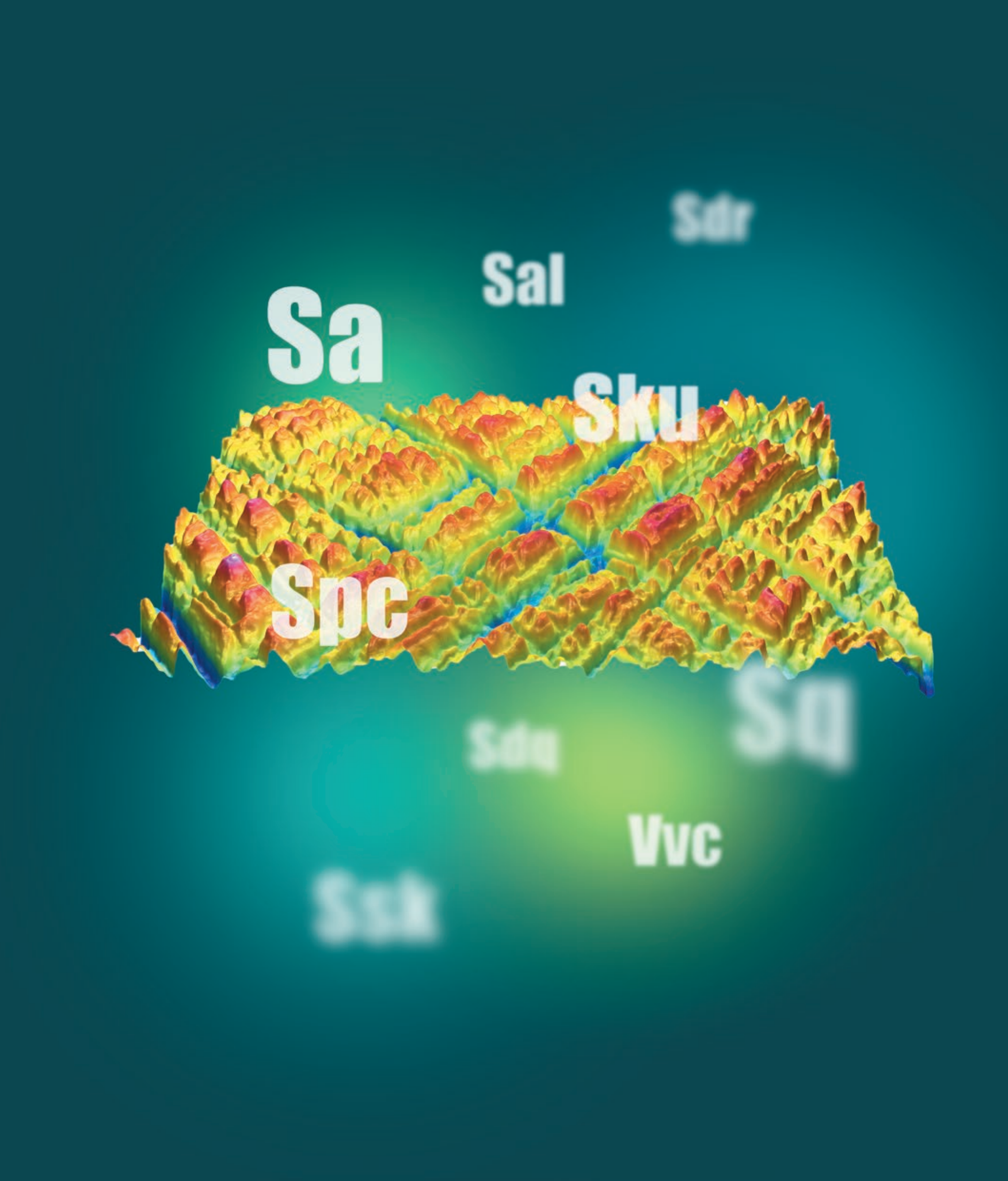


SENSOFAR

THE AREAL SURFACE TEXTURE HANDBOOK

UNDERSTANDING ISO 25178

Contents

Introduction

Introduction

This document aims to be a valuable resource for anyone seeking to understand and apply areal surface texture characterization, based on the standards and methodologies outlined in ISO 25178.

ISO 25178: Geometrical Product Specifications (GPS) – Surface texture: areal is an international standard that pertains to the evaluation of 3D areal surface texture[1]. The standard provides a framework for measuring and analyzing surface texture in three dimensions, enabling manufacturers and quality control professionals to accurately assess the topography of surfaces at the micro and nanoscale. This information is essential in ensuring that parts and products meet the required functionality, reliability, and safety standards.

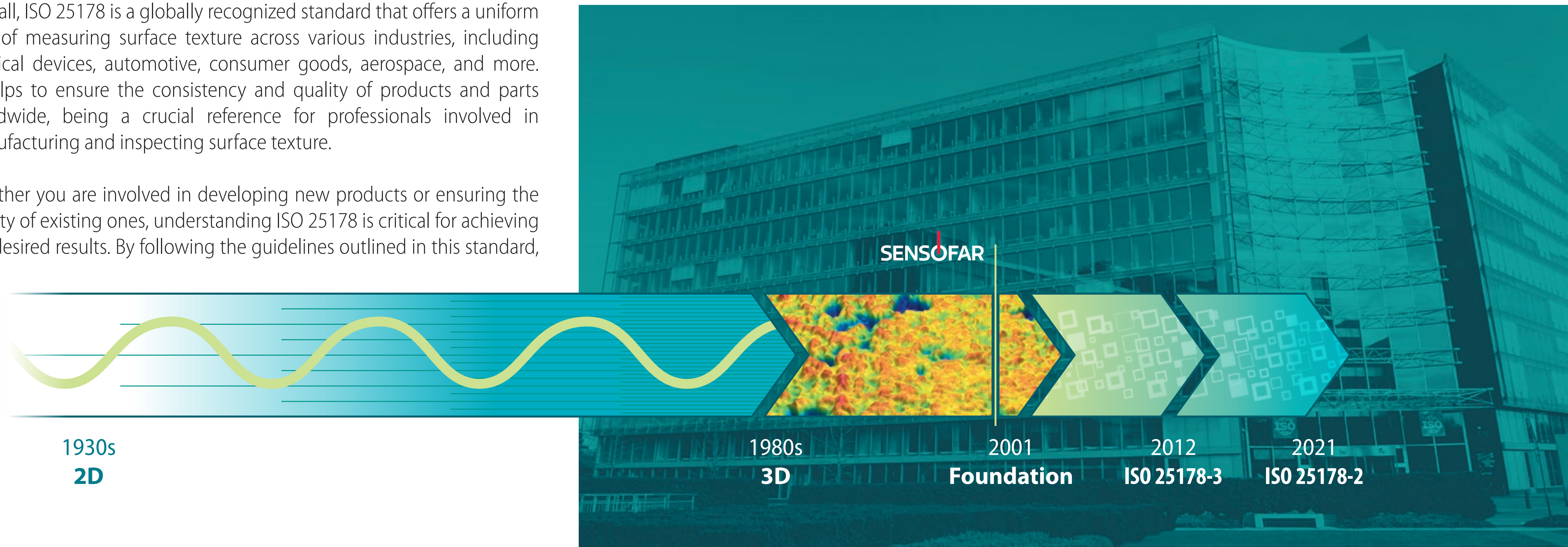
Overall, ISO 25178 is a globally recognized standard that offers a uniform way of measuring surface texture across various industries, including medical devices, automotive, consumer goods, aerospace, and more. It helps to ensure the consistency and quality of products and parts worldwide, being a crucial reference for professionals involved in manufacturing and inspecting surface texture.

Whether you are involved in developing new products or ensuring the quality of existing ones, understanding ISO 25178 is critical for achieving the desired results. By following the guidelines outlined in this standard, you can ensure that your measurements are accurate, consistent, and in line with industry standards.

This guidance document intends to be a helpful resource for manufacturing and surface texture inspection professionals. It provides a clear and concise explanation of the key elements of surface texture measurement and their practical application, helping readers to deepen their understanding of ISO 25178. This document mainly gathers information from Parts 2 and 3 of this international standard (i.e., ISO 25178-2:2021 and ISO 25178-3:2012), those defining the main concepts, parameters, and methods for extracting surface texture parameters.

The reader must note that this handbook is not intended to formally replace ISO 25178, but rather to offer practical guidance on its key concepts and their application in surface texture characterization.

Figure 1. Historical perspective Sensofar and surface texture measurement.



What is surface texture?

What is surface texture?

Surface texture refers to the irregularities and variations in the shape and form of a surface when compared to a perfectly smooth and flat surface.

The characteristics of surface texture can significantly impact the appearance, performance, and functionality of a product. Surface texture plays a critical role in determining the friction, wear resistance, and adhesion properties of a surface, among other factors. Understanding the role of surface texture in product design and manufacturing can help optimize performance and ensure that products meet the required specifications.

Surface texture, topography and roughness

The terms surface texture, roughness, and topography are often used interchangeably, but they do not have the same meaning.

Surface **topography** is the overall structure of the surface of a part, including all its features treated as a continuum of spatial wavelengths. Surface **form**, on the other hand, refers to the underlying shape of a part, such as the spheric form of a lens. Once the form is removed, the remaining surface features are considered surface **texture**, including both roughness and waviness.

Roughness refers to the small-scale components of the surface, while **waviness** pertains to larger-scale features. The term "surface finish" is often used to refer to surface texture, but it typically pertains specifically to roughness. Meanwhile, "surface lay" is commonly used to refer to the orientation of the texture, although this term is more frequently used among American English speakers.

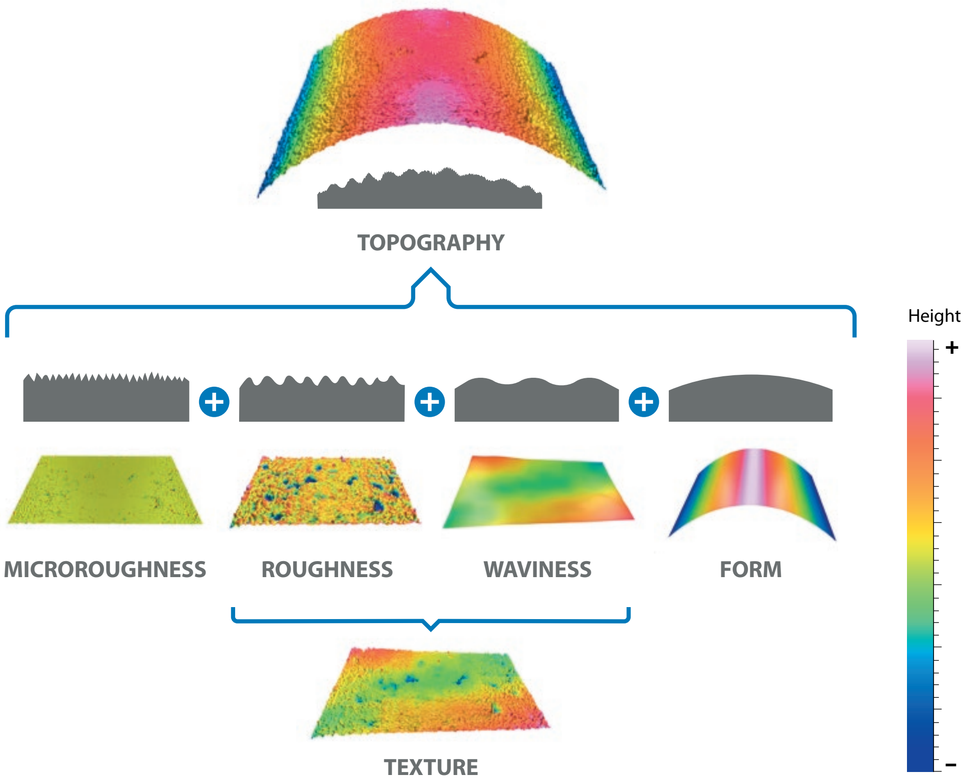


Figure 2. Wavelength components of a topography.

Surface texture terminology

The following definitions included in ISO 25178 are basic for understanding surface texture characterization and roughness parameters extraction.

- **Primary surface:** portion of the surface obtained as a result of applying an S-filter to the measured region of the workpiece. When this surface is represented by a finite set of data points, we should talk about the primary extracted surface.
- **Surface filter:** an operator used to filter a surface, typically applied to a primary extracted surface.
- **Nesting index:** it represents the threshold wavelength for surface filters and is expressed in units of length (usually microns). The nesting index may be called the "cutoff value" in specific contexts due to its correspondence with this parameter in the profile method. Essentially, the nesting index determines the level of smoothing applied to an areal surface, ensuring that only relevant features are retained.
- **S-filter:** a surface filter that acts as a long-pass filter (low-pass in frequency) by discarding small-scale lateral components from the surface and resulting in the primary surface. The nesting index for the S-filter can be refered to as Nis or Nic depending on the order of the S-filter with respect to the F-operator and thus the wavelength component that it removes (microroughness/roughness).

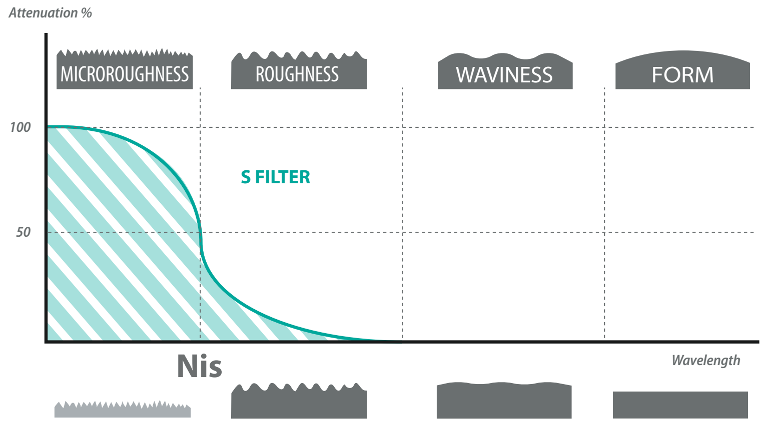


Figure 3. Effect of an S-filter with nesting index Nis on the wavelength components of a surface.

- **L-filter:** short-pass filter (high-pass in frequency) that eliminates large-scale lateral components from either the primary surface or the S-F surface. It is specifically designed to remove undulations and other lateral components from the surface, enabling the extraction of roughness components. The nesting index for the L-filter is always refered to as Nic.

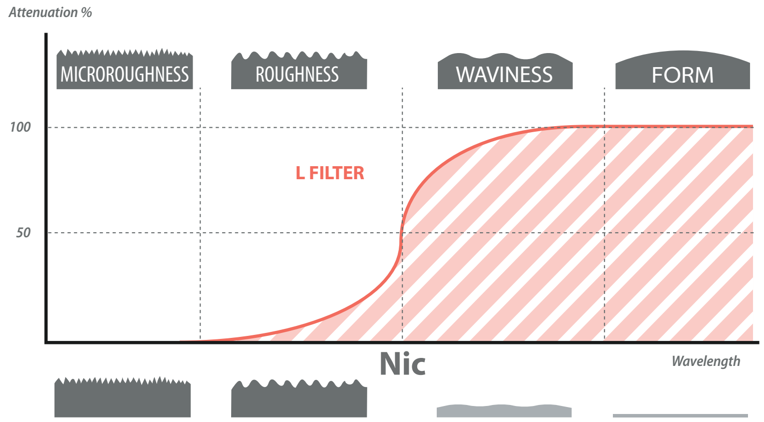


Figure 4. Effect of an L-filter with nesting index Nic on the wavelength components of a surface.

- **F-operator:** suppresses the form from the primary surface by, for example, subtracting a least-squares plane or cylinder. Since many L-filters are sensitive to form, an F-operator is often applied as a prefilter before using L-filters.

- **S-F surface:** obtained by applying an F-operator to the primary surface, which has already been filtered with an S-filter. This process eliminates both small wavelength components and form components.

- **S-L surface:** surface in which small wavelength components have been removed using an S filter, followed by the elimination of large wavelength components using an L-filter. This can be done by applying an L-filter to the S-F surface or the primary surface.

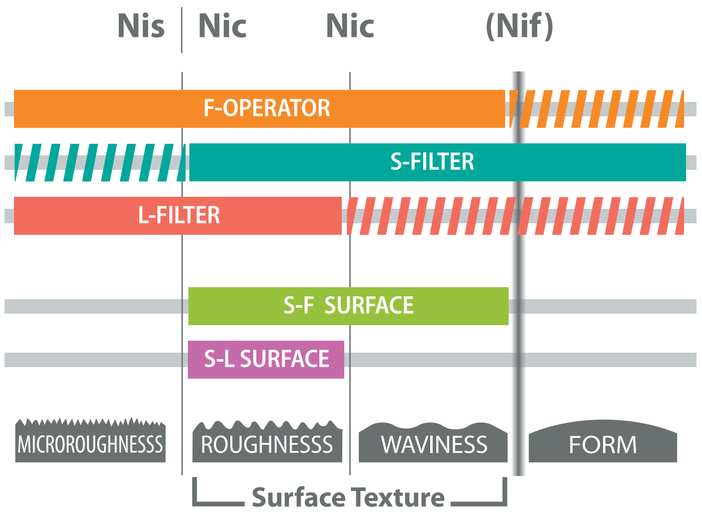


Figure 5. Scheme showing how the S-F and S-L surface are generated by the different filters and its wavelength components.

- **Scale-limited surface:** the foundation for calculating areal surface texture parameters. It refers to either the S-F or S-L surface and is sometimes known as the "surface". This surface type is comparable to the roughness or waviness profile of the surface in the profile method.

- **Reference surface:** an essential component associated with the scale-limited surface that serves as the basis for calculating surface texture parameters. While a plane at mean height is the most common reference surface, other examples include cylinders and spheres.

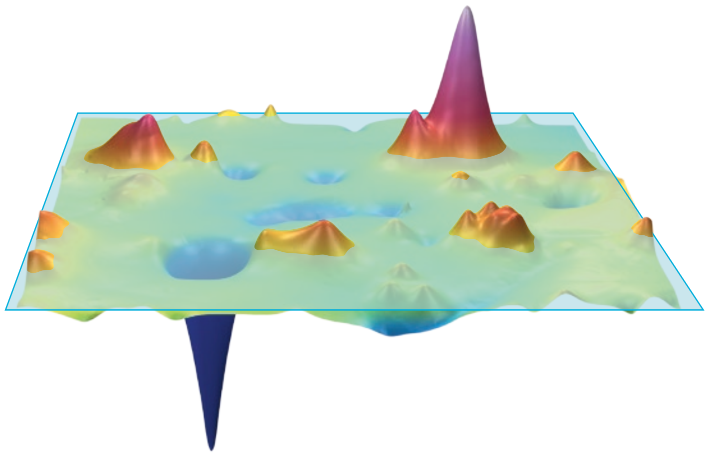


Figure 6. Example of a reference surface, in this case a mean plane of a scale-limited surface.

- **Evaluation area:** a rectangular portion of the surface used for extraction purposes. In order to ensure accuracy, typically, the sides of the rectangular area must be parallel or orthogonal to the nominal geometry because it depends on the function of the surface. The evaluation area is a square unless otherwise specified for S-F and S-L surfaces.

- **Height:** signed distance perpendicular to the reference surface and measured from the reference surface to the scale-limited surface. If the point lies in the direction of the material, the height is negative.
- **Depth:** the absolute value of a negative height.

How to evaluate and report surface texture

How to evaluate and report surface texture

When it comes to evaluating surface texture, there are a few steps to follow to allow for accurate characterization of the roughness, waviness, or other topographical features of the surface.

1 Measure with an accurate instrument

While stylus or contact profilometers can be used to evaluate surface texture by joining different profiles, non-contact or optical profilometers provide countless advantages in fidelity, accuracy, and repeatability.

ISO 25178 defines a series of different accepted non-contact techniques that can be used to evaluate surface texture. The specific adequate technology for your workpiece will depend, of course, on its characteristics. In any case, ensure that your instrument configuration (technology, objectives, etc.) provides enough lateral and vertical resolution to evaluate your surface texture.

Figure 7. Sensofar table-top solutions for surface texture characterization.

2 Filter the surface to obtain the desired scale of interest

In general, to obtain meaningful surface texture parameters, your surface must be filtered to separate roughness from waviness (or vice versa). As we will see in the following sections of this document, selecting the appropriate filtering methods to limit the surface to a specific scale of interest is essential. This creates significant parameters and ensures the objective comparison of surfaces.

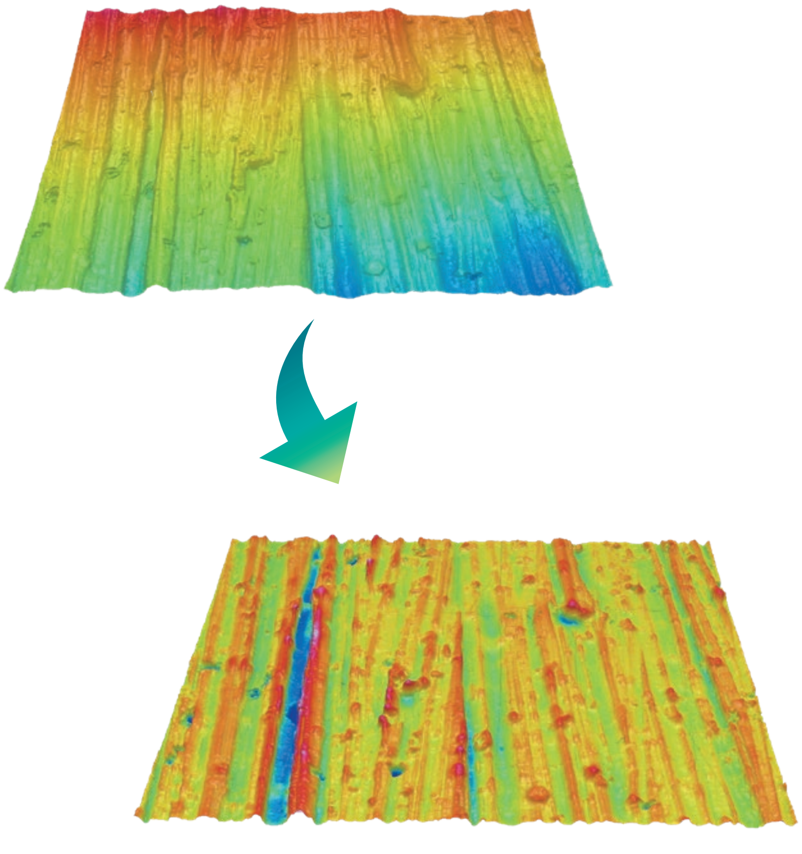


Figure 8. Extracted surface topography (top) and filtered surface (bottom).

3 Choose the proper parameter(s) for relevant results

There are many surface texture parameters, and each one provides different kinds of information about the surface. Choosing the proper surface roughness parameter or set of parameters is a must to evaluate and control surface quality accurately. The surface texture parameter chosen should be relevant to the particular application and provide meaningful information about the functional behavior of the surface.

Finally, **when reporting** the surface texture measurements we have obtained, it is crucial that we clearly **specify all the chosen acquisition and analysis parameters** that could impact the outcome. This includes variables such as optical resolution, spatial sampling, field of view, measurement method, and, most importantly, the filters applied and their nesting indexes. By providing these details, and using a properly calibrated system, we ensure that our results are unbiased and can be reproduced. In other words, if we want to compare our current results to others, we must use the same settings in terms of resolution and filtering. Only then we can have a fair and objective comparison, regardless of the system or brand used.

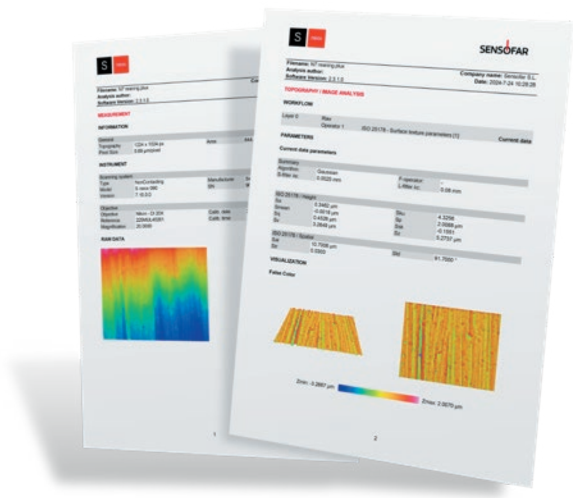


Figure 9. Measurement report.

How to filter your surface according to ISO 25178

How to filter your surface according to ISO 25178

If you want to comply with ISO 25178, you must follow a specific workflow (Figure 10) to filter your surface data. First, apply an **S-filter** to the extracted surface topography (raw data) to remove possible measurement noise and small-scale lateral components to obtain the primary extracted surface. Then, an **F-operator** can be applied to remove the form from this primary surface. At this point, you can already obtain the **Primary Parameters**. These parameters can be already helpful to characterize the surface if you want to obtain information from a wide range of surface scales at once, i.e. from "unfiltered" surface texture. Even though, it is quite common to filter the surface more and separate between roughness and waviness. This is what usually gives more insights into the properties of the surface and its manufacturing process.

To obtain the **Waviness Parameters**, you just need to apply another **S-filter** to the previously obtained surface. The goal of this second filter is to remove irrelevant small-scale components you want to separate from the waviness of the surface. The resulting surface after this process is called **S-F surface**.

Finally, to obtain the **Roughness Parameters**, you have to apply an L-filter to the S-F surface generated right after applying the F-operator. This filter will remove undesired large-scale wavelength components of the surface and keep the small-scale roughness components. A good practice for characterizing roughness accurately is to check that the first S-filter applied to the **Extracted Surface Topography** is small enough

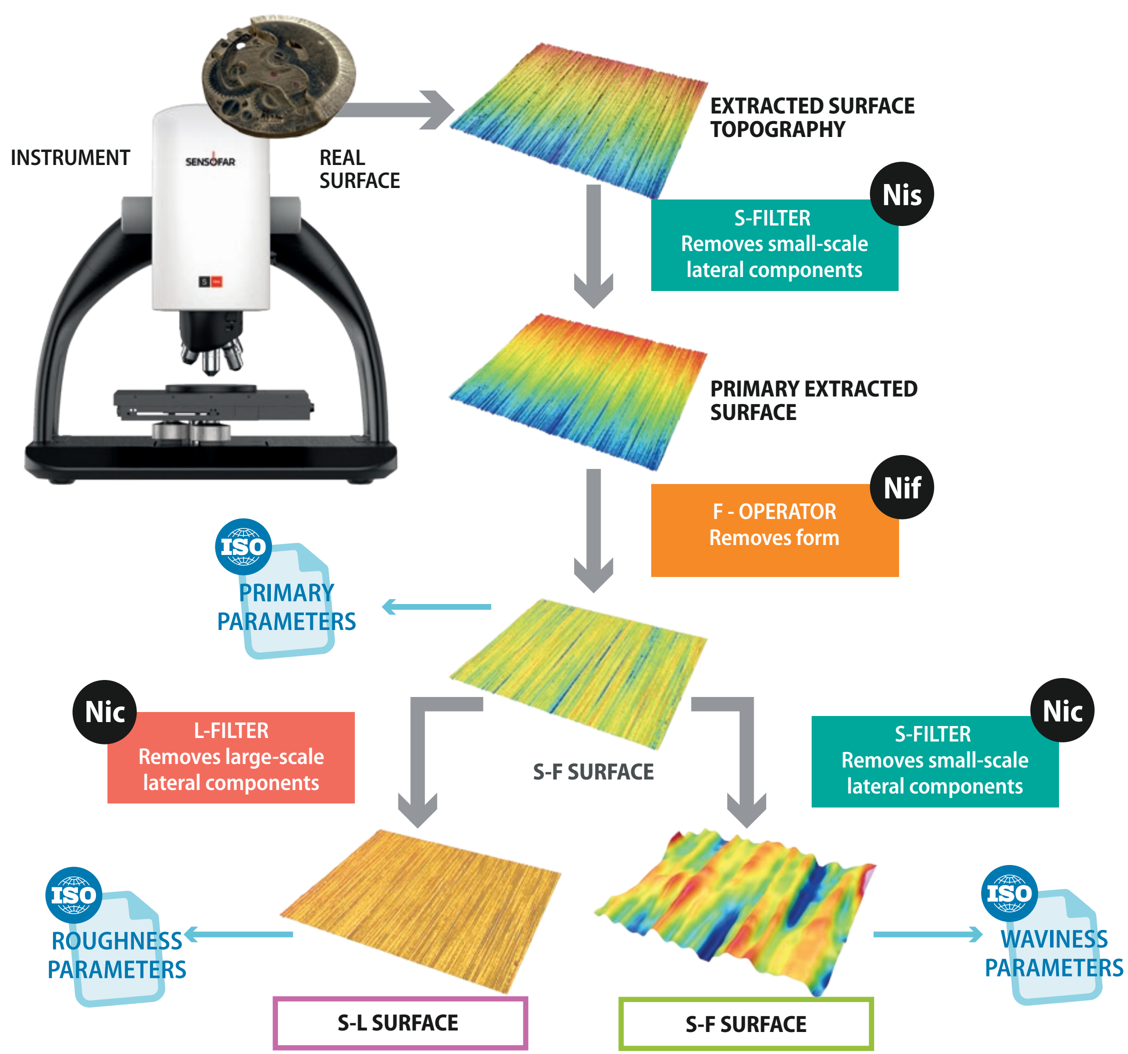


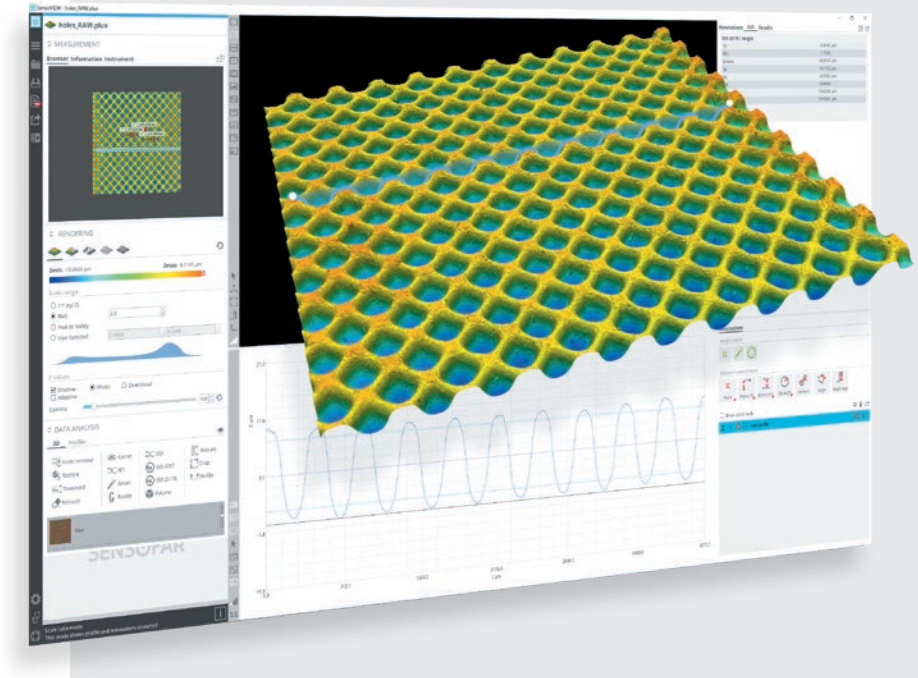
Figure 10. Filtering workflow to obtain surface texture parameters following ISO 25178 guidelines.

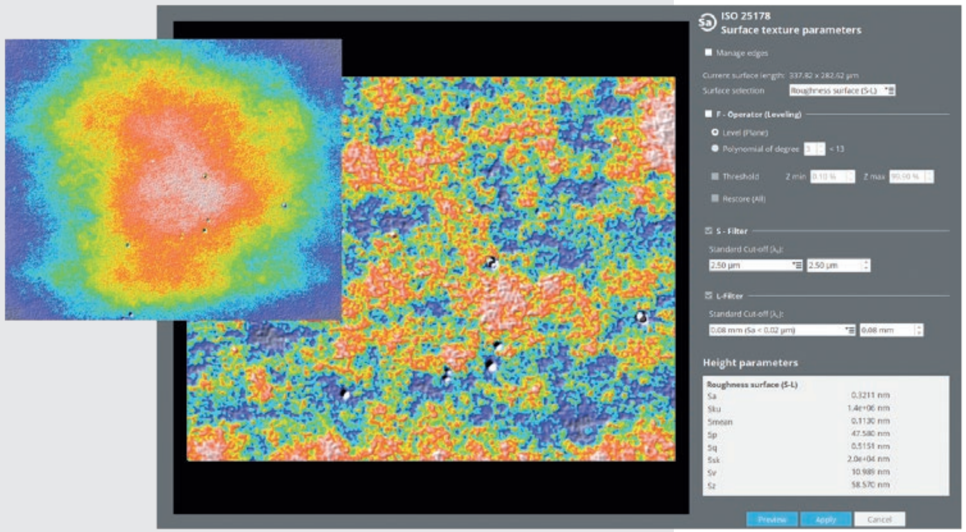
so that it only removes possible noise from the measurement and not short wavelength components that may be of interest.

Once you have your scale of interest, you can select an evaluation area from the scale-limited surface and calculate the relevant parameters using the reference surface. Following these steps ensures that your surface measurements are accurate and standardized according to ISO guidelines.

SensoVIEW

All Sensofar software follow the guidelines of ISO 25178 to provide an easy way of filtering your surface and report not only the resulting parameters but also the used processing settings. Applying the ISO guidelines ensures that your measurements are objective, repeatable, and reproducible.



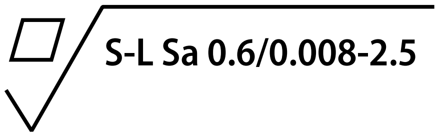


Surface texture on technical drawings

Surface texture can also be specified on technical drawings using the root symbol, which represents surface texture specifications, including filtering requirements. The root symbol in ISO 25178 is similar to those in ISO 21920 and the older ISO 1302, which are used for profile surface texture. While the symbols look alike, they should be interpreted within the context of their respective standards.

When a technical drawing includes the root symbol along with specific filtering instructions, these must be strictly followed. The information accompanying the symbol typically includes filter types, nesting indexes, and target parameters along with tolerance limits. This ensures that the surface meets the specified functionality and quality requirements.

For example:



This indicates a surface with no specific manufacturing requirements, analyzed as an S-L surface. The S-filter nesting index is 0.008 mm, and the L-filter nesting index is 2.5 mm. The chosen parameter is Sa (arithmetic mean height), with an upper limit tolerance of 0.6 µm.

For further information on how to indicate surface texture requirements on technical drawings, please refer to ISO 25178-1.

Which nesting index should I use?

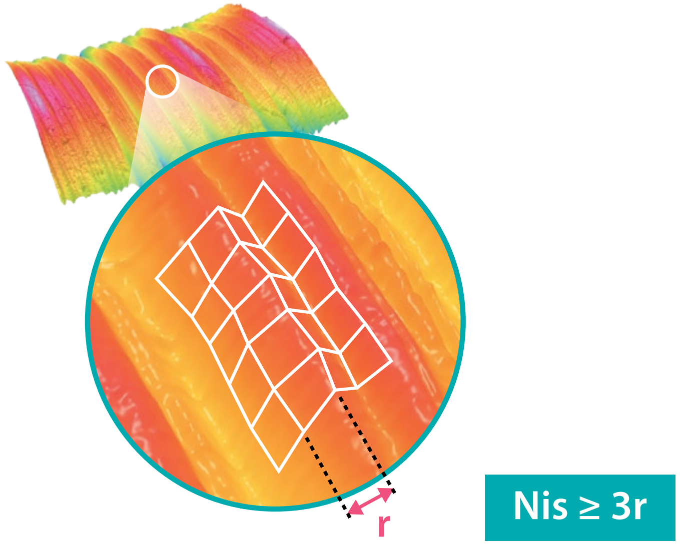
If no technical drawing provides specific nesting indexes, you will need to determine suitable values yourself, considering the surface characteristics and intended application. First and foremost, from ISO 25178, we can say there is no right value for the nesting indexes. When selecting an appropriate nesting index, it is essential to consider both the manufacturing process and the desired structural content of the surface roughness. In other words, **you need to know your scale of interest to filter your surface properly.**

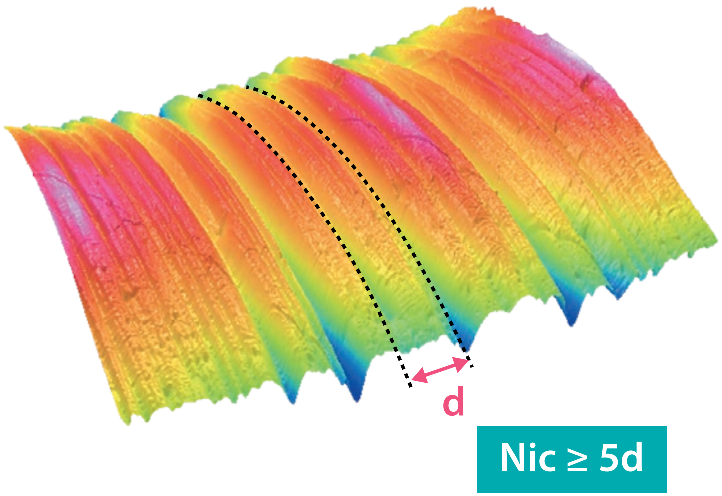
However, the ISO standard does give some recommendations for typical values of nesting indexes for S- and L-filter:

- The value of the nesting index for **S-filter** should be equal to or more than 3 times the measurement resolution for the XY plane. The value for this nesting index is normally picked from the following series: **…, 0.5µm, 0.8µm, 1 µm, 2 µm, 2.5 µm, 5 µm, 8 µm, …**

- The value of the nesting index for **L-filter** should be typically 5 times the scale of the coarsest structure of interest. The values for the nesting indexes are usually picked from the series: **…, 5 µm, 8 µm, 10 µm, 20 µm, 25 µm, 80 µm, 100 µm, ...**

Sometimes the concept of surface bandwidth is used to describe the range of wavelength information retained after the filtering procedure. Although ISO 25178 does not define official requirements or default values for surface bandwidth, common values used are 100:1 or 300:1. This means that the nesting index Nic is 100 or 300 times greater than the nesting index Nis to retain valuable information without discarding significant surface details. However, the final choice of nesting indexes should be guided by your specific application, requirements, and purpose.





Surface texture parameters

Surface texture parameters

The ISO 25178 standard introduces specific naming conventions for areal parameters, distinguishing them from profile parameters. Areal parameters are denoted by an upper-case letter S or V, which stands for Surface or Volume parameter, regardless of whether they describe roughness or waviness. This differs from profile parameters, prefixed with P, R, or W to indicate their nature.

Most surface parameters are essentially extensions of profile parameters applied to the area, thus exhibiting a direct relationship between these two types of parameters. For instance, the surface parameter Sa is equivalent to Ra, Wa, or Pa, depending on the pre-filtering applied before the calculation.

Surface texture parameters can be classified into two main groups depending on the dataset used to calculate them: field parameters and feature parameters. While field parameters use all the height dataset, feature parameters only consider specific surface motifs. Also, the parameters of each of these two groups can be classified into subgroups depending on their meaning or significance regarding the properties of the height distribution. In the following sections, you will find the definition of surface texture parameters described in ISO 25178-2.

Field parameters

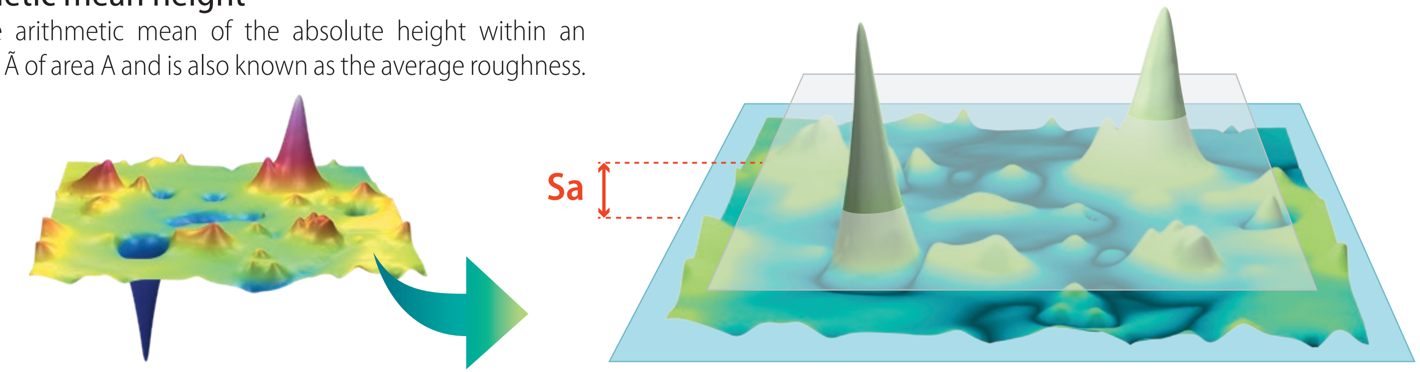
Field parameters are derived from every point on the scale-limited surface. They can be classified according to the information they provide about the surface. The main subgroups are height, spatial, hybrid, functional and related parameters, and fractal parameters.

		Parameter	Example units	Description
Height		**Sa**	µm	Arithmetic mean height
		Sq	µm	Root mean square height
		Ssk	unitless	Skewness
		Sku	unitless	Kurtosis
		Sp	µm	Maximum peak height
		Sv	µm	Maximum pit depth
		Sz	µm	Maximum height
Spatial		**Sal**	µm	Autocorrelation length
		Str	unitless	Texture aspect ratio
		Std	°	Texture direction
		Ssw	µm	Dominant spatial wavelength
Hybrid		**Sdq**	radians	Root mean square gradient
		Sdr	%	Developed interfacial area ratio
Functional and related	Functional	**Smr(c)**	%	Areal material ratio
		Smc(p)	µm	Inverse areal material ratio
		Sdc	µm	Material ratio height difference
	Areal for stratified surfaces	**Sk**	µm	Core height
		Spk	µm	Reduced peak height
		Spkx	µm	Maximum peak height
		Svk	µm	Reduced pit depth
		Svkx	µm	Maximum pit depth
		Smrk1	%	Material ratio of the hills
		Smrk2	%	Material ratio of the dales
		Sak1	$\mu m^3/mm^2$	Area of the hills
		Sak2	$\mu m^3/mm^2$	Area of the dales
	Areal material probability	**Svq**	µm	Dale root mean square deviation
		Spq	µm	Plateau root mean square deviation
		Smq	%	Plateau-to-dale material ratio
	Volume	**Vvv**	mm^3/mm^2	Dale void volume
		Vvc	mm^3/mm^2	Core void volume
		Vmp	mm^3/mm^2	Peak material volume
		Vmc	mm^3/mm^2	Core material volume
Fractal		**Svsfc**	unitless	Volume-scale fractal complexity
		Sasfc	unitless	Area-scale fractal complexity
		Slsfc	unitless	Length-scale fractal complexity
		Ssrc	unitless	Smooth-rough crossover scale

Height parameters

Sa – arithmetic mean height

Represents the arithmetic mean of the absolute height within an evaluation area Ã of area A and is also known as the average roughness.

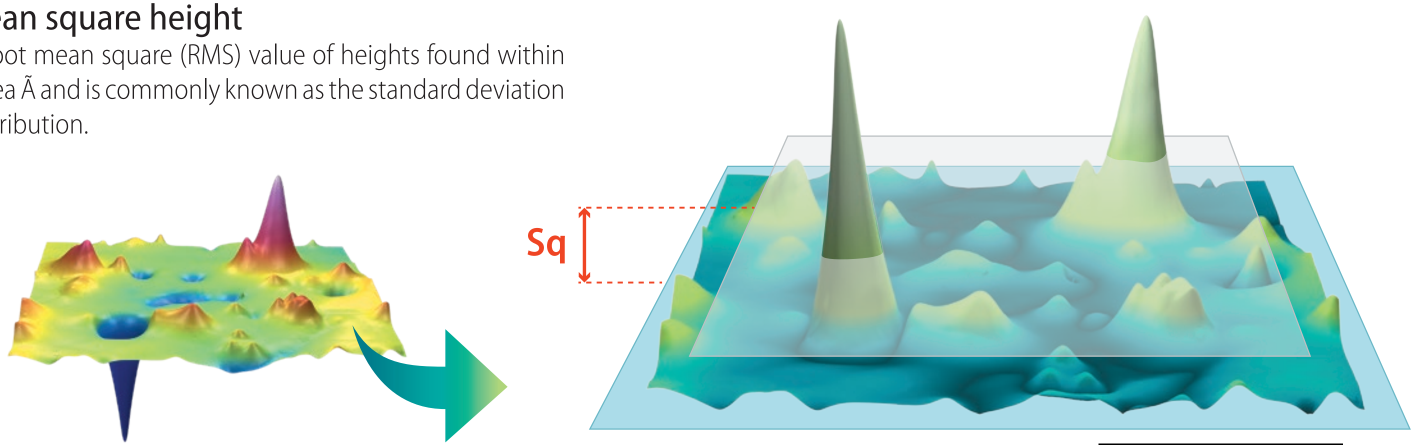


This is the most widely used parameter in surface roughness. Sa yields stable results as it is not significantly affected by outliers like measurement noise or surface contamination.

$$S_a = \frac{1}{A}\iint_{\tilde{A}} |z(x,y)|\,dx\,dy$$

Sq – root mean square height

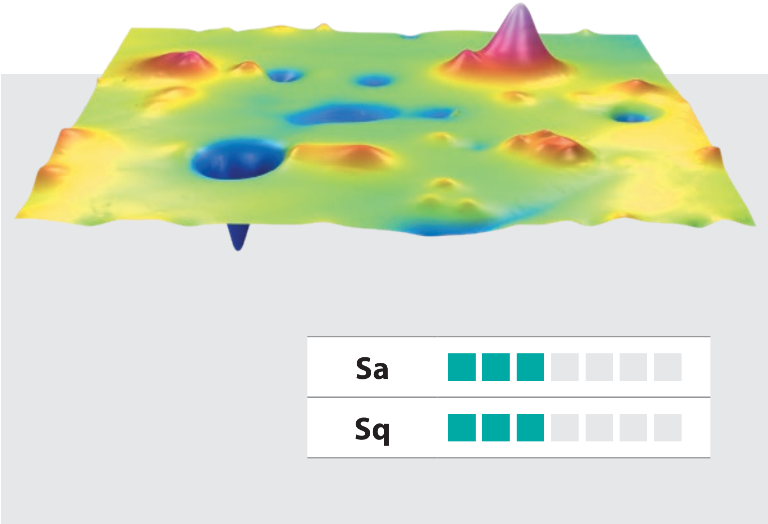
Represents the root mean square (RMS) value of heights found within the evaluation area Ã and is commonly known as the standard deviation of the height distribution.

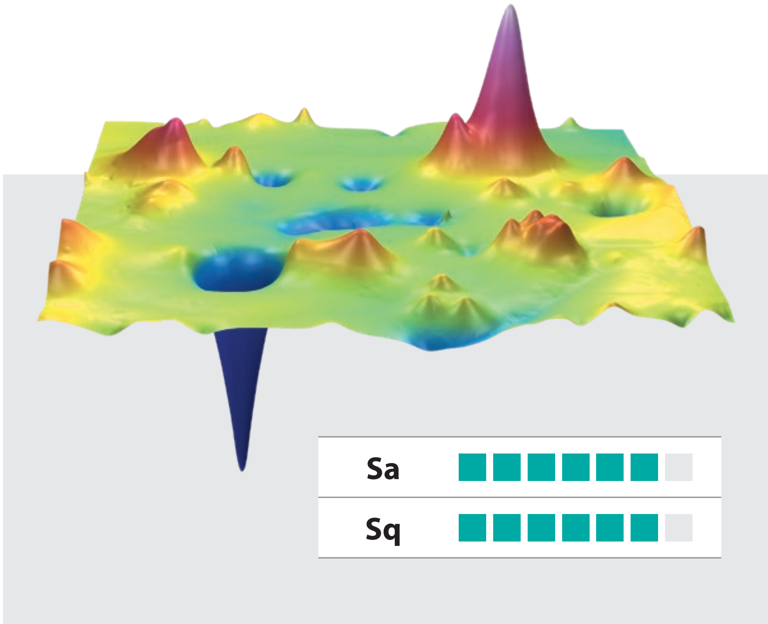


Sq also generates good statistics and stable results, being quite redundant with Sa. However, Sq is more influenced by outliers, which makes it more suitable than Sa for comparison studies among samples.

$$S_q = \sqrt{\frac{1}{A}\iint_{\tilde{A}} z^2(x,y)\,dxdy}$$

Both Sa and Sq provide information about the average height of the peaks and valleys on a surface. As these surface features become more pronounced and numerous, the Sa and Sq values increase.



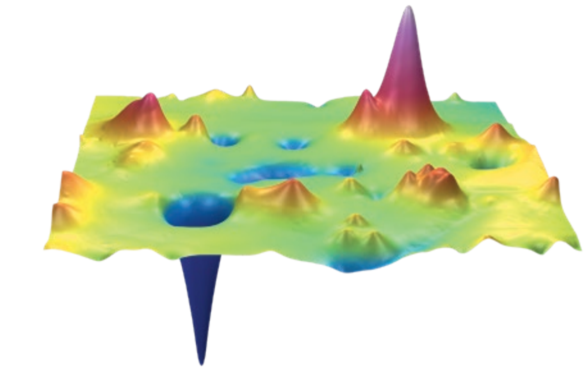


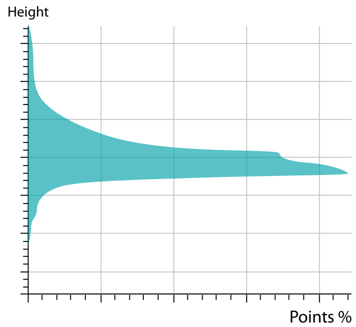
Ssk – skewness

The skewness of the height distribution is a measure of its symmetry. When Ssk is positive, the surface is mainly below the mean plane. Conversely, when Ssk is negative, the surface is mainly above the mean plane, and a value of 0 indicates a symmetric distribution with respect to the mean plane.

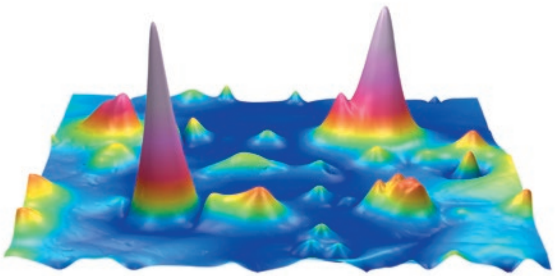
$$S_{sk} = \frac{1}{A\,S_q^3} \iint_A z^3(x,y)\,dxdy$$

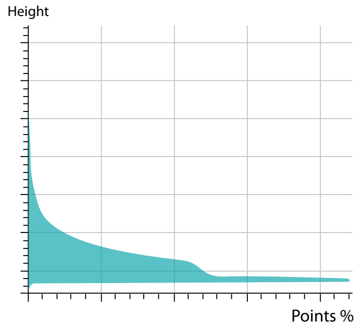
This parameter is highly sensitive to outliers, such as measurement noise, due to the large exponent involved in its calculation.



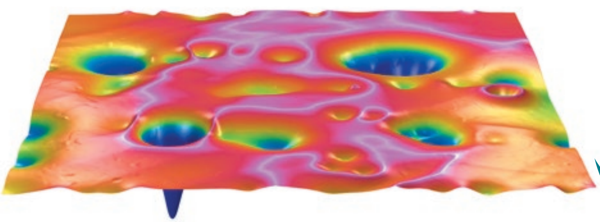


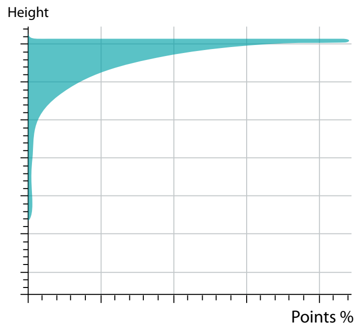
Ssk = 0





Ssk > 0





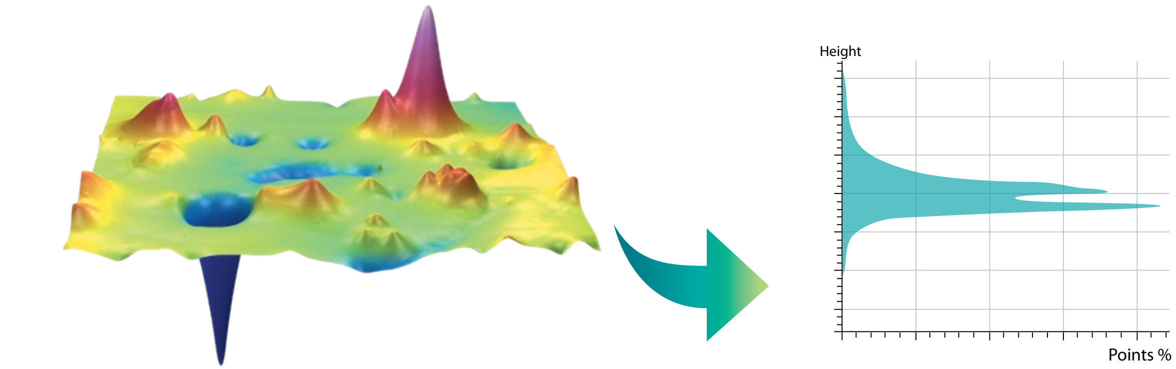
Ssk < 0

Sku – kurtosis

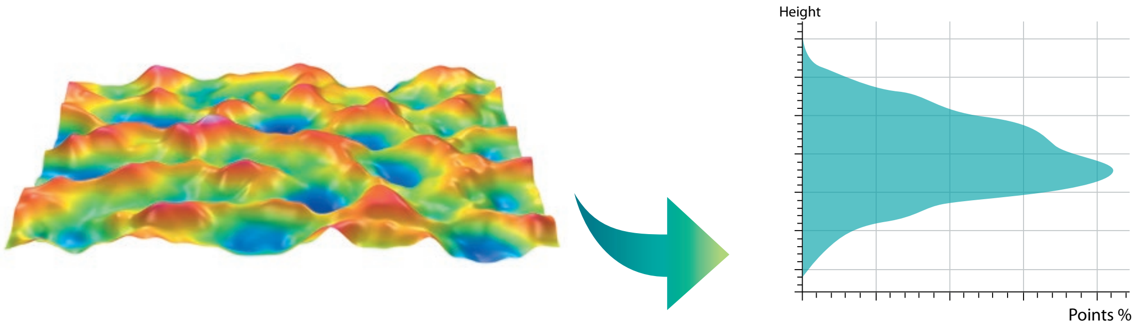
The kurtosis of the height distribution is a measure of its sharpness. A value of Sku higher than 3 indicates a sharp height distribution, while a value lower than 3 indicates an even distribution. A value of 3 indicates a normal distribution of heights.

$$S_{ku} = \frac{1}{A\,S_q^4}\iint_A z^4(x,y)\,dxdy$$

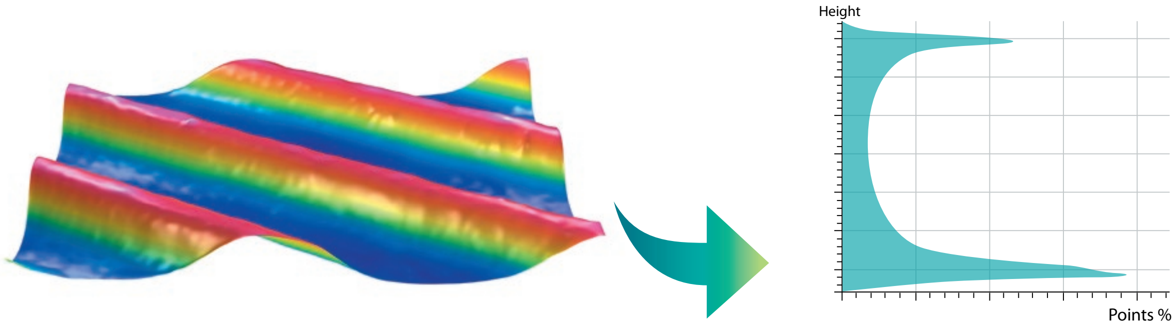
> Outliers have an even greater impact on kurtosis than on skewness because kurtosis uses an even higher exponent in its calculation.



Sku > 3



Sku $= 3$

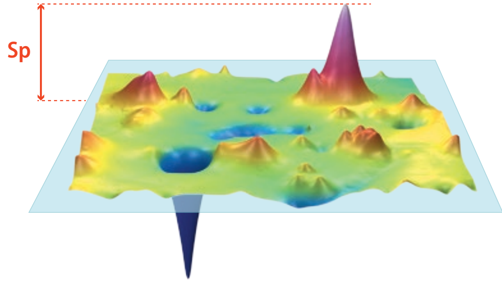


Sku < 3

Sp – maximum peak height

Maximum value for peak height in the evaluation area.

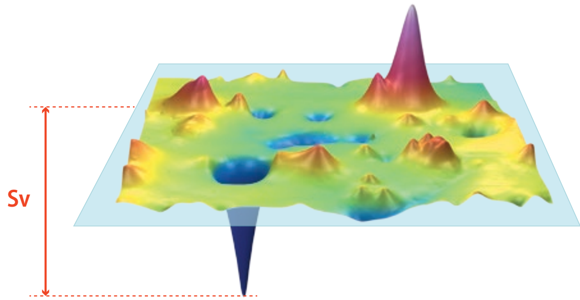
$$S_p = \max\left(z(x,y)\right)$$



Sv – maximum pit depth

Maximum value for pit depth in the evaluation area, it represents the deepest point of the surface.

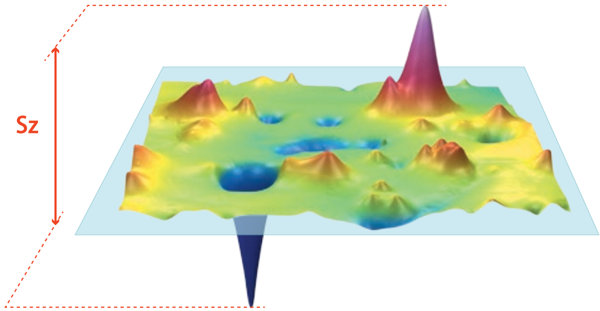
$$S_v = \left|\min\left(z(x,y)\right)\right|$$



Sz – maximum height

Sum of the maximum peak height and maximum pit depth.

$$S_z = S_p + S_v$$



Neither Sp, Sv, nor Sz are ideal parameters for general surface texture characterization because they each focus on a single extreme: the highest peak, the deepest pit, or the total "peak to valley" height. This makes them highly sensitive to outliers, especially when applied to primary or S-L surfaces, and they do not accurately represent the overall surface texture.

Spatial parameters

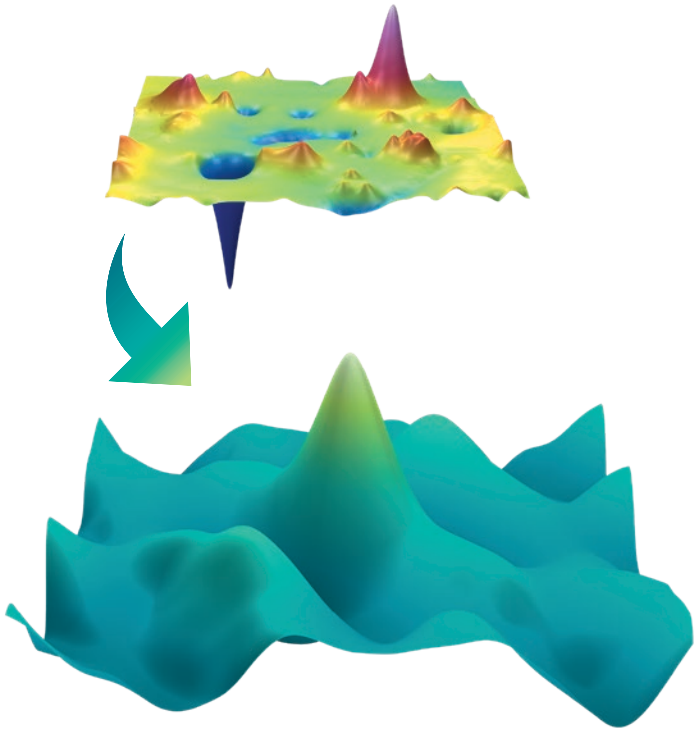
While height parameters only give information about the z coordinates of the surface points, spatial parameters provide information about the X and Y coordinates. To understand how spatial parameters are derived, it is helpful to know a couple of key concepts: the autocorrelation function and the angular spectrum.

The **autocorrelation function** (ACF) describes the correlation between surface height values at different points along the surface. It measures the degree of similarity between different points along the surface separated by a certain distance. It can provide information about the spatial frequency and periodicity of surface features, as well as the overall roughness and texture of the surface. The autocorrelation function is calculated using the following formula:

$$f_{ACF}(t_X, t_Y) = \frac{\iint_{\tilde{B}} z(x,y)\, z\left(x + t_x, y + t_y\right) dxdy}{\iint_{\tilde{B}} z^2(x,y) dxdy}$$

where $\tilde{B}$ is the intersecting area of the two surfaces at shifts t_x and t_y.

The **angular spectrum** is a polar plot of the Fourier transform of the height distribution (from the scale-limited surface) with respect to a reference angle, usually the X-axis.



Autocorrelation

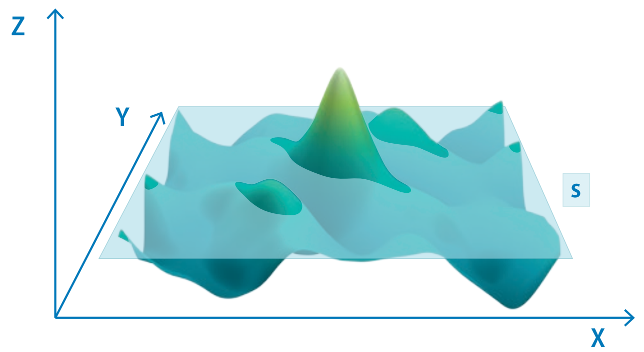
After seeing the basis of the spatial parameters, let us dive into them:

Sal – autocorrelation length

It refers to the horizontal distance of the autocorrelation function (ACF(tx,ty)), which exhibits the most rapid decay to a specific value s (0≤s<1), with a default value of s=0.2.

> This parameter reflects the wavelength content of the surface, with a large value indicating that the surface is primarily composed of low spatial frequencies (longer wavelengths) and a small value indicating the dominance of high frequencies (short wavelengths).

$$S_{al} = r_{min}$$

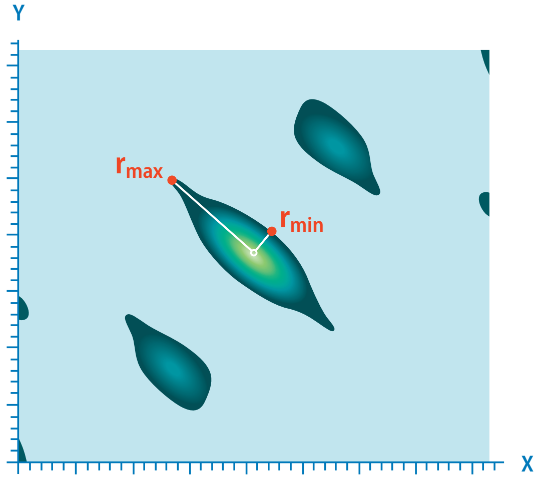


Str – texture aspect ratio

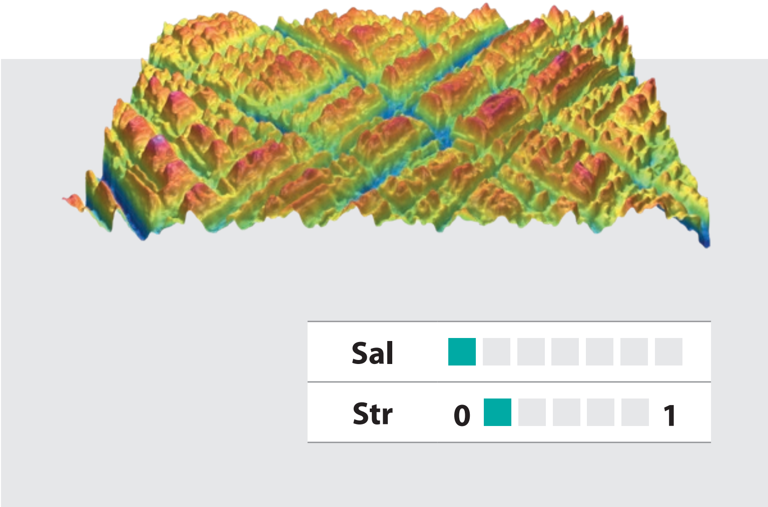
The texture aspect ratio is defined as the ratio between the horizontal distance of the ACF (tx,ty) that exhibits the most rapid decay to a specific value s (0≤s<1) and that of the ACF(tx,ty) that exhibits the slowest decay to s. In other words, the Str parameter is determined by the minimum radius (r_{min}) and maximum radius (r_{max}) observed under identical conditions on the autocorrelation plot, which has been subjected to a threshold of 0.2 (by default).

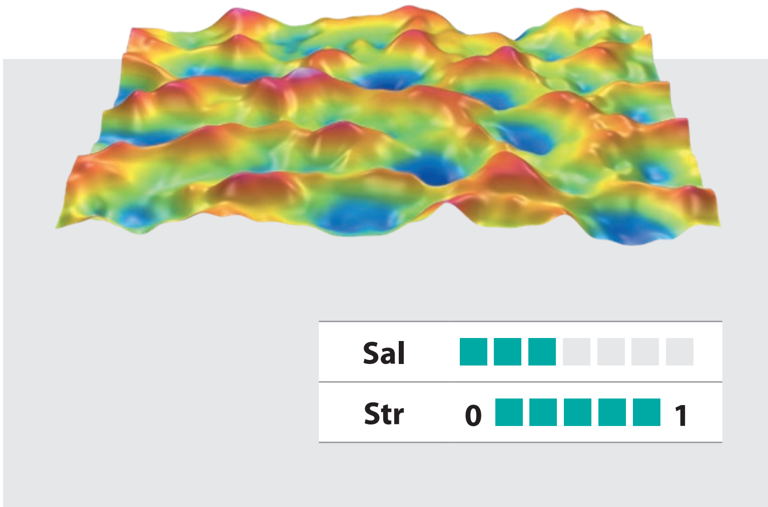
> The Str parameter yields a value ranging from 0 to 1, where a value close to 1 indicates an isotropic surface (uniform in all directions), while a value close to 0 indicates an anisotropic surface (exhibiting a periodic or directional structure).

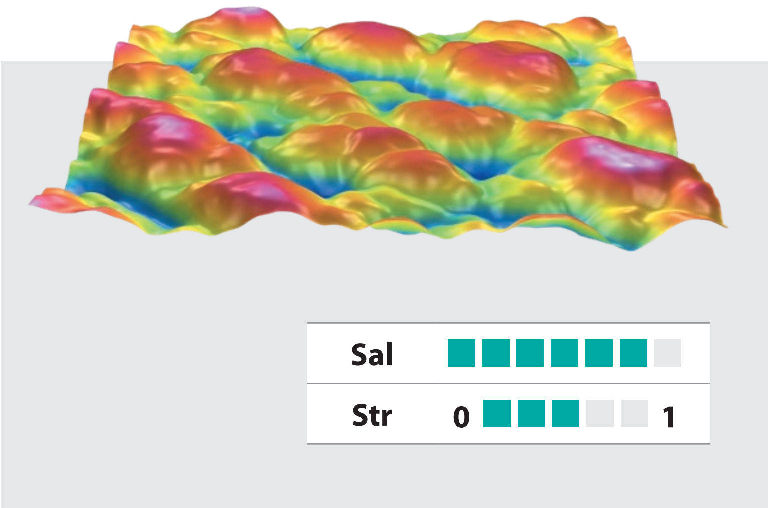
$$S_{tr} = \frac{r_{min}}{r_{max}}$$



Evaluating the Sal and Str parameters provides insights into the isotropy and directionality of a surface. A low Sal and low Str combination indicates a texture with high directionality and fine features. Conversely, moderate Sal and high Str values signify a blend of uniformity with minimal directional patterns. High Sal and moderate Str values reflect an irregular texture with some directional elements.



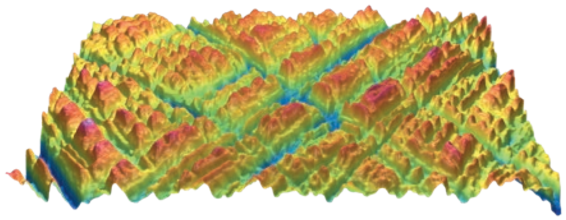


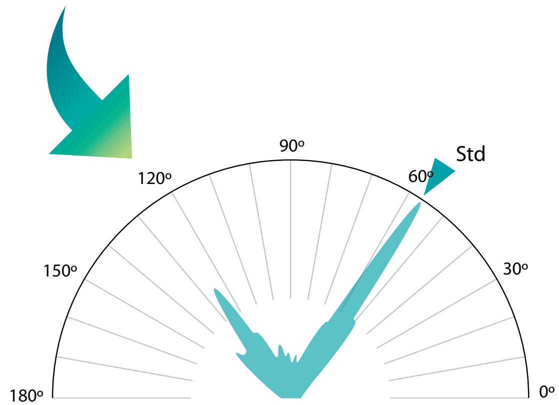


Std- texture direction

The Std parameter characterizes the orientation (or lay) of the surface texture. It is determined by the primary angle of the texture, which is identified by analyzing the angular spectrum. Generally, this parameter is most relevant when Str is below 0.5. The value of Std is given in degrees and falls within the range of 0° to 180°. According to ISO 25178 part 2, the angle may be measured relative to a reference angle θref.

> The Std parameter is a valuable metric for analyzing surfaces with scratches or directional textures. However, its accuracy is highly dependent on the sample's orientation during measurement, so careful attention must be paid to the alignment of the sample when taking measurements.

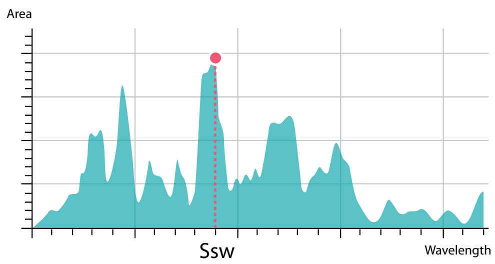




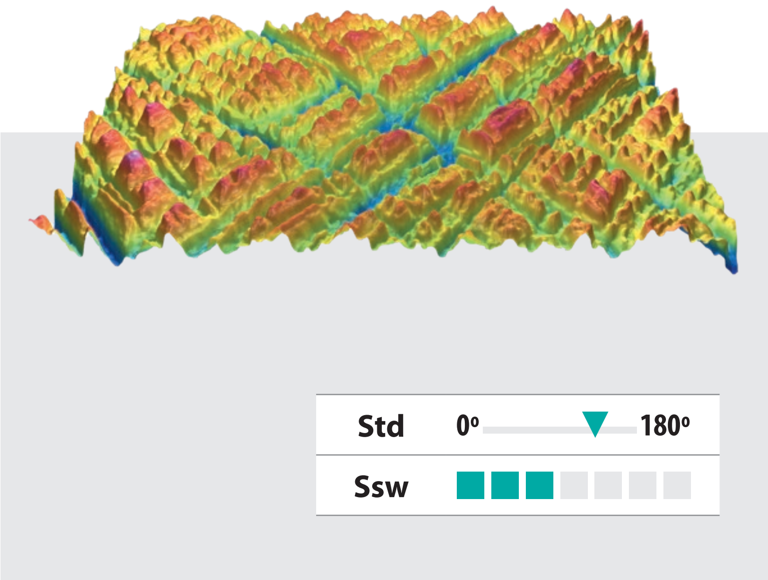
Ssw – dominant spatial wavelength

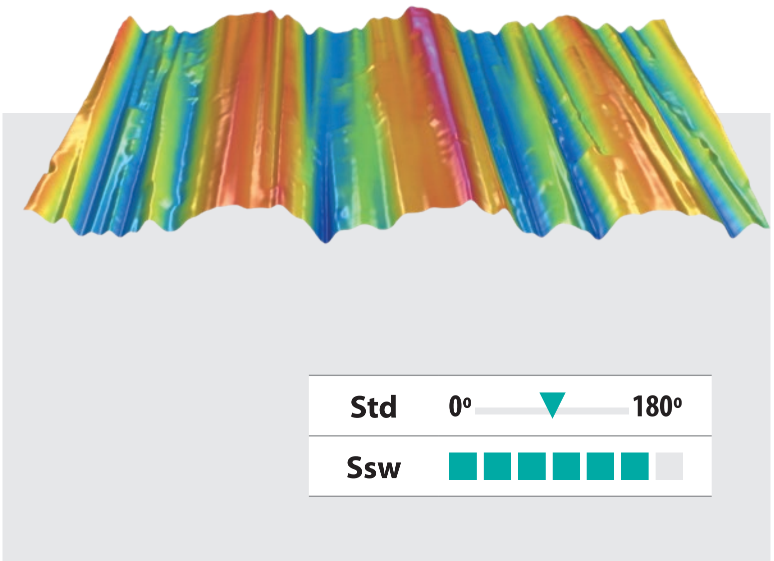
It refers to the wavelength corresponding to the largest value of the Fourier transformation. In other words, surface texture can be viewed as a combination of different-sized waves and the Fourier Transform identifies the relative contribution of each wavelength to the overall texture. Thus the Ssw parameter represents the wavelength with the largest contribution.

> It is important to note that this parameter may not be relevant for surfaces lacking distinct periodic patterns.



Std and Ssw parameters provide insights into the orientation and periodicity of surface textures. A surface with a texture direction (Std) of 56 degrees and a high Ssw value indicates a prominent directional pattern with widely spaced, dominant features. In contrast, a surface with an Std of 90 degrees and a low Ssw value suggests a strong directional alignment at a right angle, with closely spaced, dominant features.





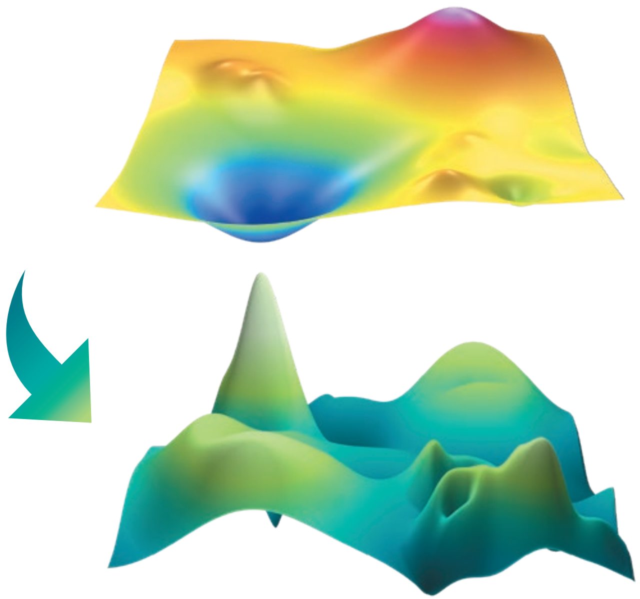
Hybrid parameters

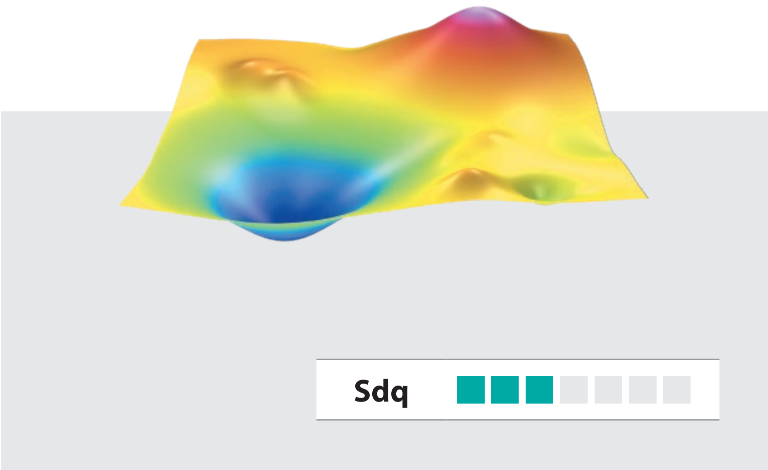
Sdq – root mean square gradient

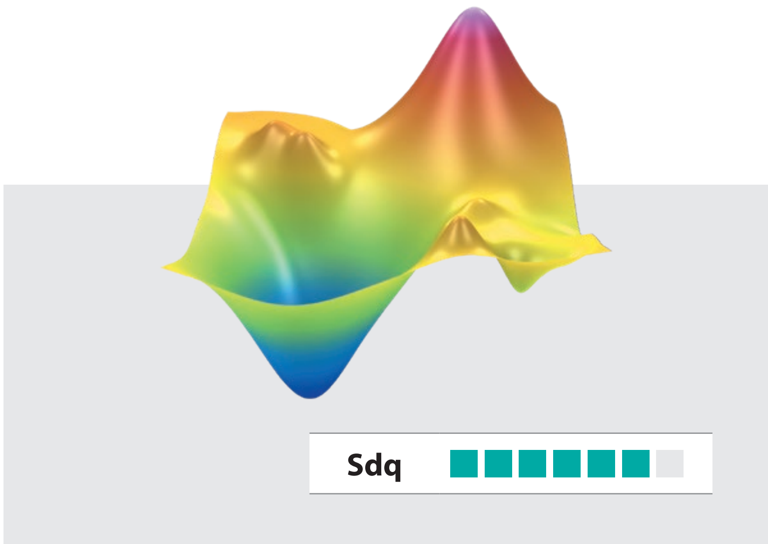
It is the root mean square of the surface gradient within the evaluation area (Ã) of the scale-limited surface and indicates the average magnitude of the local slope of the surface.

This parameter can be used to express the steepness of the surface numerically.

$$S_{dq} = \sqrt{\frac{1}{A}\iint_{\tilde{A}}\left[\left(\frac{\partial z(x,y)}{\partial x}\right)^2 + \left(\frac{\partial z(x,y)}{\partial y}\right)^2\right] dxdy}$$



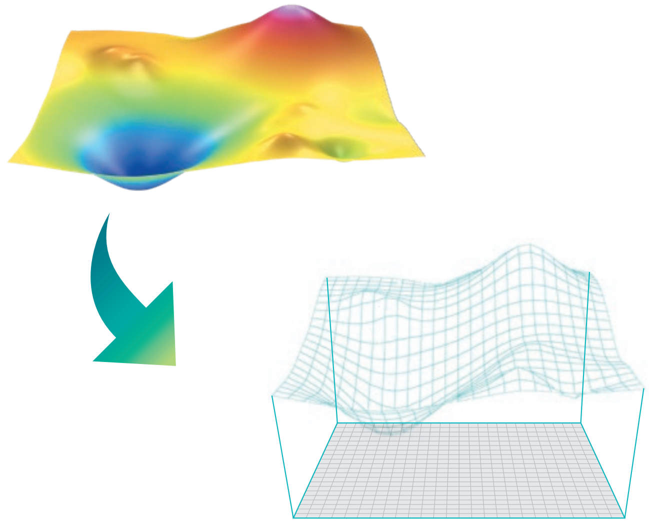




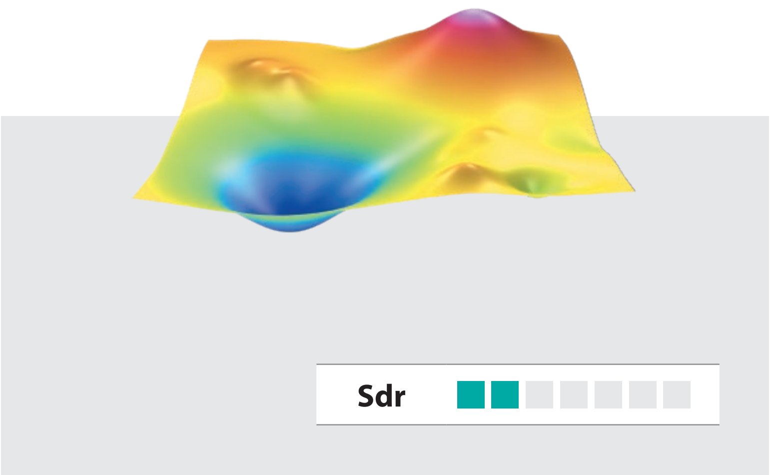
Sdr – developed interfacial area ratio

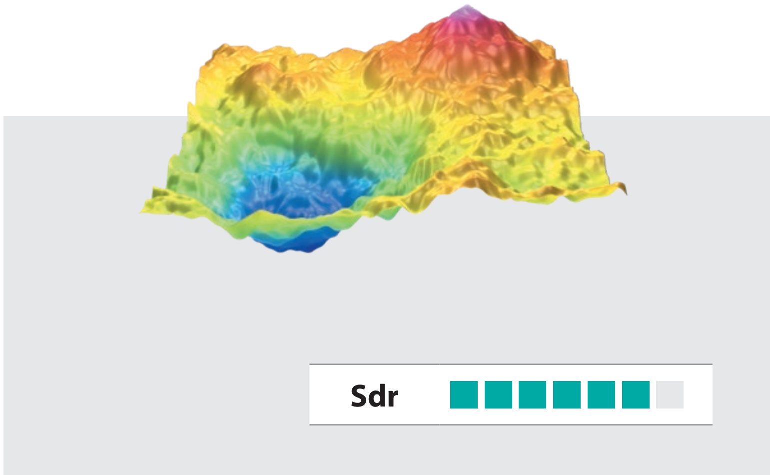
The parameter is a percentage that shows how much extra surface area the texture adds to the evaluation area, compared to the flat evaluation area.

> Sdr is a measure of surface complexity. A perfectly smooth surface will have an Sdr of 0, while rougher surfaces will have higher Sdr values. This parameter is useful for comparing different stages of surface processing. Note that the lateral sampling of the measurement setup can significantly impact this parameter.



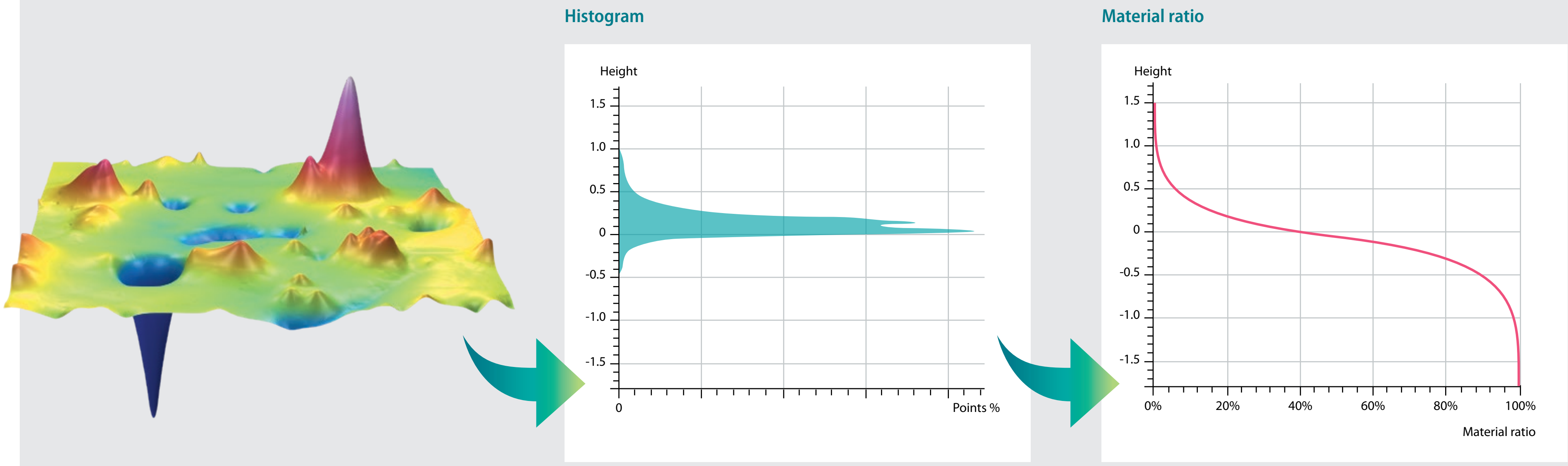
$$S_{dr} = \frac{1}{A}\iint_A \left(\sqrt{\left[1 + \left(\frac{\partial z(x,y)}{\partial x}\right)^2 + \left(\frac{\partial z(x,y)}{\partial y}\right)^2\right]} - 1 \right) dxdy$$





Functional parameters

Functional parameters rely on the material ratio curve, also called the bearing area curve (BAC) or Abbot-Firestone curve (AFC). This curve results from integrating the height distribution of the surface over its entire area.

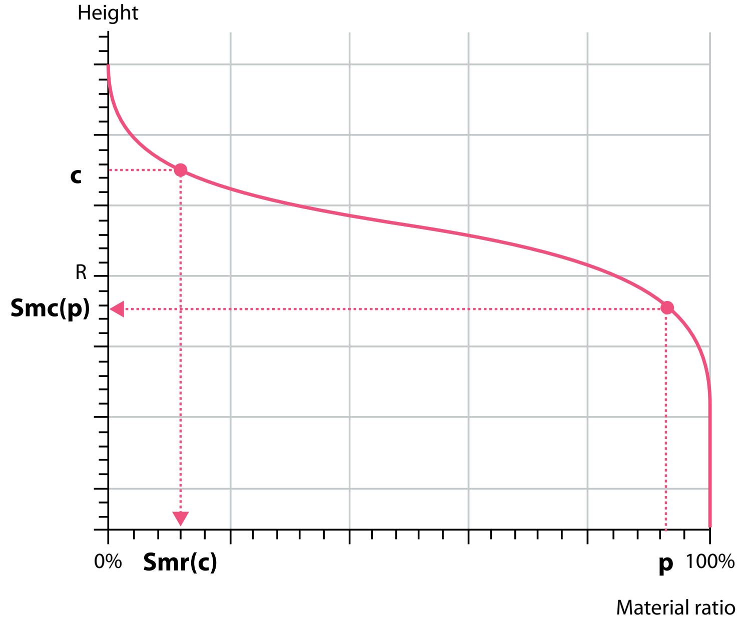


Areal functional parameters

The areal functional parameters are derived from a series of geometric calculations done in the areal material ratio curve. The resulting parameters are defined and thus have a functional meaning only for an S-shaped bearing area curve.

Smr(c) – areal material ratio

Material ratio, usually expressed as a percentage, corresponding to a specific height c of the areal material ratio curve. Height c is taken from a reference height called R, which is usually the mean plane of the scale-limited surface.



Smc(p) – inverse areal material ratio

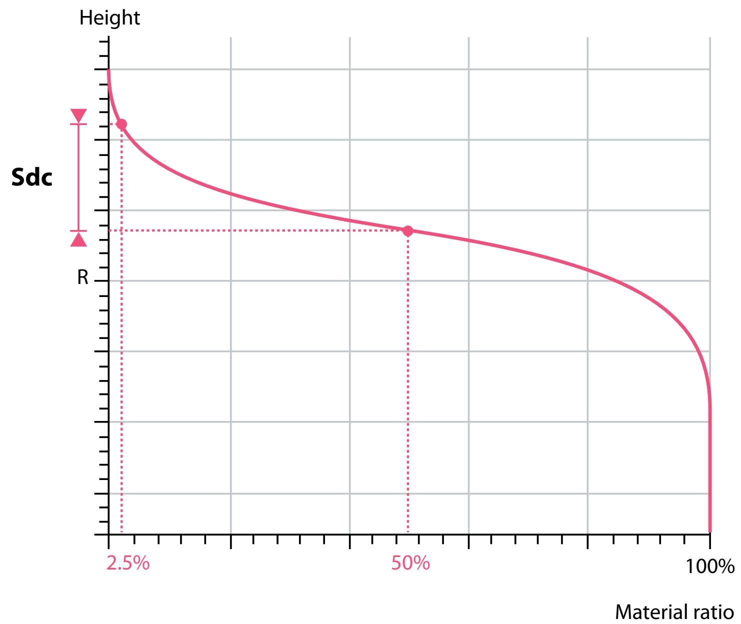
Height corresponding to a given material ratio p.

Sdc – material ratio height difference

The difference in height between the p and the q material ratio. The default values are 2.5% for p and 50% for q.

$$S_{dc} = S_{mc}(p) - S_{mc}(q) \qquad with\ p < q$$

(Previously known as Sxp, extreme peak height).



Sk – core height

The difference between the highest and lowest levels of the core surface. The core surface is defined by the Smrk1 and Smrk2 parameters and is the part of the surface which does not contain the protuding hills and dales.

Spk – reduced peak height

It refers to the height of the protruding peaks above a core surface after the reduction process.

Spkx – Maximum peak height

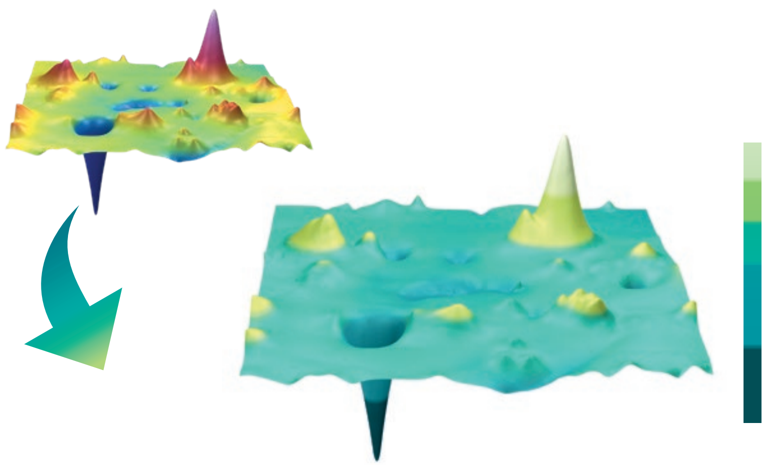
It refers to the protruding peaks above the core surface before applying the reduction process. This parameter is more sensitive to outliers because of the lack of reduction process.

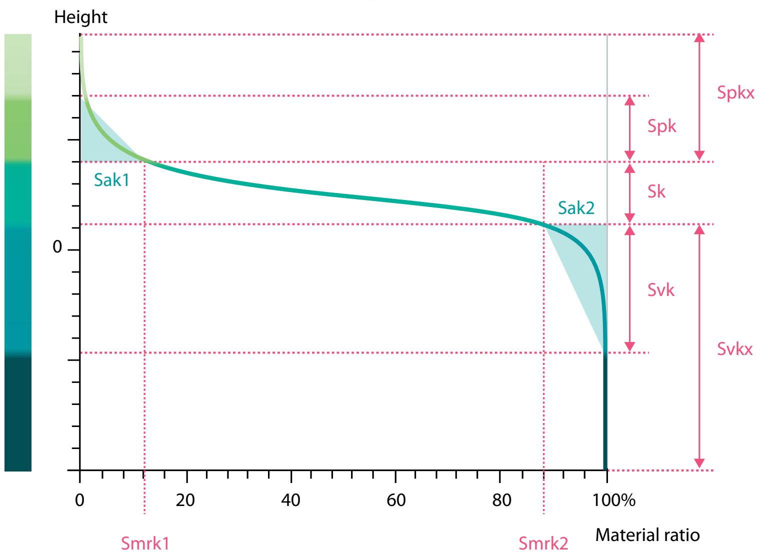
Svk – reduced pit depth

It refers to the depth of the protruding pits below a core surface after undergoing a reduction process.

Svkx – maximum pit depth

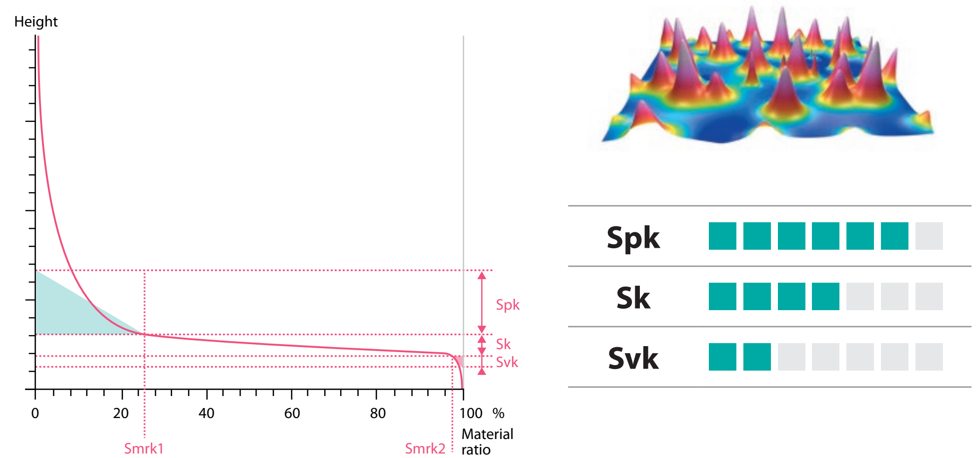
The depth of the protruding pits below a core surface before applying the reduction process.





Smrk1 – material ratio of the hills

It refers to the material ratio at the intersection line that separates the protruding hills from the core surface.



Smrk2 – material ratio of the dales

In this case, the parameter is the material ratio at the intersection line which separates the protruding dales from the core surface.

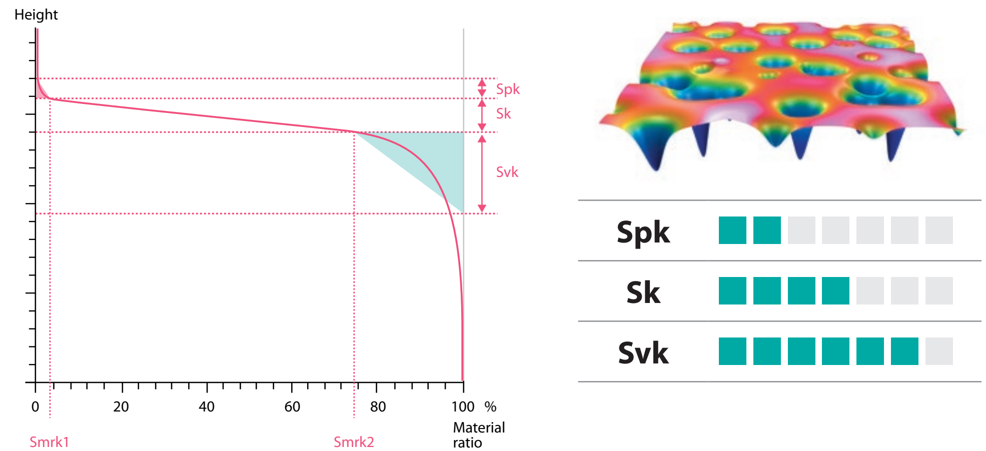
Sak1- area of the hills

The area of the triangle formed during the reduction process of the protruding hills. This triangle has Smrk1 as its base and Spk as its height.

Sak2 – area of the dales

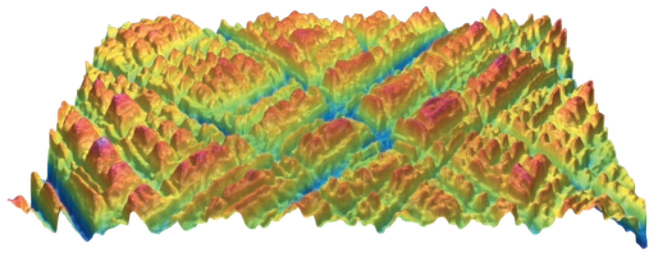
The area of the triangle formed during the reduction process of the protruding dales. This triangle has (100%-Smrk2) as its base and Svk as its height.

> The functional parameters Sk, Spk, Svk, Sak1, and Sak2 provide a detailed understanding of surface texture characteristics for surfaces with an S-shaped BAC such as mechanical components. Surfaces with higher Spk and Sak1 values are dominated by peaks, while those with higher Svk and Sak2 values have more pronounced dales. The Sk value offers a middle ground, indicating the overall roughness of the core of the surface without the peaks or valleys.



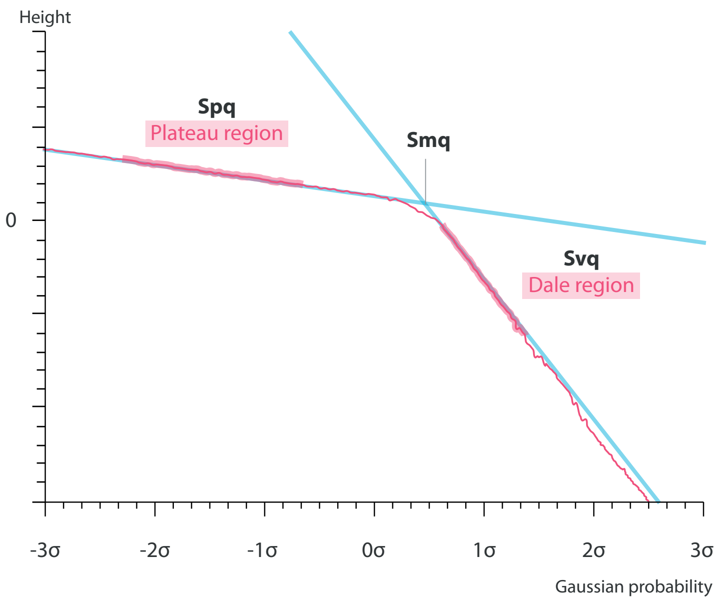
Areal Material Probability Parameters

In this case, instead of the material ratio curve, the reference for these functional parameters is the areal material probability curve. This graph shows the areal material ratio curve using a Gaussian probability distribution that is expressed in standard deviation values and plotted linearly on the horizontal axis. This means that a Gaussian distribution areal material ratio curve will appear as a straight line. The areal material probability curve will exhibit two linear regions if a surface comprises two Gaussian distributions. Note that this linear scale can help analyze and compare surface roughness data.



Svq – dale root mean square deviation

It measures the slope of a linear regression performed through the dale region of a surface and can be seen as the Sq-value (µm) of the random process that generated the dale component of the surface.



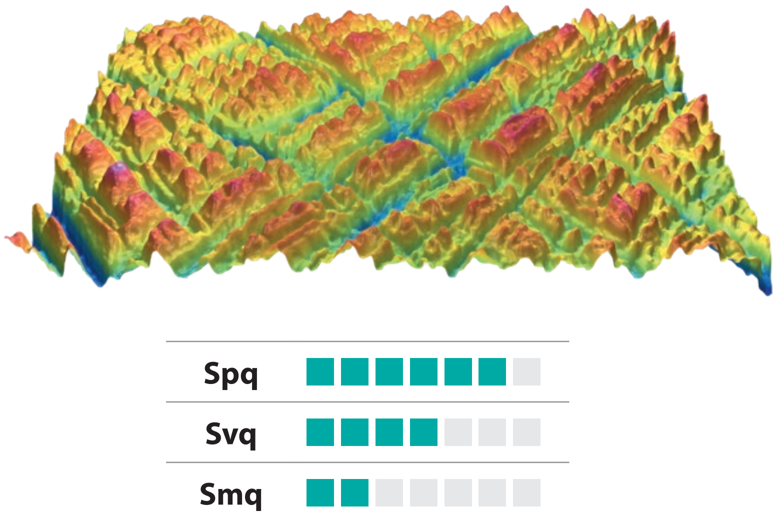
Spq – plateau root mean square deviation

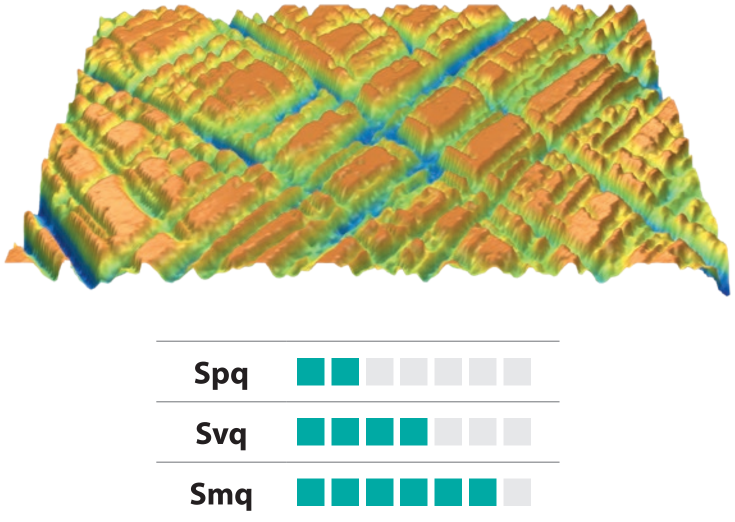
In a similar way to Svq, this parameter measures the slope of a linear regression conducted through the plateau region of a surface. In essence, it represents the Sq-value of the random process that produced the plateau component of the surface.

Smq – plateau-to-dale material ratio

It is the material ratio at the intersection between the plateau region and dale region.

The parameters Spq, Svq, and Smq offer valuable insights into the surface texture of stratified surfaces, like those that have undergone double processing. Spq measures the root mean square height of the peaks, Svq assesses the root mean square depth of the valleys, and Smq provides an overall measure of surface roughness by combining both peak and valley components. For instance, on a worn surface, Spq typically decreases as the peaks wear down, while Smq can increase if the valleys remain unaffected by the wear process.





Volume Functional Parameters

Vv(p) – void volume

The void volume parameter refers to the volume of voids per unit area at a specific material ratio p, which is calculated based on the areal material ratio curve. By default p is 10%.

$$V_v(p) = \frac{K}{100}\int_p^{100\%}\left(S_{mp}(p) - S_{mc}(q)\right) dq \ , with\ p < q$$

Vvv – dale void volume

Void volume at material ratio 80%.

$$V_{vv} = V_v(80\%)$$

Vvc – core void volume

Difference in void volume between the material ratio 10% and 80%.

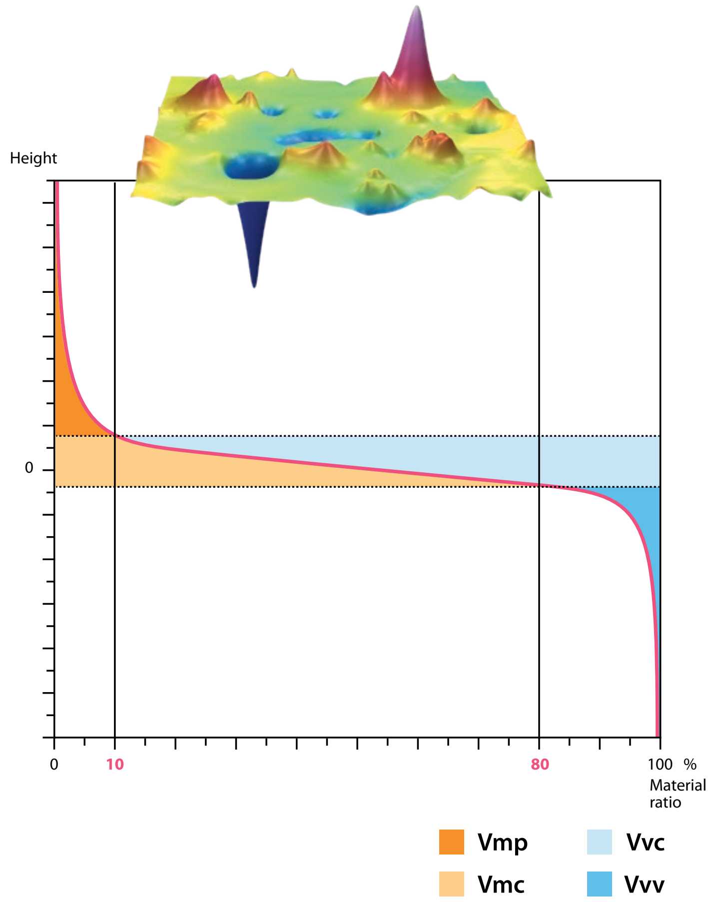
$$V_{mc} = V_m(10\%) - V_m(80\%)$$

Vm(p) – material volume

The material volume parameter refers to the volume of material per unit area at a specific material ratio p, which is calculated based on the areal material ratio curve. By default p is 10%.

$$V_m(p) = \frac{K}{100}\int_0^{p}\left(S_{mc}(q) - S_{mc}(p)\right) dq\ , with\ p < q$$

The parameter K is a constant used to convert units.



Vmp – peak material volume

Material volume at 10% material ratio.

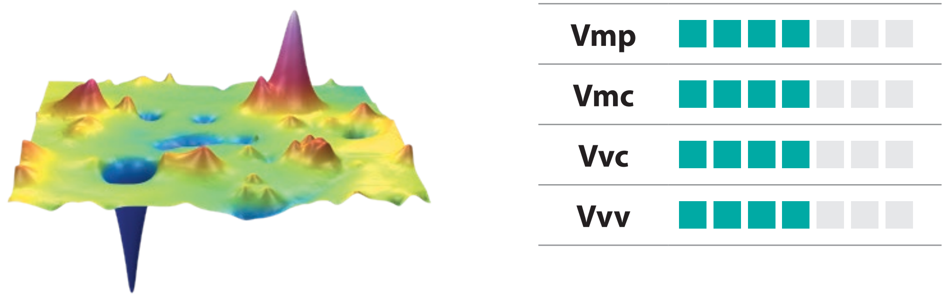
$$V_{mp} = V_m(10\%)$$

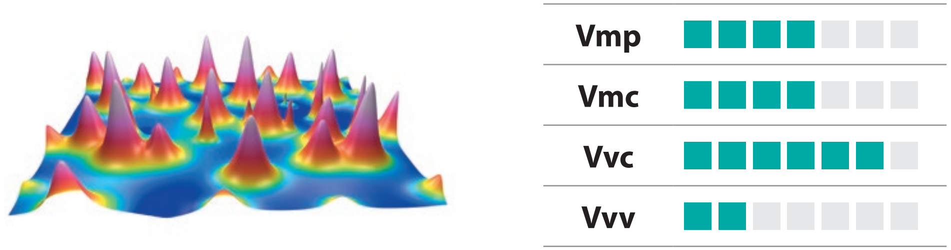
Vmc – core material volume

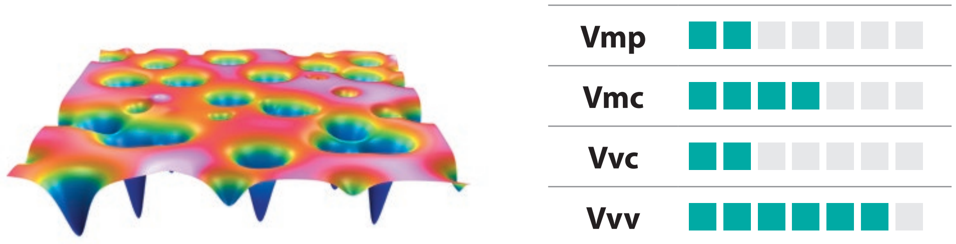
Difference in material volume between the 10% and the 80% material ratio.

$$V_{mc} = V_m(10\%) - V_m(80\%)$$

> The volume functional parameters Vmp, Vmc, Vvc, and Vvv provide detailed insights into the material and void distribution across a surface. Surfaces with higher Vmp and Vmc values are dominated by material-rich peaks, while those with higher Vvc and Vvv values have more pronounced dales.







Fractal parameters

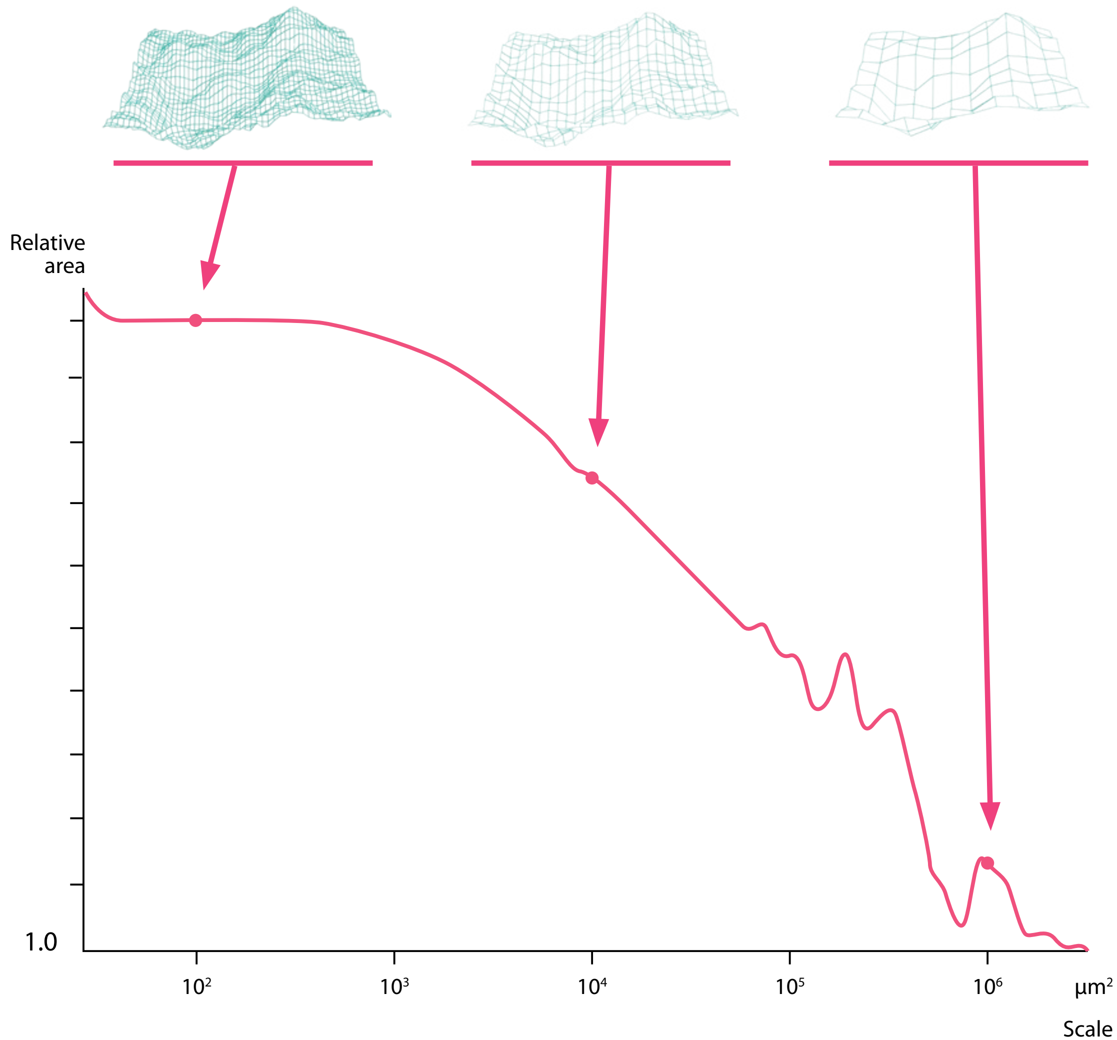
Fractal parameters describe the self-similarity and scaling properties of a surface. They are based on the concept of fractals, which are geometric shapes that exhibit similar patterns at different scales. Fractal parameters can be useful for characterizing surfaces with complex or irregular features, such as natural or engineered surfaces with functional coatings. They can also provide information about a generation process or wear behavior of a surface.

Working Principle

Fractal analysis involves measuring the scaling properties of a surface, which refers to the way that surface features repeat or vary across different length scales. Fractal analysis can be used to quantify how much the surface changes as the scale of observation changes, and to identify the degree of self-similarity or repeating patterns across different scales.

To grasp the functioning of this principle, let us break it down to different steps. Similarly to when we evaluate the Sdr parameter, we can tile the surface to calculate which is the total area covered by triangular tiles. However, the area will be directly proportional to the size of the tile. Ergo, the smaller the tile, the larger the area. The relative area of the surface at a specific scale (the size of the tile) can be obtained by dividing the area by the flat reference area.

If we compute the relative area of a surface for various sizes of tiles and plot the resultant values against the respective sizes used, we obtain the areal-scale function.



It is noteworthy that this analysis that we made with triangular tiles and relative area can be applied to lines or volumes too. The corresponding functions for the linear and volume cases are called linear-scale function and morphological volume-scale function. In all these functions the term scale of observation is used to refer to the length of the line segment (linear case), area of the triangular tiles (areal case) or size of the structuring element (volume case).

Two main fractal parameters are derived from the above-mentioned functions:

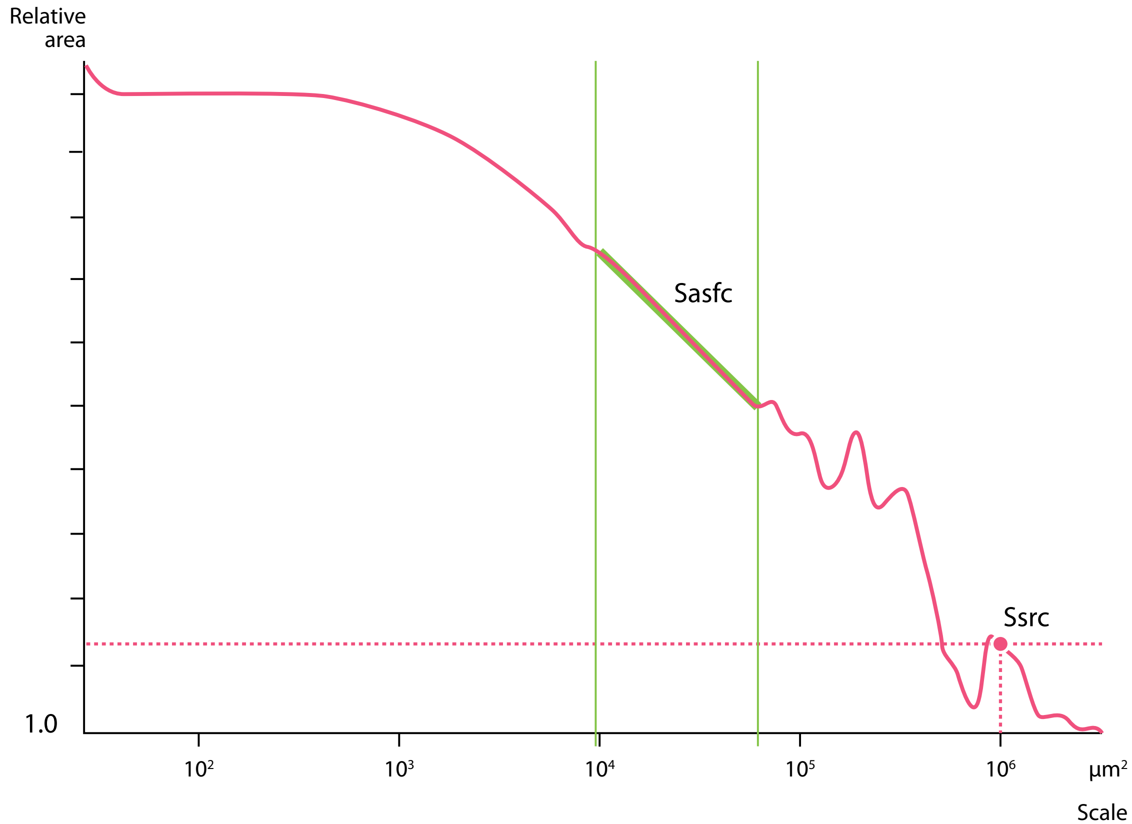
Complexity

Volume-scale fractal complexity (Svsfc), **area-scale fractal complexity** (Sasfc) or **length-scale fractal complexity** (Slsfc). It is calculated by determining the slope of the length-scale (area-scale or morphological volume-scale) function within a defined domain of scale of observation, with the result expressed as a decimal value. To avoid excessive zeros in the result, the value is usually multiplied by a factor of -1000 (1000 in the case of morphological volume-scale). This concept bears a resemblance to ISO parameter Sdq.

Ssrc – smooth-rough crossover scale

The smooth-rough crossover scale parameter determines the scale at which the surface texture transitions from appearing smooth to rough. More technically speaking, Ssrc represents the scale above which the fractal dimension is close to the Euclidean dimension and below which it is considerably greater.

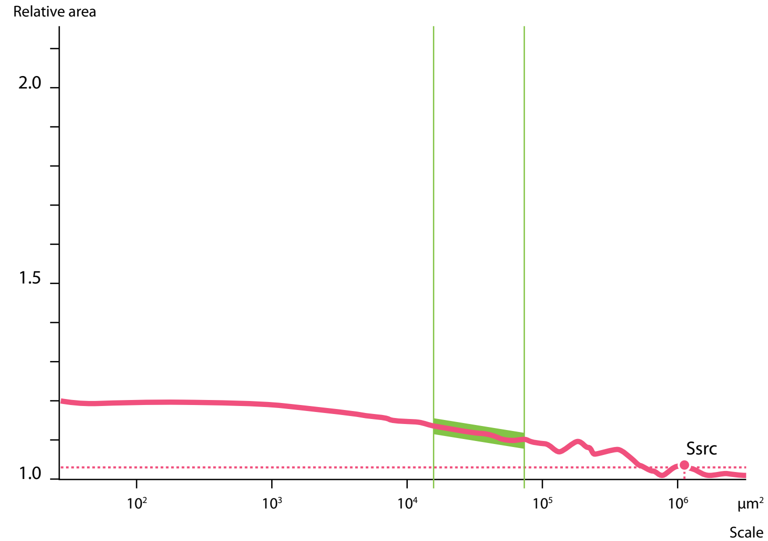
As the observation scale decreases, the first relative area or length exceeding the threshold t is used to determine the value of Ssrc. This parameter is calculated by identifying the first crossover scale (i.e., scale at which the slope of the function changes) encountered while moving from larger to smaller scales.

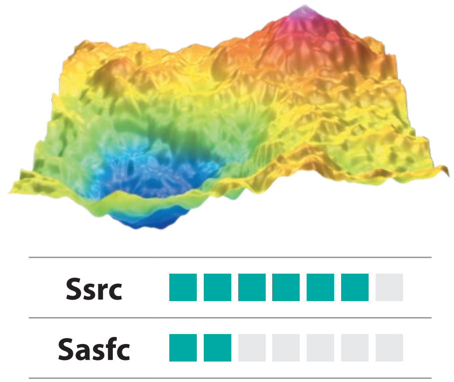


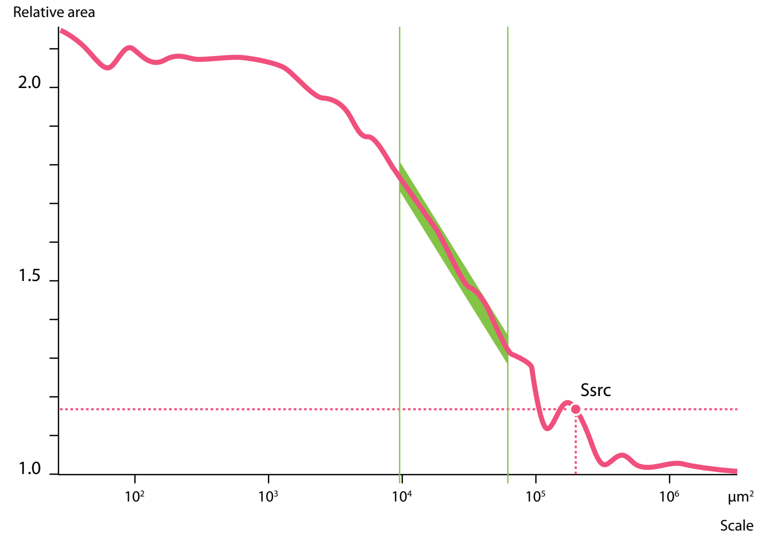
For the volume case, the smooth-rough crossover is the first crossover scale observed while transitioning from smaller scales—where the surface appears rough—to larger scales—where the surface appears smooth—.

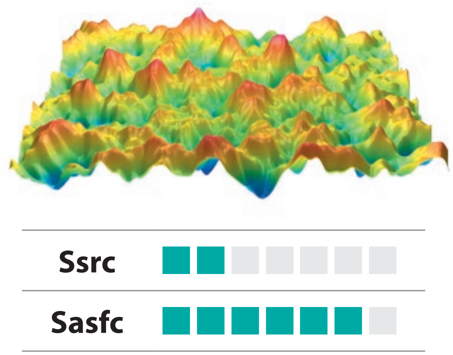
For area-scale analysis, a threshold of 10% (by default) in relative area is used to determine the crossover.

> Fractal parameters offer insights into the intricacy and scale of surface texture. These parameters are useful for characterizing multi-scale roughness in coatings, biological tissues, and geological samples. For example, high Sasfc and low Ssrc indicate fine-scale roughness, while low Sasfc and high Ssrc suggest smoother surfaces at small scales.









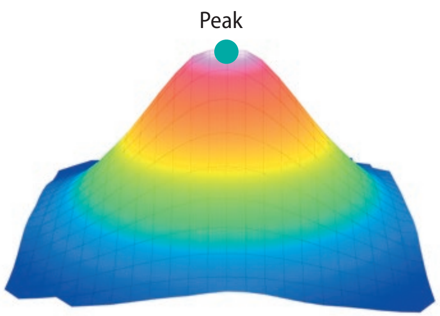
Feature parameters

While field parameters provide a comprehensive view of the surface, feature parameters provide detailed information on individual features of the surface. The motif size, shape or area of the surface are some of the quantitative values feature parameters offer.

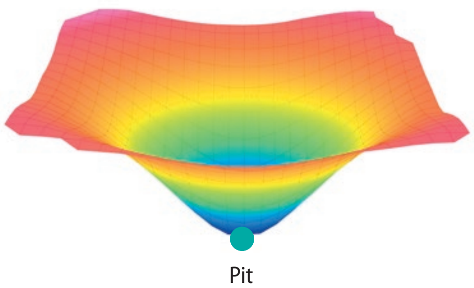
Feature-related terms

The following concepts are fundamental to understanding how feature parameters are calculated:

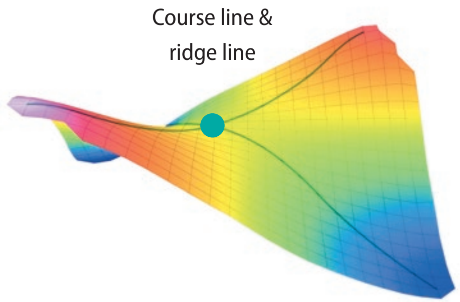
- **Peak:** point on a surface with a greater height than any other nearby points.
- **Hill:** a topographic area that surrounds a peak, defined by the property that all the highest possible paths within that area lead to the peak.
- **Course line:** a curve that separates neighboring hills.
- **Pit:** point on a surface that has a lower height than any other nearby points.
- **Dale:** a topographic area that surrounds a pit, defined by the property that all the lowest possible paths within that area lead to the pit.
- **Ridge line:** a curve that separates neighboring dales.
- **Saddle:** a set of points on a scale-limited surface where ridge lines and course lines intersect.



Hill

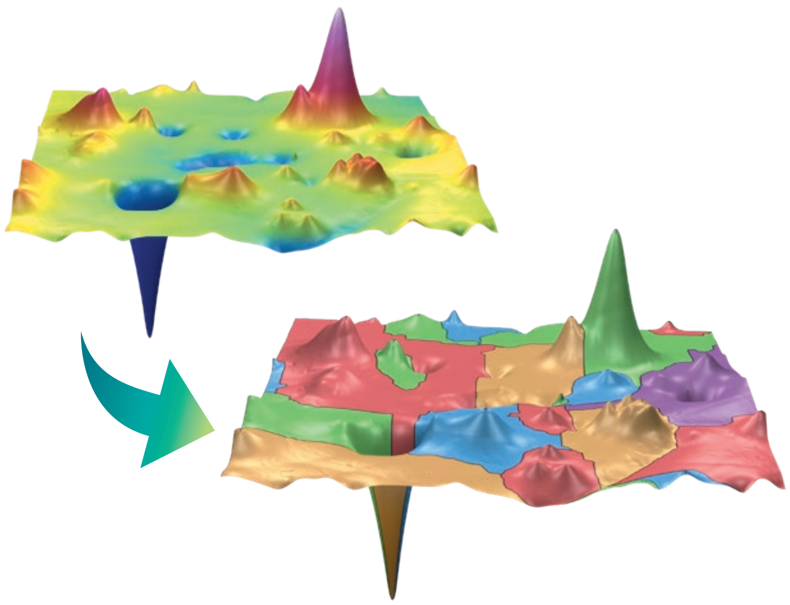


Dale

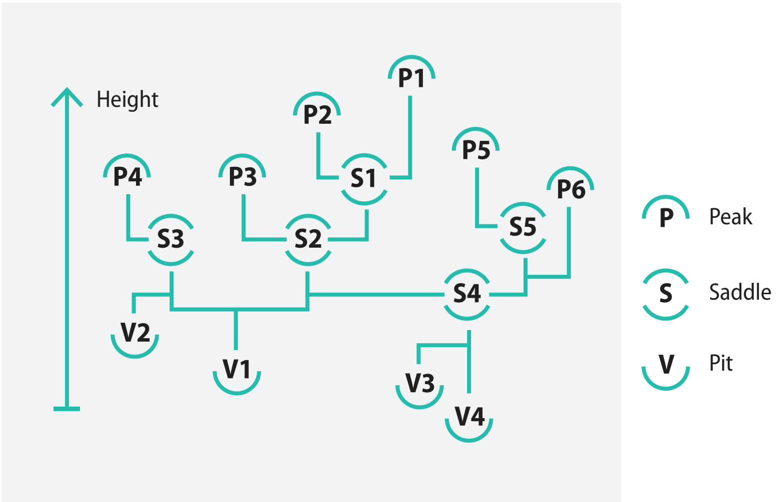


Saddle

- **Topographic feature:** areal feature (hill or dale), line feature (course line or ridge line) or point feature (peak, pit, or saddle point) on a scale-limited surface.
- **Contour line:** continuous line that connects points with the same height.
- **Segmentation:** process that divides a scale-limited surface into separate features.
- **Change tree:** graphical tool that can be used to analyze the hierarchy of features in a surface.
- **Hill local height:** difference between the height of the highest point on a hill (peak) and the height of the nearest saddle point that is connected to that peak on the change tree.
- **Dale local height:** height difference between the nearest saddle point on the change tree and the lowest part of the dale (pit).
- **Pruning:** process in which the change tree is simplified by removing points that are insignificant according to a specific criterion. By default, the pruning method used on ISO 25178 is the Wolf pruning. This method removes peaks and pits whose local height is smaller than a specific amount. By default, this amount is 5% of Sz.



Segmentation



Change tree

	Parameter	Example units	Description
Main feature parameters	**Spd**	1/mm²	Density of peaks
	Svd	1/mm²	Density of pits
	Spc	1/mm	Arithmetic mean peak curvature
	Svc	1/mm	Arithmetic mean pit curvature
	S5p	µm	Five-point peak height
	S5v	µm	Five-point pit depth
	S10z	µm	Ten-point height
Other feature parameters	**Shh**	µm	Mean hill local height
	Shhx	µm	Max. hill local height
	Shhq	µm	Std. dev. of hill local height
	Sdd	µm	Mean dale local depth
	Sddx	µm	Max. dale local depth
	Sddq	µm	Std. dev. of dale local depth
	Sha	mm²	Mean hill area
	Shax	mm²	Max. hill area
	Shaq	mm²	Std. dev. of hill area
	Sda	mm²	Mean dale area
	Sdax	mm²	Max. dale area
	Sdaq	mm²	Std. dev. of dale area
	Shv	mm³	Mean hill volume
	Shvx	mm³	Max. hill volume
	Shvq	mm³	Std. dev. of hill volume
	Sdv	mm³	Mean dale volume
	Sdvx	mm³	Max. dale volume
	Sdvq	mm³	Std. dev. of dale volume
	Shn	unitless	Hill count
	Sdn	unitless	Dale count

	Parameter	Example units	Description
Shape parameters	**Shrn**	unitless	Mean hill roundness
	Shrnx	unitless	Max. hill roundness
	Shrnq	unitless	Std. dev. of hill roundness
	Sdrn	unitless	Mean dale roundness
	Sdrnx	unitless	Max. dale roundness
	Sdrnq	unitless	Std. dev. of dale roundness
	Shff	unitless	Mean hill form factor
	Shffx	unitless	Max. hill form factor
	Shffq	unitless	Std. dev. of hill form factor
	Sdff	unitless	Mean dale form factor
	Sdffx	unitless	Max. dale form factor
	Sdffq	unitless	Std. dev. of dale form factor
	Shed	µm	Mean hill equivalent diameter
	Shedx	µm	Max. hill equivalent diameter
	Shedq	µm	Std. dev. of hill equivalent diameter
	Sded	µm	Mean dale equivalent diameter
	Sdedx	µm	Max. dale equivalent diameter
	Sdedq	µm	Std. dev. of dale equivalent diameter
	Shar	unitless	Mean hill aspect ratio
	Sharx	unitless	Max. hill aspect ratio
	Sharq	unitless	Std. dev. of hill aspect ratio
	Sdar	unitless	Mean dale aspect ratio
	Sdarx	unitless	Max. dale aspect ratio
	Sdarq	unitless	Std. dev. of dale aspect ratio

Main feature parameters

Spd – density of peaks

It is calculated by counting the number of peaks within a unit area of the surface, considering only those peaks that surpass the designated threshold.

Svd – density of pits

Number of pits within a unit surface area. In the same way as Spd, only the pits whose depth surpasses the threshold T are considered.

Spc – arithmetic mean peak curvature

It quantifies the curvature of peaks that surpass the threshold in a surface texture. It provides information on the average curvature of the peaks on a surface and is typically measured in micrometers. This parameter is often used to characterize the contact between two surfaces.

Svc – arithmetic mean pit curvature

It quantifies the average curvature of pits surpassing the surface texture threshold.

S5p – five-point peak height

It refers to the average value of the five highest peak heights on a surface texture.

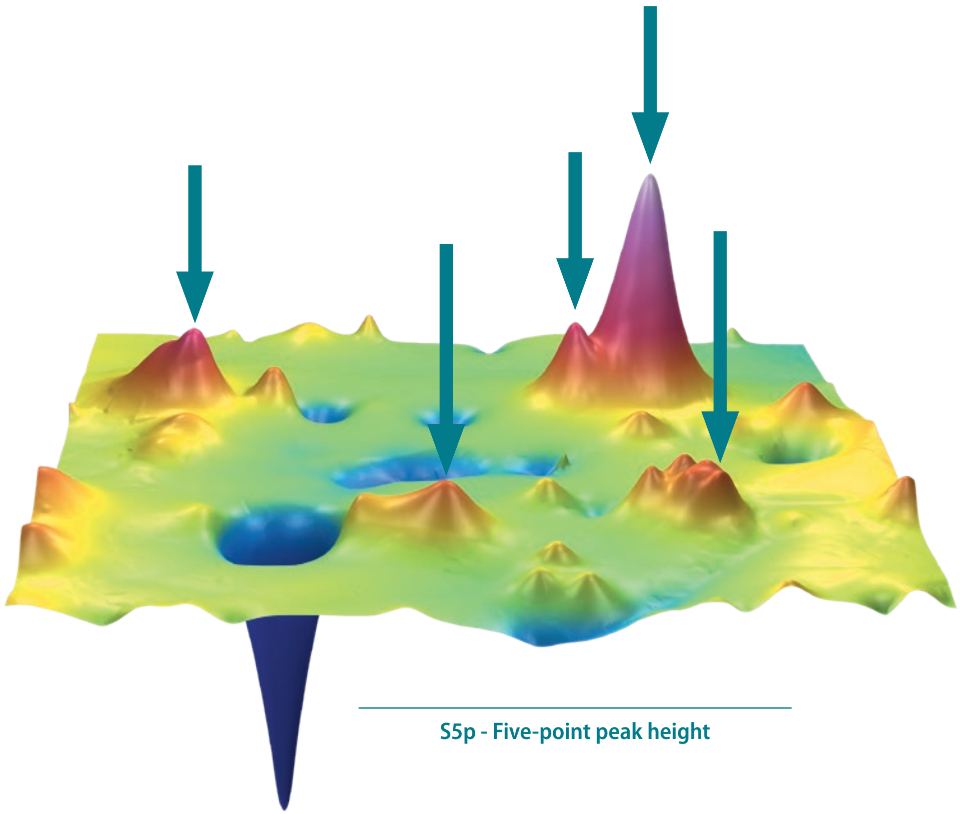
S5v – five-point pit depth

Mean height of the five deepest pits.

S10z – ten-point height

Calculated as the combination of the five-point peak height and the five-point pit depth.

$$S_{10z} = S_{5p} + S_{5v}$$



S5p - Five-point peak height

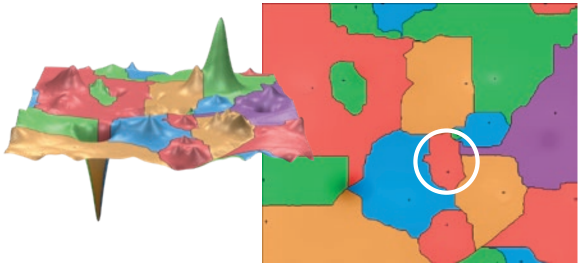
Shape and other feature parameters

While we have already discussed the primary feature parameters, it is worth noting that ISO 25178 describes additional parameters that combine various feature characteristics and statistical attributes. Most of them were introduced in the latest review of the standard, and because of that, they are not well known, but some of them, like Sha, Shv, Sda, and Sdv were already in ISO 25178-2:2012.

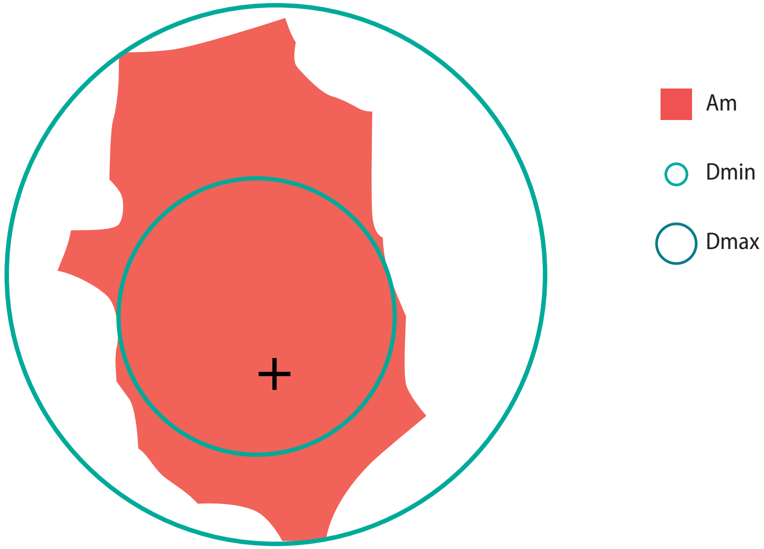
ISO 25178 follows specific naming conventions for feature surface texture parameters. Each parameter begins with an uppercase **S**, followed by either **'h'** for hills or **'d'** for dales, followed by **'h'** for height, **'d'** for depth, **'a'** for area, **'v'** for volume, or **'n'** for count. These naming rules help to ensure consistency and clarity when communicating surface texture data across various industries and applications.

ISO 25178-2 defines even more additional feature parameters based on the shape of the texture motif in the horizontal plane, further enhancing the surface texture characterization process. By considering the specific shape of surface features, these parameters provide more nuanced insights into the functionality and performance of components.

In this case, the different 2D characteristics of the surface motifs that define these extra feature parameters are roundness, form factor, equivalent diameter, and aspect ratio.



Feature



Roundness (RN)

Quantifies the circularity of surface features. This parameter is calculated by dividing the horizontal area of the texture motif (Am) by the area of a circle with a diameter equal to the maximum diameter. A perfectly round object will have a roundness value of 1, while an elongated object will have a value of less than 1. Roundness of a surface motif can be calculated with the following formula:

$$M_{RN} = \frac{4A_m}{\pi D_{max}^2}$$

where Am is the area of the motif and Dmax the maximum diameter.

Form factor (FF)

Evaluates the compactness of a surface feature. This parameter measures the filled volume fraction of the feature, with elongated objects giving a value close to zero and compact objects giving a value close to 1. Form factor can be expressed as:

$$M_{FF} = \frac{4\pi A_m}{\Pi^2}$$

where Π is the perimeter of the feature.

Aspect ratio (AR)

Is used to distinguish between compact and oblong motifs. It is calculated by dividing the maximum diameter by the minimum diameter of the texture motif.

$$M_{AR} = \frac{D_{max}}{D_{min}}$$

An aspect ratio of 1 indicates a disc-shaped motif, while a value greater than 1 indicates an oblong shape.

Equivalent diameter (ED)

Diameter of a circle that has the same area as the surface feature.

$$M_{ED} = \sqrt{\frac{4A_m}{\pi}}$$

The following table serves as a summary of the shape and other feature parameters and their meaning:

STATISTICS		HILL			DALE		
		mean	max	stddev	mean	max	stddev
Local height/depth		Shh	Shhx	Shhq	Sdd	Sddx	Sddq
Area		Sha	Shax	Shaq	Sda	Sdax	Sdaq
Volume		Shv	Shvx	Shvq	Sdv	Sdvx	Sdvq
Count		Shn			Sdn		
Shape parameters	RN	Shrn	Shrnx	Shrnq	Sdrn	Sdrnx	Sdrnq
	FF	Shff	Shffx	Shffq	Sdff	Sdffx	Sdffq
	ED	Shed	Shedx	Shedq	Sded	Sdedx	Sdedq
	AR	Shar	Sharx	Sharq	Sdar	Sdarx	Sdarq

These new parameters offer a more comprehensive approach to surface texture characterization, providing valuable insights into the functionality and performance of components.

Which surface texture parameter should I use?

Which surface texture parameter should I use?

While Sa parameter is widely recognized and frequently used in surface texture analysis due to its simplicity and ease of calculation, it may not always be sufficient for capturing the complexity of different textures. This limitation is particularly evident when two surfaces exhibit the same Sa value yet possess distinctly different characteristics and functional properties.

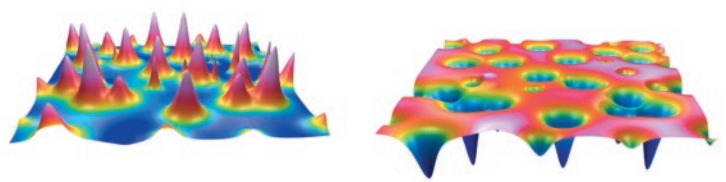


Figure 11. Two topographies with the same Sa value but radically different functional properties.

To achieve a more accurate and comprehensive understanding of surface texture, it is essential to consider additional parameters beyond Sa. But how should these parameters be selected?

From a theoretical standpoint, selecting the appropriate parameter from ISO 25178 depends on several factors, including:

- The **type and scale** of the **surface features** you want to characterize. For example, if you want to measure the roughness of a machined surface, you may use height parameters such as Sa or Sq. If you want to measure the anisotropy of a textured surface, you may use spatial parameters such as Str or Std. If you want to measure the complexity of a fractal surface, you may use hybrid parameters such as Sdq or Sasfc.
  Also note that some parameters only make sense for specific kinds of surfaces. For instance, Sk parameters (functional) are only helpful for surfaces with an S-shaped material ratio curve (like lapped, ground, or honed surfaces). Other parameters like Ssw are not relevant if the surface does not have a periodic structure. Make sure to take this into account when selecting your candidate parameter(s).

- The **purpose and context** of your measurement. For example, if you want to compare your surface with a reference or specification, you may use widely accepted and standardized parameters in your industry or domain. If you want to correlate your surface with a physical phenomenon or a performance indicator, you may use parameters that are relevant and sensitive to that phenomenon or indicator. If you want to optimize your process or product design, you may use responsive and controllable parameters by your process or design variables.

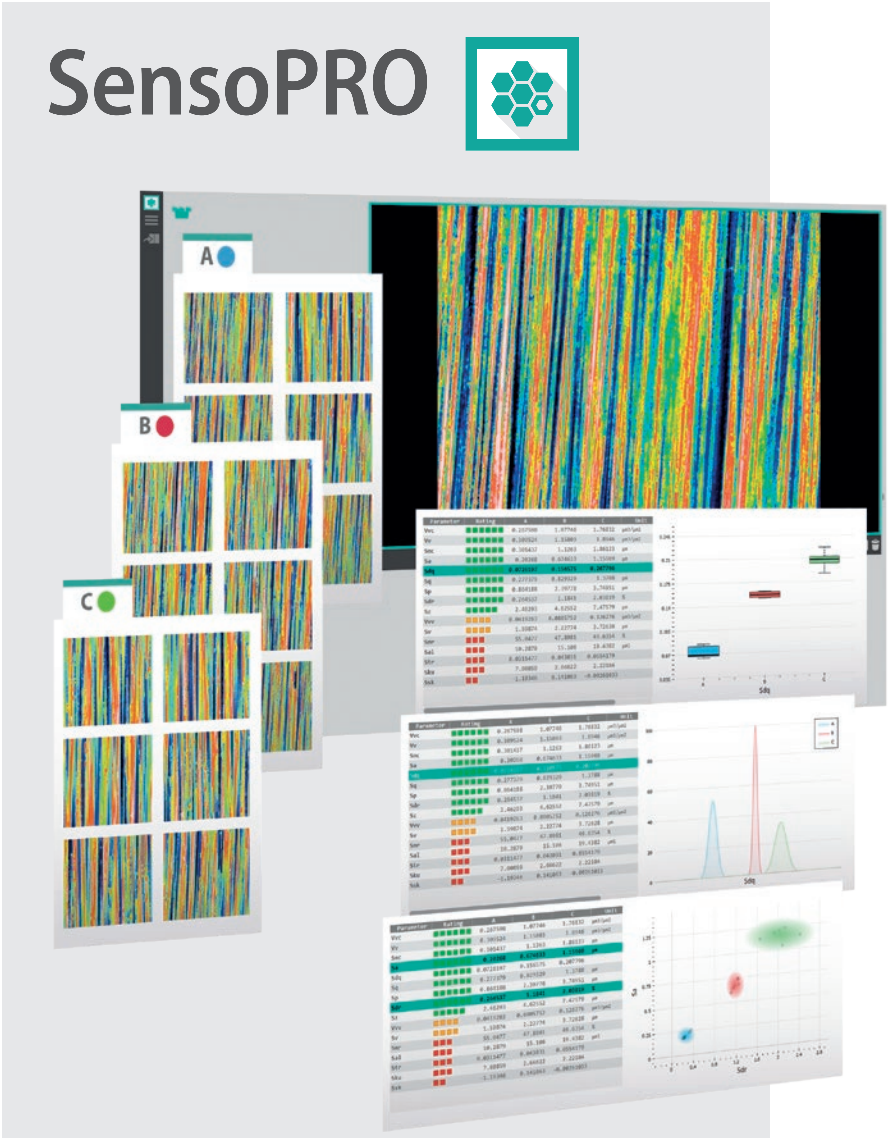
A practical method for choosing the proper texture parameter

From the practical perspective, the actual situation of your research may be more complex. It may occur that you do not know which scale of interest you should be looking for. Or perhaps your workpiece is not performing as expected, and you do not know how this relates to surface texture. That is why, as a general approach, determining the proper surface texture parameters is called a classification problem.

This classification approach is based on the fact that you have two or more groups or samples (actual samples or theoretical) that have different surface properties or simply exhibit a different functional performance. For a given sample, your final goal is to determine if this new surface belongs to one group or another based on its surface texture parameters. This situation can be found with different groups of samples having different properties or simply two groups: one for "good" samples and one for "bad" ones. There are many approaches for solving this classification problem, from statistical analysis to neural networks or machine learning.

One of the most used procedures consists of **measuring a large set of samples and using statistical analysis** to see if these can be sorted based on one or more surface texture parameters. This may seem difficult for non-mathematicians, but nowadays, different software tools can help you with this evaluation. For instance, Sensofar's SensoPRO software is an ideal tool for deciding which roughness parameter to choose. Thanks to its Multiple Group analysis tool, the software can analyze two or more groups of samples and give you a list of recommended parameters that distinguish one group from another. SensoPRO uses its Surface Texture plugin to analyze each measurement according to ISO 25178, extracts its roughness parameters and compares the average values and standard deviations. Finally, the software can even set tolerances over those parameters to provide a complete guide for a QC manager for example.

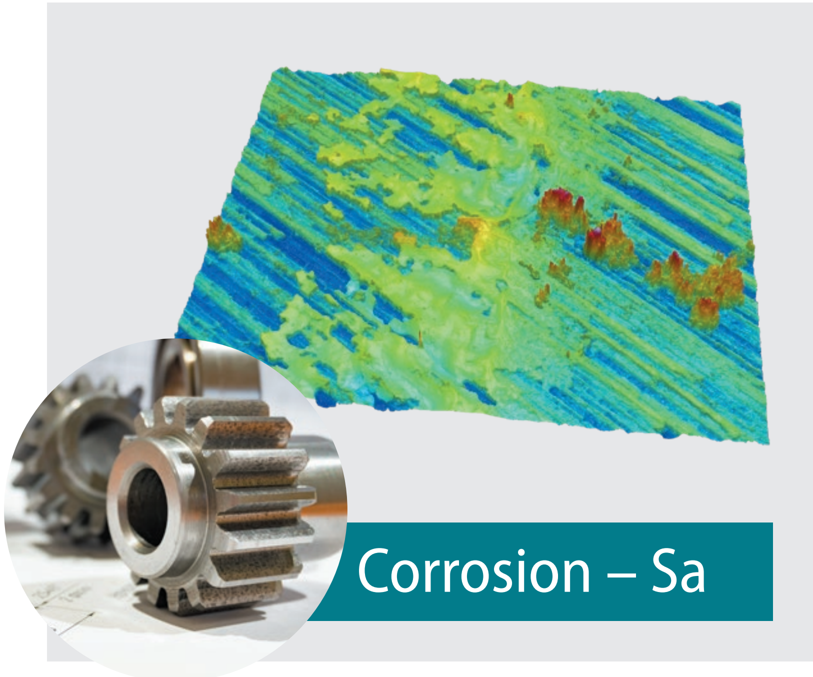
Choosing the proper surface roughness parameter for your application requires knowledge of both the surface properties of your workpiece and the surface texture parameters. However, SensoPRO is a powerful tool that can make this process easy.



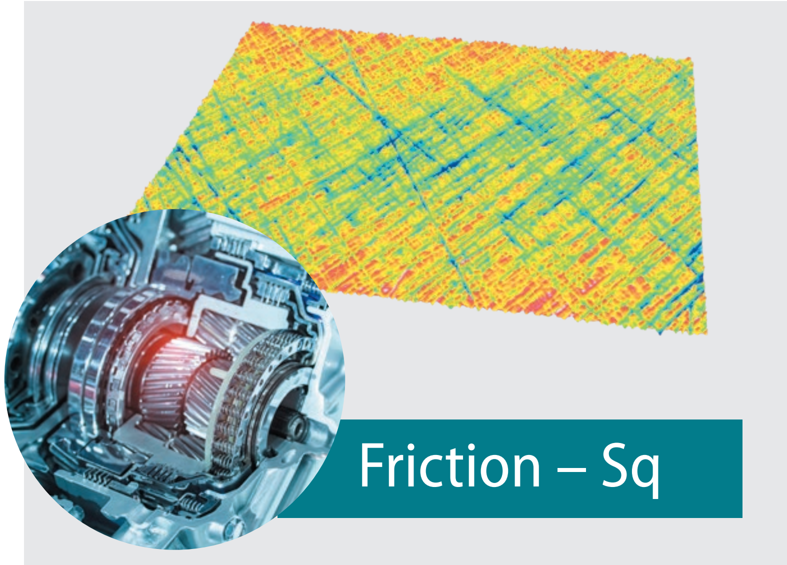
Examples of applications of texture parameters

While no universal rules exist for determining which texture parameter is suitable for a particular surface or application, academic research has found certain correlations.

- **Sa**, as the extension of Ra profile parameter, is frequently used in industrial fields like tribology[2] and machining[3, 4].
- **Sa** and **Sq** were reported to correlate to surface glossiness. Lower values of Sa and Sq were associated to glossy surfaces[5].
- A decrease in **Sa** has proved to cause a higher corrosion resistance[6].



- **Sq**, **Ssk** and **Sku** influence on friction performance[7, 8, 9].



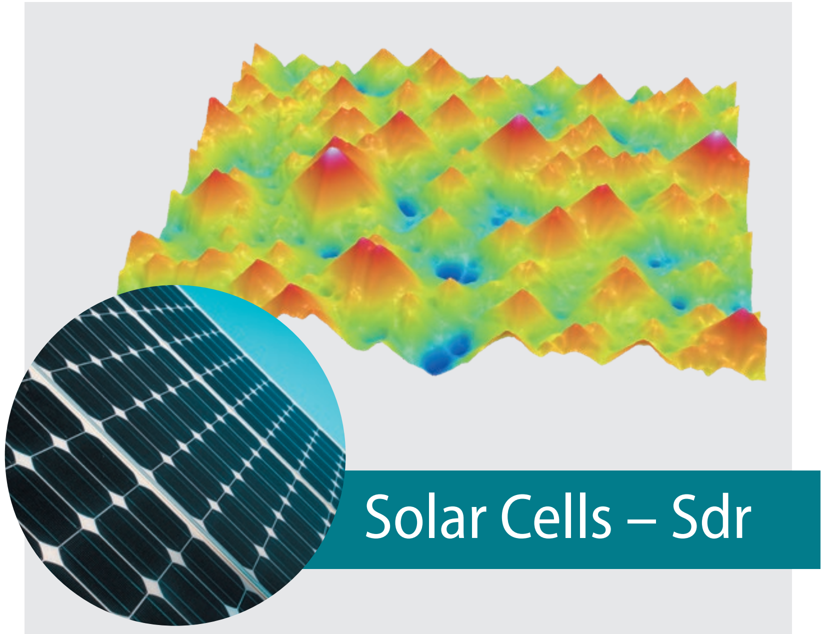
- **Ssk** and **Sku** were found to be sensitive to different machining processes[10], to burnishing parameters and are frequently used in contact studies of surfaces[11, 12, 13, 14]. Skewness can be helpful when working with textured surfaces such as laser texturing[15, 16, 17, 18, 19, 20, 21, 22] for determining lubricant retention and sliding properties, although it should be combined with other parameters such as Sq to determine the texture height[23].
- A higher value of **Sal** is usually related to better functional performance in load-carrying capacity and load wear during lubrication[24, 25].
- A relationship was found between critical load and **Spc**, **Sq**, **Vvc**, **Sdq** parameters[26].
- **Sdr** and **Sdq** can be particularly useful in applications where adhesion or friction is important, such as automotive, aerospace, and biomedical industries. For example, a higher Sdr value may indicate better adhesion between two surfaces, whereas a lower Sdr value may indicate reduced friction[27].

- **Sdr** parameter was found to be a good way of discriminating between high and low efficiency solar cells[28].

- **Spq**, **Svq** and **Smq** parameters are especially useful for analyzing surfaces that have been subjected to multiple processing steps, as they help in evaluating the effects of each process on the surface texture and in predicting performance and wear characteristics in applications where surface integrity is critical[29].

- **Fractal parameters** are useful for characterizing multi-scale roughness in biological tissues, geological samples and archeological samples[30].

- **Feature parameters** have also been found useful in surface characterization in different studies in the fields of tribology[31, 32], machining[33, 34] and biomedicine[35].



As a general summary of applications, we can show the following table[36]:

Parameters		Examples	Functional importance
Height	Amplitude	**Sa, Sq, Sv, Sp, Sz**	Surface contact, lubrication, friction, wear, fatigue, technical control of manufacturing
	Shape of the height distribution	**Ssk, Sku**	Surface contact, friction, wear
Spatial		**Sal, Str, Std**	Lubrication, friction
Hybrid		**Sdq, Sdr**	Surface contact, friction, wear, ability to adhesive junctions, sealing, and cosmetic appearance
Functional		**Smr, Smc, Sdc, Sk, Spk, Svk, Smrk1, Smrk2, Spk, Svk, Smq, Vvv, Vmp, Vmc, Vvc**	Wear, friction, oil capacity, low wear assessment, technical control of manufacturing

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