Fully Automated Roughness Measurement on Gears — Even on the Shop Floor

An Optimized System for Precision Measuring Centers

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Significance of Surface Roughness

For flawless operation of geared components in a transmission — not only the component geometry, but also the surface quality of the functional surfaces — plays a decisive role. Precise inspection of the geometry has been state-of-the-art for decades, and has since undergone further development; by contrast, insights regarding the effects of surface quality are still relatively recent. Just a few years ago, this aspect was not such a central topic for series production of standard transmissions, but thanks to new or improved machining technologies, smooth surfaces or defined surfaces can now be produced cost-effectively — even in large-scale production. Also, special manufacturing processes such as polish-grinding and chemical methods of polishing have made a contribution in this respect.

Surface properties defined with maximum precision are a key variable, and are frequently also the prerequisite for valuable improvements in drive engineering. Especially in the automotive industry, and particularly in the electric mobility area, the surface quality of the gearing components is essential. In combination with electric drives, extremely high rotation speeds are transmitted, resulting in new challenges in transmission and gearing design. But even in conventional drives with a combustion engine, smoother gearing can make a significant contribution to the running properties. The production of surfaces with an *Rz* value of less than 1 µm are now possible in series production.

Conventional Roughness Measurement Methods

As a result, the importance of roughness measurement of gearing has grown significantly. Although roughness can be measured on tooth flanks with the common roughness measurement systems, these systems are not entirely suitable for serial measurements. They are difficult to operate and they require trained technicians; measurements must be carried out in large part manually. Quite a bit of skill is required to even conduct such measurements with standard feed systems, as the component alignment also plays an important part. The setup procedure is particularly challenging with reference plane scanning systems. Due to the involute bend of the tooth contour, a curve is traced with the diamond needle. Because the feed unit executes a linear motion, the alignment must be selected so that this curve remains in the measuring range of the probe; a suitably larger measuring range is required. In addition, the diamond needle changes its alignment with respect to the surface during the motion.

When using a feed unit with a skid probe, the measuring range of the probe needle can be significantly smaller and the resolution correspondingly higher. The sensitive probe needle is protected by the skid. This makes the system quite robust. This provides advantages in handling, since it prevents needle damage when setting up the probe needle in the tooth space. Figures 2 and 3 show two linear feed systems measuring roughness on a gear. Regardless of the sensor technology, however, the above-described disadvantages apply to both systems; therefore the gear industry demanded an automated solution.

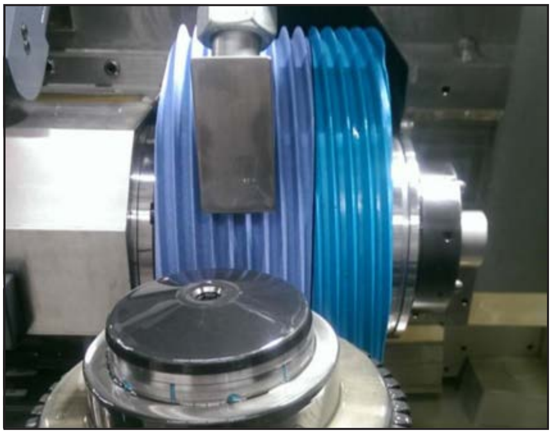


Figure 1 Polish-grinding with a combined grinding-polishing worm.

Figure 2 Reference plane scanning system.

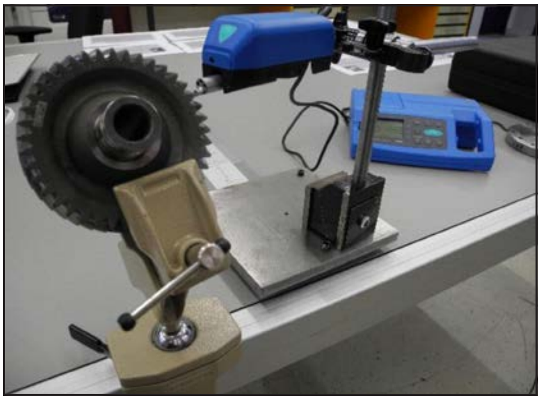


Figure 3 Skid scanning system.

Figures 4 and 5 Roughness sensor mounted on the 3-D probe:

In addition to the roughness sensor technology, a precision swivel device is also integrated into the extremely compact roughness sensor. The roughness probe can therefore be operated on the adapter plate like the tactile styluses and can be changed automatically. An especially convenient feature of this is the automatic plug-in (right picture).

A Solution Optimized for Gears

In order to realize an automated solution, it is obvious to use a gear measuring machine and to adapt a roughness sensor system. In this context the question arises, i.e. — which sensor technology is the most suitable for this combination of a gear measuring machine and roughness sensor?

Automatic measuring cylcles, which can be done in combination with the gear measurement, require a robust system in which the sensitive probe needle cannot be damaged. This was the main reason for the decision to use a skid system.

But the skid system has a well-known disadvantage, i.e. — the signal corruption due to elevations on the surface. This causes the skid to rise at a different time with respect to the needle during the measured value logging process. The measurement signal detects a recess that does not actually exist.

But on high-quality ground or polished tooth surfaces of gears, this effect is very low. This is a positive precondition that favors the use of a skid scanning system for gear measurement.

Figures 4 and 5 show how the roughness probe that was especially developed for use on gearing components is adapted on a gear measuring machine. The roughness probe can be mounted directly on the standard adapter plate of the 3-D tracer head. In order to scan in different directions, the roughness probe is equipped with an integrated swivel axis. The adaption is possible because the combination of roughness probe and swivel axis has been miniaturized very much.

Due to this arrangement, the skid of the roughness sensor behaves like the ball of a tactile stylus mounted on the 3-D tracer head. As the point of contact of the skid is only a cut-out of a ball, the swivel axis rotates the skid with the point of contact perpendicular to the surface; the diamond needle is also twisted in the same direction. To understand this function, Figure 6 shows the front

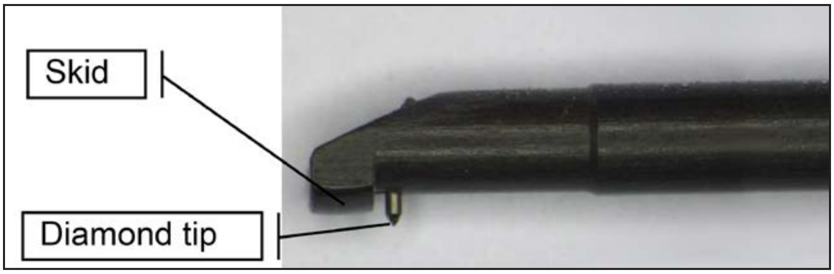
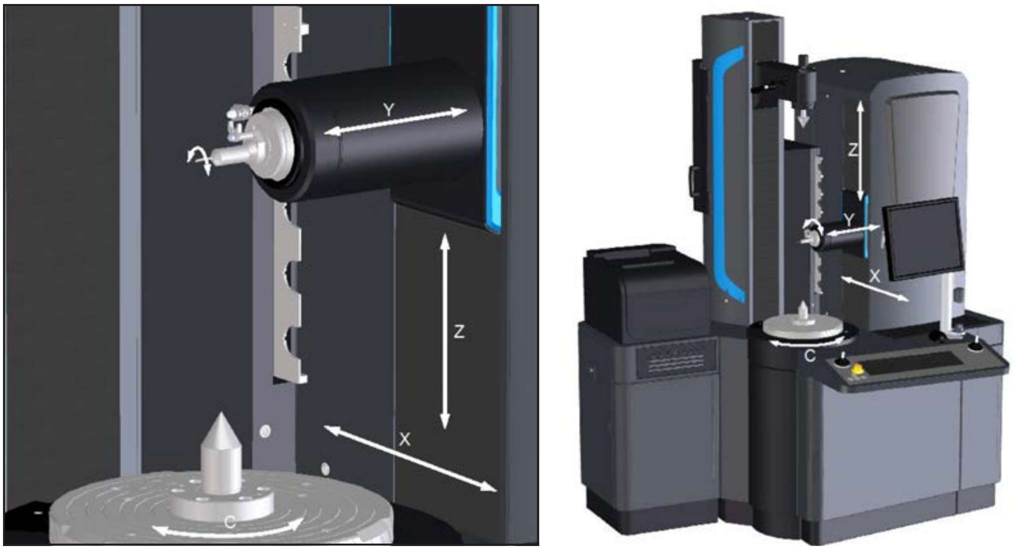


Figure 6 The front end of the roughness sensor shows the arrangement of the skid and the diamond tip. The probing force of the diamond tip is less than 0.5 mN.



Figures 7 and 8 The arrangement of the roughness sensor on the gear measuring machine and the assignment of the machine axes. The rotation direction of the sensor swivel axis is also marked. The gear measuring machine complies with class 1 of VDI/VDE 2612 and 2613. The roughness measuring system fulfills the requirements according to DIN/ISO 3274.

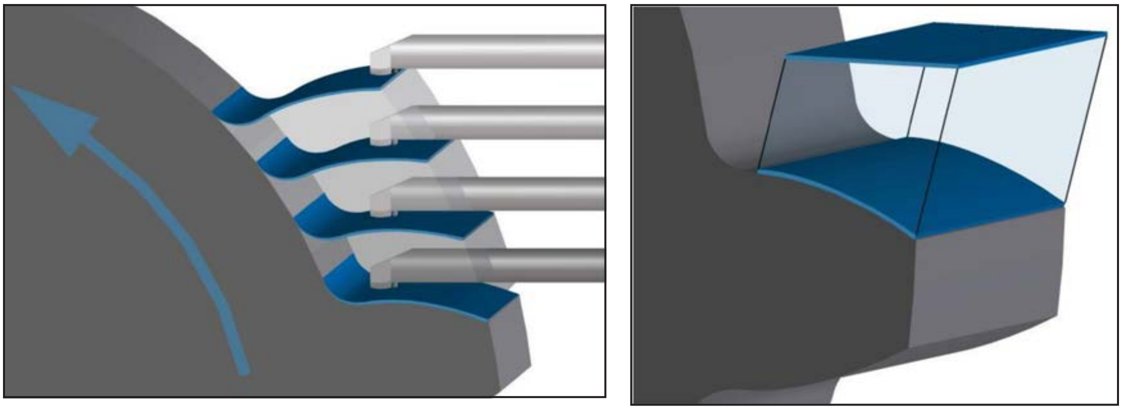
end of the roughness sensor.

Since the roughness system is optimized for recording roughness parameters specifically on gears, the same measuring cycles can be used for roughness measurement as for gear measurement — thus ensuring optimal tracing conditions. The tactile stylus and the roughness sensor can be exchanged automatically within the measuring process to have a fully automated measurement cycle — including gear measurement, size, form and position measurement — as well as roughness measurement in a single clamping.

Thanks to this integrated solution and a fully automated measurement cycle, serial measurements can be performed even by untrained staff. This requires a particularly robust system that can also be used in a production environment. This requirement is met through the arrangement of the roughness sensor with the skid. The diamond needle is actively protected from damage in cases of a collision. In addition, by using a skid system the roughness measurement is extremely insensitive to vibrations.

Figure 9 Gear measuring machines have for years been used directly in the production area. By adapting the roughness sensor on these machines, this is now also practiced for roughness measurement.

This is an important prerequisite for using the setup directly in production. For gear measurement this is already state-of-the-art. Numerous user examples have confirmed that it also works with the shown system for the roughness measurement.



Figures 10 and 11 Owing to the optimized measurement and tracing strategies of the skid probing system, the curved surface behaves like an ideal plane relative to the roughness probe; illustrated here with a sample profile measurement on involute gearing.

Another advantage of an integrated system is the chance to use the possibilities of a four-axis coordinate measuring machine with rotational axis. It allows keeping the diamond needle always exactly in normal direction to the surface, though it is an involute curvature. The curvature is fully compensated by the generative measuring movement, resulting in almost complete linearization of the scan on the gear surface (Figs. 10–11).

From the perspective of the roughness probe, the curved surface behaves like an ideal plane. The diamond needle records only the surface roughness and can therefore use an extremely small measuring range with a correspondingly high resolution. This prevents errors filtering the long-undulation curvature.

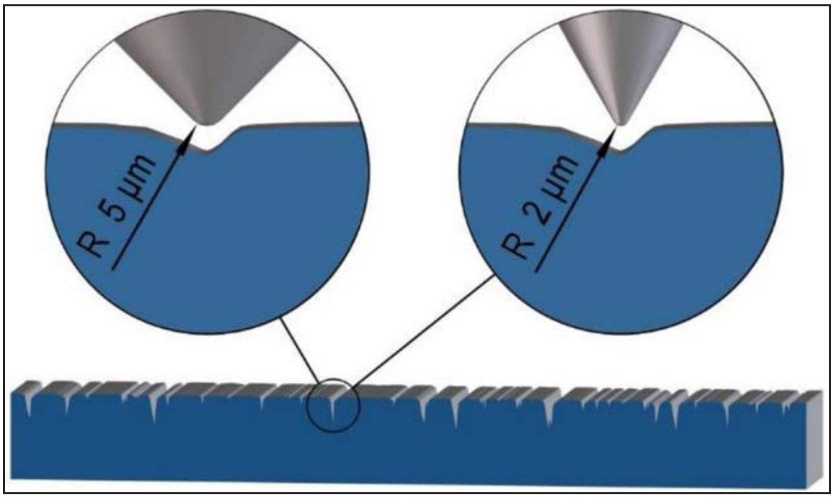
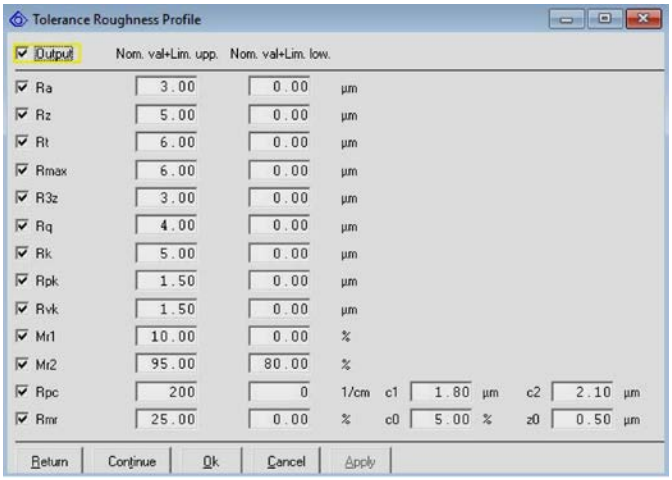
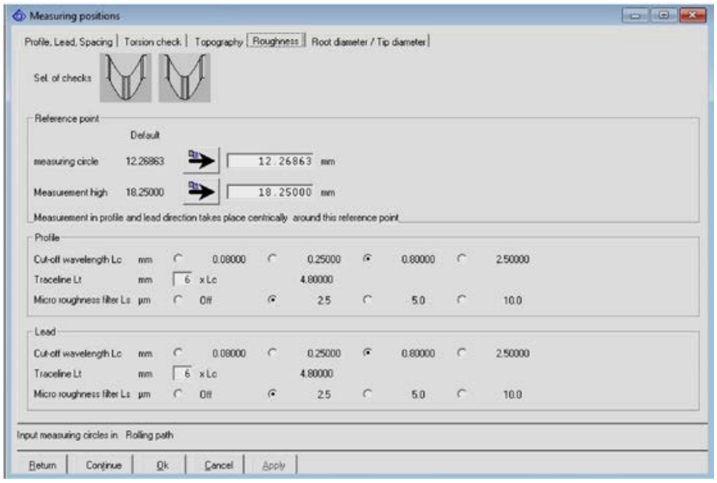


Figure 12 Graphic with the same magnification factor in all directions shows the correct relation of the diamond tip to the deepest stria. The typical roughness profile presentation has strong vertical scaling. The gaps appear much tighter than they are.



☑ Output	Nom. val+Lim. upp.	Nom. val+Lim. low.						
☑ Ra	3.00	0.00	µm					
☑ Rz	5.00	0.00	µm					
☑ Rt	6.00	0.00	µm					
☑ Rmax	6.00	0.00	µm					
☑ R3z	3.00	0.00	µm					
☑ Rq	4.00	0.00	µm					
☑ Rk	5.00	0.00	µm					
☑ Rpk	1.50	0.00	µm					
☑ Rvk	1.50	0.00	µm					
☑ Mr1	10.00	0.00	%					
☑ Mr2	95.00	80.00	%					
☑ Rpc	200	0	1/cm	c1	1.80 µm		c2	2.10 µm
☑ Rmr	25.00	0.00	%	c0	5.00 %		z0	0.50 µm

Figure 13 **Input menu for roughness parameters and tolerances.**



Reference point

	Default		
measuring circle	12.26863	12.26863	mm
Measurement high	18.25000	18.25000	mm

Measurement in profile and lead direction takes place centrically around this reference point

Profile

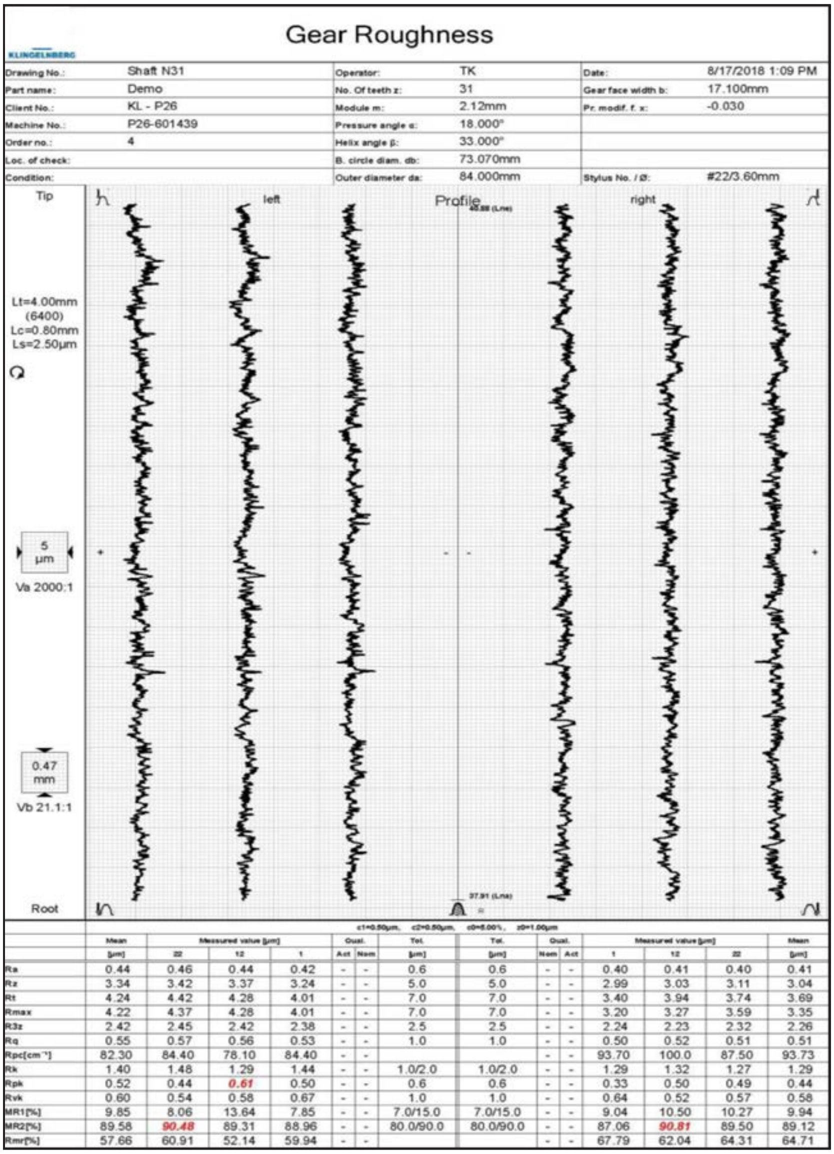
Cut-off wavelength Lc	mm	○ 0.08000	○ 0.25000	● 0.80000	○ 2.50000
Traceline Lt	mm	6 x Lc	4.80000		
Micro roughness filter Ls	µm	○ Off	● 2.5	○ 5.0	○ 10.0

Lead

Cut-off wavelength Lc	mm	○ 0.08000	○ 0.25000	● 0.80000	○ 2.50000
Traceline Lt	mm	6 x Lc	4.80000		
Micro roughness filter Ls	µm	○ Off	● 2.5	○ 5.0	○ 10.0

Input measuring circles in Rolling path

Figure 14 **Input menu for measuring length and filter parameters.**



Gear Roughness

Drawing No.:	Shaft N31	Operator:	TK	Date:	8/17/2018 1:09 PM
Part name:	Demo	No. Of teeth z:	31	Gear face width b:	17.100mm
Client No.:	KL - P26	Module m:	2.12mm	Pr. modif. f. x:	-0.030
Machine No.:	P26-601439	Pressure angle α:	18.000°		
Order no.:	4	Helix angle β:	33.000°		
Loc. of check:		B. circle diam. db:	73.070mm		
Condition:		Outer diameter da:	84.000mm	Stylus No. / Ø:	#22/3.60mm

c1=0.50µm, c2=0.50µm, c0=5.00%, z0=1.00µm

	Mean	Measured value [µm]			Qual.		Tol.	Tol.	Qual.		Measured value [µm]			Mean
	[µm]	22	12	1	Act	Nom	[µm]	[µm]	Nom	Act	1	12	22	[µm]
Ra	0.44	0.46	0.44	0.42	-	-	0.6	0.6	-	-	0.40	0.41	0.40	0.41
Rz	3.34	3.42	3.37	3.24	-	-	5.0	5.0	-	-	2.99	3.03	3.11	3.04
Rt	4.24	4.42	4.28	4.01	-	-	7.0	7.0	-	-	3.40	3.94	3.74	3.69
Rmax	4.22	4.37	4.28	4.01	-	-	7.0	7.0	-	-	3.20	3.27	3.59	3.35
R3z	2.42	2.45	2.42	2.38	-	-	2.5	2.5	-	-	2.24	2.23	2.32	2.26
Rq	0.55	0.57	0.56	0.53	-	-	1.0	1.0	-	-	0.50	0.52	0.51	0.51
Rpc[cm⁻¹]	82.30	84.40	78.10	84.40	-	-			-	-	93.70	100.0	87.50	93.73
Rk	1.40	1.48	1.29	1.44	-	-	1.0/2.0	1.0/2.0	-	-	1.29	1.32	1.27	1.29
Rpk	0.52	0.44	*0.61*	0.50	-	-	0.6	0.6	-	-	0.33	0.50	0.49	0.44
Rvk	0.60	0.54	0.58	0.67	-	-	1.0	1.0	-	-	0.64	0.52	0.57	0.58
MR1[%]	9.85	8.06	13.64	7.85	-	-	7.0/15.0	7.0/15.0	-	-	9.04	10.50	10.27	9.94
MR2[%]	89.58	*90.48*	89.31	88.96	-	-	80.0/90.0	80.0/90.0	-	-	87.06	*90.81*	89.50	89.12
Rmr[%]	57.66	60.91	52.14	59.94	-	-			-	-	67.79	62.04	64.31	64.71

Figure 15 **The picture shows the diagrams of the roughness measurement curves and the measured parameters. If tolerances are entered, the parameters are printed in red when the tolerance is exceeded.**

Influence of the Tip Radius

The DIN/ISO 3274 standard specifies under which conditions a probe tip with 5 µm tip radius or with 2 µm tip radius is to be used; in both cases the radii are very small. In order to get a better understanding of the influence of the probe tip radius to the surface, the relation to each other must be made clear.

Due to the radius of 2 µm, very fine stria can be measured better. To illustrate this, it is advantageous to represent the relation between the surface in the longitudinal and vertical directions with the same magnification.

In typical roughness profile charts a very strong vertical scaling relative to the surface is used. This makes stria that are just 0.5–1.5 µm deep appear very narrow and seemingly impossible to measure using a 90° or 60° diamond tip. By showing the actual relation through the same magnification in the lengthwise and vertical directions, the actual appearance of the seemingly narrow compared with the tip becomes apparent. In this case, the stria could be measured with both — the 2 µm and the 5 µm tip. In a case of even narrower gaps, the 5 µm tip would not reach the bottom, so that the 2 µm tip is needed; Figure 11 shows the influence of the magnification.

Measuring Results

The evaluation and output of the roughness measurement results are analogous to the toothing evaluation. The roughness curves are shown in corresponding diagrams. The calculated parameters are listed under the diagrams in tabular form.

The roughness measuring system fulfills the requirements of DIN/ISO 3274. The filters work in accordance with DIN/ISO 166110-21. The parameters are calculated according to DIN/ISO 4287.

The desired roughness parameters, the measuring lengths, the filter settings and the upper and lower tolerances can be selected in the software;

the corresponding input menus are shown (Figs. 13–14).

To ensure that the measurement results agree with the results of other measuring instruments a number of comparative measurements were carried out with reference measuring systems. The difficulty is to measure exactly at the same position. Such measurements have been done several times by customers; an example is shown (Fig. 16.) What is interesting is the correspondence of the diagram, if you actually hit the same spot.

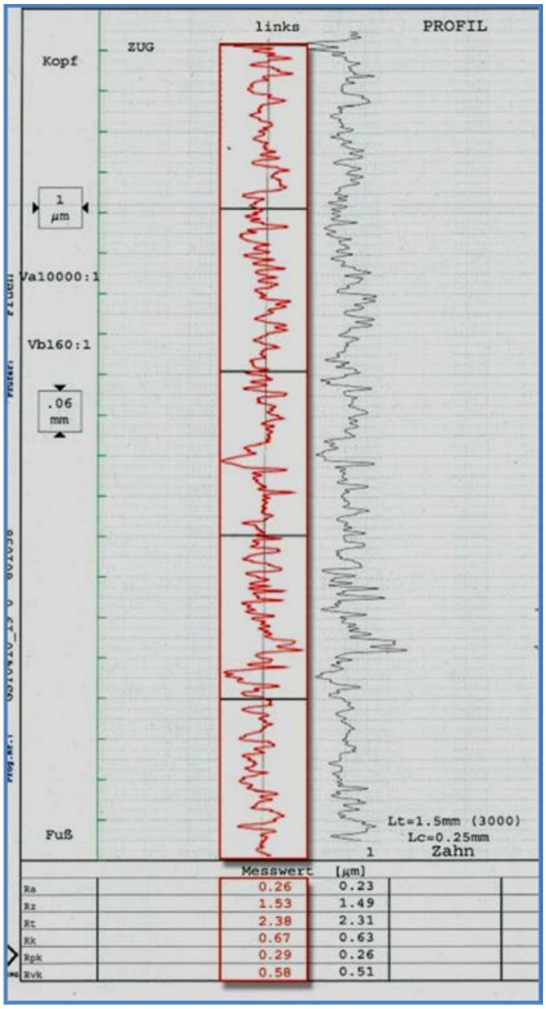
Material Ratio Evaluation

Over the years, standards committees have continually redefined new roughness parameters in order to express the surface characteristics in key values. Nevertheless an evaluation of the parameters *Ra* and *Rz*, which are very easy to describe, is still commonly used. However, this does not reveal the surface characteristic. Surfaces can have extremely different detailed structures — even though they have the same value for *Ra* or *Rz* — but in most cases different structures also mean different characteristics.

In addition to conventional evaluation of the roughness measurement curve via individual measuring sections, material ratio evaluation is now being used increasingly. This provides additional, useful parameters for evaluating the surface properties to be determined.

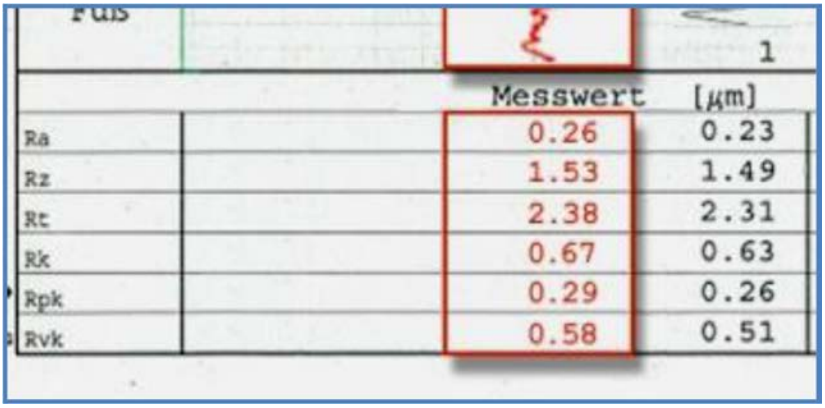
This evaluation generates cross-sections along the height of the recorded measurement curve,

Figure 16 This example comparative measurement conducted on a ground gear shows the correspondence between the measurement performed using a reference measurement system (in red) and using the gear measuring machine (in black). This is true not only for the parameters, but also for the characteristic of the two measurement curves.



	Messwert	[µm]
Ra	0.26	0.23
Rz	1.53	1.49
Rt	2.38	2.31
Rk	0.67	0.63
Rpk	0.29	0.26
Rvk	0.58	0.51

In this older diagram format the measuring length of Lt = 1.5 mm and the filter Lc = 0.25 mm are printed beside the diagram.



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Rvk	0.58	0.51

Please note that the differences are in nanometer range. However, due to the small roughness values, the percentage deviations appear large.

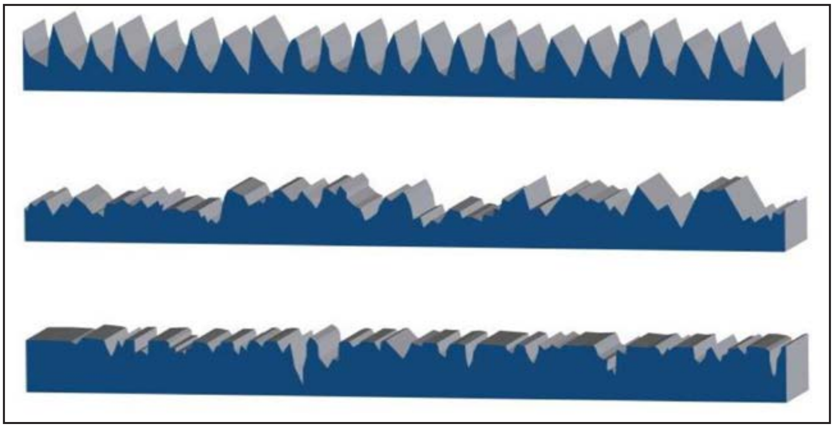


Figure 17 These three surface profiles illustrate the importance of the material ratio evaluation: although the characteristics of the surfaces are completely different because of the different production processes, the same Ra value was determined in all three cases.

in which the material ratio is calculated as a percentage value. Based on this, a so-called Abbott-Firestone curve is generated and is evaluated according to a special method.

The advantage of the material ratio evaluation is that it provides clear parameters resulting from the varying material density over the height profile — from the uppermost point on the surface to the transition into the solid material. Since gear manufacturers want to achieve very specific structures on the gear surface, this evaluation is helpful. Characteristics such as high peaks with broad plateaus, or broad plateaus with narrow grooves, are described via the material ratio parameters *Rk*, *Rvk* and *Rpk*, as well as MR1 and MR2. Accordingly, these parameters would differ significantly for the surfaces shown in Figure 16.

The parameters are calculated according to DIN/ISO 13565; this standard describes the meaning and the derivation of these parameters in detail.

Gears with Small Modules

The roughness probe design shown in Figure 6 cannot be used in combination with extremely small tooth spaces, as it does not fit in the small gaps. For this reason another roughness probe was developed with a special skid design and a parallel arrangement of the diamond needle for use on gearing as small as module 0.9 mm; the special design is shown (Fig. 19).

Because of the short distance between the tooth ground and the tooth tip, the parallel design of the needle and the skid was necessary. This design ensures that the biggest possible proportion of the short measuring section that is available with small gearing can be recorded. Because of the extremely compact design (Fig. 20), a ratio of 1:1000 was achieved between the probe tip radius (2 µm) and the skid radius (2 mm). The distance between the skid and the needle was also further reduced.

The small stylus tip radius shown (Fig. 20) is not a prerequisite for the measurement of small modules; the radius of the tip to be used is specified in the standard ISO 3274. That's why the roughness probes are optionally available with 2 µm and 5 µm tip radius.

Internal Gears

Measuring internal gears represents another challenge in that the use of reference plane scanning systems is even more complicated in the case of internal gears than for external gears.

Thanks to the highly compact roughness probe with integrated swivel device, it was possible to develop an overall system that can also be used in an automated setting. Combined with the

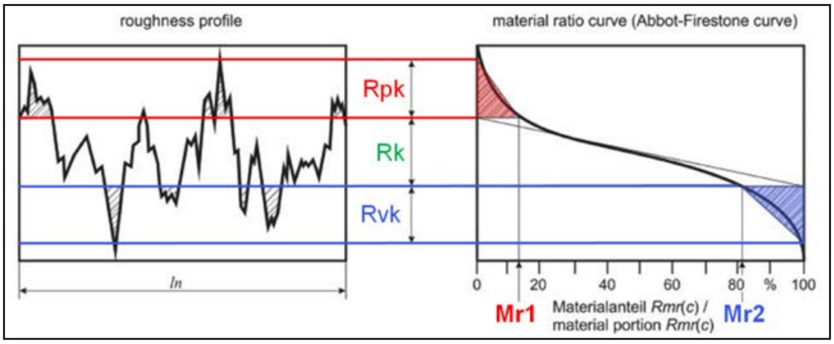


Figure 18 Generation of an Abbott-Firestone curve used for surface characterization.

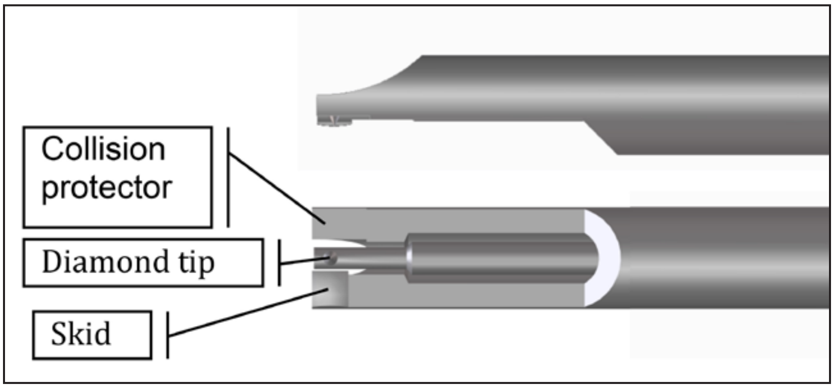


Figure 19 The front end of the roughness probe shows the arrangement of the skid and the diamond tip. The position of the skid is beside the diamond tip. On the other side there is a collision protector to protect the tip.

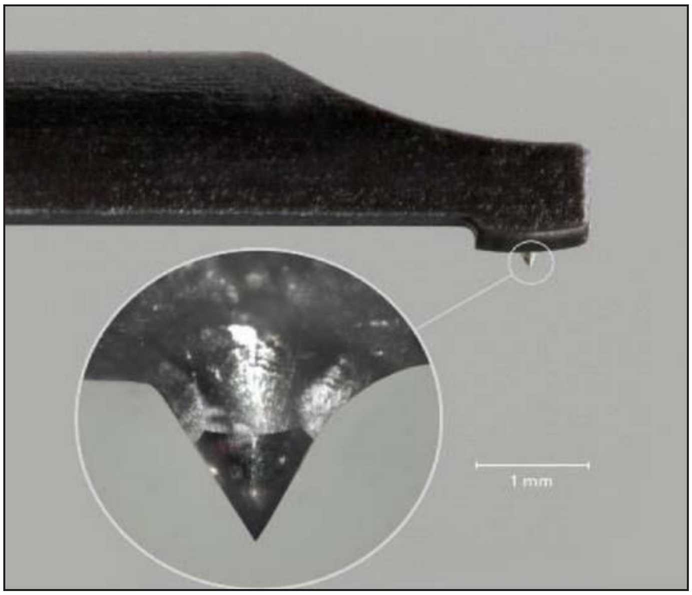
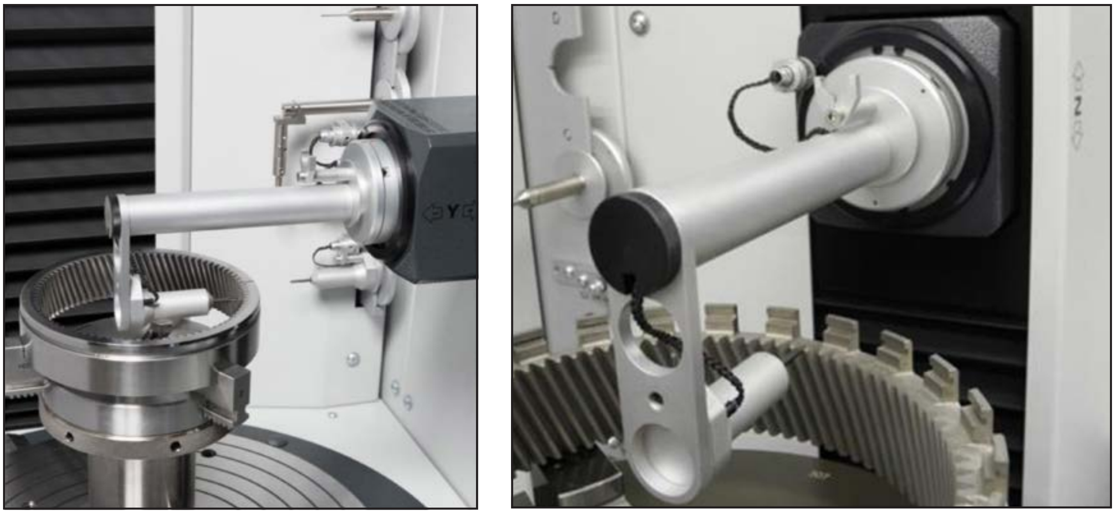


Figure 20 A close-up image of the roughness probe for gearing starting at module 0.9 mm shows the skid in relation to the diamond tip. Because of the extremely small dimensions of the overall system, a ratio of 1:1000 was achieved between the tip radius and the skid radius. This roughness probe comes equipped with the 2 µm/60° diamond tip as standard.



Figures 21 and 22 Roughness measurement of internal gears.

roughness probe for external gears starting with module 0.9 mm, the typical internal gears in complex passenger cars with automatic transmissions can also be measured. Figures 21 and 22 show the design of the system for roughness measurement of internal gearing and internal gears.

Due to the special scanning conditions, the usage of a skidded probe with a parallel arrangement of skid and diamond needle is advantageous. In this way, shaft collisions can be avoided through a significantly greater degree of freedom in the scanning angles. Also, a much larger measuring range can be executed relative to the tooth depth.

The probe rods with the roughness probe for internal gears can also be changed automatically. The electrical connection via the plug is also plugged in automatically, as with the other roughness probes.

Summary

The properties of the gear transmission can be improved by reducing the surface roughness of gears or by producing optimized surfaces. Among other things, this has a positive effect on the efficiency, power density, wear and running behavior. With modern manufacturing processes, such surfaces can be produced economically and reliably. In order to control the results of machining the surfaces, roughness measurement of gears gains importance.

With the known roughness measuring devices, these measurements are very time-consuming and require trained personnel. For series surveillance, the presented fully automatic system is better suited.

Since this system is based on a gear measuring machine, all measuring tasks of the gear measurement can be used. The developed roughness sensor with skid system is highly miniaturized so that the sensor can be adapted on the 3-D touch probe. In this case the roughness sensor is used instead of the tactile stylus. The skid and the diamond needle can be automatically rotated perpendicular to the tooth surface by means of a swivel axis integrated in the roughness sensor; the roughness sensor system complies with the DIN/ISO 3274 standard.

The use of the skid system protects the sensitive diamond needle of the roughness sensor against collision during the measurement. This makes the system very robust. The gear measuring machine is suitable for use in production. The combination with the robust roughness sensor and the automatic measuring sequences analogous to the gear measurements now makes the roughness measurement possible in the production area.

Due to the automatic change between the tactile stylus and the roughness sensor, measurements with automated processes and the combination with geometrical measurements are possible with this system. The programming of the measuring processes can be carried out by the operator of the gear measuring machine analogous to the gearing measurement.

For the measurement of gears with small modules, an additional roughness probe with a special skid design has been developed. This makes measurements from module 0.9 mm possible.

The roughness of internal gears can now also be measured with the same ease. In addition to the conventional evaluation of *Ra*, *Rz*, *Rt* and *Rmax*, etc. contact ratio parameters such as *Rk*, *Rpk*, *Rvk*, MR1 and MR2 can also be evaluated. The contact ratio parameters are evaluated according to the DIN/ISO 13565 standard. The roughness parameters are evaluated according to DIN/ISO 4287.

For more information. Comments or questions regarding this paper? Contact Georg Mies at *g.mies@klingelnberg.com*.

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