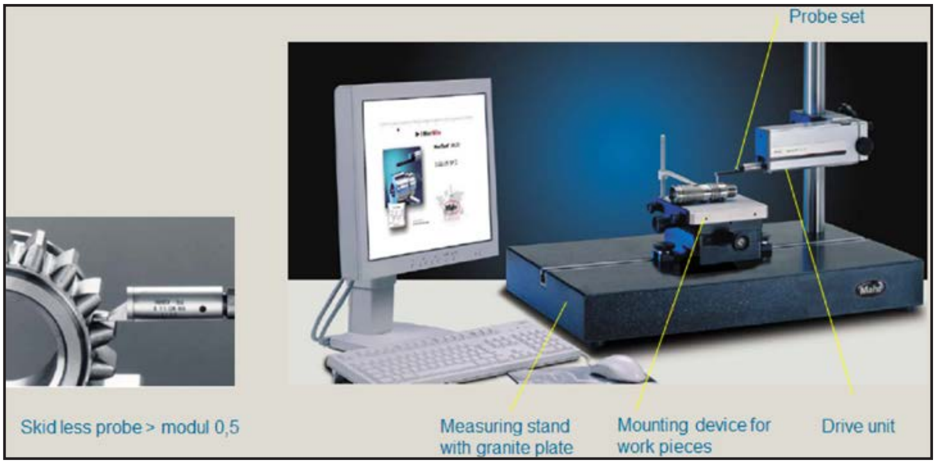


Figure 9 Standard roughness test device — example stationary surface measuring station for gears (Mahr catalog).

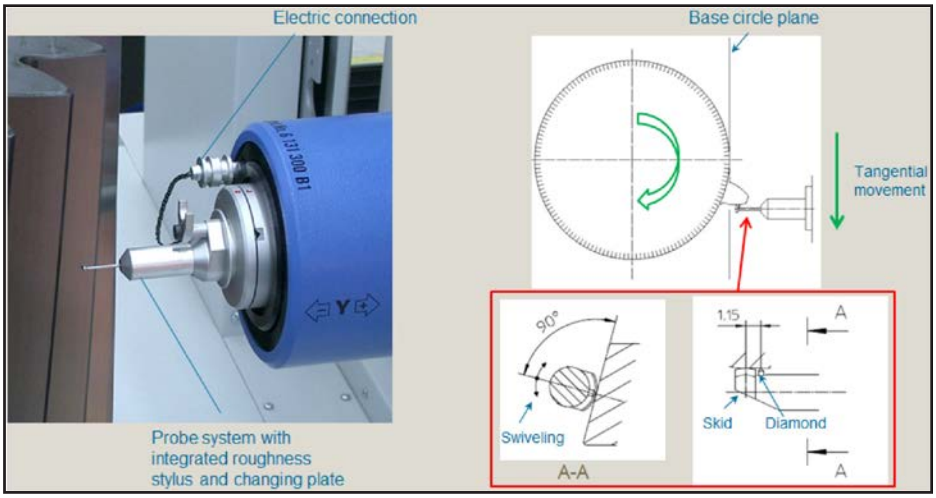


Figure 10 Roughness testing device (cylindrical gear) on gear measuring centers — roughness inspection in profile direction (involute reference).

Table 4 Technical data for roughness probe systems		
Length *Lt* **(mm)**	**1.5**	**4.8**
Cut-off filter *λc* **(mm)**	**0.25**	**0.8**

Technical data:

Device class to DIN EN ISO 3274 (DIN 4772), Class 1

Output values to DIN EN ISO 4287 (DIN 4762), Ra, Rz (DIN), Rt, Rmax

Resolution: *Ra* 0.01 µm (< 0.1 µm: 0.001 mm), all other parameters: 0.1 µm

Cut-off filter *λc* to DIN EN ISO 11562: phase correct digital Gaussian filter (M1)

Sampling length *Lt*/Cut-off filter λc (fixed correlation

Micro-roughness filter *λc*: 2.5 µm

Evaluation of single measured lengths

Skid radius: lengthwise 10 mm, crosswise 1.0 mm

Feed rate *vt*: 0.5 mm/sec

Static probe force on the sliding skid: < 200 Nm (< 20 g)

Static measuring force on the probe tip: < 0.5 Nm

Probe tip: diamond, conical form

Probe tip radius: 5 µm

Probe tip angle 90°

Offset between probe tip and sliding skid: lengthwise 1 mm, crosswise 0 mm

Maximum measuring stroke of probe tip: ±100 mm

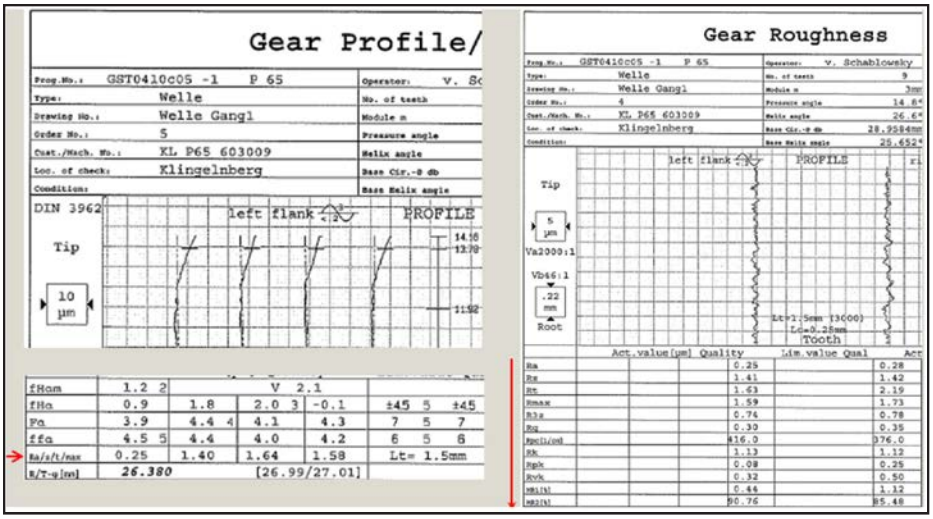


Figure 11 Results output: roughness measurement on gear measuring centers.

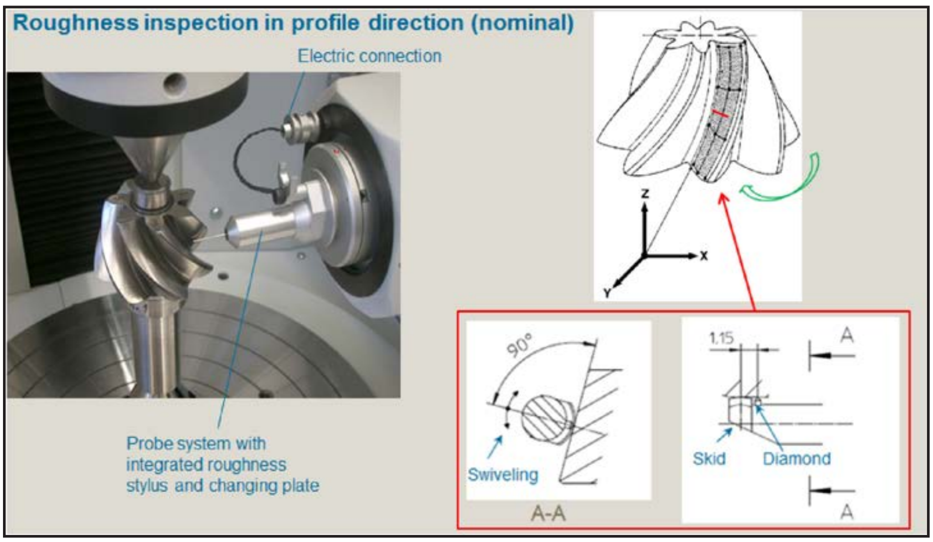


Figure 12 Roughness testing device (bevel gear) on gear measuring centers.

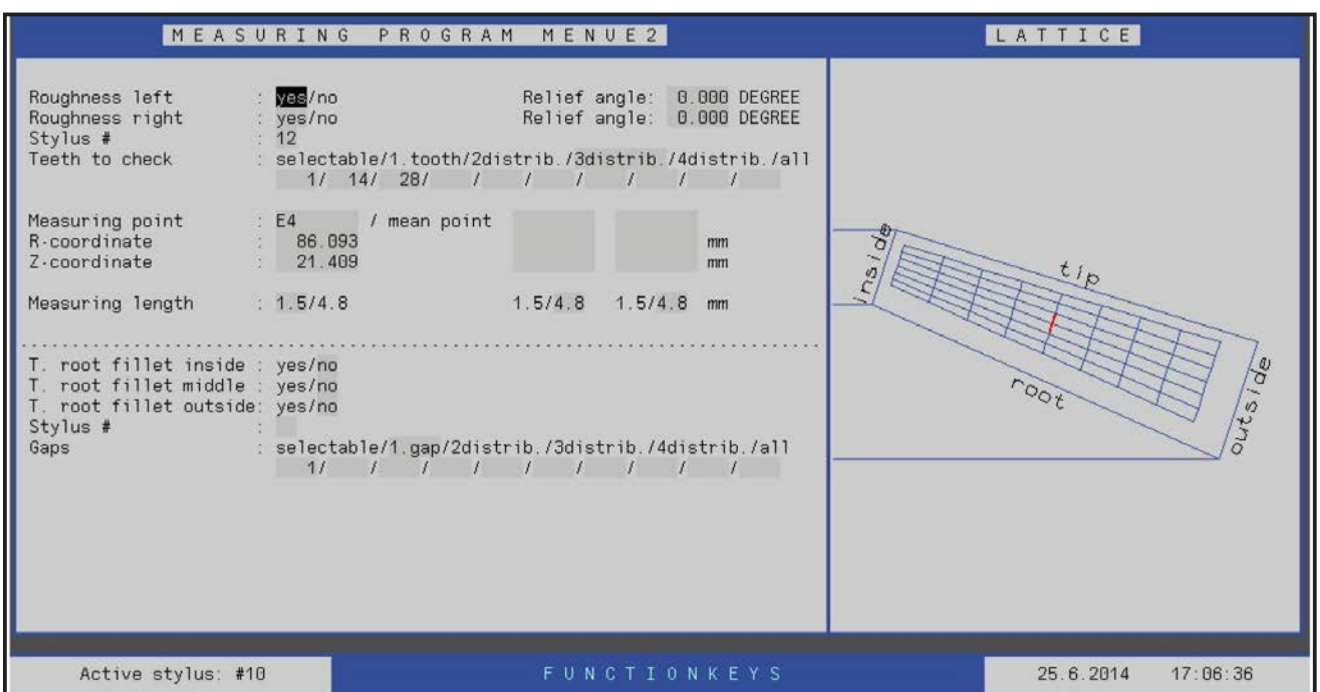


Figure 13 Operator guidance: roughness measurement on gear measuring centers.

the design of the bevel gears pinions/ring gears. For pinion shafts a straight probe system is used — exactly like the probe system for cylindrical gears (Fig. 12) — and an angled system is used for ring gears.

A fully automatic test sequence can also be specified via the software operator guidance. Measuring positions, measuring paths, and the number of flanks to be tested, etc., can be programmed individually (Fig. 13). The measuring results are displayed numerically on the screen for the selected flanks (Fig. 14); measured values can also be printed out with diagrams (Fig. 15).

Thus the device presented here offers a reliable, convenient measuring method for roughness measurement on spiral bevel gears with spatially pronounced curves. Large-module bevel gears can also be tested in conjunction with suitable probe systems.

Concluding Remarks

These important measured values can be carried out quickly and easily in conjunction with conducting roughness measurements of tooth flanks on gear measuring centers using the equipment presented here.

Measurements on both smaller and larger gear teeth can be taken in a single

Measuring position: E4; R: 86.093,Z: 21.409 mm
Length of traceline (Lt): 1.500 mm Cutoff filter (Lc): 0.250 mm

Tooth	Flank	Ra µm	Rz(DIN) µm	Rt µm	Rmax µm	R3z µm	Rq µm	Rpc 1/cm	Rk µm	Rpk µm	Rvk µm	MR1 %	MR2 %	R µm	AR µm
1	concave	0.96	6.01	8.42	7.29	1.98	1.27	240.00	3.62	0.69	2.45	0.44	83.3	0.00	0.00
1	convex	0.66	3.66	4.81	4.44	0.98	0.84	232.00	2.61	0.37	1.33	0.40	83.9	0.00	0.00
14	concave	1.04	6.07	8.23	7.15	2.32	1.33	232.00	3.89	0.56	2.50	0.20	83.1	0.00	0.00
14	convex	0.52	3.17	4.77	4.00	1.11	0.66	208.00	2.28	0.58	1.03	0.36	89.7	0.00	0.00
28	concave	0.87	5.68	7.38	7.25	2.09	1.12	352.00	3.44	0.39	1.89	0.64	85.3	0.00	0.00
28	convex	0.70	4.10	6.24	5.91	0.00	0.93	176.00	2.36	0.34	2.15	0.72	82.9	0.00	0.00
Mean	concave	0.96	5.92	8.01	7.23	2.13	1.24	274.67	3.65	0.55	2.28	0.43	83.9	0.00	0.00
Mean	convex	0.63	3.64	5.27	4.78	0.70	0.81	205.33	2.42	0.43	1.50	0.49	85.5	0.00	0.00
Mean	cv.+cx.	0.79	4.78	6.64	6.01	1.41	1.02	240.00	3.03	0.49	1.89	0.46	84.7	0.00	0.00

Figure 14 Results output: roughness measurement on gear measuring centers.

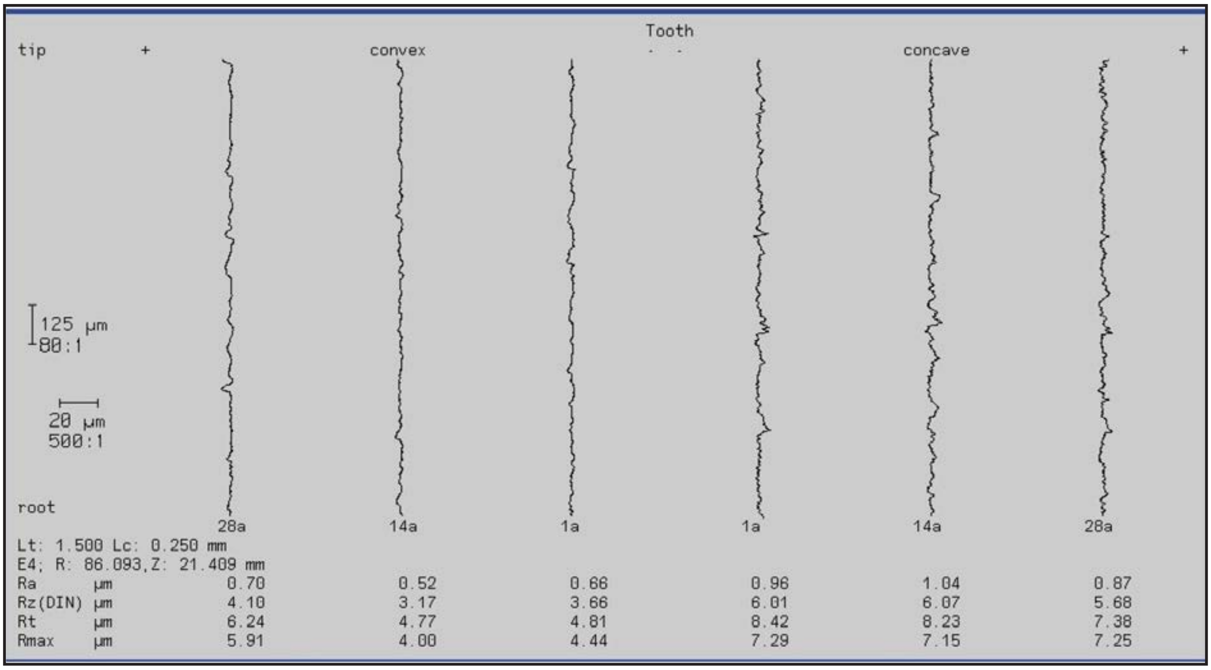


Figure 15 Roughness bevel diagram.

clamping in conjunction with standard test parameters.

The measurement conditions for standardized roughness measurements are largely met by measured value logging in the profile direction with CNC-controlled contouring in generation mode for each tooth profile.

References

1. VDI/VDE 2612; Sheet 5. *Measurement and Testing of Gearings: Surface Roughness Measurement of Cylindrical Gears and Bevel Gears by Means of Stylus-Type Instruments* (Release 2014/2015).
2. Jenoptik publication.
3. Mahr publication. "Mar Surf XR 20 Roughness Testing Device."

Dipl.-Ing. Guenter Mikoleizig currently heads the product management and application engineering department for gear inspection machines at Klingelnberg GmbH, Germany. With more than 30 years in the field of gear inspection technology, he is fully experienced with the design and development of inspection machines and their product management. He in fact developed a product line of inspection machines for an array of gears and related parts, with small dimensions up to the very large-sized. Mikoleizig has presented papers about gear inspection worldwide and is also an active member of national and international standardization committees.