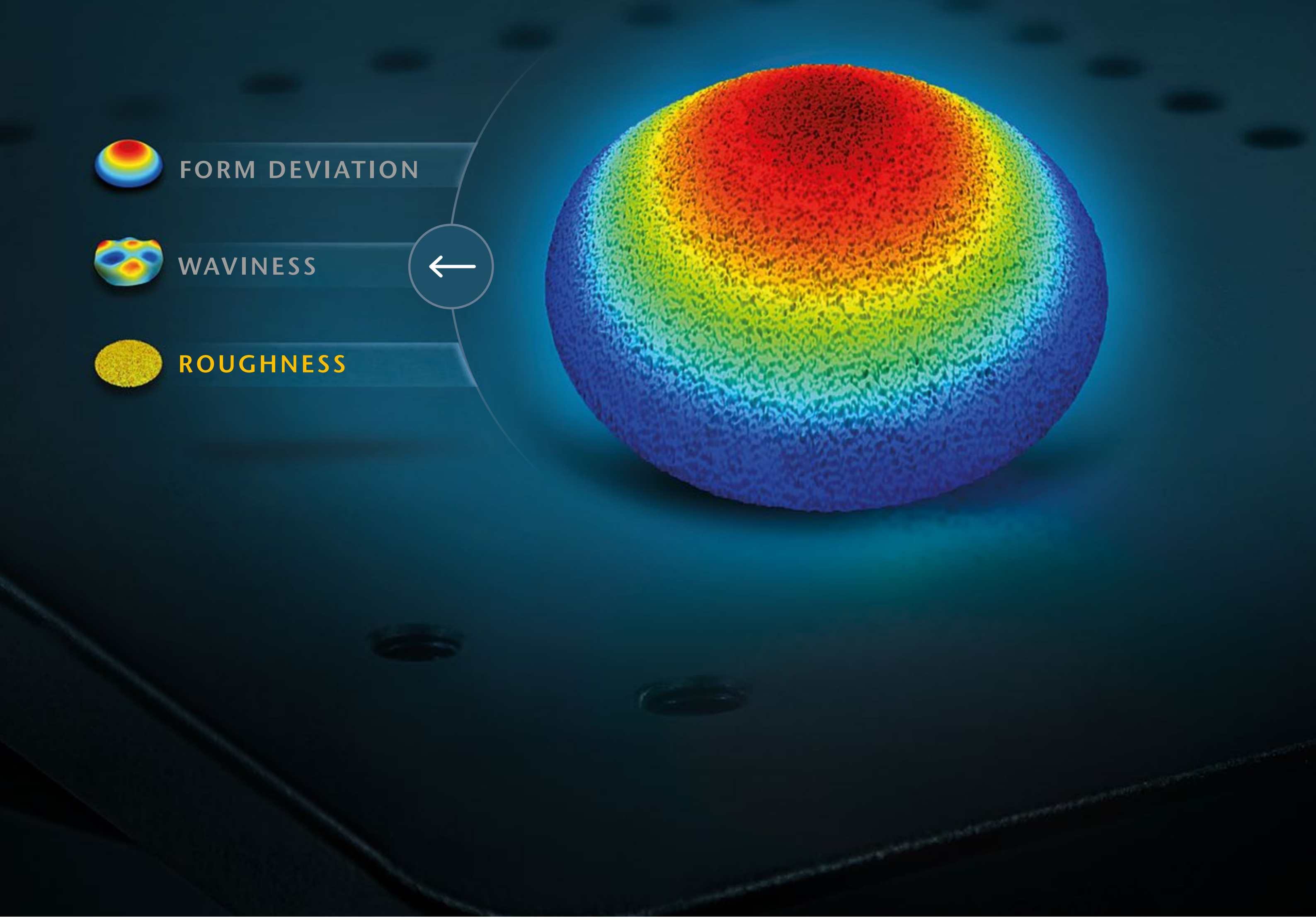
Polytec

Whitepaper

Surface metrology
Roughness measurement

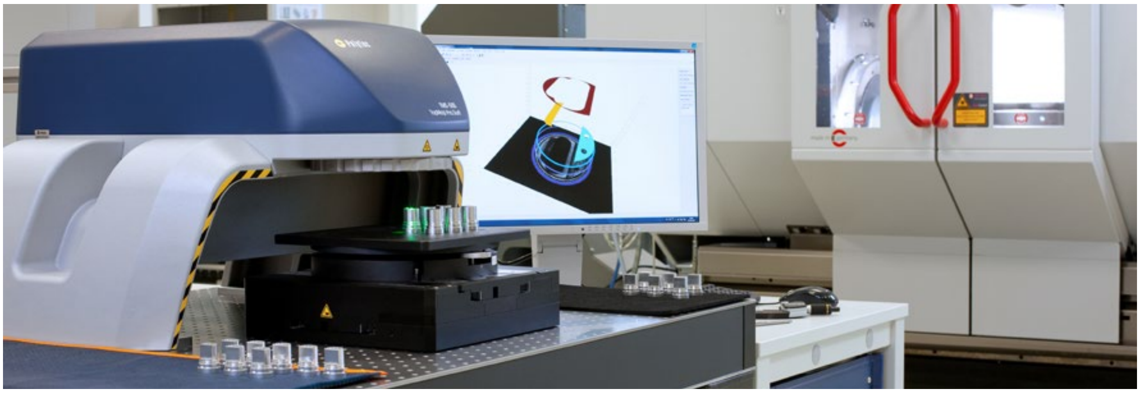


Surface components and the concept of roughness measurement

The design of a technical surface plays the key role for the functionality of the component. This applies equally to machine components as well as to medical products, the semiconductor industry and consumer goods of all kinds. As the link to the outside world, the surface of a workpiece affects many functional properties like sliding, wear resistance, sealing or the visual appearance. A surface can be designed to resist large forces, to adhere well or to slide smoothly. It can be optimized for easy sterilizability, low-resistance electrical conductivity or for an optimized heat transfer.

Finally, the design of the surface determines the aesthetics and impression and thus the visual and haptic perception of quality. The microscopic structure of a surface is therefore of great importance. Form deviations due to manufacturing can affect functionality or lead to unexpected failure of the component in operation.

The surface is usually the result of a multi-step manufacturing process. Only a consequently quality-monitored manufacturing process can meet the high demands on surface quality.

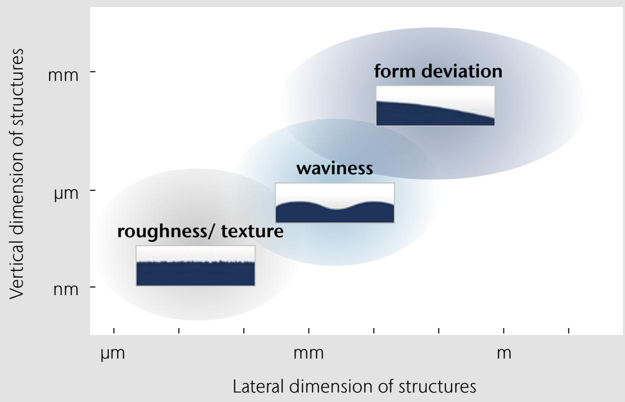


Taking a closer look will show that every surface is a complex unit – containing various structures of different scales and dimensions. The surface components include form, waviness and roughness. The deviations from an idealized surface are usually caused by the manufacturing process.

Very often, a specific characteristic of a surface component is explicitly required to fulfill a certain functionality. However, incorrect operation of machining tools, improper fixation of the workpiece or distortion due to thermal stress can cause unwanted form deviations. Unbalanced operation and machine vibrations will appear as waviness on the surface, while machining processes and chip formation will lead to a characteristic surface roughness.

Surface measurement results can provide valuable information for the optimization of the manufacturing process as well as its continuous monitoring.

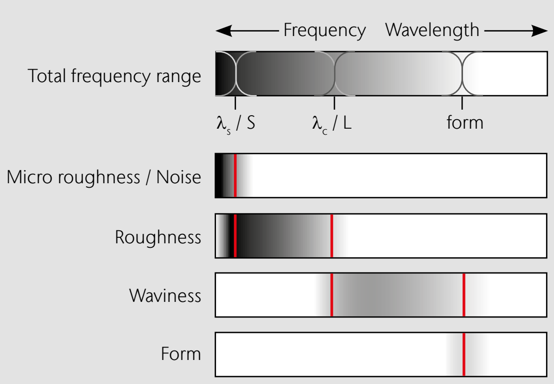
Longitudinal scale of surface components



Form, waviness, and roughness are not sharply defined but rather defined close to each other. A surface can be described as a superposition of numerous wavelengths, where the transition within surface components from form (particularly long-wavelength) over waviness to short-wavelength roughness components takes place smoothly.

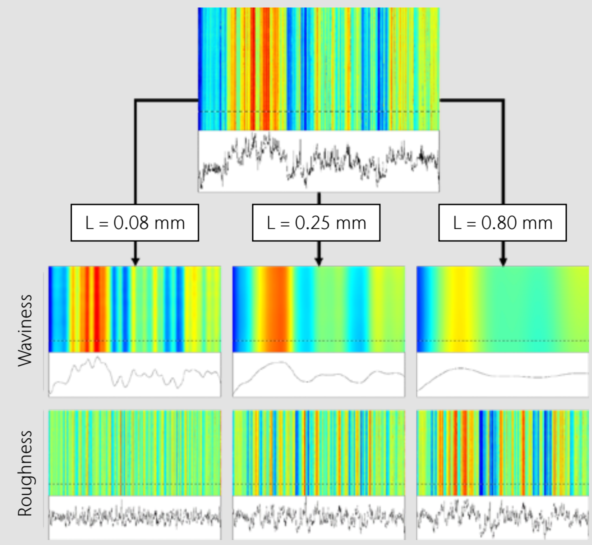
The separation of roughness from waviness is carried out by means of frequency filters, where their parametrization essentially determines which surface features are to be treated as waviness and which as roughness. They must be evaluated within a measurement chain. A frequency filter separates those components of the surface that are smaller or larger than a certain threshold value, the so-called cut-off wavelength (profile-based evaluation) or the nesting index (areal evaluation). To be in line with the smooth transition of surface components, their separation is not performed sharply at one wavelength, but through continuous attenuation of frequency components to be removed. In the profile-based roughness analysis, filter to separate micro-roughness is called to be λs filter and the filter to separate waviness and roughness is called to be λc filter. In areal roughness evaluation they are called as S- and L-filters, accordingly.

These are actually low-pass and high-pass filters with Gaussian characteristics. According to application of this Gaussian filter, a bandwidth-limited profile or a bandwidth-limited surface remains for further evaluation.



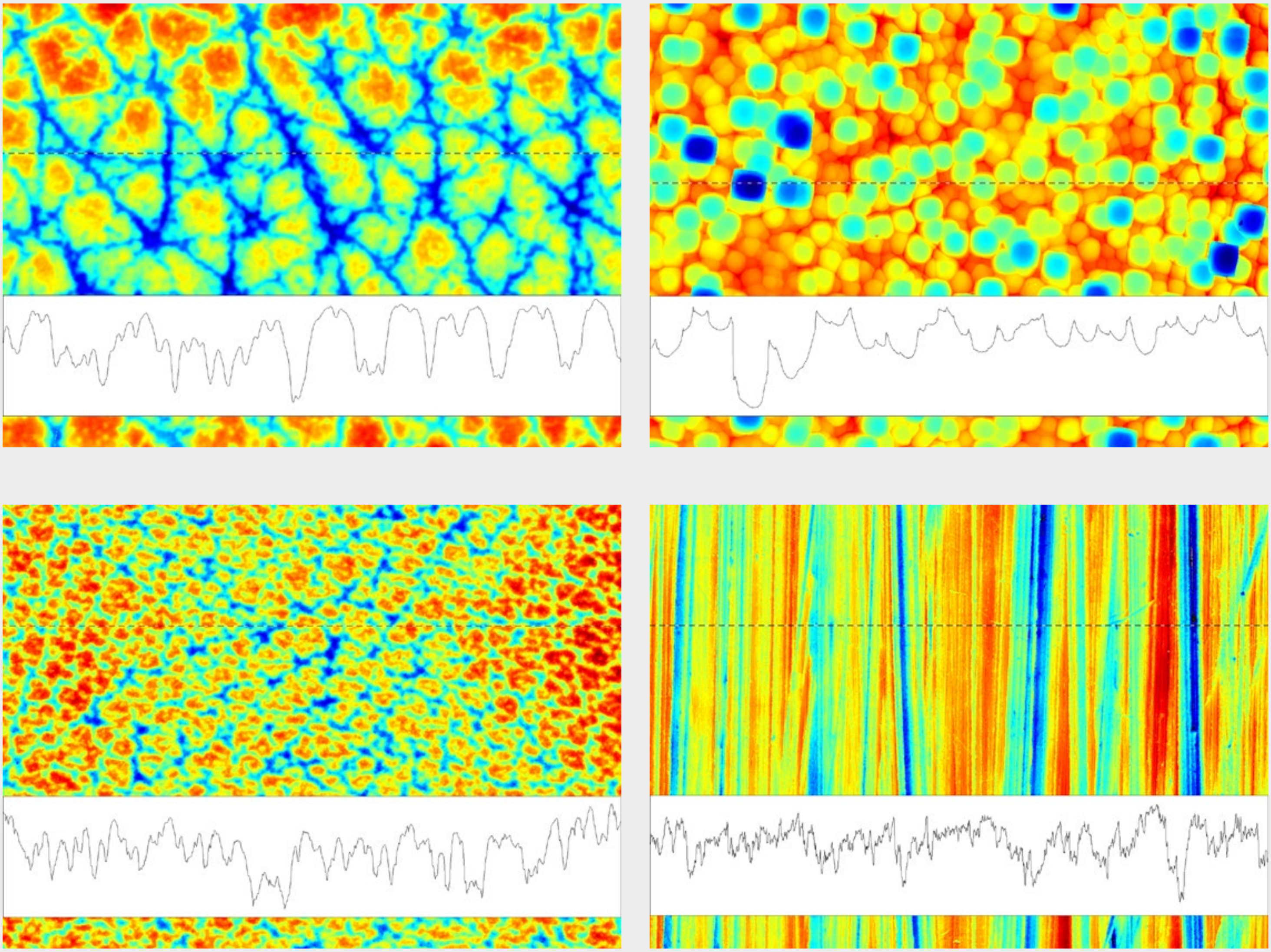
The characteristics "roughness" and "waviness" obviously have no unique definition, but depend on the selected cut-off wavelength. Therefore they are the result of a mathematical separation of frequency components. For a better understanding, it can be thought that superimposing the waviness profile with the roughness profile results in the measured profile.

Influences of the selected cut-off wavelength



Especially for surface parameters, the choice of the cut-off wavelength has a significant importance. By changing cut-off, some components that previously were described as waviness, will be assigned to roughness or vice versa. The smaller the selected cut-off wavelength, the more the high-frequency components (= roughness) are included in the waviness profile. The remaining roughness profile decreases in its amplitude and the roughness values are smaller. In consequence changing the cut-off wavelength the calculated surface parameter value.

Profile and areal evaluation of roughness



Areal measurement data provides an easy and complete view of an entire surface. In contrast, a profile measurement contains only a limited section of the entire surface and is less intuitive.

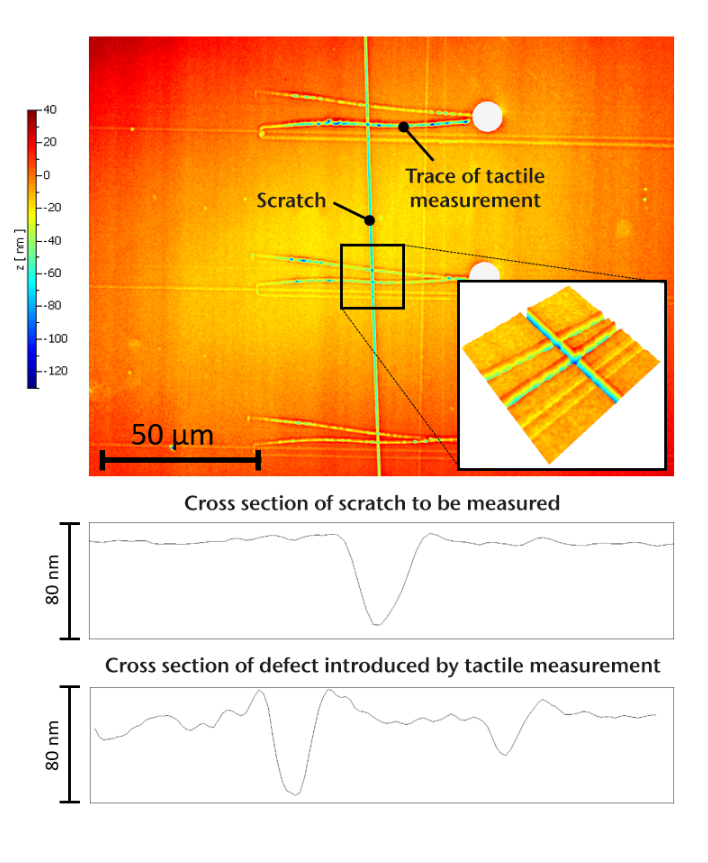
The surface is traditionally inspected using tactile stylus-based profilometers (stylus instruments), whose probe tip is guided over the surface and is deflected vertically by the surface texture. With this method, the information about the surface is obtained along a 2D profile.

The profile-based measurement and its evaluation has long been anchored in standardization and is widely used in industrial practice. It is questionable to which extent profile-based information could describe surface characteristics and provide function-oriented information.

If the surface has randomly distributed features, the result for the roughness parameter is strongly influenced by the measuring position. In many cases, profile-based surface description is insufficient to provide information about functional behavior of the surface. Profile based surface characterization allows only limited information about the cause of poor functionality and so includes limited information for quality control purposes.

Three-dimensional, areal measurement is not subjected to those limitations. Not only does it provide an image of the surface that makes it easier to understand, but areal measurements also enable a function- and structure-oriented evaluation. Furthermore, 2D profiles can easily be extracted from the areal measurement data which can be evaluated according to the rules of profile-based roughness evaluation. In contrast to tactile measurement, three-dimensional optical roughness measurement is non-contact and non-reactive avoiding any damage or influence on sensitive surfaces by the measurement.

Surface defects produced by tactile profilers

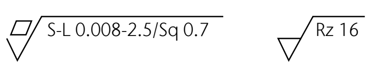


Tactile measurement leaving scratches/defects on the sample surface from the same size of the step height to be measured (70 nm).

The measurement chains for the areal or profile-based surface evaluation are described in ISO 25178 or ISO 4287, they differ from each other with some details:

- The designations of frequency filters and band-width-limited surfaces have been modified in the recent ISO activities for areal evaluation. When determining waviness and roughness parameters, the surface to which they refer must be specified clearly. For profile-based evaluations, this reference is clear from the designation of the parameter itself. Here, the first letter of the texture parameter specifies whether the calculation is to be performed on the primary (P), waviness (W) or roughness (R) profile.

Example of specifying roughness data in a technical drawing:

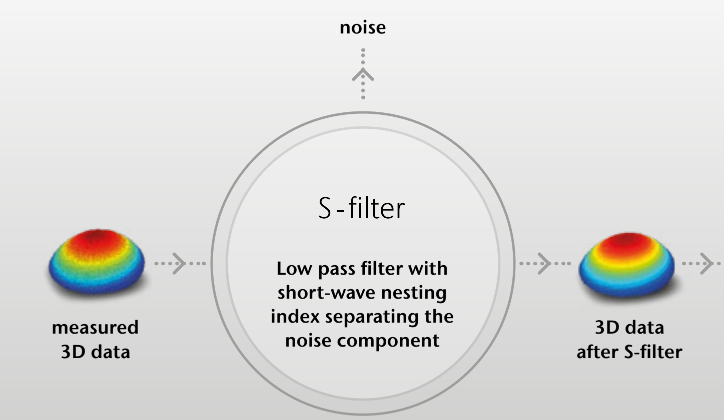


- The sequence for the application of λs/S filters and form removal is reversed in both series of standards.

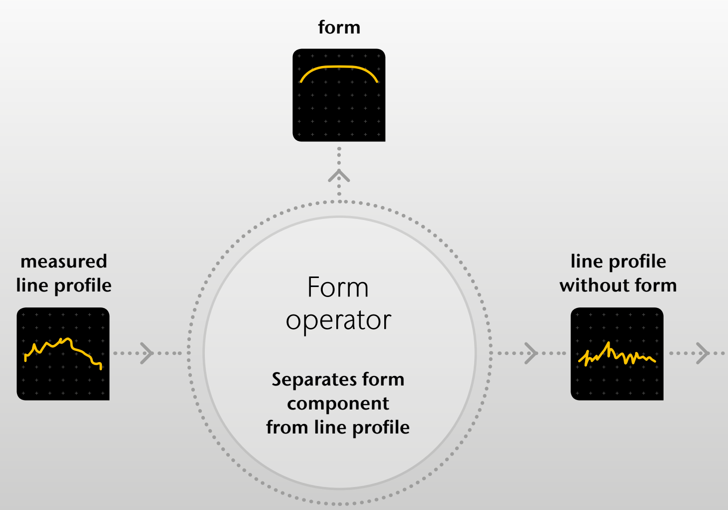
- The cut-off wavelength, the single sampling length and the evaluation length are determined based on the surface properties given in a table. For this purpose, the expected texture parameter is estimated, and a test measurement is carried out with the setting variables corresponding to this estimation. Depending on the profile characteristics, the texture parameters Rsm, Rz or Ra are calculated. Then, the measured value is compared with the wavelength, which is valid for this range. For a correct evaluation, the smallest cut-off wavelength for the given range must be selected. The designer/developer can specify a different procedure and note it in the technical drawing. This is particularly useful if the measured variable is at the limit of a range. Otherwise, two parts of the same type need to be handled differently (different cut-off, different sampling and evaluation lengths), if the described procedure is consistently applied.

For the areal evaluation, there is no such table for determining the nesting index. However, for the comparability of the surface texture parameters with profile texture parameters, it is recommended to choose the same lengths and a comparable nesting index.

Areal evaluation (ISO 25178-1, -2, -3)

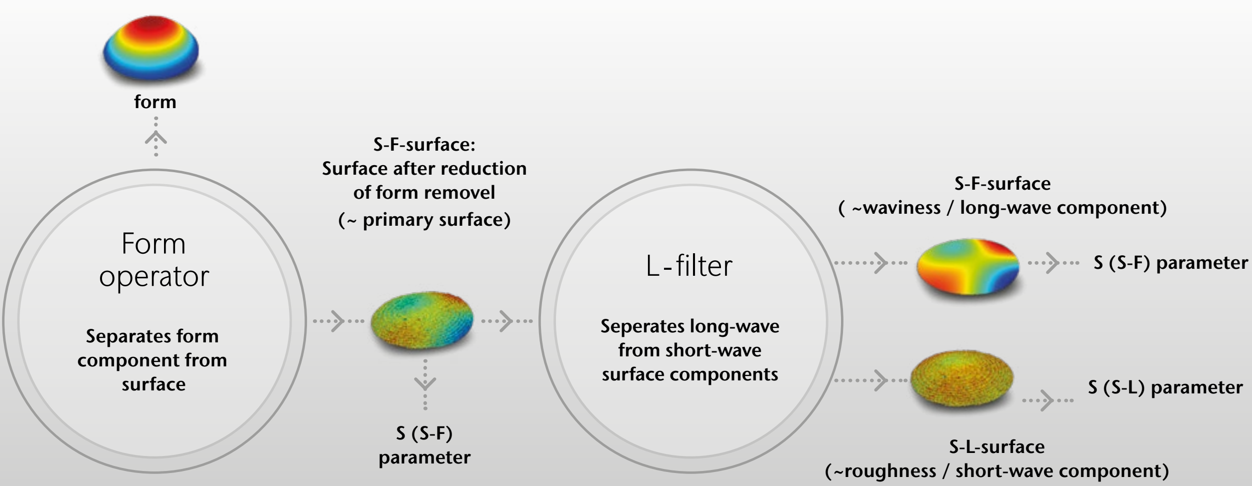


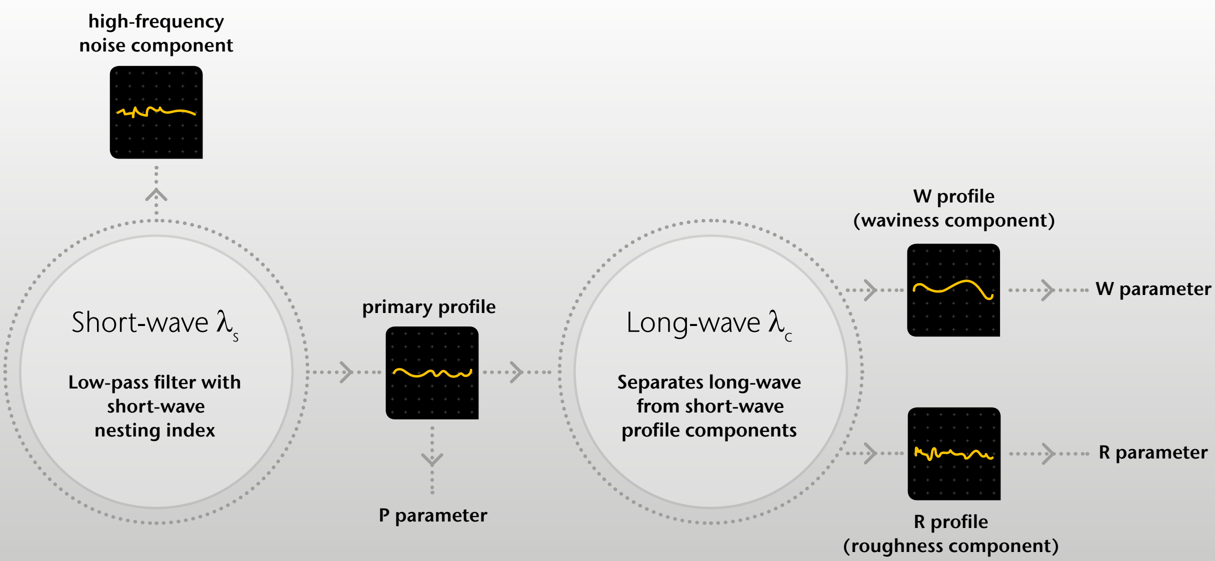
Profile evaluation (ISO 4287, 4288 and ISO 3274)



Periodic profile
R_{sm} (mm)
>0.013 ... 0.04
>0.04 ... 0.13
>0.13 ... 0.4
>0.4 ... 1.3
>1.3 ... 4

R_a column also to be used when determining R_q, R_{sk}, R_{ku} and $R\Delta_q$,
R_z Ra column also to be used when determining R_v, R_p, R_c and R_t





Aperiodic profile		Nesting index/cut-off wavelength	Sampling length/evaluation length
R_z (µm)	R_a (µm)	λ_c (mm)	L_r / L_n (mm)
>0.025 ... 0.1	>0.006 ... 0.02	0.08	0.08 / 0.4
>0.1 ... 0.5	>0.02 ... 0.1	0.25	0.25 / 1.25
>0.5 ... 10	>0.1 ... 2	0.8	0.8 / 4
>10 ... 50	>2 ... 10	2.5	2.5 / 12.5
>50 ... 200	>10 ... 80	8	8 / 40

Parameters in surface metrology

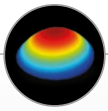
The mathematical description of numerous surface parameters can be found in various international standards. In practical application, ISO 4287 and ISO 13565 for 2D parameters and ISO 25178 for areal surface roughness are of particular importance. These standards define and describe the commonly used texture parameters.

For the large number of parameters from profile standards, an equivalent areal parameter can be found in the published standard. Beyond that, areal topography evaluation offers additional benefit due to third dimension.

Surface parameters

ISO 4287, ISO 13565

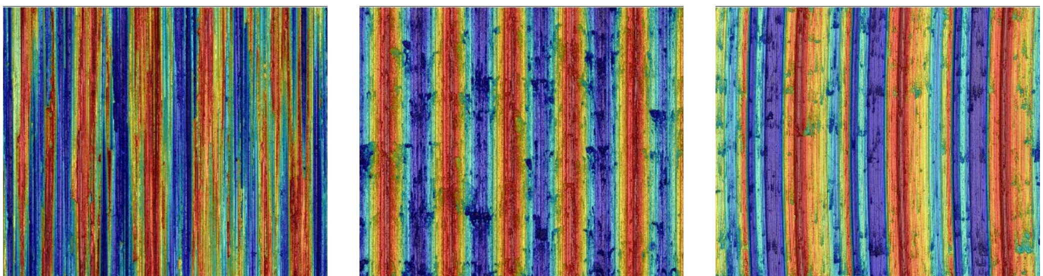
2D parameters
Amplitude parameters Ra, Rq, Rz, Rp, Rv, Rc, Rsk, Rku, Pt
Spacing parameters RSm, RPc
Mixed parameters Rdq
Material ratio parameters Rmr, Rpk, Rk, Rvk, Mr1, Mr2, Rdc



ISO 25178

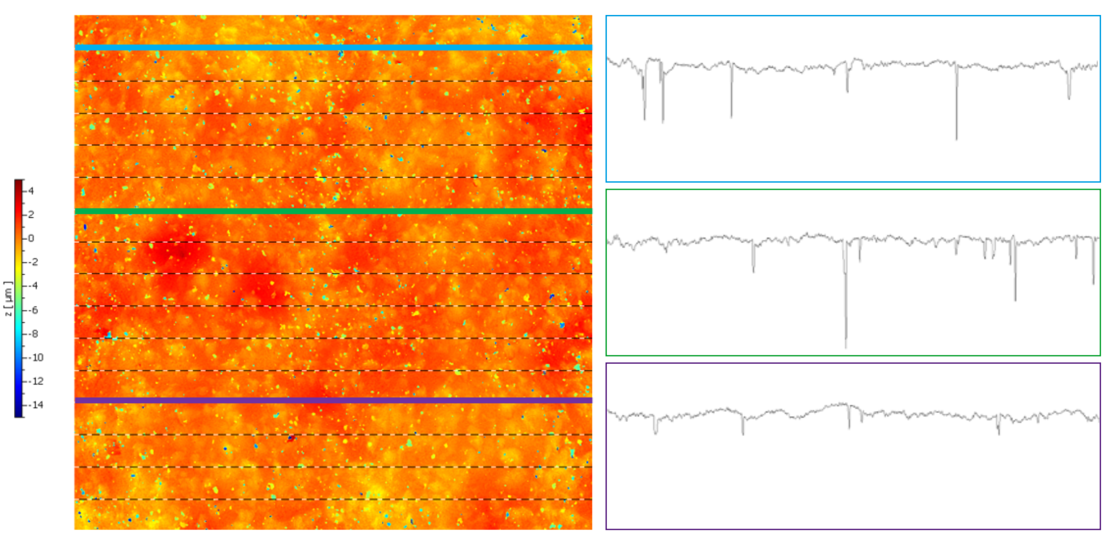
3D parameters
Height parameters Sa, Sq, Sz, Sp, Sv, Ssk, Sku
Functional parameters (area) Smr, Smc, Spk, Sk, Svk, Smr1, Smr2, Spq, Smq, Svq, Sxp
Functional parameters (volume) Vvc, Vw, Vmp, Vmc
Spatial parameters Sal, Str
Hybrid parameters Sdq, Sdr
Mixed parameters Std
Feature parameters Spd, Spc, S10z, SSp, SSv

The amplitude/height parameters frequently used in practice were mostly extended to the areal evaluation. The areal evaluation of the topography has the advantage that measuring position is not as important as in profile-based evaluation and thus provides more reliable results, especially for inhomogeneous and defective surfaces. However, the parameter family as a whole has in common that they cannot represent the functional differences between different types of surfaces. This means that very differently manufactured and designed surfaces can nevertheless show the same results for these surface parameters.



Grinding | Turning | Milling

Height parameters allow limited statements about the surface shape. Surfaces with different structures (and with different manufacturing processes) can show the same roughness (here: $S_a/R_a \approx 1.6$ µm).



ISO 4287					
		Min	Max	Ø	Std
Ra	µm	0.40	0.93	0.58	0.108
Rq	µm	0.53	2.00	1.04	0.287

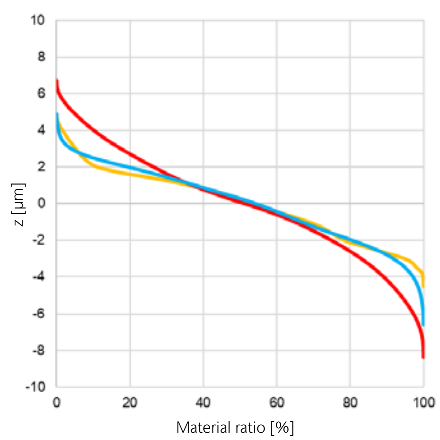
ISO 13565					
		Min	Max	Ø	Std
Rk	µm	0.92	2.24	1.44	0.265
Rpk	µm	0.13	1.38	0.52	0.241
Rvk	µm	0.67	5.10	2.16	0.902

ISO 25178		
Sa	µm	0.63
Sq	µm	1.13
Sk	µm	1.61
Spk	µm	0.67
Svk	µm	2.36

In case of surfaces with randomly distributed structures, the roughness values (based on profile measurement) is sensitive to the measurement position. 3D surface roughness parameters provide more stable and reliable results.

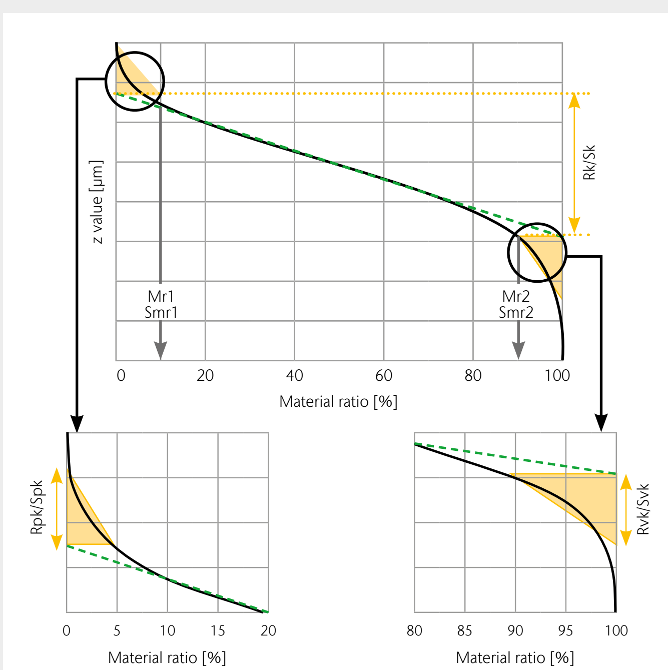
The functional parameters allow a function-oriented evaluation of the surface characteristics. This evaluation is based on the material ratio curve. The material ratio curve is generated by successive cutting of the measured data over the entire height range (like cutting into thin slices). The material ratio curve states the percentage of material present at different heights. The material ratio curve can be divided into three sections: peak (Xpk), core (Xk) and valley (Xvk) areas. By evaluating the absolute magnitudes and the relations between the three areas, the functional behavior of the surface can be described. The peak area is subject to increased wear. Load-bearing surfaces bundle a lot of material in the core area. The valley area provides a reservoir for coolants or lubricants. Depending on the functional requirements on the surface, the manufacturing process resulting in a suitable material distribution must be chosen.

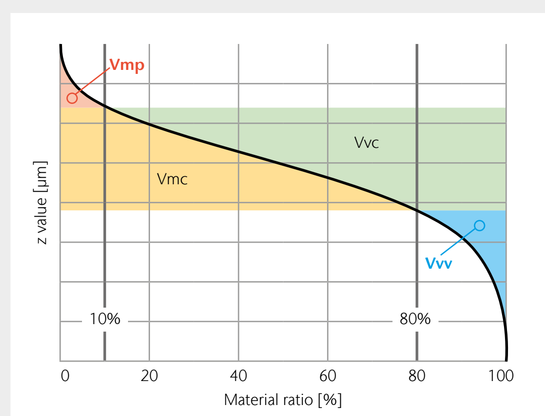
The same procedure can be extended by one dimension to the material volume parameters.



Surface machining	Grinding	Turning	Milling
Spk	1.9 µm	2.1 µm	0.8 µm
Sk	3.3 µm	4.5 µm	5.3 µm
Svk	2.2 µm	0.8 µm	1.9 µm

Functionally relevant properties of a surface can be derived from the material ratio curve.





Thanks to the available spatial measurement data, additional evaluation options are available for surface-based versus profile-based measurements. With the help of the developed interfacial area Sdr, the actual size of the surface that is in contact with the surroundings can be determined. The characteristic value indicates the proportion by which the surface is larger than its projection. For a perfectly flat surface Sdr is 0, for very fissured surfaces the value can be more than 100 %. Sdr can be useful when a surface is to be wetted or is in energy exchange with its surroundings. The root mean square gradient Sdq is calculated as the root mean square of the slopes at all points. For a perfectly flat surface, Sdq is 0 and increases with the slopes. Using the parameters Sal (fastest decay autocorrelation length), Str (texture aspect ratio) , and Std (texture direction), a surface can be examined for similarity to itself, its uniformity in the X and Y directions, and a preferred texture direction. In addition, there is another new family of parameters in the surface standard, areal feature parameters. Here, after segmenting the surface, the topography elements are counted (density of peaks, Spd) or averaged (five-point peak height, S5p, and others).

Summary

Roughness measurement is used in a wide range of industries. Optical profilometers are increasingly replacing tactile measuring systems. It can be assumed that in near future, 2D parameters will only endure where their informative value is sufficient. 3D characterization of the surface with the aid of optical surface measurement technology not only offers better visualization of measurement data, but also permits more extensive evaluation options. Measuring equipment should therefore be supplemented or replaced at the latest when 2D characteristic values cannot describe the characteristics or functional behaviour of the surface with sufficient accuracy and reliability.

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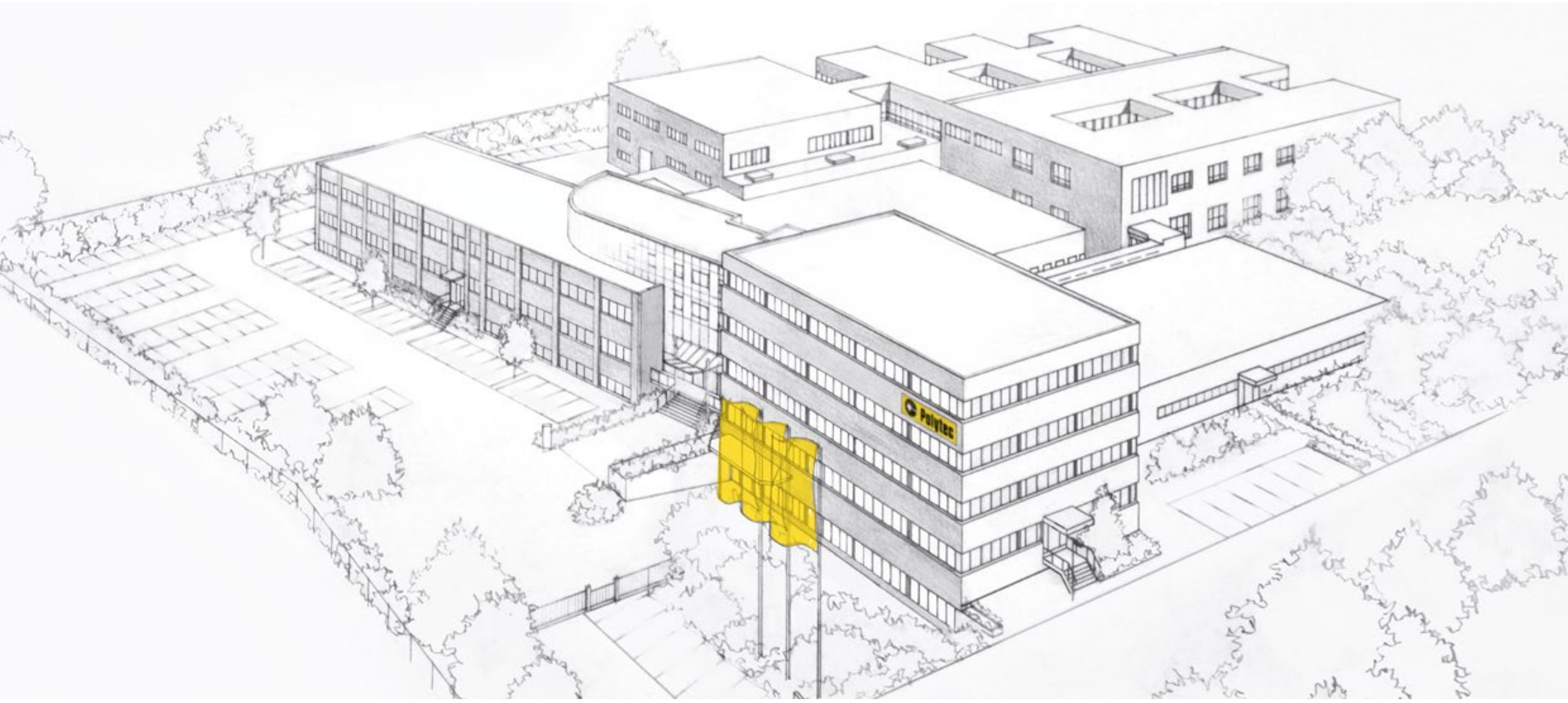

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