New 3D Parameters and Filtration Techniques for Surface Metrology

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For a long time surface metrology has been based upon contact measurement using 2D profilometers. Over the past twenty years the appearance of 3D profilometers and non-contact gauges has created a need for the standardization and formalization of the analysis of 3D surface texture. This paper presents the current status of the standardization process and includes a short description of the tools and parameters that will become available to users when work on the definition of the new standards, which is being carried out by working groups WG15 and WG16 of ISO technical committee TC213, has been completed.

1. Introduction

Since the first roughness meters appeared at the beginning of the 1930s, the measurement of surface texture has always been based on 2D profilometry and contact gauges. We had to wait until the beginning of the 1980s to see the appearance of instruments for measuring 3D surfaces, such as white light interferometers and 3D profilometers `[WHI94]`. The first tools for analysing measurements generated by these instruments were developed by each manufacturer, often extrapolating from existing tools for 2D profilometry. It was only when research programmes were initiated in Europe that we saw the beginning of the rationalization and formalization of these tools. Today, the international standardization of analysis tools for 3D surface texture is under way and has led to an in-depth revision of the concepts and practices used for 3D analysis and equally for 2D profilometry.

2. Areal surface finish: the research and development phase

The first important work on 3D surface texture was carried out by a European programme, led by Pr K. Stout from Birmingham university. This programme, which took place between 1990 and 1993, ended with the publication of the famous *Blue Book*, and the definition of the so-called Birmingham 14 parameters `[STO94]`. The final report served as a reference for almost all instrument manufacturers during the 90s.

Following this programme, technical committees TC57 then TC213, in charge of ISO standards for surface texture, realized that it was time to start standardization work on 3D surface texture. But ISO experts rapidly found out that further research work was needed to determine the stability of 3D parameters and their correlation with the functional criteria used by industry. They also decided to cover instruments as well and their 3D calibration. The research work was then subcontracted to another European programme, called SURFSTAND.

This programme was carried out between 1998 and 2001, by a consortium of universities and industrial partners, led by Pr. L. Blunt. It ended with the publication of the *Green Book* `[BLU03]` and generated the basic documents for forthcoming standards. The programme results were presented to ISO in January 2002, during the Madrid meeting, and officially transferred to the TC213, in order to start the standardization process.

3. Towards a complete rework of all surface texture standards

In June 2002, the TC213 voted the creation of a new working group `[N499]` and assigned it the task of developing future international standards for 3D surface texture. This group met for the first time in January 2003, in Cancun. During the past three years, the architecture of the new standard has been designed and described in a *master plan*, and the content of several fundamental documents has been written, based upon the results of the SURFSTAND program. Towards the end of 2005, the ISO secretary allocated the number ISO 25178 to this areal surface texture standard, thereby giving the standard its official birth.

The task allocated to WG16, which should be implemented in the ISO 25178 standard, contains two parts:

- *to define the content of the areal surface texture standard, for specification and verification;*
- *to revise the existing profile standards to bring them into line with the new areal standard.*

Currently all efforts are being put into the definition of the areal standard, in order to create a consistent set of definitions and concepts, founded upon a solid mathematical base, without taking existing standards into account. The basic premise is that Nature is intrinsically 3D and that surface texture should be defined in 3D first, and that 2D profilometry should be derived from this definition as a simplified model. This is the opposite of what happened before, when the first areal parameters were extrapolated from existing profile parameters. This should avoid the known drawbacks of some 2D parameters and provide a more rigorous definition of several concepts that have been used in existing standards for twenty years. Nevertheless, this should also create some differences between the new concepts and the existing ones that are in use in industry. A transition period during which things will probably appear a little bit fuzzy to users is expected. During this period, information and training should be provided, and metrology tools should provide users with a smooth transition from old to new standards, in order to ensure upward compatibility.

The first parts of the ISO 25178 [1], concerning the areal case, should be published in 2007; the remaining ones, concerning the profile case, should not appear before 2009.

4. 3D surface texture parameters

The first manufacturers of 3D surface texture measurement instruments initially proposed characterization methods that were mainly based upon a simple extrapolation of 2D methods. In the absence of official documentation, the manufacturers made up solutions that were more or less felicitous, with parameters sometimes calculated as the simple mean of 2D parameters evaluated for each line on the surface, or for radial profiles extracted from a circle with its origin at the centre of the image.. The naming rules for the parameters were also derived from the 2D parameters (*sRa*, *sWa*...). Nonetheless good practices were disseminated, notably thanks to publications by Stout and his collaborators at Birmingham, and with the release of Talymap Macintosh software in 1993, developed by Digital Surf for Taylor Hobson's Form Talysurf.

4.1. Naming rules for 3D parameters

All of the 3D parameters start with the upper case letter S or the upper case letter V. In contrast with 2D naming rules, the prefixes of the 3D parameters do not reflect the nature of the surface, distinguishing between roughness and waviness. In 2D, we have *Pa*, *Ra* et *Wa*; in 3D we only have *Sa*. *Sa* will therefore be a 3D parameter of roughness, or waviness, or of the raw surface, depending upon the prefiltering that is carried out before the parameter is calculated. This decision is based upon the multiplicity of processing and filtering methods that are available to metrologists for extracting information from a surface. These processing methods do not necessarily separate the surface texture into two components that are roughness and waviness but in certain cases alter the surface in a more subtle manner.

4.2. Amplitude parameters

Most of the 2D parameters defined in ISO 4287 have a mathematical expression that can easily be extended to 3D. For example, *Sq* is simply an extension to a plane of the equation of *Rq* that is defined for a line:

$$Rq=\sqrt{\frac{1}{lb}\int_{lb} Z^2(x)dx} \qquad Sq=\sqrt{\frac{1}{A}\iint_{A} Z^2(x,y)dxdy}$$

Sa, Sq, Ssk, Sku, Sp, Sv, etc. can be defined straightforwardly in the same way. Nonetheless, certain parameters pose problems. *Rz* is defined in ISO 4287 as the maximum height on a *base length*, but it is averaged on the number of base lengths that contain the evaluation length. In general, *Rz* is less than *Rt*. This parameter has known numerous declensions, first of all defined in ISO 4287 (1984) as the ten point height, then modified in 1997, and it has remained confusing notably because of its similarities with the *Ry* and *Rmax* parameters. It is worth noting that *Sz* will be defined in the ISO standard simply as the maximum height from the highest point to the deepest valley, as *St* was once defined, with *St* disappearing from the standard altogether!

4.3. Bearing ratio parameters

Since bearing ratio parameters are related to height distribution, they can easily be extended to 3D:

Smr : areal material ratio
Sdc : areal section height difference
Smc : inverse areal material ratio

Note the appearance of a new parameter, *Smc*, which simply provides the inverse value of the bearing ratio, as opposed to *Sdc* which is the difference between two *Smc*.

4.4. Spectral analysis of a surface and associated parameters

A surface is said to be *isotropic* when it presents identical characteristics regardless of the direction of measurement. This is the case, for example, for surfaces with a random surface texture that do not have any texture that stands out. This type of surface is unhappily fairly rare and most of the surfaces encountered in industry have an oriented surface (turned, ground or brushed surfaces) or a periodic structure (EBT impacts, grained plastics). In this case the surface is said to be *anisotropic*.

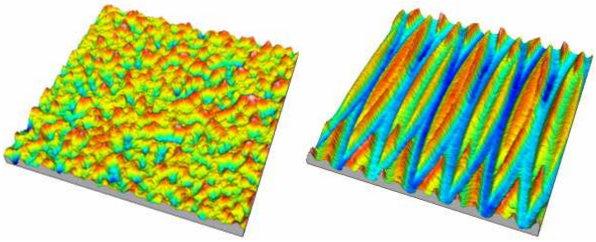

Figure 1: surface with an isotropic texture (left); surface with an anisotropic texture (right)

The isotropy of a surface can be determined and quantified by tools based upon the Fourier transform and autocorrelation.

Autocorrelation is a function described by the following equation:

$$ACF(\tau x,\tau y)=\frac{\iint_A Z(x,y)Z(x-\tau x,y-\tau y)dxdy}{\iint_A Z^2(x,y)dxdy}$$

This function makes it possible to generate an image on which it is possible to measure characteristic quantities.

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[1] Since work on the standard is still in progress, it is still possible that there will be some changes before publication. The reader of this article should refer to official documents for all practical applications.

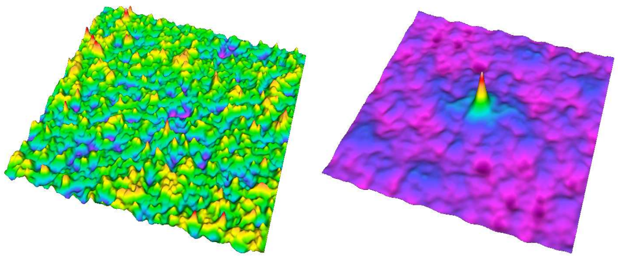

Figure 2: surface (left) and autocorrelation (right)

The autocorrelation image always includes a central peak with a standard amplitude of 1. In certain cases the image includes secondary peaks that indicate a certain correlation between a portion of the surface with the surface itself. This is the case with surfaces including periodic or pseudo-periodic motifs. Indeed the form of the central peak is an indicator of the isotropy of the surface.

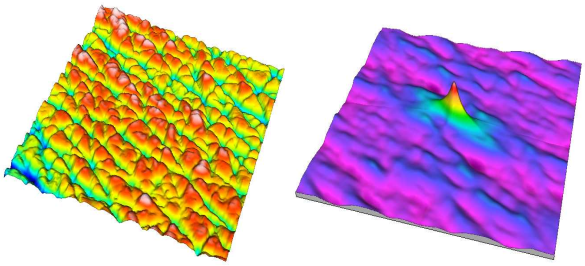

Figure 3: anisotropic surface (left) and autocorrelation (right) showing an oblong central lobe

In order to characterise the form of the central peak, one carries out thresholding at 0.2 and then one quantifies the central zone of the image corresponding to the portion of the peak that remains after thresholding.

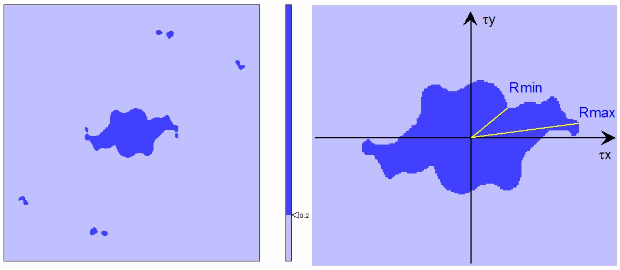

Figure 4: thresholded autocorrelation (left) and central lobe with radii measurement (right)

The minimum and maximum radii are sought on the image of the central lobe (generated by thresholding the central autocorrelation peak). If the surface presents the same characteristics in every direction, the central lobe will be approximately circular and the min and max radii will be approximately equal. If the surface presents a strong privileged orientation, the central lobe will be very stretched out and the max radius with be much greater than the min radius.

In this way it is possible to construct a parameter that will be an indicator of surface isotropy:

Str : texture aspect ratio.

$$Str = \frac{R\min}{R\max}$$

where *Rmin* and *Rmax* are the min and max radii calculated with respect to the perimeter of the central lobe. The radii are calculated from the coordinates of point (τx,τy) on the perimeter. Note that the threshold value of 0.2 is a default value but that for certain applications it can be advisable to choose a higher or lower value, notably to assure that the central lobe is well defined and does not touch the edges of the image. The *Str* parameter takes a value between 0 and 1, without a unit. It can also be expressed as a percentage between 0% and 100%. An isotropic surface with have *Str* close to 1 (100%) while a strongly anisotropic surface will have *Str* close to 0.

The value *Rmin* equally provides a useful indication of the spectral content of the surface. A surface that is essentially made up from spectral components with long wavelengths yields a high *Rmin*, and inversely. Hence the parameter *Sal* is defined as follows:

Sal, fastest decay autocorrelation length.

Sal = Rmin

This parameter is expressed in µm.

The Fourier spectrum, when it is integrated in polar coordinates makes it possible to determine the privileged direction of surface structures. The polar spectrum takes into account the power spectrum of the surface in each direction. The angle with the largest power spectrum corresponds to the privileged surface direction.

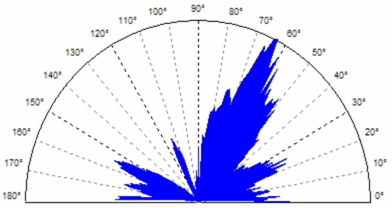

Figure 5: polar spectrum of a surface

The representation of the polar spectrum clearly shows the privileged directions. The angle corresponding to the polar spectrum maximum makes it possible to define the *Std* parameter:

Std : texture direction.

This angle is expressed in degrees, anticlockwise.

4.5. Functional parameters

For a long time the mechanical engineering industry, and in particular the automotive industry, has tried to find ways of optimizing parameters and filtering methods in order to make them more effective and to improve their correlation with functional phenomena.

The functional characterisation of surface texture is of fundamental importance for all mechanical parts that are in contact with another part, in other words for all parts with the exception of parts that are responsible for external look only.

4.5.1. Parameters extrapolated from the ISO 13565-2 standard

The first reflex was to reproduce in 3D the graphical study of functional parameters defined in the ISO 13565-2 standard, based upon the *Rk*, *Rpk* and *Rvk* parameters initially defined by the German automotive industry. In 3D, their counterparts *Sk*, *Spk* and *Svk* are calculated in the same way, with respect to the Abbott curve, itself calculated on the entire surface. Nonetheless in due course the new volume parameters are expected to replace these functional parameters that were derived from profilometry standards.

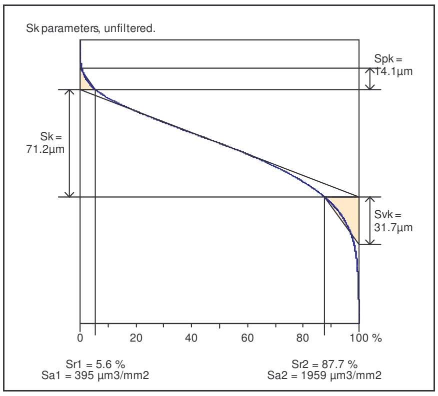

Figure 6: functional parameters after ISO 13565-2

4.5.2. Functional indices

The European SURFSTAND project defined a set of functional indices making it possible to characterize surface zones involved in lubrication, wear and contact phenomena.

Sbi, *surface bearing index* characterizes, following *Spk*, the upper zone of the surface involved in wear phenomena.

Sci, *surface core fluid retention index* characterizes the main void volume acting as a lubricant reserve.

Svi, *surface valley fluid retention index* characterizes, following *Svk*, the void volume of the deepest valleys.

These parameters, despite their utility, only represent an intermediate step towards the definition of volume parameters that further improve correlation with functional phenomena and are more relevant, while continuing to provide the support that has been provided by the functional indices. As a result, in the ISO 25178 3D standard the functional indices have been superseded by volume parameters.

4.5.2. Functional volume parameters

These parameters represent an evolution of the functional indices and are defined, like the functional indices and the family of *Sk* parameters, with respect to the Abbott curve:

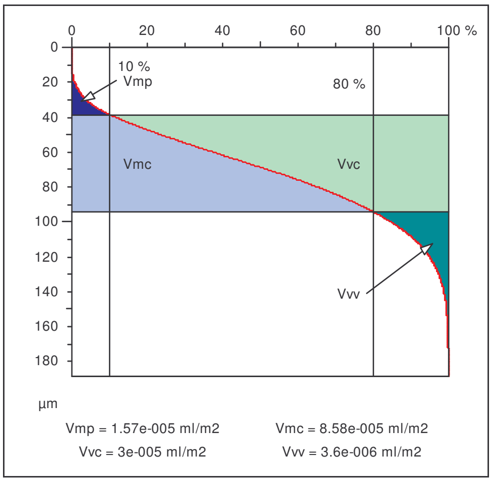

Figure 7: Volume parameters calculated on the areal material curve and using default material threshold (10% and 80%)

The parameters are defined with respect to two bearing ratio thresholds, set by default to 10% and 80%. Two material volume and two void volume parameters are defined:

Vmp: *peak material volume*

Vmc: *core material volume*

Vvc: *core void volume*

Vvv: *valley void volume*

These parameters are expressed in units of volume per unit of surface (ml/m^2 ou µm^3/mm^2).

5. Topological characterization of surface motifs

In the 1970s, in France, engineers from the school of Arts and Professions, Peugeot and Renault conceived a graphical method for analysing motifs, adapted to the characterization of functional surface texture. The great interest of this method is that it takes the functional requirements of the surface into account and attempts to find relationships between peak and valley locations and these requirements. This method had a great success in French industry and ended up being incorporated into an international standard in 1996 `[12085]`. During the past ten years, many players have tried to extrapolate this method to 3D, with little success. It was only when methods derived from image analysis were applied to 3D surface texture that the benefits of the motifs method were rediscovered `[BAR97, SCO97]`. This method is now officially integrated into the forthcoming ISO standard on 3D surface texture, as a method of discriminating between significant peaks and holes, and equally as a method of characterizing 3D motifs.

The method, currently called *segmentation*, is based upon the application of a watersheds algorithm, associated with an algorithm for simplifying graphs that describe the relationships between individual points (Wolf pruning).

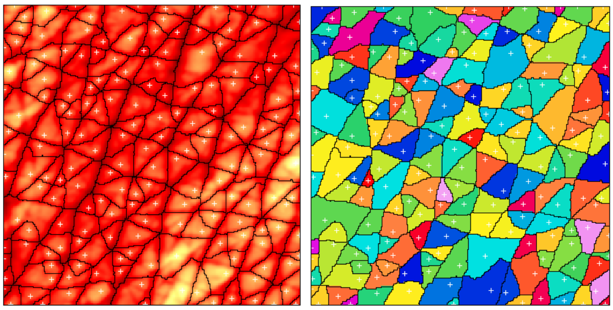

Figure 8: Segmentation of a skin surface. The crosses show the location of the peaks on each motif. Each motif represents a constituent element of the surface texture, capable of affecting the functionality of the part (lubrication, contact, etc.) To the right, each motif is represented by a different colour. The software makes it possible to count and quantify the motifs, to sort them into open and closed motifs, and to measure their area, mean depth, volume, etc.

Segmentation is also a powerful tool for separating out significant peaks, and is recommended for use with the *Sds* and *Ssc* parameters.

Sds : density of peaks

Ssc : mean summit curvature

With segmentation, these parameters become more relevant than they were previously (when they were applied in accordance with the definitions in preceding European reports).

In addition, specific parameters have been created to quantify the area and mean volume of motifs identified by segmentation, distinguishing between open and closed motifs, depending upon whether or not they touch the edge of the image.

6. New filtration techniques

At the same time as the group WG16 was created to work on 3D surface texture, ISO TC213 also created another work group, WG15, and gave it the task of developing a toolbox containing different types of filter, valid in 2D and in 3D. Since then this group has developed a multi-part specification, ISO TS 16610. For the sake of simplicity, filters are first of all defined for profiles and then extended to surfaces. At the current time, only the 2D versions exist `[RAJ02]`.

6.1. Linear fiilters

The Gaussian filter used in profilometry `[11562]` was easily extrapolated into 3D by instrument manufacturers a number of years ago, in order to allow users to separate waviness and roughness in a surface measurement. This filter should be defined officially by WG15 in a forthcoming standard `[16610-60]`. Other linear filters exist and each provide specific advantages in given applications. Thus, the *cubic spline* filter `[16610-22]` includes end-effect management in its definition in order not to reduce the size of the profile (or surface) that is filtered.

6.2. Filtres robustes

The Gaussian filter has a drawback that was identified by industry long ago: the sensitivity of the waviness profile to local features on the profile. The automotive industry tried to correct this problem with the double Gaussian filter `[13565]` then with the development of a number of filters know as *robust* filters, in other words filters that are insensitive to deviations due to peaks and valleys. Several approaches are possible here. The first approach uses an iterative method based upon Gaussian regression. It is possible to apply it to any linear filter, like the Gaussian and spline filters, for example. The robust Gaussian filter `[SEE05, 16610-31]` is already used in the automotive industry, notably in Germany. The second approach is based upon a non-linear filter equation, directly integrating robustness and end-effect management. This *robust spline* filter `[16610-32]` is more complex but at the same time performs better than robust filters based upon regression.

In general, these robust filters improve the separation between waviness and roughness, reducing neighbouring peak and valley errors and, in particular, making evaluations based upon the bearing ratio much more reliable.

6.3. Morphological filters

Metrologists have been practising metrological filtering for a long time without knowing it: the point of a contact profilometer carries out morphological filtering of the surface, in the form of morphological filtering with a sphere with a 2 µm radius. This example makes it possible to understand the two basic morphological operations: a structuring element (sphere or plane) is displaced in contact with the surface, above the surface (dilatation) or below it (erosion), and the trajectory of this element is recorded.

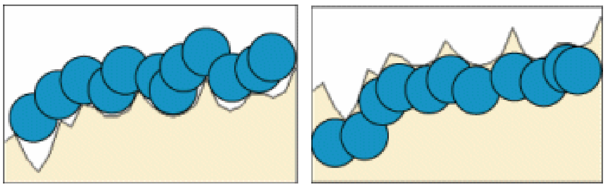

Figure 9: Dilation (left), erosion (right)

Two operations are defined with respect to these basic operations: *closing*, the successive application of a dilation and an erosion; and *opening*, the successive application of an erosion and a dilation. These two filters are defined in the WG15 toolbox `[SRI88, 16610-40]`.

6.4. Wavelet filtering,
scale space decomposition

The toolbox created by WG15 also includes techniques for analysing the scale at which such and such a phenomenon occurs. Wavelet decomposition makes it possible to generate a profile (or a surface) that only contains elements belonging to a given scale level. By repeating this operation in a cascade, it is possible to visualise and analyse all of the relevant scale levels and to detect the presence of significant events in space and on a scale level at the same time.

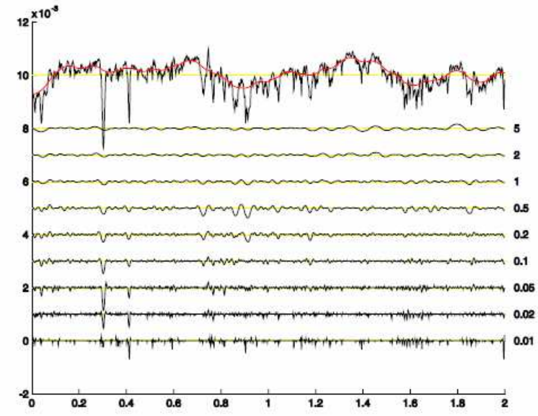

Figure 10 : Decomposition of a profile into its scale levels by using cascaded wavelet filters. Certain events are only visible at certain scales.

Note that decomposition into scale levels can equally be carried out by using morphological filters `[16610-49]` and a series of smaller and smaller structuring elements.

6.5. Filtering and associated concepts

As shown above, the goal of the new standard is to define concepts on new bases, without necessarily being inspired by what already exists. Existing concepts, defined for 2D profilometry, do not always accommodate the needs of 3D surface textures or new types of filter.

An interesting example is the notion of *cut-off*. This term results from using filters that eliminate spatial wavelengths. But certain filters, such as morphological filters and wavelet filters, have nothing to do with the notion of wavelength. Because of this, the term *cut-off* will be replaced by the term *nesting index*.

Rather than talking of spectral content with more or less wavelengths included in waviness depending upon the value of the cut-off, one will talk in the future of sets containing more or less *information* depending upon the value of the nesting index. In the case of a linear filter, the nesting index is equivalent to the cut-off. In the case of a morphological filter, the nesting index will be, for example, the radius of the spherical structuring element.

Even the notions of waviness and roughness must be extended, in particular for 3D surface texture. In the same way that a waviness filter eliminates the smallest wavelengths, an S (for small) filter eliminates information on the smallest scale. Symmetrically, the roughness filter will be replaced by an L filter (for large). Finally, an F filter (for form) eliminates the nominal form.

One also speaks of an *SL surface* to indicate that a surface has been filtered. This surface can be equivalent to a roughness surface if the S filter is equivalent to λs and the L filter to λc.

Equally one speaks of an *SF surface*, which will now be equivalent to the raw surface if the nesting index of the S filter is equivalent to λs. But this could equally correspond to a waviness surface if the nesting index of the S filter is equivalent to λc.

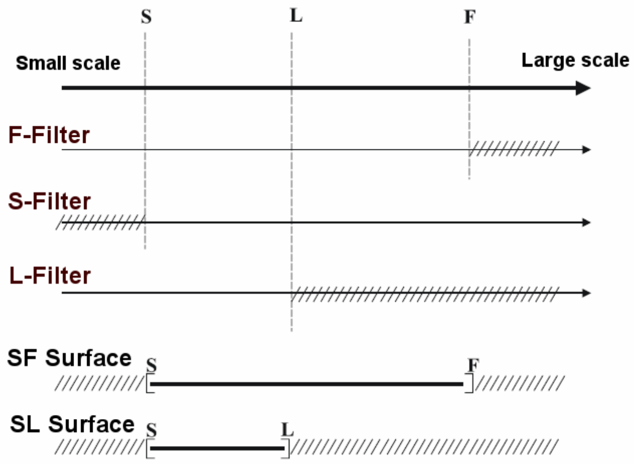

Figure 11: Representation of filters and surfaces as described in the new standard on 3D surface texture.

Contrary to the case for profiles, the cut-off (or nesting index) does not define the size of the sampling surface. All of the parameters are calculated on the whole surface, and if several surfaces are considered, it is possible to average the parameters.

7. Availability of tools for industry

The set of tools defined in the ISO 25178 and ISO 16610 standards must now be made available to the scientific community and industry. MountainsMap® software from Digital Surf `[MNT]` already includes the majority of these tools. Nonetheless, since the standards are still under development, certain parts that have not yet been fixed in the standard will only be available in future versions of the software. Equipped with these tools, users now have the task of trying them out with their own applications and publishing the results.

8. Conclusion

The metrology of surface texture has reached a turning point in its history. For the first time 3D surface textures are taken into account in standards, and will serve as the basis for a far-reaching revision of 2D standards. Numerous new tools are available in a toolbox and each of them provides a specific service depending upon the application. At last non-contact metrology is taken into account thanks, in the first instance, to the description of chromatic confocal sensors and fringe-shift interferometers. Industry will not abandon traditional methods straight away and the transition will take time. But it is the responsibility of metrologists and academics to put these new tools in place and to contribute to the understanding of their advantages for each type of application.

9. Acknowledgements

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10. About the author

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11. References

[BAR97] BARRÉ F., *Contribution de l'analyse d'images à la caractérisation morphologique des surfaces industrielles*, PhD Thesis of University of Saint-Etienne, France, 1997

[BLU03] BLUNT L., XIANGQIAN J., *Advances techniques for assessment surface topography*, Kogan Page Science, 2003, ISBN 1903996112

[RAJ02] RAJA J., MURALIKRISHNAN B., SHENGYU F., *Recent advances in separation of roughness, waviness and form*, J. of Int. Soc. for Precision Engineering and Nanotechnology, 2002.

[SCO97] SCOTT P., *Foundation of topological characterization of surface texture*, Proc. 7th Int. Conf. on metrology and properties of engineering surfaces, Göteborg, 1997

[SEE05] SEEWIG J., *Linear and robust gaussian regression filters*, Proc. Int. Symp. on Meas. tech. and intelligent instruments, 2005

[SRI88] SRINIVASAN V., *Discrete morphological filters for metrology*, Proc. 6th. Symp. on Quality Control in Production, 1988

[STO94] STOUT K. et al., *The development of methods for the characterisation of roughness in three dimensions*, European Report EUR 15178N, 1993, ISBN 0704413132

[WHI94] WHITEHOUSE D. J., *Handbook of surface metrology*, Institute of Physics Publishing, Bristol, 1994, ISBN 0750300396

[499] ISO/TC213-N499 resolution 512 (St Petersburg 14/2002), *decision to create WG16 Areal and Profile Surface Texture*, 2002-06-27

[11562] ISO 11562, *Geometrical Product Specification (GPS) — Surface texture: Profile method — Metrological characteristics of phase correct filters*

[12085] ISO 12085, *Geometrical Product Specification (GPS) — Surface texture: Profile method — Motifs parameters*

[13565] ISO 13565, *Geometrical Product Specification (GPS) — Profile method; surfaces having stratified functional properties – part 1 : filtering and general conditions*

[16610-22] ISO DTS 16610-22, *Geometrical Product Specification (GPS) — Filtration – Linear profile filters: Spline filters*

[16610-31] ISO DTS 16610-31, *Geometrical Product Specification (GPS) — Filtration – Robust profile filters: Gaussian regression filters*

[16610-32] ISO DTS 16610-32, *Geometrical Product Specification (GPS) — Filtration – Robust profile filters: Spline filters*

[16610-49] ISO DTS 16610-49, *Geometrical Product Specification (GPS) — Filtration – Morphological profile filters: Scale space techniques*

[16610-40] ISO DTS 16610-40, *Geometrical Product Specification (GPS) — Filtration – Morphological profile filters: Basic concepts*

[16610-61] ISO WD 16610-61, *Geometrical Product Specification (GPS) — Filtration – Linear areal filters: Gaussian*

[25178-2] ISO CD 25178-2, *Geometrical Product Specification (GPS) – Surface Texture: Areal – Part 2: Terms, definitions and surface texture parameters*

[25178-3] ISO CD 25178-3, *Geometrical Product Specification (GPS) – Surface Texture: Areal – Part 3: Specification Operators*

[MNT] MountainsMap® software from Digital Surf: `www.mountainsmap.com` and `www.digitalsurf.fr`